



Assessing the potential for restoring Mediterranean coastal dunes under pressure from tourism

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Abstract

Mediterranean dune systems have undergone a large reduction in the last decades. The main factors involved in this process are urbanisation promoting an alteration of dune morphology and changes in plant communities. The most representative coastal dune systems of Sardinia have been selected as a study case and analysed to evaluate their environmental status, vulnerability, and the potential for dune restoration. Thirty coastal-dune systems, ranging from high natural sites to urbanised areas were analysed. A matrix of 35 variables × 30 sites was built to calculate the relationship among dune development (StaDun) and other indices related to the coastal dunes potential to host dunes (BeaPot), the conservation actions and management of coastal-dune systems (CoMan), and the anthropogenic pressure and the transgression capacity of the sand (SurLan). The values obtained for StaDun and Dune restoration potential index (DPR) were clustered. The results highlighted the relationship among StaDun, BeaPot and CoMan indices. The geomorphological and ecological characteristics determine the main factors that influence the presence, typology, and development of dunes in each site. Conversely, StaDun was weakly correlated to SurLan index. The DPR index allowed to discriminate the coastal dunes that required management actions. The first group included well-developed dune systems for which conservation and management actions were not necessary. The second one consisted of sites for which these previous actions and restoration measures were necessary. DPR index provides a tool useful to assess and classify coastal dune areas based on their potential for restoration, and to plan appropriate management actions.

Keywords Conservation status · Management plan · Mediterranean Basin · Potential for dune restoration · Sardinia · Vulnerability indices

Introduction

Coastal sand dunes are found in the transition zones between terrestrial and marine ecosystems, being one of the patchiest landscapes on earth (e.g., Carranza et al. 2008; Carboni et al. 2009; Fenu et al. 2013a; Malavasi et al. 2018). Coastal dunes are among the most important ecosystems on account of their high ecological diversity in terms of environmental heterogeneity and variability of species composition (e.g., van der Maarel 2003; Martínez and Psuty 2004; Carranza et al. 2008; Acosta et al. 2009). These peculiar ecological features are due to the abiotic and biotic factors that interact

constituting a complex sea-to-inland environmental gradient (Carranza et al. 2008; Fenu et al. 2013a).

Nevertheless, coastal dune systems are particularly fragile environments (van der Meulen and Salman, 1996; Carboni et al. 2009; Feola et al. 2011; Fenu et al. 2012, 2013a); in particular, the Mediterranean coastal dune systems seem those that have undergone a greater reduction in the last decades (Feola et al. 2011; Delbosc et al. 2021; Prisco et al. 2021). One of the main factors involved in the alteration and destruction of Mediterranean coastal dunes is the process of urbanisation and the adaptation of coastal dunes for tourism and recreational purposes (e.g., van der Meulen and Salman, 1996; Alonso et al. 2002; Santana-Cordero et al. 2016; Ciccarelli et al. 2017; Garcia-Lozano et al. 2018; Delbosc et al. 2021; Prisco et al. 2021).

Despite recreational activities represent an important advantage over the world (Propín-Frejomil and Sánchez Crispín 2007), the quick and often unregulated

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development of touristic residential areas, resorts, marinas, and recreation parks, etc., result in severe pressures on the coastal dune systems of the Mediterranean. In particular, activities associated with tourism, such as dune reshaping or flattening, beach cleaning, motor vehicle traffic, and trampling are threats that cause serious environmental degradation (Nordstrom 2008). These threats, along with numerous other modifications of coastal dune ecosystems, provoke the alteration of the dune morphology, activate erosive processes or favour changes in plant communities (e.g., Kerbirou et al. 2008; Santoro et al. 2012; Fenu et al. 2013b).

In the context of growing touristic pressure, it is necessary to constantly evaluate or update the conservation status of coastal dune systems (Pinna et al. 2019). To achieve this goal, coastal management often relies on the use of indices that quantify the vulnerability of different dune systems and represent a useful tool to facilitate the decision-making process (Ciccarelli et al. 2017; Garcia-Lozano et al. 2020). Particularly, numerous indices and protocols, focused on floristic patterns, diagnostic species, plant communities' structures, diversity indices, landscape cover, characteristic plant communities, marine effects, and type of human impacts have been suggested (e.g., Grunewald and Schubert 2007; Fenu et al. 2013b; Pinna et al. 2015, 2019). Furthermore, a set of indices have been developed and used to study the vulnerability of coastal dune systems. Specifically, García-Mora et al. (2001) proposed a methodology for studying the vulnerability of the southern Iberian Peninsula dune systems; afterwards the same procedure was adopted in other studies for the coastlines of the Gulf of Mexico (Martínez et al. 2006), for the Canary Islands (Peña-Alonso et al. (2017, 2018) and for Italy (Ciccarelli et al. 2017). A breakthrough for this type of research has been made by introducing the potential for dune restoration. One of the most significant contributions in this regard was provided by Lithgow et al. (2015, 2020) that developed “ReDune” index which made it possible to establish whether the coastal dunes (foredunes) required to be restored and to classify those with the most urgent need for restoration measures in the Gulf of Mexico.

Following this criterion, a body of research evaluated the most representative coastal dune systems in Sardinia (e.g., Fenu et al. 2013b; Ciccarelli et al. 2017; Pinna et al. 2019; Calderisi et al., 2021). To assess the potential for dune restoration of Mediterranean coastal sand dunes, we analysed the selected dune systems by applying the protocol proposed by Garcia-Lozano et al. (2020). Our study's specific aims were: 1) to evaluate the environmental status and vulnerability of the selected dune systems; 2) to assess the potential for dune restoration actions and to classify the sites according to the intervention actions required.

Materials and methods

Study area

Sardinia is the second largest island in the Mediterranean Basin, located in the western part of the Basin, and includes a coastal length of approx. 1,896 km (> 20% of Italian coasts), of which 24% comprises low, sandy, and pebbly shores (Atzeni et al. 2000). Geologically, the Sardinian coastal areas mainly consist of Quaternary deposits, particularly Holocene sandstones and aeolian sands (Carmignani et al. 2001). All sites showed the typical Mediterranean annual trend of temperatures and precipitation (Pinna et al. 2015).

In Sardinia there are numerous dune systems, some of which are the most extensive and well preserved in the western Mediterranean and, therefore, Sardinia represents one of the most important tourist destinations in the Mediterranean Basin. As has already happened for many other Mediterranean islands, Sardinian tourist activities grew rapidly in the last decades. On the island about 3,300,000 arrivals were recorded in 2017 (data from <https://www.istat.it/it/files/2019/12/C19.pdf>). Seasonal (summertime) coastal tourism is one of Sardinia's leading economic sectors (Pungetti et al. 2008; Pinna et al. 2019). For this reason, several measures to mitigate or reduce the human impacts on dune habitats have been undertaken on the island.

This study was carried out on 30 representative coastal sand dunes, distributed along the coastline of the entire island (see Fig. 4 in Appendix). All sites were selected based on the data availability and according to their geomorphological evolution (accretional, stable, or erosional), biological and ecological characteristics (presence of plant communities), and human impacts (different human pressures; see Table 1 for details), with the purpose of covering the widest range of coastal ecosystems ranging from high natural and low disturbed sites to urbanised and disturbed areas.

According to Ariza et al. (2008), the study sites were classified into three classes: urban coastal dunes (within the main nucleus of the municipality with at least 60% of urbanised hinterland and a 500 m wide strip along the coast), urbanised coastal dunes (in residential areas outside the main nucleus of the municipality with a maximum of 50% of urbanised hinterland), and natural coastal dunes (up to a maximum of 30% of urbanised hinterland). These coastal sand dunes were also characterised by infrastructure and recreational facilities mainly linked to the tourism activities carried out in the study sites (see Table 3 in Appendix).

In addition, Sardinian coastal sand dunes are included within or close to Sites of Community Importance (SCIs) and other Protected Areas, except for few cases (i.e., Maimoni, Cala Sinzias and Poetto; see Fig. 4 in Appendix).

Table 1 Variables used in the checklist indices (Garcia-Lozano et al. 2020)

StaDun	0	1	2	3	4
1. Types of dunes according to Garcia-Lozano and Pintó (2018)	Absent	Incipient	Dune ridge	Dune ridge with semi-fixed dunes	Dune field
2. Surface area of the dune system (ha)	< 0.1	< 5	< 10	< 15	> 15
3. Area occupied by the dunes in relation to the beach-dune system	< 5%	< 25%	> 25%	> 50%	> 75%
4. Maximum height of the foredune	< 1 m	> 1 m	> 3 m	> 4 m	> 5 m
5. Incipient morphologies on the dune face	0,00%	< 5%	> 5%	> 25%	> 50%
6. Evolution of the dune front since 1956	Disappearance	Retreated	Stability	Recovery	Progression
7. Structural status of the foredune according to Hesp (2002)	5	4	3	2	1
8. Type III species on the dune front according to García-Mora et al. (2001)	< 5		> 5		> 10
9. Beach-dune system restricted plants according to Pintó et al. (2012)	< 10		> 10		> 15
10. Invasive species	> 4	3	2	1	0
11. Ruderal species	> 7	> 5	> 3	> 1	< 1
BeaPot	0	1	2	3	4
1. Slope of the beach (°)	> 0.2		< 0.2		< 0.1
2. Evolution of the beach during the period 1995–2004 (m/year)	< -3	< -2	< -1	< 0	> 0
3. Beach orientation in relation to the prevailing winds	Perpendicular seaward	Oblique seaward	Parallel	Oblique landward	Perpendicular landward
4. Average intensity of the wind (m/s)	< 3		< 3.5		> 3.5
5. Significant Wave Height (m)	> 1		> 0.7		< 0.7
6. Diameter of the sediment (d ₅₀)	> 2	> 1	> 0.5	> 0.25	< 0.25
7. Sands < 0.5 mm	< 5%	> 5%	> 15%	> 25%	> 50%
8. Area of the beach covered in pebbles	> 50%	> 25%	> 15%	> 5%	< 5%
9. Width of dry beach	< 15 m	> 15 m		> 35 m	> 50 m

Table 1 (continued)

CoMan	0	1	2	3	4
1. Human frequen- tation (m2/user)	< 3	< 5	< 8	< 15	> 15
2. Information boards	Absent or inefficient				Efficient
3. Managed paths	Not regulated	In access	On land	Suspended	Lateral
4. Dune area with restricted access	< 25%	> 25%	> 50%	> 75%	100,00%
5. Sand traps	Inefficient or absent		Stable		Efficient/ unnecessary
6. Revegetation	Inefficient or absent				Adequate or unnecessary
7. Mechanical cleaning/levelling the beach in the high season	Causing dune scarp	Daily	Weekly	Occasionally	Absent
8. Eradication of invasive species	Not occurring/not effective			Effective	
9. Surface area occupied by seasonal services and amenities on or less than 5 m from the dunesa	> 15%	> 10%	> 5%	< 5%	0,00%
10. Surface area occupied by car parks or other permanent ser- vices on or less than 5 m from the dunesa	> 75%	> 50%	> 25%	< 25%	0,00%
11. Protection of the system and the immediate environment	0,00%	< 25%	> 50%	> 75%	100,00%
12. Degree of pro- tection according to the IUCN clas- sification (IUCN, 2019)	No protection		Level VI	Level V	Level I—IV
SurLan	0	1	2	3	4
1. Urbanised area in the first 100 m	100,00%	> 75%	> 25%	< 25%	0,00%
2. Impact according to the predomi- nant land category in the first 100 m	Concentrated urban areas	Urban dispersed areas	Urban land	Croplands	Natural areas
3. Area surrounding the beach with sand transgression capacity	100,00%	< 75%	> 25%	> 25%	100,00%

Methodology

The protocol proposed by Garcia-Lozano et al. (2020) based on “checklist indices” for assessing coastal sand

dunes and their potential for dune restoration was applied. These indices are based on the five main factors that interact in the system and describe its status, topography, geomorphology, climatology, ecology, and human-related

factors, with the aim of studying the coastal sand dunes in an integral way (García-Lozano et al. 2020).

Four indices (Table 1) were calculated to describe the beach-dune systems based on the basic dimensions that control the formation of the dune systems: Geomorphological and ecological status of dunes (StaDun), Beach potential to host dunes (BeaPot), Conservation actions and management of the beach-dune systems (CoMan), and Surrounding landscape (SurLan). Specifically, 35 variables (Table 1) grouped into four groups were considered. These variables were the same as those described by García-Lozano et al. (2020), except for "Beach-dune system restricted plants" according to Pintó et al. (2012)".

Each selected variable was associated with a five-point sliding scale ranging from 0 (being a negative indicator) to 4 (a positive indicator). The index of each block is a value that ranges from 0 to 1, with 0 as the minimum value and 1 as the maximum value of each index (García-Lozano et al. 2020):

$$IB = \sum B/B_{max}$$

where:

- IB is the index value of each dimension.
- B is the value of each variable within the dimension.
- max is the maximum possible value of each group.

Each dimension is described in Table 1, together with the variables related to the dune systems selected to define each index. These variables were obtained from bibliographic sources (i.e., topographic and geological maps, orthophotos, and available literature) and field investigation carried out over the last ten years.

Geomorphological and ecological status of dunes (StaDun)

StaDun index includes 11 of the 12 variables already proposed by García-Lozano et al. (2020) except for "Beach-dune system restricted plants" according to Pintó et al. (2012)", because this information was considered included in other variables (see Table 1). To obtain information about the vegetation cover and richness of each site, data relative to vegetational surveys were extrapolated from the literature and technical reports related to these areas (available from the website of Sardinian Autonomous Region, hereafter RAS, <https://portal.sardegnaasira.it/ricerca-sic-zps>; Valsecchi 1983).

The plant species were listed to describe the plant composition of the dune systems. Specifically, for the identification of ruderal (including synanthropic and nitrophilous) plants we followed Pignatti et al. (2017), we referred to Galasso et al. (2018) for alien plants, while for the classification

of the plant functional types we followed the approach of García-Mora et al. (2001).

In addition, geomorphological data were acquired from the orthophotos from webGIS of RAS (<http://www.sardegnaoportale.it/webgis2/sardegnafotoaeree/>). Orthophotos were processed in a GIS environment, with Gauss Boaga (Fuso 32 N) a geo-referencing system (Surace 1998; Pinna et al. 2019). Profiles of some beaches have been deducted from the bibliography (i.e., Antonioli et al. 2007; Fenu et al. 2012; Ciccarelli et al. 2017).

Beach potential to host dunes (BeaPot)

The BeaPot index is made up of nine variables. Information related to marine and wind data was obtained from the literature (Di Gregorio et al. 2000; De Muro et al. 2010a, b; De Falco et al. 2014, 2015; Pinna et al. 2019); pebble cover was obtained by Simeone and De Falco (2012) and verified in the field. Data on sand particle size were extrapolated from the available literature (De Falco et al. 2003; Fenu et al. 2012). Additional information was acquired from fieldwork and orthophotos interpretation (webGIS of RAS).

Conservation actions and management of the beach-dune systems (CoMan)

The CoMan index consisted of 12 variables that cover management, uses, and aspects of protection of the beach-dune system (Table 1). Data on management of dune systems, like the information boards, sand traps and managed paths, were collected in the field or acquired by SCI Management Plan (website of Sardinia Region). Other data were obtained by orthophotos interpretation (webGIS of RAS), whereas the degree of protection of each area was assessed according to the IUCN classification (IUCN 2019).

Surrounding landscape (SurLan)

The three variables included in SurLan index represent the landscape elements in the immediate surroundings of the beach-dune system, which determine its rigidity and human pressure. Information on the degree of urbanization, land use and sand transgression capacity were obtained by orthophotos interpretation (webGIS of RAS) and the Corine land cover map (CORINE Land Cover on the website of RAS).

Dune restoration potential index (DRP)

Finally, we calculated the dune restoration potential index (DRP) by using two of the four indices described above. This

index, starting to the potential of the beach to host dunes “BeaPot” measures how much develops according to the geomorphological and environmental characteristics of the beach, and the management measures implemented there (CoMan). The DRP increases as the beach potential to host dunes (BeaPot) increases and DRP decreases as the conservation actions and management measures applied to the beach-dune systems increase (CoMan; Garcia-Lozano et al. 2020):

$$DPR = BeaPot(1 - CoMan)$$

The DRP ranges from 0 to 1, where values close to 0 indicate the little potential for restoration and values close to 1 high potential for restoration.

This indicator considers both the physical parameters that favour dune development (BeaPot), and the management measures (CoMan) that contribute to the preservation, degradation and restoration of coastal dune systems depending on how they are applied. The DRP evaluates whether restoring the dunes according to BeaPot is possible in a management system geared to this end (Garcia-Lozano et al. 2020).

StaDun, BeaPot, CoMan, and SurLan were thoroughly assessed to describe the beach-dune systems from different perspectives (Table 1). Moreover, the StaDun index was related to the other indices (BeaPot, CoMan and SurLand) to link the factors that explain the geomorphological and ecological status of the dunes.

The five indicators were applied to 30 selected coastal dune systems, which were categorized based on the degree of dune development and the potential for restoration, according to Garcia-Lozano et al. (2020).

Each index was classified depending on the values obtained in low, medium, or high. Low for scores < 0.33; medium for values between 0.33 and 0.66; and high for scores > 0.66 (Garcia-Lozano et al. 2020).

A matrix of 35 variables × 30 sites was built to calculate the relationship among StaDun values and those of other indices (BeaPot, CoMan and SurLand), estimated with regression analysis. Moreover, the values obtained for StaDun and DRP were clustered using the SPSS software, and the method of Ward and the square Euclidean distance were used for the cluster analysis (IBM SPSS Statistics for Windows, Version 20.0).

Results

Checklist indices: StaDun, BeaPot, CoMan and SurLan

The most developed dunes from a geomorphological and ecological point of view (StaDun) were: 1-Chia,

4-Villasimius, 13-Capo Teulada, 18-Capo Comino, followed by 9-Is Arenas-Or, 10-Buggerru, 14-Funtanamare, 20-Spalmatore-Tavolara and 26-Porto Ferro (Table 2). These coastal dune systems included both natural (sites 9, 10, 13, 14, 20, 26) and urbanised areas (sites 1, 4, 18, Fig. 4).

The StaDun values were different depending on the type of dune systems: most part of urbanised coastal sand dunes showed dune systems highly developed (StaDun values ranging from 0.65–0.85); urban coastal dunes included mainly dune systems with medium–high development level (StaDun values ranging from 0.40–0.75); natural coastal sand dunes consisted of dune systems well-developed (StaDun values higher than 0.66), except for the beaches of 5-Maimoni, 29-Mal di Ventre and 30-Isola dei Cavoli (Fig. 1, 4).

The regression analysis (Fig. 1) indicated the relationship among StaDun and the other indicators. Specifically, StaDun showed a low positive correlation with SurLan, with R scores of 0.229. The StaDun index also had a medium positive correlation both with BeaPot and CoMan, with R scores of 0.350 and 0.304, respectively (Fig. 1).

Potential for dune restoration (DRP)

Results of DRP were summarised in Table 2. The DRP index calculated for each site showed that assessed beaches with low scores (DRP < 0.33, 15 beaches) and medium scores (0.33 < DRP < 0.66, 15 beaches) of this index were equally distributed among the study sites. The coastal dune systems with low DRP scores were mostly natural coastal dunes, on the contrary, sites with medium DRP scores were mainly urbanised coastal dunes.

The coastal sand dunes with the most potential for dune restoration (high DPR scores) generally were those with a high potential to host dunes and few management actions (high BeaPot and low CoMan scores), as well as partly vulnerable due to human pressure and system rigidity (medium–high SurLan scores). On the contrary, the sites with less potential for dune restoration (low DRP scores) were commonly coastal sand dunes with low potential to have dune field or with lots of management actions already applied (low BeaPot or high CoMan scores), besides coastal sand dunes with little human pressure and a high sand transgression capacity (high SurLan scores; Table 2). In addition, the results also revealed a low and negative correlation between DRP and StaDun, with $R = -0.160$ (Fig. 2).

The clusters analysis carried out between the DRP and StaDun values of the 30 cases studied (Figs. 2 and 3), enabled us to classify the variability of the results obtained into 4 groups:

Table 2 Scores of the 30 sites for the proposed indices: StaDun, BeaPot, CoMan, SurLan and DPR

Code	Beach	Type of coastal sand dune	StaDun	BeaPot	CoMan	SurLan	DRP
1	Chia	Urbanised	0.95	0.72	0.56	0.67	0.32
2	Poetto	Urban	0.40	0.75	0.15	0.33	0.64
3	S'Ena Arrubia	Urbanised	0.43	0.78	0.23	0.42	0.60
4	Villasimius	Urbanised	0.83	0.81	0.75	0.83	0.20
5	Maimoni	Natural	0.65	0.67	0.52	1.00	0.32
6	San Giovanni	Urbanised	0.65	0.58	0.44	0.83	0.33
7	Le Saline-Sant'Antioco	Urbanised	0.58	0.64	0.48	0.58	0.33
8	Porto Botte-Is Solinas	Natural	0.70	0.61	0.50	0.92	0.31
9	Is Arenas_Or	Natural	0.78	0.56	0.60	0.92	0.22
10	Buggerru	Natural	0.78	0.50	0.48	0.92	0.26
11	Piscinas	Natural	0.90	0.61	0.54	0.75	0.28
12	Porto Pino	Urbanised	0.63	0.67	0.44	0.83	0.38
13	Capo Teulada	Natural	0.90	0.67	0.60	0.83	0.26
14	Funtanamare	Natural	0.78	0.64	0.73	0.83	0.17
15	Cala Sinzias	Urbanised	0.55	0.67	0.31	0.67	0.46
16	Feraxi	Natural	0.53	0.53	0.46	0.83	0.29
17	S' Acqua Durci	Natural	0.40	0.50	0.33	0.83	0.33
18	Capo Comino	Urbanised	0.85	0.69	0.35	0.83	0.45
19	Budoni	Urbanised	0.75	0.58	0.40	0.58	0.35
20	Spalmatore-Tavolara	Natural	0.78	0.44	0.63	0.92	0.17
21	Cala Spalmatore-La Maddalena	Urbanised	0.30	0.50	0.40	0.67	0.30
22	Marina di Sorso	Urbanised	0.65	0.56	0.33	0.67	0.37
23	Platamona	Urbanised	0.65	0.64	0.33	0.50	0.43
24	Le Saline, Stintino	Urbanised	0.60	0.78	0.33	0.92	0.52
25	La Pelosa, Stintino	Urban	0.58	0.64	0.46	0.67	0.35
26	Porto Ferro	Natural	0.78	0.58	0.56	0.92	0.26
27	Porto Conte	Urbanised Urbanised	0.40	0.67	0.40	0.58	0.40
28	Maria Pia, Alghero	Urban	0.75	0.56	0.52	0.92	0.51
29	Mal di Ventre	Natural	0.45	0.33	0.75	1.00	0.08
30	Isola dei Cavoli	Natural	0.23	0.22	0.75	1.00	0.06

- Group 1: coastal sand dunes with highly developed dune fields (StaDun > 0.66) and low-medium dune restoration index scores (DRP ranging from 0.17 to 0.51), the most part of these are natural systems.
- Group 2: coastal sand dunes with low-medium StaDun scores (ranging from 0.30 to 0.43) and low-medium DRP scores (from 0.30 to 0.64), mostly urbanised sites.
- Group 3: coastal sand dunes with medium-high StaDun scores (ranging from 0.53 to 0.75) and low-medium DRP scores (from 0.29 to 0.52), mainly urbanised and urban systems.
- Group 4: included two coastal sand dunes with low-medium StaDun scores (0.23, 0.45) and low DRP scores (0.06, 0.08), both natural systems.

Discussion

The rapid growth of touristic activities caused enormous pressure on the sandy coastal ecosystems of the Mediterranean Basin, including Sardinia. Hence, assessing or updating the conservation status of coastal dune ecosystems is essential to preserve these extremely vulnerable environments through proper management strategies (Pinna et al. 2019). In this study we applied the protocol proposed by Garcia-Lozano et al. (2020), aiming to assess the conservation status of the coastal sand dunes systems of Sardinia, and their potential for dune restoration.

In a large body of research indices have been used for measuring the conservation status and vulnerability of different dune systems. Among these studies, the Mediterranean dune vulnerability index (MDVI) was proposed for assessing dune vulnerability according to the status of the coastal sand dunes, based on geomorphological variables,

Fig. 1 Relationship between dune development (StaDun) and the rest of the coastal sand dunes system indicators (BeaPot, CoMan and SurLan)

marine and aeolian effects, vegetation condition, and human frequentation of the dune systems (Ciccarelli et al. 2017). In the present study, these factors were included in the BeaPot and CoMan indices, which allowed to measure the potential for dune restoration (DPR). In general, the results of our study are consistent with those reported in Ciccarelli et al. (2017), in fact the Sardinian coastal sites show a vulnerability mainly influenced by geomorphological features, therefore they need restoration actions to aim to ameliorate the ecosystem quality and resilience.

Our results highlighted the relationship between dune development and the potential of coastal sand dunes to host dune fields with good conservation status. Therefore, the greater are the conservation measures applied (CoMan), the better is the geomorphological and ecological status of the dunes and their development (StaDun). Such outcome is in accordance with those obtained by Garcia-Lozano et al. (2020) for Catalan dune systems, in which coastal sand dunes that held developed dunes usually have high management scores (CoMan). In fact, well-conserved and recovered dunes are generally highly associated with management measures (Roig-Munar et al. 2020).

Furthermore, we found that the better is the geomorphological and ecological status of the dunes and their development (StaDun), the greater is the potential of the beaches to host dunes (BeaPot). This confirms that the geomorphological and ecological characteristics are the main factors influencing the state of development of dunes (Hesp 1988, 2002; Nield and Baas 2008), as well as clearly promoting the presence and variety of sandy dunes (Garcia-Lozano et al. 2020). However, this result contrasts with that one was highlighted by Garcia-Lozano et al. (2020), in which study no correlation between StaDun and BeaPot was found. This difference seems to be related to the geomorphology of Sardinian coastal sand dunes, the latter consisting mainly of well-developed dune systems (Pinna et al. 2015, 2019).

To summarise, coastal sand systems with developed dune fields (StaDun) have a high score in management measures (CoMan) and high potential values for hosting large dune complex (BeaPot). In fact, the most developed coastal dune systems are the natural ones, with only two exceptions that are urbanised systems (Chia and Capo Comino); however, in both exceptions, the urbanized areas are adjacent but external to the dune systems and only indirectly affect their evolution. The less developed dunes have low scores in management measures (CoMan) and are found in urban and urbanised coastal sand dunes contexts, such as Poetto and S'Ena Arrubia. On the contrary, other sites, such as Mal di Ventre and Isola dei Cavoli, although are very natural

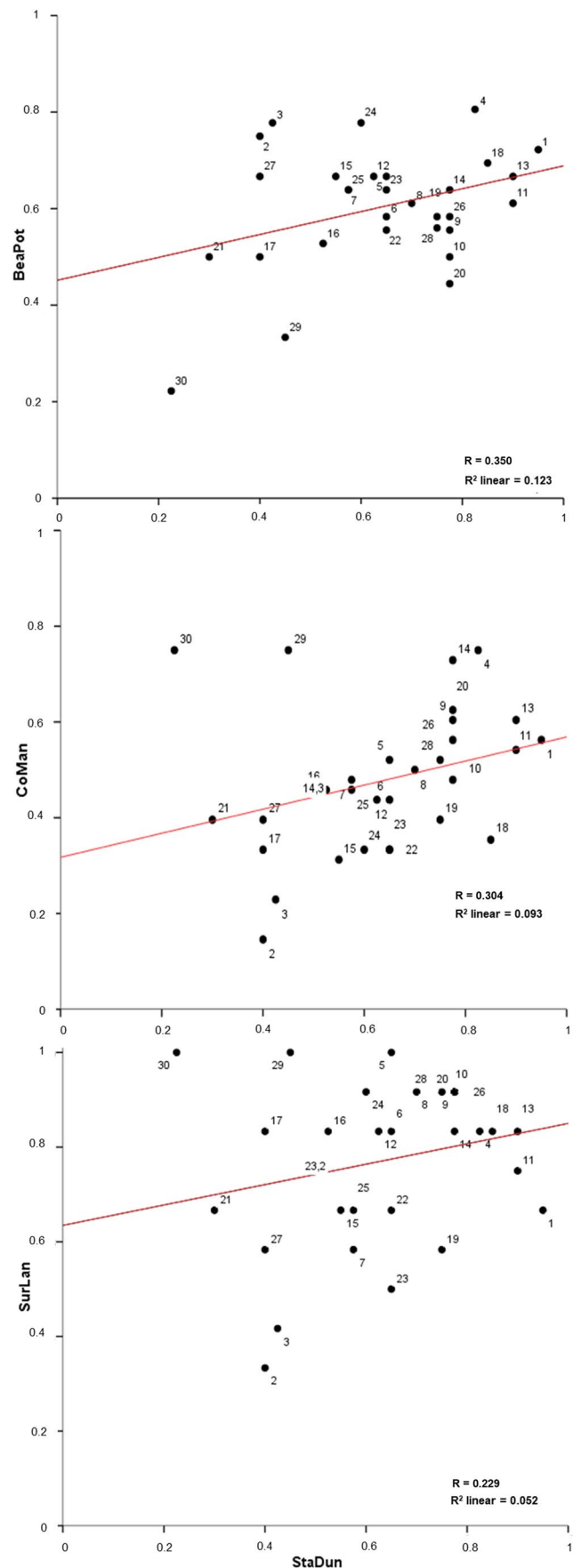
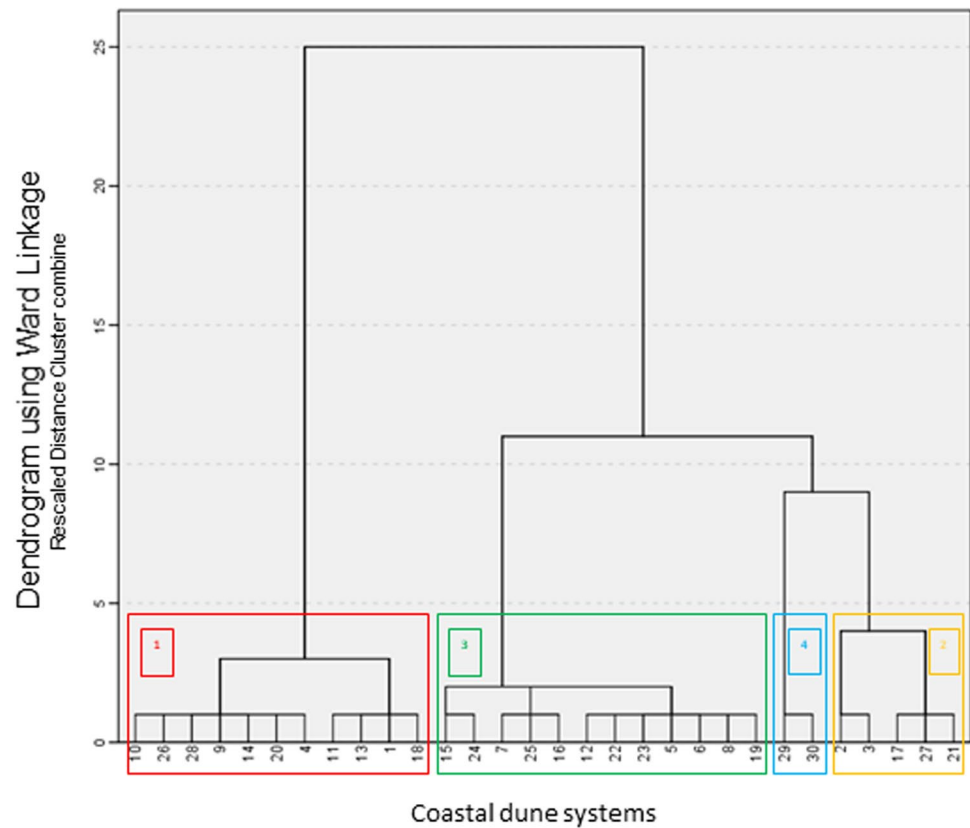


Fig. 2 Dendrogram of cluster analysis between StaDun and DRP for 30 coastal sand dunes, by using method of Ward and the square Euclidean distance



places included in Marine Protected Areas and subjected to management measures (high scores of CoMan), have little developed dune fields (StaDun). This is because these sites are located within small rocky islands, therefore they are not able to develop a large dune system; moreover, since most of the coastal dune systems are of aeolian origin, the morphology and exposure to the prevailing winds of these sites prevent the accumulation of aeolian sands. This condition occurs in island contexts, and generally in all those of the small islands of Sardinia, where there are no rivers, the main source of beach sand. The latter result highlights a limit of StaDun index, which seems less effective for small areas such as islets, according to Garcia-Lozano et al. (2020).

Geomorphological and ecological status of the dunes is weakly correlated to the human pressure and the transgression capacity of the sand. In fact, among the sites analysed there are well-developed dune systems with a low-medium level of human pressure and sand transgression capacity, even if classified as urbanised coastal sand dunes. This is the case of Villasimius, coastal dune system with wide dune fields but highly urbanised in its back-dune area. On the contrary, other coastal dune systems with less developed dune systems and a medium level of human pressure, such as Cala Spalmatore, Porto Conte and S'Acqua Durci, are characterized by low height dunes with fine sediments or are located in small bays that represent a limit to the expansion of dune field inland.

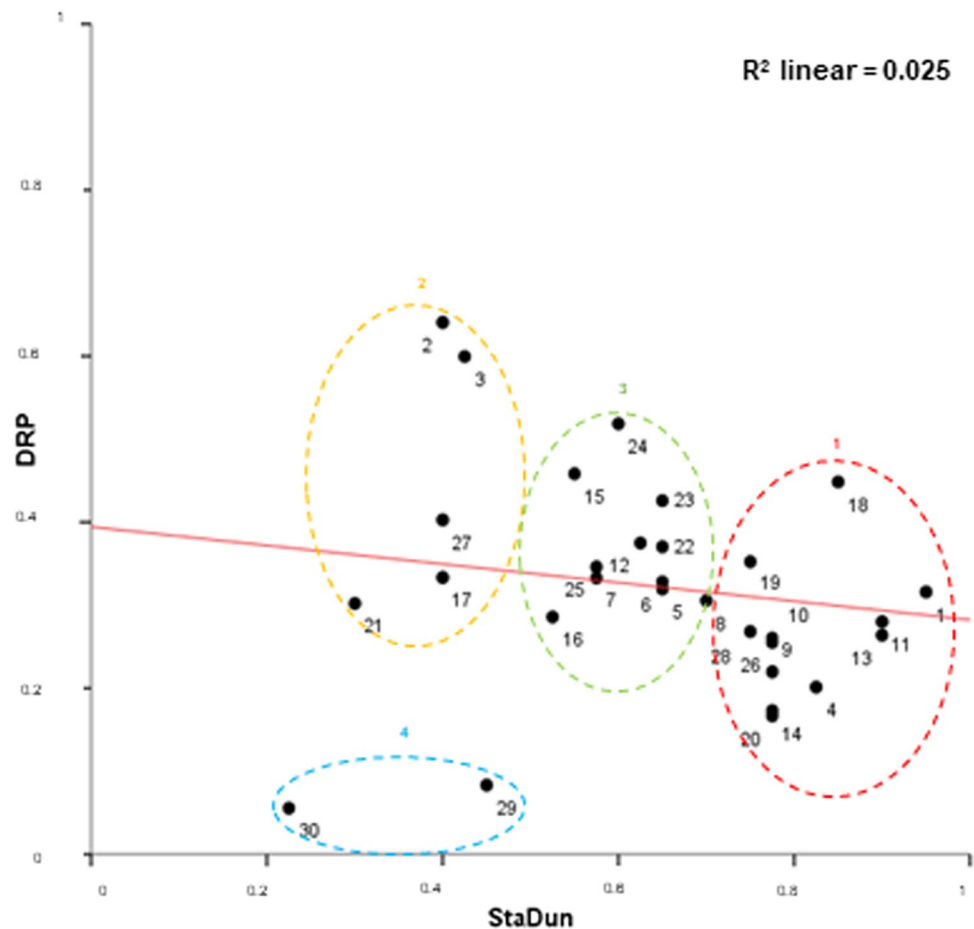
The cluster analysis of DRP and StaDun indices allowed to pinpoint four groups of coastal sand dunes in Sardinia, each group consisting of systems with different types of shared management and conservation measures to be implemented. These groups can be included in two main sets.

The first set (groups 1 and 4) includes a total of 13 sand dunes systems, situated mainly in natural areas, with low-medium DPR scores. In particular, group 1 is characterised by large dune systems with the highest StaDun scores, which due to their geo-environmental characteristics do not require to be restored through management and conservation interventions, in accordance with the results by Garcia-Lozano et al. (2020). Conversely, group 4 includes natural coastal sand dunes with low StaDun scores, such as Isola dei Cavoli and Mal di Ventre, without dune systems or at the embryo dune stage, within small islands located in Marine Protected Areas (MPAs) with low human impacts.

Even for this set of coastal sand dunes, the lack of room for improving their ecological and morphological status makes conservation interventions not required, if not those that might improve the management of beach access and regulate the entrances (Garcia-Lozano et al. 2020).

The second set (groups 2 and 3) includes a total of 17 coastal dune systems with medium DPR index scores. Specifically, in group 2 there are mainly coastal sand dunes in urbanised environments, such as Poetto and S'Ena Arrubia,

Fig. 3 Classification of the 30 sites according to the relationship between DRP and StaDun



characterised by a high level of vulnerability (Ciccarelli et al. 2017), where tourism pressure, the presence of several paths, and narrow foredune fields do not allow the development of their dune systems (low-medium StaDun scores). In these sites management measures already applied were not sufficient to avoid the degradation of dune systems.

Group 3 consists of coastal sand dunes with wide foredunes (medium–high StaDun scores), and high tourism, where previous restoration interventions by means of roped-off areas and walkways were present. For these sets of coastal sand dunes, in contrast with results achieved by Garcia-Lozano et al. (2020), suitable management actions required should be those aimed at re-naturalisation of dune systems. Naturalistic engineering techniques (such as sand trapping fences and mesh) to avoid the sand erosion caused by wind, infrastructures to reduce walking traffic and vehicles transit (walkways and fences), as well as systems to protect vegetation (sowing native germplasm by using seeds of local autochthonous structural species; Pinna et al. 2017) are recommended.

Finally, it is important to highlight that the Sardinian coastal sand dunes systems examined (except for Maimoni, Cala Sinzias and Poetto beaches) are located within or near

protected areas (MPAs and Regional Parks) and Sites of Community Importance (SCIs). In general, the presence of protected areas in coastal sites seems to have a positive impact for the coastal sand dunes included there, that have the least potential for restoration and do not need dune management measures. However, not for all sites the interventions applied were sufficient to halt ecosystem alteration by pressures coming from outside and to guarantee their conservation. This occurred mainly for coastal sand dunes within SCIs, which represent a ‘passive’ application of the legislative constraints in the coastal zones (Parravicini et al. 2013).

Conclusions

In the frame of coastal management actions, indices became a widely used tool since they allow to assess the status of coastal sand dunes and to inform decision-makers regarding potential for restoration of dune systems. Therefore, the proper selection of effective measures to conserve, restore and manage coastal areas requires that several factors be considered. Firstly, it is essential to obtain an adequate

Appendix

Fig. 4 Coastal dunes considered in this study. 1: Chia; 2: Poetto; 3: S'Ena Arrubia; 4: Villasimius; 5: Maimoni; 6: San Giovanni; 7: Le Saline-Sant'Antioco; 8: Porto Botte-Is Solinas; 9: Is Arenas Or; 10: Buggerru; 11: Piscinas; 12: Porto Pino; 13: Capo Teulada; 14: Funtanamare; 15: Cala Sinzias; 16: Feraxi; 17: S' Acqua Durci; 18: Capo Comino; 19: Budoni; 20: Spalmatore-Tavolara; 21: Cala Spalmatore-La Maddalena; 22: Marina di Sorso; 23: Platamona; 24: Le Saline, Stintino; 25: La Pelosa, Stintino; 26: Porto Ferro; 27: Porto Conte; 28: Maria Pia, Alghero; 29: Mal di Ventre; 30: Isola dei Cavoli. In bold the coastal systems included in protected areas (Sites of Community Importance, Marine Protected Areas, and Natural Parks)



assessment of these areas, including the geomorphological, ecological, and management aspects that would restrict, or facilitate, restoration and conservation actions.

In this perspective, in this paper the environmental status and vulnerability of the Sardinian dune systems were evaluated using the “checklist indices” and their potential for dune restoration (DPR; Garcia-Lozano et al. 2020). The selected sites include all the well-developed dune systems of Sardinia, this result confirms that geomorphological and ecological characteristics strongly influence the status of development of foredunes. The analysis of the different components that interact in the Sardinian dune systems showed that there is a significant relationship among the degree of dune development (morphologically more complex and larger) and the capacity of coastal sand dunes to host dune fields and have conservation and management measures. In addition, the DPR index was useful for discriminating the coastal sand dunes that required management actions, which were classified into two types. The first type encompassed well-developed and large dune systems for which were not necessary conservation and management actions, most of these included in protected areas. The second one consisted of sites for which conservation and management actions, such as re-naturalisation measures, were necessary. These findings highlighted that DPR index provides a tool to assess the status of coastal sand dunes areas and classify them based on their potential for restoration, to be used to plan appropriate management actions. Therefore, the index should be considered in future management decisions for each dune system on Mediterranean coasts.

CRedit authorship contribution statement

M.S. Pinna: Methodology, Formal analysis, Conceptualization, Investigation, Data curation, Writing—original draft, Writing—review & editing. D. Cogoni: Methodology, Formal analysis, Data curation, Writing—review & editing. G. Bacchetta: Writing—review & editing. G. Fenu: Conceptualization, Investigation, Data curation, Methodology, Supervision, Validation, Writing—original draft, Writing—review & editing.

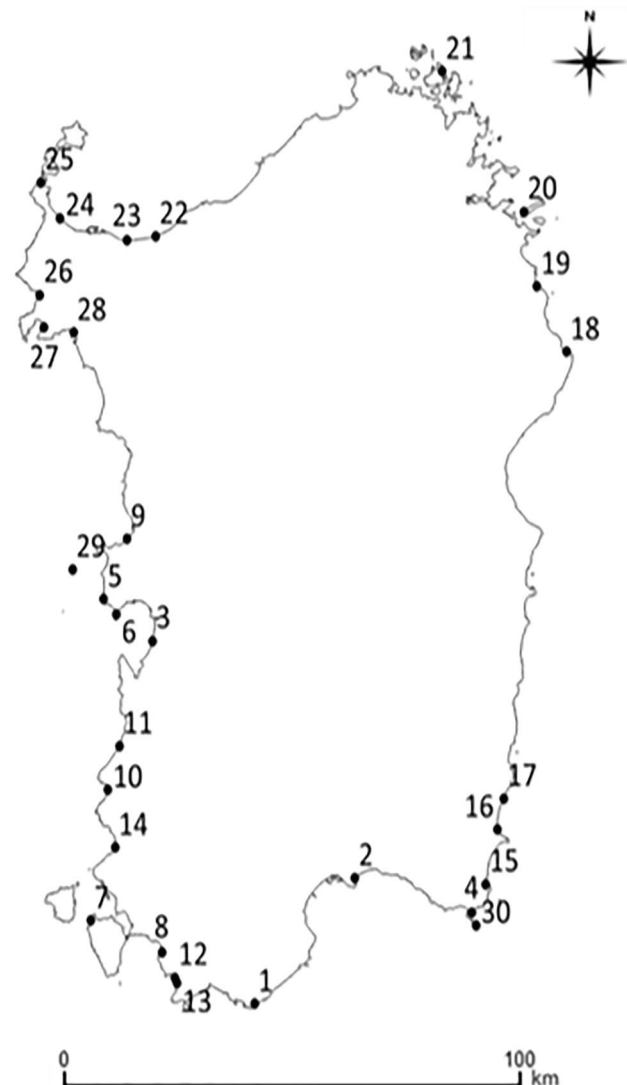


Table 3 Tourism infrastructures, facilities and recreational activities carried out in the study sites

Code	Beach	Infrastructure and recreational facilities						
		Beach sports and activities (beach volleyball, beach tennis, beach soccer)	Recreational fishing	Beach horse riding	Permanent services (Beach and dune camping, Hotel golf-camp, Pools)	Seasonal services	Recreational boating	Nautical and water sports
1	Chia	x	x	x	x	x		x
2	Poetto	x	x	x	x	x	x	x
3	S'Ena Arrubia	x			x	x		
4	Villasimius	x		x	x	x	x	x
5	Maimoni					x		
6	San Giovanni				x	x		
7	Le Saline-Sant'Antioco				x	x		
8	Porto Botte-Is Solinas			x	x	x		x
9	Is Arenas_Or	x	x		x	x	x	x
10	Buggerru	x	x		x	x		x
11	Piscinas			x	x	x		
12	Porto Pino	x	x		x	x	x	x
13	Capo Teulada		x					
14	Funtanamare		x	x	x	x		x
15	Cala Sinzias	x	x	x	x	x	x	
16	Feraxi		x		x	x		
17	S' Acqua Durci	x	x		x	x		
18	Capo Comino			x	x	x	x	
19	Budoni		x	x	x	x	x	x
20	Spalmatore-Tavolara				x	x	x	
21	Cala Spalmatore-La Maddalena				x	x	x	
22	Marina di Sorso		x		x	x	x	
23	Platamona	x	x		x	x	x	x
24	Le Saline, Stintino		x		x	x		x
25	La Pelosa, Stintino				x	x	x	x
26	Porto Ferro			x	x	x		x
27	Porto Conte			x	x	x	x	x
28	Maria Pia, Alghero				x	x	x	x
29	Mal di Ventre						x	
30	Isola dei Cavoli						x	

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Declarations

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.

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