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Using dune-restricted species to assess the degree of natural diversity of dune systems on Mediterranean tourist coasts

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A R T I C L E I N F O

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A B S T R A C T

Here we focus on an improved floristic understanding of the condition and impacts to coastal dunes along the Catalan coastline of Spain. We identified 21 native dune-restricted plant species that can serve as indicators of the ecological integrity of these coastal dunes, a habitat that has been impacted by both urbanization and tourism. To that end, we employed a new analysis approach that calculated the ratio of the diversity of the dune restricted species to the overall plant diversity of the site. Values of this analysis could range from 0 to 1, with 1 corresponding to the most ecologically intact habitats. Our analyses revealed that regardless of habitat size, sand dunes that lacked significant human activity and that were not adjacent to urbanization had more dune restricted plant species present and so had values closer to "1″. However, larger dune habitats retained a higher number of dune-restricted species despite their proximity to urbanization or levels of tourism, indicating that their larger size provided resilience to negative anthropogenic effects. By first identifying key, dune restricted plant species that should occupy this dune landscape we were able to then provide an independent, objective indicator of the impacts of human activity on this ecologically important habitat.

1. Introduction

Due to the loose, mobile character of their "soils", along with the low levels of organic material, sand dune habitats world-wide are often populated with endemic species which have evolved the ability to tolerate and thrive in those challenging conditions (Maun, 1998). Because of that endemism many dunes are centers of high levels of biodiversity. Due to these characteristics the European Union (E.U.) has included Mediterranean coastal dunes in Council Directive 92/43/EEC on the conservation of wild fauna and flora (European Commission, 1992; European Commission, 2007).

The main controlling drivers for the composition and distribution of coastal plant communities are factors related to temperature, rainfall and wind speed. Edaphic factors refer above all to saline aerosol, pH, texture, organic matter, and nutrients (Wilson and Sykes 1999; Maun 2004; Fenu et al., 2013; Ruocco et al., 2014; Pinna et al., 2015). The numerous adaptations of foredune vegetation to withstand recurrent burial, particularly the stimulation of growth provides them with a competitive advantage to survive in these conditions (Maun, 1998). Negative impacts on dune ecosystems are the result of human activity, such as the high number of people on beaches, coastal urbanization, trampling, pollution, and the spread of invasive species (Honrado et al., 2010; Fois et al., 2016). Most of these factors vary along a coast-inland gradient that hosts distinct zones, each characterized by typical species and plant communities (Doing, 1985; Sýkora et al., 2006; Lane et al., 2008; Isermann, 2011).

Previous studies have shown that dune systems that remain in little disturbed natural environments present patches with elongated and irregular shapes (Carboni et al., 2009). Thus, the different habitats share extensive borders, a fact that helps maintain high biodiversity (Acosta et al., 2009). On the contrary, on the most disturbed systems patches have more compact and regular shapes. Species richness has also been shown to be sensitive to variables related to the spatial pattern, such as the area and width of the dune system (Malavasi et al., 2013).

Nevertheless, dune habitats are in decline across the whole of Europe (European Commission, 2008), and the biodiversity of even the most protected dune systems is severely threatened (Cori, 1999; La Posta et al., 2008). In fact, almost 70 % of European dune systems have disappeared over the past century. This is particularly the case along the Mediterranean coast, and is the result of coastal development and its

Abbreviations: Lenght:, m, km; Surface:, ha., m^2.

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Fig. 1. Examples of urban beaches: A) Creixell Mar, with only a narrow dune ridge trapped between the beah and a promenade. B) Pals, with a wider dune system. And non-urban beaches: C) els Muntanyans, with a transition zone to salt marshes. D) Riumar, a complex dune system with several dune ridges.

associated factors (Van der Meulen and Salman, 1996; McLachlan and Brown, 2006; Garcia-Lozano et al., 2018).

Most of the dune systems on the Mediterranean tourist coasts are narrow, with just a single foredune, so vegetation zonation is usually very compressed (Feola et al., 2011) (Fig. 1).

On some beaches far from urban centers it is still possible to observe a wide range of dune morphologies and habitats. From the sea inland the following habitats can be observed: the backshore of the beach, embryonic dunes, shifting dunes and semi-fixed and fixed dunes (European Commission, 2008; Vigo et al., 2008).

On urban and suburban beaches, the remaining dunes are limited inland by buildings, boardwalks, or various communication infrastructures. The dunes on these beaches consist of small ridges and shallow blankets of sand where the habitats are altered and intertwined with each other, but nevertheless retain a good number of the psammophyllous species characteristic of dune habitats (Fig. 2).

However, the dunes are on beaches that welcome a large number of tourists in summer. Coastal urbanization, trampling, pollution, and the spread of invasive species are threats to the conservation of the morphology of the dunes, as well as of the most susceptible species and communities (Honrado et al., 2010; Fois et al., 2016).

These impacts mainly affect species that have their exclusive habitat in the dunes. However, little information exists on which species should be considered typical of the dunes. Therefore, one objective of this work is to clarify this aspect.

We have considered as typical species of the dunes those plants that have their exclusive habitat in them. In other words, species that are not found in habitats other than dunes. We have named these species as dune-restricted species and developed a procedure to identify them. The more dune-restricted species are in a dune system, the greater its degree of conservation is.

Then, the dune-restricted species have been used to calculate a new D_{ex} index that evaluates the conservation status of dune systems. The results of this index have been compared with those obtained with the Grunnewald & Schaubert natural diversity index N, which uses a modification of Shannon's H' diversity index for its calculation (Grunewald and Schubert, 2007).

Taking into account the above, this work sets out to evaluate the influence of different levels of human pressure on biodiversity, differentiating between dune systems located in urban environments (URB) and those located in natural or agricultural environments (*N*-URB). Based on our field data we examined the species richness of dune systems accounting for the entire pool of plants and for three appropriate species guilds (dune-restricted species, non-dune coastal habitats, and Mediterranean xerophytic species). In addition, the influence of some landscape metrics (area, width, shape index) on the biodiversity of dunes has also been evaluated.

Specifically, the aim is to answer the following questions:

- What richness of flora are retained by the dunes on the tourist coasts?
- How do spatial pattern variables such as surface area, width and shape index, of urban and non urban dune systems affect the degree of natural diversity?
- What differences are there between urban beach dunes and non urban beach dunes in terms of plant diversity?
- Can we use the dune-restricted species guild as genuine dune-typical species, and therefore assess the conservation status of dune habitats by calculating D_{ex}?

1.1. Study area

Located in the northeast of the Iberian Peninsula, the Catalan coast is one of the major coastal areas for tourism in the north-western Mediterranean. Its coastline of approximately 650 km stretches from Cap de Creus to the Ebro Delta, and features a wide variety of coastal morphologies, including cliffs, coves, large bays, and long straight beaches of mainly medium and fine sands.

The area has hot and dry summers with wet, cool winters almost without frost. Mean monthly temperatures vary between 8 and 10 °C

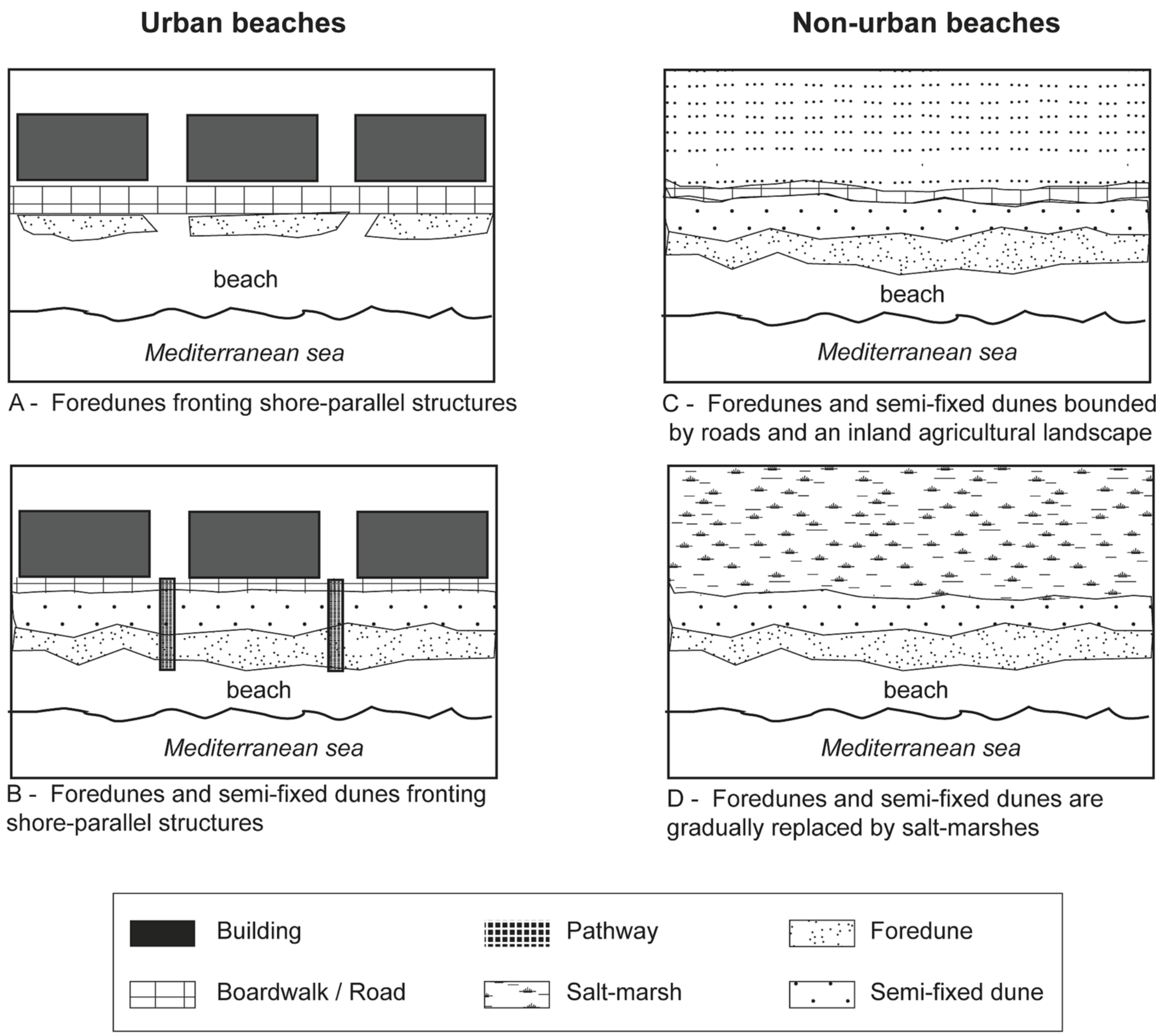

Fig. 2. Schemes of the different types of urban and non-urban dunes that have been studied in this work.

Table 1
Habitats surveyed and relationships with Natura 2000 code and phytosociological associations according to Vigo et al., (2008).

Natura 2000 code	Habitat	Phytosociological association
1210	Annual vegetation on drift lines	*Salsolo-Cakiletum aegyptiacae* Costa et Mansanet 1981
2110	Embryonic shifting dunes	*Cypero mucronati-Agropyretum juncei* Kühnholtz-Lordat et Br.-Bl. 1933
2120	Shifting dunes along the shoreline with *Ammophila arenaria*	*Ammophiletum arundinaceae* Br.-Bl. (1921) 1933
2210	*Crucianellion maritimae* fixed beach dunes	*Crucianelletum maritimae* Br.-Bl. (1931) 1933
2230	*Malcolmietalia* dune grasslands	*Desmazerio marinae-Medicaginetum inermis* Curcó 1990
2190	Dune-slack reedbeds, sedgebeds and canebeds	*Eriantho-Holoschoenetum australis* O. Bolòs 1962
1410	Mediterranean salt meadows (*Juncetalia maritimi*)	*Schoeno-Plantaginetum crassifoliae* Br.-Bl. 1931

(January) and 23–25 °C (July). Mean annual rainfall is 475–600 mm (SMC, 2022).

The main pressures exerted on beaches result from the combination of natural and societal factors. The Catalan coast can be considered as an eroding coast, due to the fact that about 70 % of beaches have been retreating over the last decades (Jiménez et al., 2017). One of the causes of this is the proliferation of marinas, harbours and ports over recent years, which interfere with longshore drift. There are currently 45 commercial, fishing and recreational ports on the coast, a ratio of 1 port for every 14.4 km of coastline. The coastal zone also suffers from high demographic pressure as the 70 municipalities located on the Catalan coast concentrate 43.3 % of the population of Catalonia in just 6.7 % of its surface area (Institut d'Estadística de Catalunya 2016).

The economy of the Catalan coastal zone is based on tourism, commerce and residential development (Sardá et al., 2005). Tourism is one of the main economic activities, providing about 11 % of GDP. The coast was the most popular destination for decades, nowadays only superseded by the city of Barcelona.

Low-lying sandy coast of alluvial flatland and deltas occupies almost 60 % of the total. The coast has over 800 beaches of different sizes, coves and small bathing spots, and 110 of them support some kind of dune-system, but most are limited in size and can be classified as simple dune crests or foredunes (Garcia-Lozano and Pintó, 2018), and many of them are in erosion stages 4 or 5, as established by Hesp (2002) in his foredune type model. The coastal flatlands are, however, heavily urbanized. Prior to the massive development of the coastline, the sandy coast was home to a number of habitats. From the coast-inland, these comprised sandy beaches, dune systems, old spits, wetland with lakes, and then agricultural land. But the rise in tourism and construction has resulted in great changes to its dune landscape. From the mid-20th century to the present day, 60 % of the existing dunes have

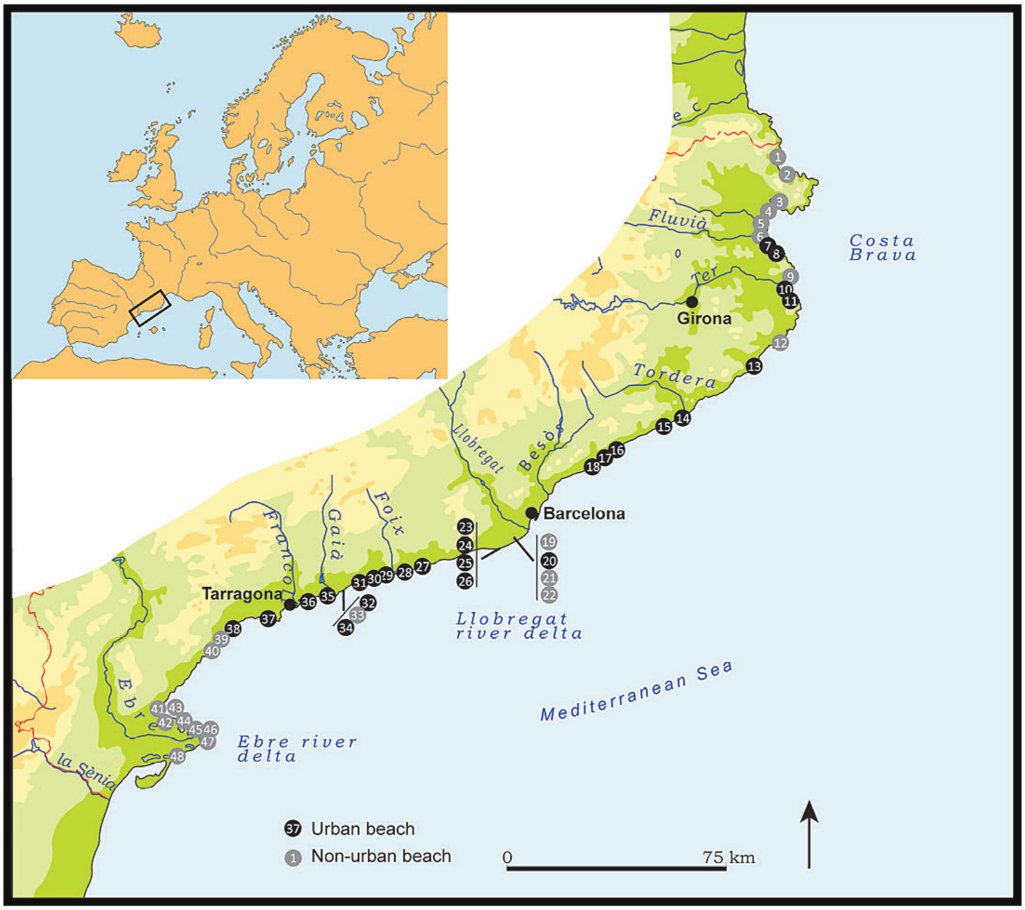

Fig. 3. Coastal dunes considered in this study: 1: Garbet; 2: Borró; 3: la Rovina: 4: can Comes; 5: can Martinet; 6: cal Cristià; 7: Cortal de la Devesa; 8: Empúries; 9: la Pletera; 10: la Fonollera; 11: Pals; 12: Castell; 13: Sant Pol; 14: Malgrat de Mar; 15: Cavaió; 16: Mataró; 17: Vilassar de Mar; 18: Premià de Mar; 19: Carrabiners; 20: el Prat e Llobregat; 21: el Remolar; 22: la Pineda; 23: Gava nord; 24: Castelldefels; 25: Covafumada; 26: Ginesta; 27: Llarga de Vilanova i la Geltrú; 28: Cubelles; 29: el Francàs; 30: Llarga de Berà; 31: Creixell Mar; 32: Creixell Antines; 33: els Muntanyans; 34: la Paella; 35: Tamarit; 36: Llarga de Tarragona; 37: Llarga de Salou; 38: l'Arenal; 39: el Torn; 40: cala Ronyosa; 41: Arenal de l'Ampolla; 42: el Goleró; 43: el Fangar; 44: la Marquesa; 45:Bassa de l'Arena; 46: casa dels Prats; 47: Riumar; 48: l'Aluet.

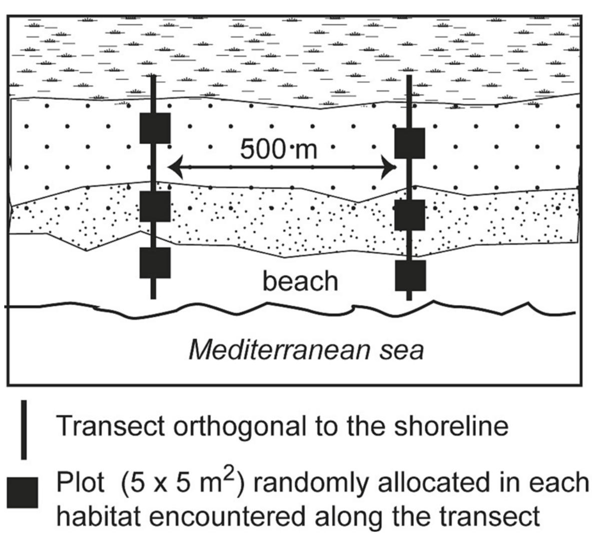

Fig. 4. Scheme of the sampling method used in each dune system.

disappeared, and nearly 30 % have declined in area (Pintó and Garcia-Lozano, 2016). The protection of dune systems began very late, at the end of the 1990 s, when in many cases the dunes were in states of considerable degradation, and it has mainly consisted of rope boundary fences and educational signs (Garcia-Lozano et al., 2018).

The present study concentrates on recent dunes which in natural conditions are relatively low, <8 m in height, and simple in structure only one dune ridge. In the best conserved sites, dune systems are characterized by the presence of a range of habitats: upper beach or drift line, foredunes (embryo and main dune), semi-fixed dunes and transition dunes to salt marshes. These habitats follow a coast-inland gradient, but are usually in a complex mosaic pattern (Table 1).

2. Methods

We selected 48 representative dune systems on the Catalan coast and

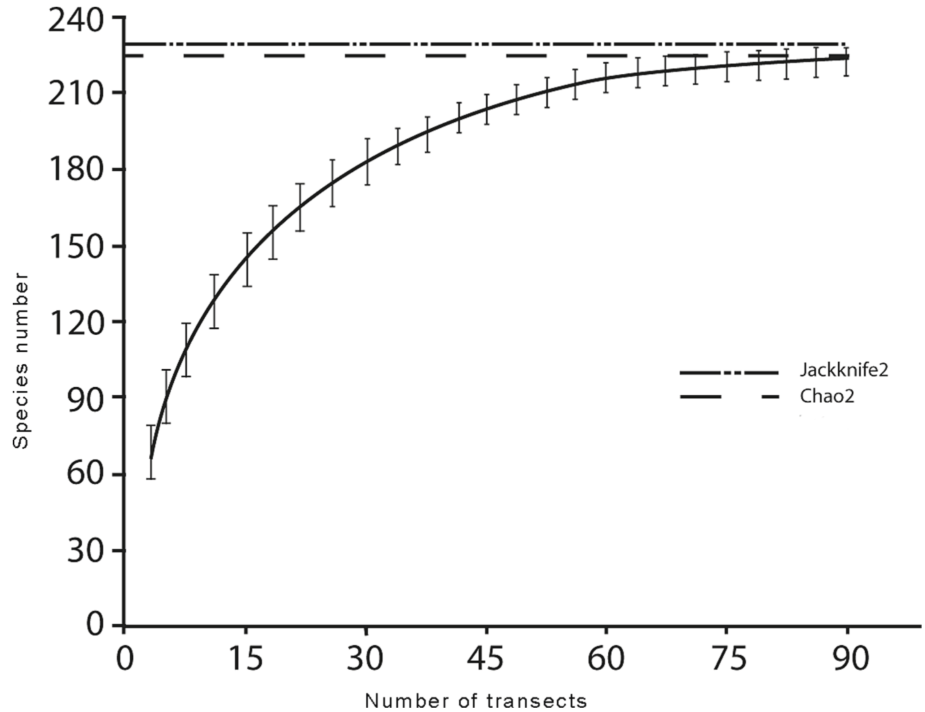

Fig. 5. Species accumulation curve of dune plant species richness $\hat{S}_{MaoTao}$ (95 % CI).

grouped them into two major categories according to whether they are in urban / suburban locations (URB) or non-urbanized locations (*N*-URB). The URB sites (26) are located on highly developed coastal tracks, and the dune system in these locations are on urban or suburban beaches or next to campsites. These kinds of beaches host thousands of people in the summer and are therefore subjected to high amount of human pressure. On the other hand, the *N*-URB sites (22) are located far from cities and towns, with natural beaches and a lower amount of human pressure (Fig. 3).

2.1. Species sampling and plant guilds

The data regarding the plant species that colonize these dune systems was compiled during the spring, summer and autumn seasons of 2018–2021, using a random stratified sampling design.

The 48 selected dune systems were classified into three groups according their surface area, giving rise to the following distribution: 11 under 1 ha.; 19 between 1 and 5 has. and 18 over 5 has.

In each dune system, transects orthogonal to the shoreline, 500 m apart, were randomly established. The total number of transects was 83. The transects stretched from the annual vegetation on the drift line to the inland limit of the dune system: embryo dunes, mobile dunes, semi-fixed dunes, and transition dunes to the beginning of saltmarshes or crops, where those exist, were sampled. Transects length ranged from 5.1 to 103.2 m, depending on dune morphology and width. Qualitative and quantitative sampling were performed of the plant species in each transect. On the one hand, the species present along the whole transect were recorded. For each type of dune habitat encountered along the transect a plot of 5 m × 5 m (25 m^2) was randomly established. In each sampling plot, a list of the plant species presence and coverage was taken. A total of 323 plots were extracted, scattered within the dune systems of the two types of site: 130 URB plots and 193 *N*-URB plots (Fig. 4).

We only included species that were found at >10 % and <90 % of our sampling sites in order to identify what guilds of plants, in terms of their habitat preferences, colonize the dunes. According to Chase et al., (2000) the species found in fewer samples are likely to be accidental species and not at all characteristics of dune habitats, while the species found in almost all samples cannot represent within-habitat variation in richness and floristic composition, derived from human disturbances.

The habitat preferences of the species recorded was verified using our expert knowledge about Catalan flora and the information contained in the Biodiversity Data Bank of Catalonia (Font, 2018). This database contains the computerization of all the available citations of the species found in the Catalan territory. Containing details on the locations of their observations, which are displayed on a map, as well as the ecological traits of the ecosystems where they thrive. This procedure allowed us to identify a guild of species that only grow on dunes, the dune-restricted species, and three other guilds (non-dune coastal habitat, Mediterranean xerophytes and alien species).

2.2. Diversity indices

We used *N* index to assess the degree of natural diversity per site according with Grunewald and Schubert (2007). With this index, Grunnewald and Schubert intended to discriminate between those species typical of dunes and those that find their ecological optimum in habitats other than dunes. However, in some works alien species have been used instead of “non-dune” species (Attorre et al., 2013; Ciccarelli, 2014; Pinna et al., 2019). Due to this misunderstanding most sites have high *N* values in the literature, due to the fact that they usually have few alien species. This means that an adequate assessment of the degree of natural diversity is not carried out when alien species are taken instead of species not typical of the dunes. So by “species typical of the dunes” we have interpreted the dune-restricted species, that is, those species that have their exclusive habitat on dune systems. Then we have proceed to calculate the *N* index as follows:

$$NH'_{dune-restricted\ species}/H'_{dune}$$

The *N* index ranges from 0 to 1, where 0 indicates that the plant diversity is composed exclusively of non dune-restricted species, and 1 denotes all species in the plant community are dune-restricted.

Previously, the calculation of H'_{dune} is needed:

Table 2
Dune-restricted species identified on the Catalan coast.

Dune-restricted species	Protected	Range	EU Habitat Code			
			1210	2110	2120	2210
Ammophila arenaria subsp. *arundinacea*		Med/Atl		**	***	
Cakile maritima subsp. *maritima*		Med/Atl	**	***	***	
Calystegia soldanella	3, 4	Med/Atl		**	**	
Crucianella maritima		Med/SAtl		*	**	**
Cutandia maritima		Med/SAtl		**	***	*
Cyperus capitatus		Med			*	**
Echinophora spinosa		WMed		**	***	**
Eryngium maritimum		Med/Atl		**	**	*
Euphorbia paralias		Med/Atl		**	**	
Matthiola sinuata subsp. *sinuata*		Med/SAtl		*	**	
Medicago marina		Med/SAtl		***	***	**
Ononis ramosissima		WMed			*	**
Pancratium maritimum	3, 4	Med/SAtl		**	***	**
Polygonum maritimum		Med/SAtl	*	**		
Pseudorlaya pumila		Med		*	*	*
Rostraria litorea		WMed				*
Silene nicaeensis		Med		**	***	**
Sporobolus pungens		Med/SAtl		**	**	**
Teucrium dunense		WMed				**
Thinopyrum junceum		Med/Atl	*	***	***	**
Vulpia fasciculata		Med/Atl			**	**

Protected: Sites in which the species has a protected status. Range: Geographic distribution of each species on European coasts from Gbif data base. EU Habitat Code: see Table 1 for habitat descriptions. Asterisks indicate the degree of abundance of each species in the indicated habitats, according their presence in the plots surveyed: * (10–25 %); ** (25–50 %); *** (>50 %).

Table 3
Non-dune coastal habitats guild.

Non-dune coastal species	Range	EU Habitat Code			
		1210	2110	2120	2210
Artemisia gallica	WMed				*
Atriplex halimus	Plurireg.		*	*	
Crithmum maritimum	Plurireg.		**		
Halimione portulacoides	Plurireg.		*	*	
Inula crithmoides	Plurireg.				*
Juncus acutus	Med/Atl				*
Juncus maritimus	Plurireg.				*
Panicum repens	Paleotrop.				**
Phragmites australis	Plurireg.	*	*	*	**
Plantago coronopus	Plurireg.				*
Plantago crassifolia	Med				**
Salsola kali subsp. *ruthenica*	Med	***	*	*	
Sarcocornia fruticosa	Med	*			*
Scirpoides holoschoenus	Med				**
Suaeda maritima	Plurireg.				*
Tamarix canariensis	WMed	*	*		

Range: Geographic distribution of each species on European coasts from Gbif data base. EU Habitat Code: see Table 1 for habitat descriptions. Asterisks indicate the degree of abundance of each species in the indicated habitats, according their presence in the plots surveyed: * (10–25 %); ** (25–50 %); *** (>50 %).

Table 4
Alien species guild.

Alien species	Range	EU Habitat Code			
		1210	2110	2120	2210
Arctotheca calendula	S Africa		*	*	
Carpobrotus edulis	S Africa		*	*	
Cenchrus spinifex	Neotrop.				*
Erigeron canadensis	N America				*
Lotus creticus	S Med		*	*	
Oenothera biennis	N America				*
Spartina patens	N America				*
Tribulus terrestris	Plurireg.				*
Xanthium orientale	America	*	*		

Range: Geographic distribution of each species on European coasts from Gbif data base. EU Habitat Code: see Table 1 for habitat descriptions. Asterisks indicate the degree of abundance of each species in the indicated habitats, according their presence in the plots surveyed: * (10–25 %); ** (25–50 %); *** (>50 %).

Table 5
Mediterranean and multiregional xerophytes guild.

Mediterranean xerophytes	Range	EU Habitat Code			
		1210	2110	2120	2210
Asphodelus fistulosus	Med			*	**
Bromus diandrus	Med.				*
Centaurea aspera	WMed			*	**
Cynanchum acutum	Med/Iran			*	*
Cynodon dactylon	Plurireg.	*	*		*
Dittrichia viscosa	Med				*
Euphorbia terracina	Med		*	**	*
Glaucium flavum	Plurireg.	*	*		
Helichrysum stoechas	Med			*	***
Lagurus ovatus	Med			**	**
Lobularia maritima	Med		***	**	
Medicago littoralis	Med			*	**
Parapholis incurva	Med/Atl				*
Paronychia argentea	Med				**
Pinus halepensis	Med				*
Pistacia lentiscus	Med				*
Plantago lagopus	Med				*
Portulaca oleracea	Plurireg.				*
Reichardia picroides	Med				*
Scabiosa atropurpurea	Med				***
Scolymus hispanicus	Med				*
Sedum sediforme	Med				*
Sonchus bulbosus	Med		*	**	
Sonchus tenerrimus	Med				*
Thymelaea hirsuta	Med				**

Range: Geographic distribution of each species on European coasts from Gbif data base. EU Habitat Code: see Table 1 for habitat descriptions. Asterisks indicate the degree of abundance of each species in the indicated habitats, according their presence in the plots surveyed: * (10–25 %); ** (25–50 %); *** (>50 %).

$$H'_{dune} = -\Sigma p_i * \ln p_i$$

where p_i = % cover of the i^{th} plant species.

H'_{dune} is the Shannon's index of diversity modified by Grunewald and Schubert (2007) to measure and compare plant diversity between perturbed and non perturbed plant communities on dune systems. It is based on the coverage of each species rather than the number of individuals. The H'_{dune} value rises as the diversity in the plant community increases.

In addition, to calculate the degree of presence and the contribution of the dune restricted species in the species richness of the plant community of each site, a new index D_{ex} was introduced according to the formula:

$$D_{ex} = S_{dune-restricted\ species}/S_{\max}$$

Table 6
Area (ha), Shape Index (SI), Species Richness (SR) and number of dune-restricted species (DRS) for each dune system considered in this study.

Urban Sites	Area	SI	SR	DRS	*N*-Urban Sites	Area	SI	SR	DRS
7	3.54	5.82	46	16	1	0.31	1.52	31	8
8	4.01	1.49	33	17	2	0.56	1.52	45	13
10	13.82	3.34	62	20	3	13.9	3.66	45	19
11	13.9	5.29	60	19	4	5.7	11.34	41	16
13	0.38	2.32	12	10	5	6.16	4.55	23	7
14	7.35	3.29	26	5	6	2.51	3.57	42	16
15	0.46	1.19	14	1	9	5.89	5.75	31	13
16	2.2	2.14	19	4	12	0.36	1.77	33	15
17	0.99	4.81	22	7	19	3.07	4.53	46	14
18	1.1	1.55	18	4	21	6.3	1.83	46	17
20	14.6	3.04	62	17	22	9.9	3.06	54	19
23	2.5	4.49	60	19	33	11.85	4.30	58	20
24	5.1	4.12	45	16	39	1.86	5.75	46	16
25	8.37	3.28	52	16	40	0.126	1.99	15	9
26	0.26	1.99	22	6	41	4.73	3.96	73	11
27	2.11	2.65	41	9	42	6.01	3.11	18	3
28	2.59	3.99	37	5	43	15.25	4.72	26	9
29	0.08	4.60	10	7	44	5.7	3.7	17	7
30	1.37	3.03	24	12	45	2.77	5.41	32	5
31	1.47	4.53	28	14	46	5.15	4.98	31	4
32	1.78	3.48	43	15	47	41.27	5.44	59	15
34	0.33	1.15	13	7	48	1.35	3.75	31	9
35	2.08	3.79	24	11					
36	3.58	7.83	46	20					
37	0.57	2.19	23	4					
38	3.59	4.09	63	18					

Urban sites. 7: Cortal de la Devesa; 8: Empúries; 10: la Fonollera; 11: Pals; 13: Sant Pol; 14: Malgrat de Mar; 15: el Cavaió; 16: Mataró; 17: Vilassar de Mar; 18: Premià de Mar; 20: el Prat de Llobregat; 23: Gavà nord; 24: Castelldefels; 25: Covafumada; 26: Ginesta; 27: Llarga de Vilanova i la Geltrú; 28: Cubelles; 29: el Francàs; 30: Llarga de Berà; 31: Creixell Mar; 32 Creixell Antines; 34: la Paella; 35: Tamarit; 36: Llarga de Tarragona; 37: Llarga de Salou; 38: Arenal de l'Hospitalet de l'Infant.
Non-urban sites: 1: Garbet; 2: Borró; 3: la Rovina; 4: can Comes; 5: el Martinet; 6: cal Cristià; 9: la Pletera; 12: Castell; 19: Carrabiners; 21: el Remolar; 22: la Pineda; 33: els Muntanyans; 39: el Torn; 40: cala Ronyosa; 41: l'Arenal de l'Ampolla; 42: el Goleró; 43: el Fangar; 44: la Marquesa; 45:Bassa de l'Arena; 46: Casa dels Prats; 47: Riumar; 48: l'Aluet.

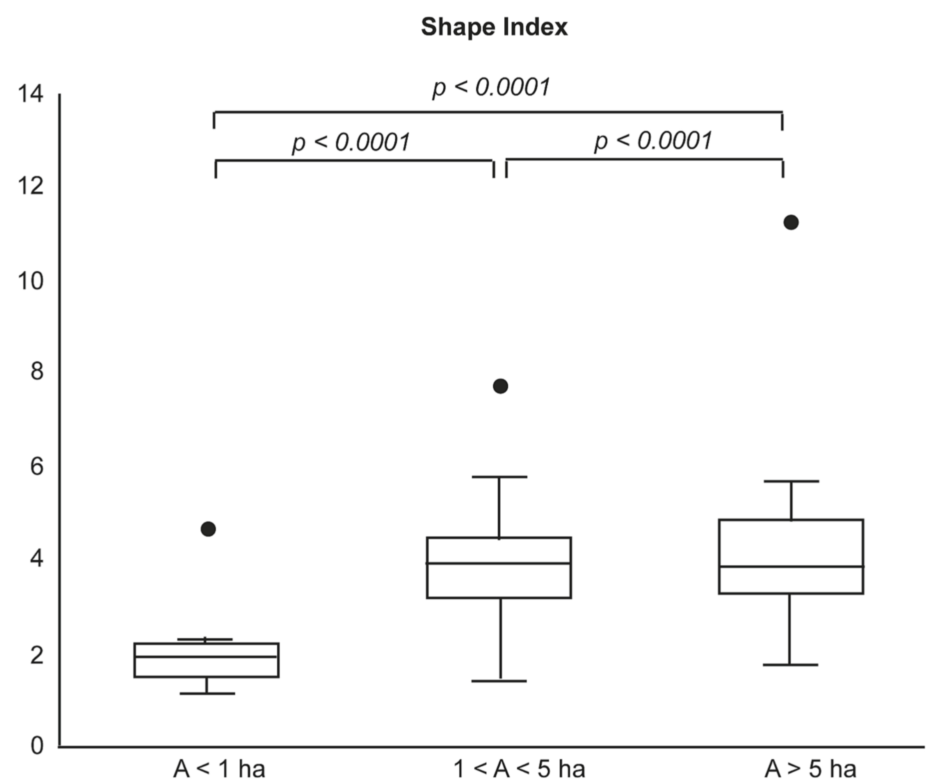

Fig. 6. Distribution of Shape index for the three types of dune area according to the non-parametric two-tailed Kruskal-Wallis test.

Where $S_{\text{dune-restricted species}}$ is the number of dune restricted species taxa reported in a site and $S_{\max}$ is the maximum possible value of dune restricted species taxa on that coast. The value of D_{ex} ranges from 0 when there are no dune restricted species in the dune system to 1 when all possible dune restricted species are present in the site. This index

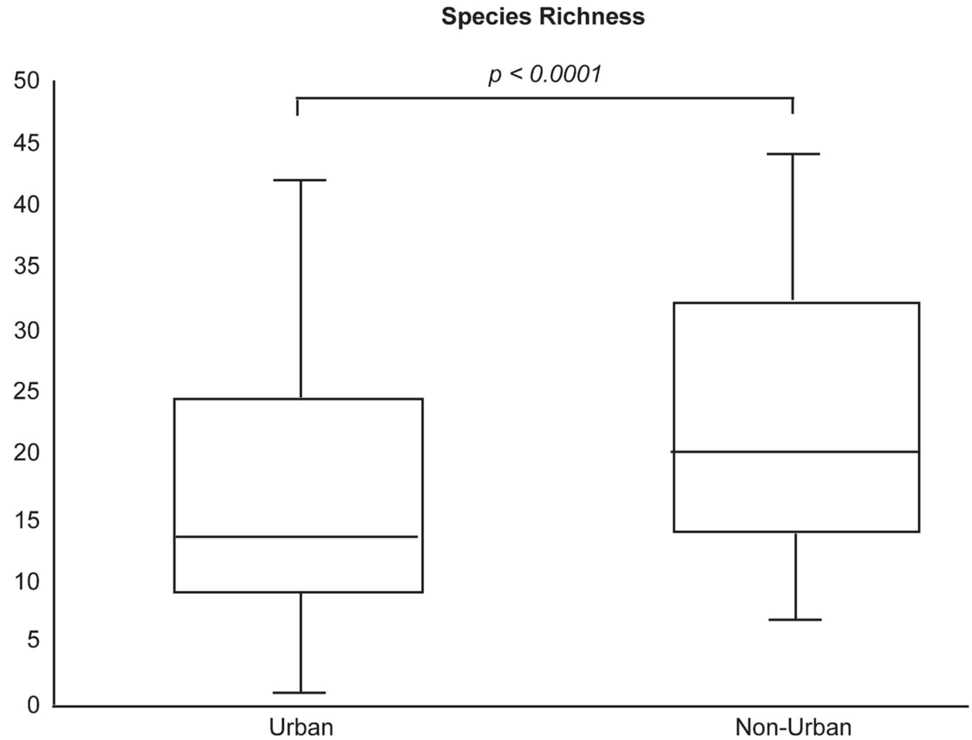

Fig. 7. Comparison of species richness between Urban and Non-Urban sites applying the Mann-Whitney *U* test.

underline the dune-restricted species as a bioindicators of the sound conservation status of a dune system.

2.3. Spatial pattern analysis

As indicated in the introduction section, certain characteristic variables of the spatial pattern exert great influence on biodiversity. In our case we have tested whether the area, the width and the shape index influence the biodiversity of dune systems located in urban and non-urban environments.

To do that, we previously mapped the dune systems on the Catalan coast. The maps were derived from panchromatic digital aerial orthophotographs with a resolution of around 0.5 m and interpreted on screen in a geographic information system environment (QGis). Doubtful systems identified on the screen were verified on their real existence and their limits in the field work.

The polygons obtained in the cartography of the 48 dune systems were considered as patches. For each patch a set of metrics was calculated capable of describing the basic characteristics of the spatial pattern. Thus, patch size and shape index were calculated. These two parameters have been shown to be useful for describing the landscape mosaic. The former is a good indicator for calculating the effects of disturbances induced by human action in the habitats. Thus, the smaller the patch size, the greater the fragmentation of the dune landscape. Shape index, on the other hand, allows for discrimination between elongated patches and compact ones. Elongated and irregular shaped patches are characteristic of undisturbed dune landscapes while compact shapes predominate in degraded and fragmented dune landscapes, sometimes originating from restoration processes (Ciccarelli and Baccaro, 2016).

Area (A) and perimeter (P) were calculated through analysis of maps in QGis. The shape index (SI) indicates the patch shape complexity and was calculated as $SI = P/[2 \times (\pi \times A)^{0.5}]$. SI is 1 when a patch is a perfect circle and increases as the shape becomes more irregular and complex.

With the objective of evaluating if the spatial pattern exerts any influence on the composition of the plant guilds, significant differences in the number of species belonging to each guild in relation to the area of the dune systems were checked.

The average length of the transects perpendicular to the dune system used for data collection was also taken as a variable to correlate with the number of species found. The longer the transect length, the more likely there will be an increase in the diversity of the habitat, and therefore the number of species (Gaston, 1996).

2.4. Statistical analysis

As a result of the sampling, we obtained two types of data. On the one hand, an estimate of the floristic richness from the presence of the species found along the transects and in the plots established in the dune habitats.

These data were used to obtain the floristic richness (SR) and the number of dune-restricted species (DRS) present in each dune system.

On the other hand, the values of H'_{dune} and $H'_{\text{dune-restricted species}}$ were calculated for each plot established along the transect. The value of both *H’* indices for the whole dune system was obtained as the mean value of all plots. And then the value of the index *N* was achieved.

To estimate the total species richness in the set of dune systems analysed, we developed the rarefaction curve using the software EstimateS v. 9.1.0 (Colwell, 2013). The $\hat{S}_{\text{MaoTao}}$ was calculated for a confidence interval of 95 % in order to see whether the overall estimate of species approximated the total number of species recorded. Richness values were obtained through the overall simple-based rarefaction curve ($\hat{S}_{\text{MaoTao}}$), and compared with the two estimators of total species richness, Chao2 (Chao, 1987) and Jacknife2 (Colwell and Coddington, 1994), which have proven to be accurate in estimating true species richness.

A one-way analysis of variance (ANOVA) was used to test for significant differences in some variables (patch size, shape index, transect length and plant species guilds) among URB and *N*-URB sites, in order to verify the influence of disturbances induced by human action on the selected variables.

The Mann-Whitney *U* test was used to assess the significance of *N*

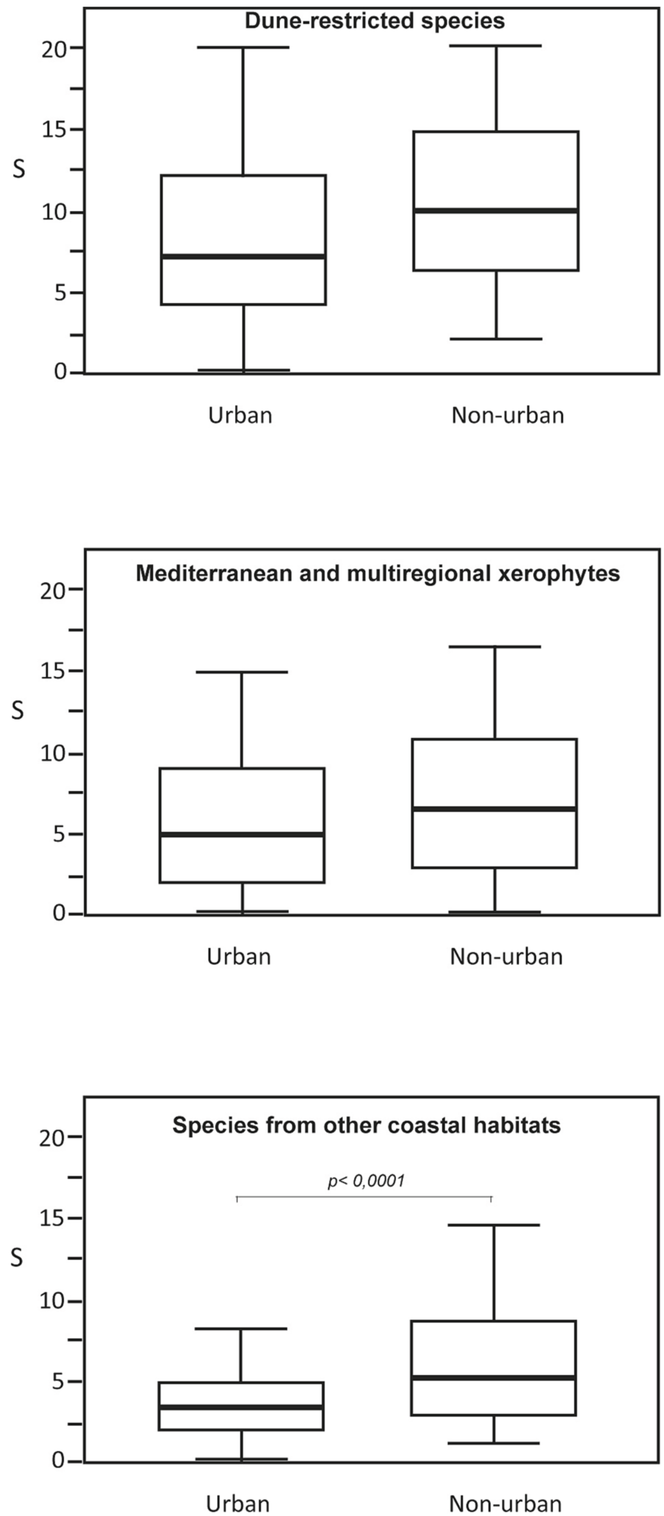

Fig. 8. Comparison of the presence of guild's species between Urban and Non-urban dune systems. Significant differences were found only for the Other Coastal Habitats guild.

index values on URB and *N*-URB systems, while the Kruskal-Wallis *H* test was used to evaluate the behaviour of the same index between dune systems classified into three types according to their surface area.

Tests related to the spatial pattern variables were performed using the statistical package SPSS Statistics 25, whereas Mann-Whitney and Kruskal-Wallis tests were calculated using the statistical package XLSTATS 2018.

3. Results

3.1. Plant guilds

Overall, 224 vascular plant species corresponding to 56 families and 179 genera were recorded (the complete floristic list is reported in Supplementary data 1). The families with greatest species richness were Graminae (38), Compositae (32), and Chenopodiaceae (16). The most widespread species were: *Thinopyrum junceum*, *Eryngium maritimum*, *Salsola kali*, *Cynodon dactylon*, *Medicago marina*, *Silene nicaensis*, *Pancratium maritimum*, *Medicago littoralis*, *Lagurus ovatus*, *Lobularia maritima*, *Cakile maritima*, *Scabiosa atropurpurea*, *Sporobolus pungens*, *Calystegia soldanella* and *Echinophora spinosa*, all of which were present in over 80 % of the systems sampled.

Fig. 5 shows the global rarefaction curve based on the $\hat{S}_{MaoTao}$ statistic. The curve is practically asymptotic and the two estimators of total species richness, Chao2 and Jackknife2, yielded respective values of 226 and 229 species, figures very close to the 224 species recorded.

Having applied the criterion of focusing on the species recorded at >10 % and <90 % of our sampling sites, 71 species remained as most typical of these dune habitats (Supplementary data 2). The analysis of the geographical distribution of these 71 species produced a group of 21 species (29.6 %) exclusive to dune habitats (Table 2). These 21 plants are specialist indicator species that characterize dune communities and some of them are rare. Being sensitive to human disturbances and habitat modifications, their absence can be interpreted as a signal about the loss or degradation of dune habitats (Santoro et al., 2012). These plant species are widely distributed and found along the entire coast; they were therefore used to calculate both the *N* index and the D_{ex} index.

Another species guild comprised of 16 plant species (22.5%) that have optimum habitats in other neighbouring coastal environments, such as rocky coasts, wetlands and salt flats. Some examples of plants species that belong to this guild were: *Artemisia gallica*, *Atriplex halimus*, *Juncus acutus* and *Sarcocornia fruticosa* (Table 3). The guild of alien comprised 9 plant species (12.7%) (Table 4). The most frequent of which were: *Xanthium orientale*, *Carpobrotus edulis* and *Conyza canadensis*. Finally, the Mediterranean and multiregional xerophytes guild, proper of dry ecosystems, which have optimum habitats are others than dunes, comprised 25 plant species (35.2%) (Table 5). *Cynodon dactylon*, *Helichrysum stoechas*, *Lobularia maritima*, *Asphodelus fistulosus*, *Sonchus tenerrimus* and *Centaurea aspera* were some examples of plants belonging to that guild.

3.2. Spatial pattern

The values and the range of variation of the spatial metrics no showed clear differences between urban and non-urban sites (Table 6). The patches of non-urban systems differed from those of systems located in urban environments, in the sense that they were more elongated, so that the mean values for patches on the non-urban sites being significantly larger ($\overline{X} = 6.9$). However, some urban systems located on long sandy beaches and limited inland by campsites and buildings have elongated shapes and also showed high values in terms of their area. The Shape Index (SI) values, on the other hand, did show significant differences between the three categories of dune systems according to their size, with the SI values being lower in the smaller surface systems ($\overline{X} = 2.28$) while in the larger systems were higher ($\overline{X} = 4.38$) (Fig. 6).

The floristic composition differed between each type of dune system. The dune systems on urban (URB) sites showed a significant lower species richness than those on non-urban (*N*-URB) sites ($F = 4.735$ and $p < 0.05$) (Fig. 7).

Next, we analyse the influence of human pressure on the richness of species belonging to each of the identified plant guilds. A higher presence of species from the coastal habitats guild was observed in the dune systems located in non-urban sites ($F = 20.872$ and $p < 0.0001$), but no

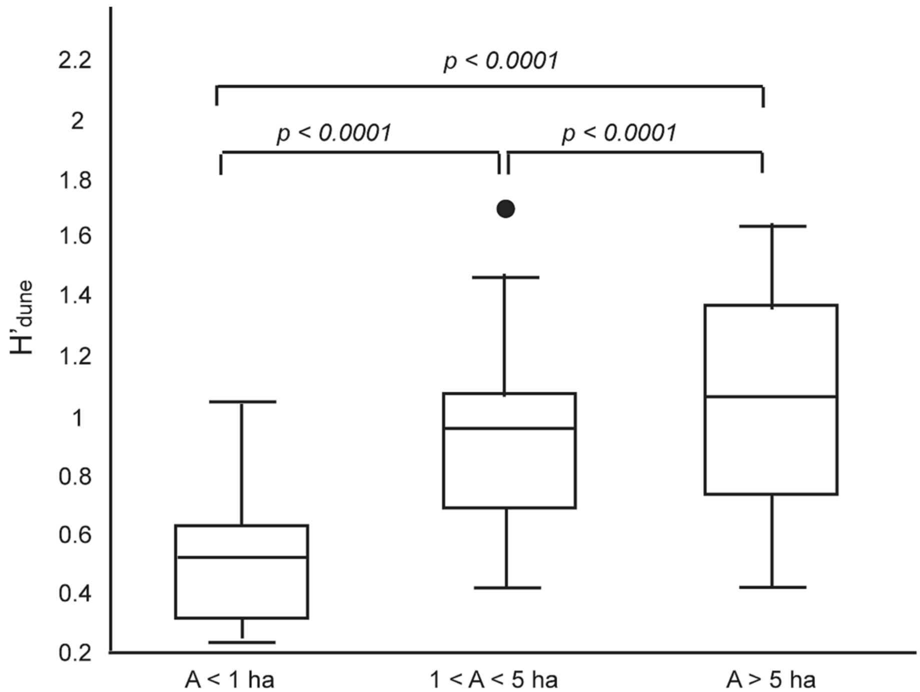

Fig. 9. Distribution of H'dune values for the three types of dune area according to the non-parametric two-tailed Kruskal-Wallis test.

Table 7
Values of the indices $H'_{dune\text{-}restricted\ species}$, H'_{dune}, N and D_{ex}.

Urban Sites	$H'_{dune\text{-}restricted}$	H'_{dune}	N	Dex	N-Urban Sites	$H'_{dune\text{-}restricted}$	H'_{dune}	N	Dex
7	0.710	1.065	0.567	0.762	1	0.219	0.718	0.306	0.381
8	0.425	0.764	0.556	0.809	2	0.724	1.042	0.694	0.619
10	1.197	1.436	0.833	0.952	3	0.753	1.042	0.722	0.905
11	0.926	1.390	0.667	0.905	4	0.659	0.950	0.694	0.762
13	0.077	0.278	0.278	0.476	5	0.237	0.533	0.444	0.333
14	0.139	0.624	0.222	0.238	6	0.730	0.973	0.750	0.762
15	0.036	0.324	0.111	0.048	9	0.399	0.718	0.556	0.619
16	0.086	0.440	0.192	0.190	12	0.361	0.764	0.472	0.667
17	0.142	0.510	0.278	0.333	19	0.740	1.065	0.694	0.667
18	0.069	0.417	0.167	0.187	21	0.651	1.065	0.611	0.810
20	0.878	1.425	0.611	0.810	22	0.799	1.251	0.639	0.905
23	0.965	1.378	0.694	0.904	33	1.269	1.343	0.944	0.952
24	0.770	1.042	0.739	0.761	39	0.740	1.065	0.694	0.810
25	0.903	1.204	0.750	0.760	40	0.106	0.347	0.306	0.429
26	0.142	0.502	0.267	0.286	41	1.597	1.691	0.944	0.524
27	0.554	0.950	0.583	0.429	42	0.174	0.417	0.417	0.143
28	0.381	0.857	0.444	0.238	43	0.284	0.602	0.472	0.429
29	0.058	0.232	0.250	0.331	44	0.120	0.394	0.306	0.333
30	0.232	0.556	0.417	0.571	45	0.412	0.741	0.556	0.238
31	0.306	0.649	0.472	0.667	46	0.339	0.718	0.472	0.190
32	0.664	0.996	0.656	0.714	47	1.253	1.367	0.917	0.714
34	0.067	0.301	0.211	0.330	48	0.379	0.718	0.528	0.429
35	0.247	0.546	0.431	0.524					
36	0.769	1.065	0.722	0.949					
37	0.104	0.533	0.194	0.191					
38	1.257	1.459	0.861	0.807					

Mean values of indices for each urban and non-urban dune system.
Urban sites. 7: Cortal de la Devesa; 8: Empúries; 10: la Fonollera; 11: Pals; 13: Sant Pol; 14: Malgrat de Mar; 15: el Cavaió; 16: Mataró; 17: Vilassar de Mar; 18: Premià de Mar; 20: el Prat de Llobregat; 23: Gavà nord; 24: Castelldefels; 25: Covafumada; 26: Ginesta; 27: Llarga de Vilanova i la Geltrú; 28: Cubelles; 29: el Francàs; 30: Llarga de Berà; 31: Creixell Mar; 32 Creixell Antines; 34: la Paella; 35: Tamarit; 36: Llarga de Tarragona; 37: Llarga de Salou; 38: Arenal de l'Hospitalet de l'Infant.
Non-urban sites: 1: Garbet; 2: Borró; 3: la Rovina; 4: can Comes; 5: el Martinet; 6: cal Cristià; 9: la Pletera; 12: Castell; 19: Carrabiners; 21: el Remolar; 22: la Pineda; 33: els Muntanyans; 39: el Torn; 40: cala Ronyosa; 41: l'Arenal de l'Ampolla; 42: el Goleró; 43: el Fangar; 44: la Marquesa; 45:Bassa de l'Arena; 46: Casa dels Prats; 47: Riumar; 48: l'Aluet.

significant differences were observed between urban and non-urban dune systems for the figures pertaining to the rest of species guilds (Fig. 8).

3.3. Calculation of indices

Regarding the influence of the mosaic pattern on species richness, significant differences were found between the values of the H'_{dune} index, and the area of the dune systems sampled. The Kruskal-Wallis H

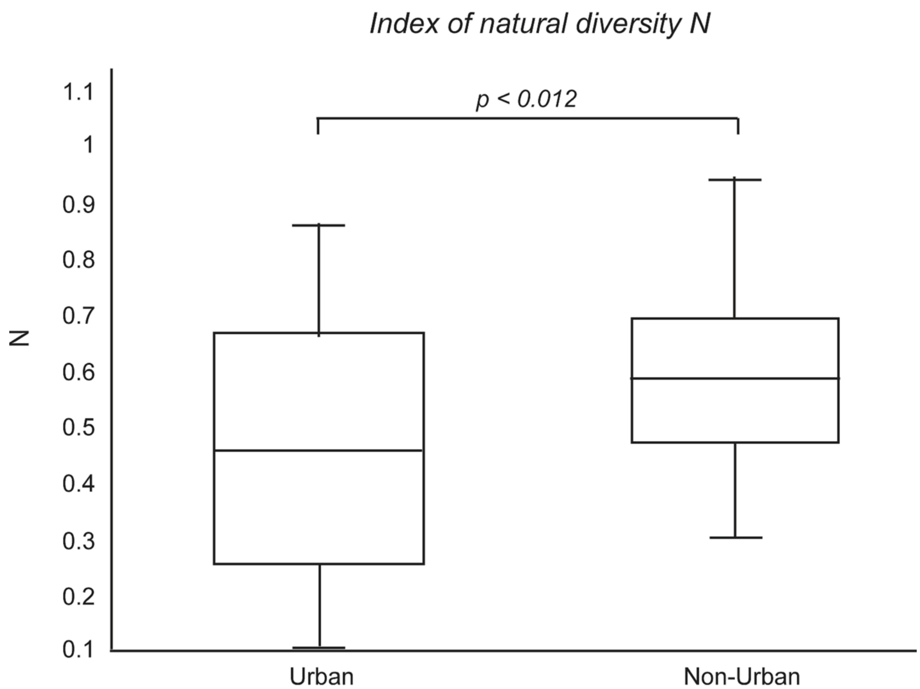

Fig. 10. Comparison of N values between Urban and Non-Urban sites using the Mann-Whitney U test.

test indicated that these differences were statistically significant ($p <$ 0.0001 for an $\overline{X} = 0.05$) (Fig. 9).

In urban systems, the values of H'_{dune} ranged from 0.232 to 1.459, whereas in non-urban systems values ranged from 0.347 to 1.343. In both cases, lower values were achieved by systems with a reduced area (most of them with area <1 ha) (Table 7).

Values of natural diversity N was significantly greater in dune systems located on non-urban beaches (N-URB). The Mann-Whitney U test indicated statistically significant differences in the N values between URB and N-URB sites ($p = 0.012$; $\overline{X} = 0.05$) (Fig. 10). This index ranged from 0.111 to 0.861 in urban sites and from 0.306 to 0.944 in non-urban ones. A very wider range than if only exotic species had been discarded in the calculation of the index. The results of the miscalculation of the N index using the values of $H'_{\text{dune without alien species}}$ can be seen in Table 8. The results show values very similar for each dune system, as it was expected, ranging from 0.887 to 1. They are a very high values due to the low incidence of the alien plants. These results make the index useless to discriminate the dune systems concerning the natural diversity.

The results of the index D_{ex}, related with the richness of dune restricted species in each site, showed a wide range of values, both in urban and in non-urban dune systems. In this case the Mann-Whitney U test indicated no statistically significant differences between URB and N-URB sites for the values of the D_{ex} index.

The highest values of D_{ex} were found in dune systems, mostly with areas>5 ha, in which a coastal-inland zonation of dune habitats is maintained, even in systems located in urban environments.

4. Discussion

Since the middle of the 20th century, the Mediterranean coast has undergone a very intense transformation due to tourism. Extensive construction along the coast has led to the disappearance of the smaller dune systems or the reduction of the surface area of many of the remaining systems (Spanou et al., 2006; De Luca et al., 2011; El Mrini et al., 2012; Anthony, 2014; Garcia-Lozano et al., 2018; Abdelaal et al., 2019).

The overwhelming frequenting of beaches by sun and beach tourism and the need to offer the beach services demanded by bathers has led to several impacts on the dune systems' plant communities, especially those located on urban beaches (Santoro et al., 2012; Fenu et al., 2013; Pintó et al., 2014; Pinna et al., 2015). It is important to assess the state of conservation of dune plant communities in order to protect these vulnerable environments through adequate management. In this study, we have used the dune-restricted species to calculate the diversity index and assess the conservation status of 48 dune systems along the Catalan coast, as well as the impact on diversity of spatial pattern variables and dune systems being located in urban or natural environments.

Regarding total richness, or gamma richness, the 224 taxa found are in line with the results of studies carried out in other Mediterranean countries, such as the 182 species identified by Spanou et al. (2006) on the Western coast of Greece; and the 206 species found by Malavasi et al., (2016) on the Thyrrhenian coast of central Italy. However, the figure is somewhat higher than the 149 identified in Molise (Italy) by Izzi et al., (2007) and much higher than the figure of just 63 vascular plants found by Ciccarelli and Baccaro (2016) in two regional parks in Tuscany (Italy). The difference may be due to the greater number of sampled dune systems (48) and the length of the coastal stretch (approx. 650 km) in which they are located, since an increase in the sampling surface always entails an increase in the number of species found (Gaston, 1996).

The values of the considered spatial metrics show significant differences related to the area of the dune systems. The dunes with the smallest surface are dunes located in urban environments and have lower shape index (SI) values. Dune patches located in urban environments tend to have compact shapes, as a result of the fragmentation processes. On the contrary, larger systems, located on non-urban beaches tend to have more elongated shapes, as is typical of slightly altered dune systems, as observed by Malavasi et al., (2016).

Both species richness and the values of the N index are influenced by human disturbance, as previous studies have highlighted (Grunewald and Schubert, 2007). The lowest N values (0.111 and 0.194) are for dune systems that occupy a small area (<1 ha) in urban beaches. These and the rest of dune systems with low values are geomorphologically underdeveloped and environmentally homogeneous, with no zonation of sea-inland habitats to favour species diversity.

There are some cases of beaches located in suburban environments

Table 8
Miscalculation of N using H'_{dune} without alien (exotic) species, instead of $H'_{\text{dune-restricted species}}$.

Urban Sites	H'_{dune} without alien	H'_{dune}	N	N-urban sites	H'_{dune} without alien	H'_{dune}	N
7	0.996	1.065	0.935	1	0.695	0.718	0.968
8	0.741	0.764	0.970	2	1.031	1.042	0.989
10	1.401	1.436	0.976	3	0.996	1.042	0.956
11	1.343	1.390	0.967	4	0.892	0.950	0.939
13	0.278	0.278	1.000	5	0.510	0.533	0.957
14	0.567	0.624	0.909	6	0.950	0.973	0.976
15	0.301	0.324	0.929	9	0.672	0.718	0.935
16	0.405	0.440	0.921	12	0.741	0.764	0.970
17	0.475	0.510	0.932	19	1.019	1.065	0.957
18	0.405	0.417	0.972	21	0.973	1.065	0.913
20	1.309	1.425	0.911	22	1.170	1.251	0.935
23	1.309	1.378	0.942	33	1.309	1.343	0.974
24	0.973	1.042	0.933	39	1.031	1.065	0.967
25	1.123	1.204	0.933	40	0.347	0.347	1.000
26	0.475	0.502	0.932	41	1.575	1.691	0.932
27	0.869	0.950	0.915	42	0.405	0.417	0.972
28	0.799	0.857	0.932	43	0,591	0.602	0.981
29	0.220	0.232	0.950	44	0.382	0.394	0.971
30	0.510	0.556	0.917	45	0.672	0.741	0.906
31	0.625	0.649	0.964	46	0.637	0.718	0.887
32	0.950	0.996	0.953	47	1.285	1.367	0.941
34	0.301	0.301	1.000	48	0.660	0.718	0.919
35	0.544	0.546	0.979				
36	1.019	1.065	0.957				
37	0.486	0.533	0.913				
38	1.401	1.459	0.960				

Mean values of indices for each urban and non-urban dune system.
Urban sites. 7: Cortal de la Devesa; 8: Empúries; 10: la Fonollera; 11: Pals; 13: Sant Pol; 14: Malgrat de Mar; 15: el Cavaió; 16: Mataró; 17: Vilassar de Mar; 18: Premià de Mar; 20: el Prat de Llobregat; 23: Gavà nord; 24: Castelldefels; 25: Covafumada; 26: Ginesta; 27: Llarga de Vilanova i la Geltrú; 28: Cubelles; 29: el Francàs; 30: Llarga de Berà; 31: Creixell Mar; 32 Creixell Antines; 34: la Paella; 35: Tamarit; 36: Llarga de Tarragona; 37: Llarga de Salou; 38: Arenal de l'Hospitalet de l'Infant.
Non-urban sites: 1: Garbet; 2: Borró; 3: la Rovina; 4: can Comes; 5: el Martinet; 6: cal Cristià; 9: la Pletera; 12: Castell; 19: Carrabiners; 21: el Remolar; 22: la Pineda; 33: els Muntanyans; 39: el Torn; 40: cala Ronyosa; 41: l'Arenal de l'Ampolla; 42: el Goleró; 43: el Fangar; 44: la Marquesa; 45:Bassa de l'Arena; 46: Casa dels Prats; 47: Riumar; 48: l'Aluet.

(La Fonollera, Pals, Castelldefels) where the dune systems are large (area >5 ha), morphologically complex and well-developed, allowing differentiation between foredune and semi-fixed dune habitats. In addition, they have some form of protection, such as the use of rope boundary fences to avoid trampling. In these cases, the degree of natural diversity (*N*) is similar to that achieved by the best-preserved dune systems on non-urban beaches. These results highlight the importance of coastal dune zonation in species conservation, as previously indicated by Acosta et al., (2009), due to their harbouring progressively higher species richness. In addition, human influence on dune systems is minimized if they enjoy some type of protection measure (Santoro et al., 2012).

Dune systems located on non-urban beaches (*N*-URB) generally display a high degree of naturalness according to the *N* index. This is true for systems no matter how large they are as long as they maintain a certain dune habitats zonation. The high *N* values indicate that dune-restricted species play a main role in maintaining the structure and functionality of these habitats.

Some authors such as Malavasi et al., (2018) have found that neither habitat loss nor fragmentation greatly affect species richness in dunes, since due to their dispersal strategies they are species that have adapted to these types of disturbance. But in this study, we have in fact observed a positive relationship between different spatial pattern variables (area, width, location in non-urban environments) and degree of natural diversity on tourist coasts. And that, in agreement with the findings by Cicarelli (2014), it is natural factors such as the zonation of dune habitats that best explain differences in the degree of natural diversity. A coast-inland zonation that is related to the surface area and width of the dune systems, as well as their location in a non-urban environment.

Use of the dune-restricted species guild in calculating the *N* index has made it possible to discern the diversity of dune systems more accurately. Thus, a very wide range was found in the distribution of values obtained in the case of systems located in urban environments (URB) ($r = 0.111$–0.861; $\overline{X} = 0.474$). Also, the range displayed a lot of variability ($r = 0.306$–0.944; $\overline{X} = 0.597$) in the case of dune systems located in non-urban environments (*N*-URB). In some previous works, much fewer wide ranges of *N* had been found since in the calculation of the index $H'_{dune\ without\ alien}$ was used (Attorre et al., 2013; Ciccarelli, 2014; Pinna et al., 2019).

These results validate the use of dune-restricted species as a key component for calculating the *N* index. They allow for a very accurate discrimination of the degree of natural diversity in each system and therefore the influence of factors related to the spatial pattern and the human pressure on the dune systems on tourist coasts.

The results of the D_{ex} index indicate that dune-restricted species are found at a similar frequency in both URB and *N*-URB systems, a fact also observed by Calderisi et al., (2021), and that must attribute to the adaptations of these species to the environmental conditions of dune habitats.

Given that most of the 21 dune-restricted species identified in this work have a Mediterranean range area and have been reported as members of dune communities on stretches of the Italian (Malavasi et al., 2016; Ciccarelli and Baccaro, 2016; Pinna et al., 2019 and Pinna et al., 2022), Greek (Sýkora et al., 2003), Egyptian (Abdelaal et al., 2018), Portuguese (Martins et al., 2013), and the southern sector of the French Atlantic coasts (Torca et al., 2019), this list could be adapted to calculate the degree of natural diversity on each of these coasts.

5. Conclusions

The results of this study show that the high human frequency endured by tourist coasts affects the diversity of plant species that colonize dune systems, those located in non-urban environments having a higher diversity than those located in urban environments. However, the larger dune systems (area > 5 ha) with sufficient width to maintain dune habitat zonation from coast to inland retain a high diversity even when located in urban environments.

In this work we have used the *N* index of naturalness proposed by Grunewald and Schubert (2007) in its literal sense, identifying a group of 21 dune-restricted species as typical dune species and using this guild of plants as a reference group for the calculation of *N*.

The use of only the dune-restricted species in the calculation of the index has made it possible to assess the degree of natural diversity in much more detail.

The dune-restricted species identified in this study have been shown to be good indicators of the naturalness and degree of conservation of dune systems.

A new D_{ex} index, to assess the presence of dune-restricted species in both urban and non-urban systems, was presented and applied to many representative coastal dunes at the Mediterranean level. The ease of its calculation allows it to be used by managers, together with the other indices, as a proxy to identify the degree of natural diversity and to assess the conservation status of such a threatened systems.

CRediT authorship contribution statement

Josep Pintó: Conceptualization, Methodology, Supervision, Writing – original draft, Funding acquisition. **Carla Garcia-Lozano:** Visualization, Formal analysis, Writing – review & editing. **Diego Varga:** Data curation, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110004.

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