Title: Development of a coastal dune vulnerability index for Mediterranean ecosystems: A useful tool for coastal managers?

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Abstract

Coastal dune ecosystems have been severely degraded as a result of excessive natural resource exploitation, urbanisation, industrial growth, and worldwide tourism. Coastal management often requires the use of vulnerability indices to facilitate the decision-making process. The main objective of this study was to develop a Mediterranean dune vulnerability index (MDVI) for sandy coasts, starting from the existing dune vulnerability index (DVI) proposed by Garcia-Mora et al. (2001) related to the oceanic coasts. Given that the Mediterranean sandy coasts are quite different from the Atlantic coasts, several adjustments and integrations were introduced. Our proposed index is based on the following five main group of factors: geomorphological conditions of the dune systems (GCD), marine influence (MI), aeolian effect (AE), vegetation condition (VC), and human effect (HE), for a total of 51 variables derived (and adapted) from the bibliography or proposed for the first time in this study. For each coastal site, a total vulnerability index, ranging from 0 (very low vulnerability) to 1 (very high vulnerability), was calculated as the unweighted average of the five partial vulnerability indices. Index computation was applied to 23 coastal dune systems of two different contexts in Italy, i.e. peninsular and continental island territories representative of the W-Mediterranean Basin, in order to compare the dune systems with different geomorphology, shoreline dynamics, and human pressure. In particular, our research addressed the following two questions: (1) Which variables are the most critical for the Italian coastal systems? (2) How can the coastal dune vulnerability index be used to develop appropriate strategies of conservation and management for these ecosystems? Cluster analysis and non-metric multidimensional scaling separated the peninsular from the insular sites, both of which were characterised by low to moderate values of vulnerability ($0.32 < MDVI < 0.49$). The most critical factors for the coastal systems examined in this study were marine negative influence, low stabilising ability of vegetation, and human disturbance. Hence, coastal managers are encouraged to plan specific management actions such as protection of foredunes from marine factors (particularly erosion), to promote dune formation with the reintroduction of native dune builder species and to minimise human pressure where vulnerability depends on these variables.

Keywords: coastal management, coastal vegetation, Mediterranean dune vulnerability index (MDVI), NMDS, plant functional types (PFTs)

1. Introduction

Coastal dune ecosystems are highly dynamics because of shifting substrates, burial by sand, bare areas among plants, the porous nature of sands, and little or no organic matter, particularly duringthe early stages of dune development (Maun, 2009). In addition, these ecosystems have been severely degraded as a result of excessive natural resource exploitation, urbanisation, industrial growth, and worldwide tourism (Brown and McLachlan, 2002; Defeo et al., 2009); consequently, coastal management often requires the use of vulnerability indices to facilitate the decision making process. In literature, the fact that the vulnerability of any system at any scale reflects (or is a function of) the exposure and sensitivity of that system to hazardous conditions and the ability, capacity, or resilience of the system to cope, adapt, or recover from the effects of those conditions is accepted (Smit andWandel, 2006). Adaptations are therefore manifestations of the adaptive capacity that represents ways of reducing vulnerability. In addition, a system can be vulnerable to certain perturbations and not to others. Two other widely accepted arguments include (i) the multi-scale nature ofdisturbances and (ii) the fact that most ecosystems are typically exposed to multiple, interacting perturbations (Gallopin, 2006). In particular, the concept of vulnerability is associated with the tendency or the predisposition to be negatively affected by natural or human factors (IPCC, 2014). Although different perspectives on the meaning of coastal vulnerability exist (Green and McFadden, 2007; Vafeidis et al., 2004), the main objective of vulnerability assessment is to provide information to guide the process of adaptation and enhance society's adaptive capacity (Kelly and Adger, 2000; Smit and Wandel, 2006). Therefore, the function of the vulnerability index is to simplify a number of complex and interacting parameters, represented by diverse data types, to a form that is more readily understood and therefore has greater utility as a management tool (McLaughlin and Cooper, 2010). In fact, vulnerability is affected by a diverse range of parameters such as interactions among airflow, sediment transfers, and vegetation that drive landform and habitat dynamics within coastal dunes; hence, these parameters should be considered simultaneously to estimate the vulnerability of a dune system. Recently, Newton and Weichselgartner (2014) reviewed the coastal vulnerability terminology focusing on key terms such as natural hazard, disaster risk, sensitivity, and resilience. They proposed that human drivers and pressures act in synergy with environmental drivers and contribute to the coastal vulnerability. This interaction is very important to develop and use a novel conceptualisation of risk that includes broader societal causes. One of the first pioneer works on coastal vulnerability was conducted by Dal Cin and Simeoni (1994) who analysed the morpho-dynamic risk of the Adriatic littoral (Italy). Subsequently, many authors attempted to assess the beach/dune/coastal vulnerability of sandy coasts worldwide. Most of them analysed (i) physico-geographical characteristics such as beach and coastal morphology, sedimentology, climatic parameters, and marine hydrodynamic factors (Alexandrakis and Poulos, 2014; Anfuso and Martínez Del Pozo, 2009; Domínguez et al., 2005; Satta et al., 2016); however, the other authors integrated abiotic variables with (ii) human influence and/or biotic factors such as vegetation conditions and animal biodiversity (e.g. Bernatchez et al., 2011; Corbau et al., 2015; García-Mora et al., 2000, 2001; Idier et al., 2013; Martínez et al., 2006). Agreement on how many variables must be pooled into any vulnerability index and whether each variable should be weighted or not has not been achieved. Given that coastal dune environments are complex systems whose equilibrium depends on several abiotic and biotic factors, the need to assess vulnerability by adopting a holistic and multidisciplinary approach becomes evident (e.g. Alexandrakis and Poulos, 2014; Bagdanavičiūte et al., 2015; Botero et al., 2015; Ruocco et al., 2014; Fenu et al., 2013a). The objective of this study was to develop a Mediterranean dune vulnerability index (MDVI) for sandy coasts, starting from the existing dune vulnerability index (DVI) developed for oceanic coastal environments (García-Mora et al., 2000, 2001). In fact, the Mediterranean Sea exhibits unique characteristics because it is a semi-enclosed basin surrounded by a complex orography, which strongly affects the local climate (Ruti et al., 2008). Further, it is characterised by high water temperature and salinity, more limited tides, and waves and meteorological phenomena with respect to the oceanic storms and hurricanes. These characteristics are attributed to the scarce exchange with the low-salinity water from the Atlantic Ocean and mainly to the high levels of evaporation (Weyl, 1970; King, 1975). Moreover, confined air circulation and strong seasonal variability also make the Mediterranean climatology peculiar (D'Ortenzio et al., 2005). Given that the Mediterranean sandy coasts are quite different from the oceanic coasts, we elaborated an MDVI introducing several adjustments and integrations.

The first step of the present work was to assess the vulnerability of the coastal dune systems along the Mediterranean Basin by adopting a multidisciplinary methodology. Second, we developed an easy-to-use instrument as the MDVI, which likely to be a valuable support to improve the management of the Mediterranean coastal areas. In particular, our research addressed the following questions: (1) Which variables among the geomorphological conditions of the dune system (GCD), marine influence (MI), aeolian effect (AE), vegetation condition (VC), and human effect (HE) are the most critical for the Mediterranean coastal systems? (2) How can the MDVI be used to develop appropriate strategies of conservation and management for these ecosystems?

2. Materials and Methods

2.1. Study Area

The study was conducted on coastal dunes in the Tuscany and Sardinia regions (Italy; W-Mediterranean Basin). In Tuscany, 11 coastal sites, belonging to two natural parks – Migliarino/San Rossore/Massaciuccoli Regional Park (San Rossore) and Maremma Regional Park (Maremma) - have been studied (Fig. 1). San Rossore (20 km in length) faces the southernmost sector of the Ligurian Sea, whereas Maremma (10 km in length) faces the northernmost sector of the Tyrrhenian Sea. The coast is characterised by sand beaches formed by Late Quaternary deposits (Ciampalini et al., 2015). Both parks are characterised by a typical Mediterranean climate with arid summers and mild winters (Rapetti and Vittorini, 2012).

In Sardinia, 12 coastal dune systems, distributed in the south west and south part of the island, have been investigated (Fig. 1). Sardinian sites included the most important and well-preserved dune systems of the island, and, in particular, all the complex dune systems located along the western coast were considered. Geologically, these areas mainly consist of Quaternary deposits, particularly Holocene sandstones and aeolian sands. All the sites exhibited the typical Mediterranean annual trend of temperatures and precipitations.

In both the regions, plant communities follow a typical sea-inland zonation related to an ecological gradient, starting from the annual vegetation of the strandline zone of the beach to the shrubby or forest communities on the stabilised dunes (Ciccarelli, 2014, 2015; Fenu et al., 2012, 2013a).

Almost all Tuscan coastal systems and all Sardinian coastal systems, except Maimoni and Poetto beaches, are within or close to the Sites of Community Importance (SCIs). All these sites were selected according to their geomorphological (accretional, stable, or erosional), ecological (presence of plant communities), and anthropogenic (different human pressures) characteristics in order to cover the widest range of coastal ecosystems ranging from high natural and low disturbed sites to urbanized and disturbed areas (see Appendix 1 for details).

2.2. Methodology

A Mediterranean dune vulnerability index (MDVI) methodology was developed for this research on the basis of an adaptation of the protocol proposed by García-Mora et al. (2000, 2001) and integrated by Idier et al. (2013). The following five groups of variables have been studied: geomorphological conditions of the dune system (GCD), marine influence (MI), aeolian effect (AE), vegetation condition (VC), and human effect (HE). However, our coastal vulnerability index was adapted to the specific peculiarities of the Mediterranean Sea. In our study, 51 variables, including both the quantitative and the qualitative parameters, were considered in the dune vulnerability classification procedure. These variables related to the dune systems were obtained from several bibliographic sources (i.e. topographic and geological maps, orthophotos, and available literature) and the predominant field investigation carried out over the last three years. We did not weigh the different variables because it could be difficult and subjective to rank variables. Each selected variable was associated with a five-point sliding scale ranging from 0 (absence of vulnerability) to 4 (very high vulnerability) as follows (Table 1).

2.2.1. Geomorphological Condition of the Dune System (GCD, 7 Variables)

These variables were the same as those described by García-Mora et al. (2001), except for their units of measure, which were converted from kilometres to metres in order to fit the specific characteristics of the Mediterranean coasts.

Geomorphological data were acquired from the orthophotos (available from the website of Tuscany Region: http://www502.regione.toscana.it/geoscopio/ortofoto.html, from webGIS of Sardinia Region: http://www.sardegnageoportale.it/webgis2/sardegnafotoaeree/), and from topographic profiles made in the field; in Sardinia, profiles of some beaches have been deducted from the bibliography (i.e. Fenu et al., 2012). Orthophotos were processed in a GIS environment, with Gauss Boaga (Fuso 32 N)- a geo-referencing system.

Data relative to the sand particle size were extrapolated from the available literature (Bertoni and Sarti, 2011a-b; Ruocco et al., 2014; for Tuscany; and De Falco et al., 2003, 2014; De Muro et al., 2010a-b; Di Gregorio et al., 2000; and Fenu et al., 2012 for Sardinia).

2.2.2. Marine Influence (MI, 13 Variables)

We introduced the new variable "shoreline change" because erosional phenomena have been highlighted as factors that are closely correlated with degradation and habitat loss along the Italian littorals (Ciccarelli et al., 2012; Ciccarelli, 2014).

For Tuscany, marine data were obtained by Servizio Idrologico Regionale (SIR, http://www.sir.toscana.it/index.php?IDS=191&IDSS=821), storm frequency and duration were acquired from APAT (2004), and information relative to the shoreline changes was deducted from Bini et al. (2008) and Cipriani et al. (2013). In the case of Sardinia, information related to marine data was obtained from De Muro et al. (2010a-b), Simeone and De Falco (2012), Antonioli et al. (2007), and De Falco et al. (2015); additional information was acquired from orthophotos (webGIS of Sardinia Region) and topographic profiling carried out in the field. Shoreline changes were deducted from surveys and by comparing historical orthophotos (webGIS of Sardinian Region). Data relative to the storm frequency and duration were acquired from ISPRA (http://www.mareografico.it/).

2.2.3. Aeolian Effect (AE, 6 Variables)

These variables were the same as those described by García-Mora et al. (2001), except for four variables (see Table 2 in García-Mora et al., 2001, variables 2, 4, 8, 10) that were considered redundant with the other parameters included in the group related to the VC. In the case of Tuscany, wind data were obtained from Consorzio LAMMA (2004-2014, Laboratory for Meteorology and Environmental Modelling, http://www.lamma.rete.toscana.it), natural litter and pebble cover were determined in the field, and the other variables were calculated from the orthophotos processed in the GIS environment. In the case of Sardinia, wind-related data and pebble cover were determined in the field, natural litter cover data were obtained by Simeone and De Falco (2012) and determined in the field, and the percentage of seaward dune vegetated was directly obtained by orthophoto interpretation.

2.2.4. Vegetation Condition (VC, 9 Variables)

We introduced the variable “alien species along the whole transect” because several studies highlighted the impact of alien plants, particularly on the transition and fixed dunes along the Italian coasts (Carboni et al., 2010; Pinna et al., 2015b). The other two variables, i.e. relative proportion of endemics in the seaside of the frontal dune and along the transect, were added because coastal dune habitats may host endemic plant species that contribute to the high ecological diversity of these systems (Acosta et al., 2009; Ciccarelli et al., 2014; Pinna et al., 2015a-b). Finally, the “number of plant associations along the transect” was used here as an indirect estimate of the conservation status of the coastal system (Carboni et al., 2010; Ciccarelli, 2014; Pinna et al., 2015a). In order to obtain information about the VC, in each site, a transect orthogonal to the seashore was randomly located. The percentage cover of each vascular plant was visually estimated in plots of 2 × 2 m along the transect. Classification of the plant functional types followed the approach of García-Mora et al. (1999). Field work was conducted in 2015. The taxonomic nomenclature followed the checklist of the Italian vascular flora (Conti et al., 2005, 2007) for native species, whereas for alien plants, the checklists of Arrigoni and Viegi (2011) and Podda et al. (2012) for Tuscany and Sardinia respectively, were adopted.

2.2.4. Human Effect (HE, 16 Variables)

These variables were the same as those described by García-Mora et al. (2001), except for the variable “horse riding”, which was substituted by the more generic trampling by animals, and “rabbit numbers”, which was omitted because it was redundant with variable grazing on the active system. In the case of Tuscany, data related to the HE were collected in the field during May-June 2015 (variables 1-6, 10, and 16; Table 1) or deducted from the orthophotos processed in the GIS environment. Data on Sardinian dune systems were collected in the field from April to July 2015, whereas variables 7, 14, and 15 (Table 1) were obtained by orthophoto interpretation.

2.2.5.Data Analysis

The partial and total vulnerability indices were calculated for each selected coastal dune site. For each vulnerability group (GCD, MI, AE, VC, HE), the sum of the ranked variables divided by the sum of the maximum ranking attainable within each group yielded a partial vulnerability index expressed as a percentage. The total MDVI was computed as the unweighted average of the five partial vulnerability indices as follows:

$$MDVI = (GCD + MI + AE + VC + HE)/5$$

MDVI ranging between 0 and 1, and in accordance with García-Mora et al. (2001), as the index increases, the ability of a dune system to withstand further intervention decreases.

A matrix of 51 variables × 23 Italian sites was subjected to cluster analysis using average-linkage clustering and Euclidean distance as the dissimilarity index. The same resemblance matrix was used to perform non-metric multidimensional scaling (NMDS), which is a technique that represents samples in a low-dimensional space by optimising the correspondence between original dissimilarities and distances in the ordination (Økland, 1996). The Spearman product-moment correlation coefficient was calculated in order to indicate the variable that was more correlated to the NMDS axes. The non-parametric test of Kruskal-Wallis with Bonferroni correction for multiple comparisons was applied to compare the partial and total vulnerability values in the groups defined by cluster analysis. Statistical analyses were performed in the R 2.14.1 environment (R Development Core Team, 2012) using the “vegan” package (Oksanen et al., 2012).

3. Results

The total MDVI of Italian coastal dunes ranged from 0.32 in T1 to 0.49 in S6 (Table 2). The geomorphological condition of dune system (GCD) and the vegetation condition (VC) partial indices showed the highest vulnerability values in Tuscany (0.71 in T5 and T8 and 0.72 in T6). Sardinian sites showed the highest values of the aeolian effect (AE) partial index (0.58) in S4, marine influence (MI) index (0.52) in S11, and human effect (HE) partial index (0.48) in S6 (Table 2).

Cluster analysis of the 23 sites defined two main groups related to the geographic location of the sites with a Euclidean distance of ~13% (Fig. 2):

- Group I, formed by Tuscan coastal dunes (T1-T11), which can be subdivided into two main clusters (IA and IB). MDVI ranged from 0.32 (T1) to 0.45 (T9).
- Group II, formed by Sardinian sites (S1-S12), which encompassed a relatively high heterogeneity with S3, S6, and S12 that segregated separately and the other sites forming two subgroups (IID and IIE). MDVI varied between 0.37 (S4) and 0.49 (S6).

This classification was supported by NMDS (Fig. 3), which resulted in a clear separation of the peninsular and insular sites in the bidimensional space (the stress value of 0.12 corresponds to a good ordination). Italian coastal sites seemed to differentiate particularly along the first NMDS axis: Tuscan samples were dominated by the MI such as the width of the intertidal zone (MI-03); however, Sardinian sites were mostly influenced by the mean wave height (MI-10), storm frequency (MI-12), and VC such as the relative proportion of type-II plants in the seaside of the frontal dune (VC-03) with a Spearman correlation coefficient > 0.8. The second NMDS axis was dominated by HEs, in fact, the visitor pressure and frequency (HE-01 and HE-02) were determinants for separating subgroup IA from IB and IID from IIE.

Analysis of variance revealed statistically significant differences in the values of the GCD and MI vulnerability indices between groups I and II (Table 3). Among the Tuscan coastal sites, subgroup IA comprised five coastal segments (T1, T2, T3, T8, and T9) showing the significant lowest value of MI and AE partial index (Table 3, Fig. 4). All these sites were located along no retreating shoreline tracts open to public frequentation. Conversely, subgroup IB comprised six coastal segments (T4, T5, T6, T7, T10, and T11), which were characterised by the significant lowest vulnerability value of the HEs (Table 3, Fig. 4). These sites were located in the erosional coastal tracts (with the exception of T11), which either had low accessibility or were closed to public access.

In general, the Sardinian coastal sites were divided along a gradient related to the human pressure in two main subgroups (IID and IIE); a third subgroup consisting of the sites that segregate separately may also be identified (S3, S6, S12). No statistical differences in the partial vulnerability indices were found among the Sardinian subgroups. Subgroup IID, encompassing five coastal systems (S1, S2, S5, S7, and S10), showed high values of GCD and low HE partial indices (Table 3, Fig. 5); this subgroup contained a coastal dune system with high tourist frequentation, particularly in summer. Conversely, subgroup IIE, that encompasses four dune sites (S4, S8, S9, and S11), showed high values of MI and AE but low values of HE corresponding to a relatively low MDVI total index (Table 3, Fig. 6).

Finally, the last three coastal dune sites (S3, S6, S12) constitute an independent and heterogeneous subgroup. This subgroup is characterised by a high level of touristic exploitation and a consequent alteration of dune systems, particularly S6 and S12, as well as by a peculiar system located within the Oristano Gulf (S3) with extremely low values of MI (Fig. 6).

No differences were found for the total dune vulnerability indices of each group or subgroup (Table 3).

4. Discussion

A coastal vulnerability index, aiming to simplify a number of complex and interacting parameters, has a relatively high utility as a management tool, particularly in the Mediterranean coastal regions, which have been exploited considerably by humans. One of the most important characteristics of the MDVI is its multidisciplinary nature. It takes into account the geomorphological factors, marine and aeolian influences, vegetation characteristics, and human effects. All of these parameters are recognised as determinant variables for assessing the vulnerability status of coastal dune systems worldwide (e.g. Alexandrakis and Poulos, 2014; Bagdanavičiūte et al., 2015; Satta et al., 2016).

The obtained results highlighted that all the analysed Italian coastal sites showed a medium vulnerability value (ranging from 0.32 to 0.49). In particular, the GCD, MI, and VC parameters showed intermediate values of vulnerability along the Italian coasts. The most well-preserved coastal segment was located in northern Tuscany (Viareggio – T1) where the littoral is prograding and large; however, Poetto (S6) in south Sardinia, a beach that is approximately 8-km long and highly frequented by the inhabitants of Cagliari throughout the year and additionally by tourists in the summer, exhibited the highest MDVI value.

This result is also consistent with the result of a previous study, carried out at the Italian level and considering five types of pressures (land-use, river, industry, ports, and artificial structure), showing significant human-induced pressures in this coastal site (Lopez y Royo et al., 2009)

Both cluster analysis and NMDS separated the peninsular from the insular sites. In particular, the vulnerability of the Tuscan coasts was related to the GCD and VC parameters. Among them, the variables with the highest vulnerability values were average height of the secondary and frontal dunes (GCD-02/03), cover percentage of type-III plants (VC-01/02), and relative proportion of endemics (VC-07/08). In fact, in Tuscany, coastal dune systems are more or less flat, except where erosion has degraded the foredunes. In this case, secondary dunes, which are higher, become exposed (Bertoni et al., 2014; Ciccarelli, 2014). The low percentage of type-III plants, which are pioneer psammophilous species characterised by stronger adaptations to the harsh ecological conditions of foredunes (see García-Mora et al., 1999, for a detailed classification of plant functional types in coastal foredunes), could be linked not only to the shoreline erosion that disrupts plant communities of the embryo and mobile dunes but also to the visitor presence and summer beach cleaning operations (Ciccarelli, 2014).

Conversely, the vulnerability of Sardinian sites was mostly related to the MI and the AE. Among them, the variables with the highest vulnerability values were the orthogonal fetch, the width of the zone between the HWSM and the dune face, and the shoreline changes (MI-01/06/09), in addition to the supply input and the percentage of system with blowouts (AE-01/02). In particular, a group of coastal sites with similar characteristics is clearly gathered. These coastal systems are morphologically complex and large, generally with western exposure, which implies an exposure to prevailing winds (west and mistral), relatively high tidal phenomena, and relatively strong storms; moreover, it is difficult for humans to access a large portion of these coastal sites. In fact, the Sardinian sites, particularly those of the western part of the Island, are dune systems with established foredunes and oriented to the prevailing western winds (in particular, the mistral) that also represent the main drivers of the most meteoric-marine events that cause erosion processes and shoreline movement (Fenu et al., 2012, 2013a; Pinna et al., 2015b). Additionally, the AEs can also act directly on the beaches. Blowouts are common in coastal dune environments, particularly where beaches and foredunes are occasionally eroded and/or receding; however, they can also occur in stable and accretionary environments where wind and wave energy are high (Hesp, 2002). Moreover, the blowouts are developed as a result of pedestrian trampling and track creation (Bate and Ferguson, 1996; Hesp, 2002). Therefore, the low sand supply and the presence of blowouts are related to erosive phenomena that affect this type of dune systems. Additionally, this effect can be exacerbated by the indirect effect of human attendance; in fact, the volume of sediment removed accidentally is proportional to the number of beachgoers and tourists, and it increases with the number of visitors. In particular, in the case of Sardinian embayed beaches under static equilibrium, with little or null sediment exchange with neighbouring areas, each action that modifies the state of the beach may influence the sediment budget and cause an alteration of the equilibrium of the beach.

The NMDS ordination of the Italian samples in the bidimensional space was mainly associated with the width of the intertidal zone (MI-03), mean wave height (MI-10), storm frequency (MI-12), and relative proportion of type-II plants in the seaside of the frontal dune (VC-03) along the first axis; however, it was influenced by the visitor pressure and frequency (HE-01/02) along the second axis. In other words, the marine and vegetational variables were significant to discriminate between the peninsular and the insular sites, which were characterised by relatively intense tidal phenomena, strong storms, and a predominance of type-II plants, which are favoured by persistent natural disturbances (García-Mora et al., 1999). The second NMDS axis highlighted the HEs that were determinants for separating coastal sites with relatively high vulnerability values with regard to human pressure and disturbance (subgroups IA and IID) from other sites characterised by low tourist attendance (subgroups IB and IIE).

To answer the first question posed at the beginning of the paper, vulnerability assessment revealed that the most critical factors affecting Mediterranean coastal systems examined in this study are: (i) marine negative influence, (ii) low stabilising ability of vegetation, and (iii) human disturbance. Moreover, vulnerability was strongly and homogeneously affected by geomorphological variables, as observed in other studies (García-Mora et al., 2001; Martínez et al., 2006). MI has been highlighted as one of the main disturbance factors for coastal dune systems: sea-level rise, storms, tidal phenomena, and shoreline erosion may act as destabilising agents to coastal ecosystems, particularly in those littorals where vegetation cover is scarce and the foredunes are directly exposed to waves (Ciccarelli et al., 2012; Ciccarelli, 2014; Gornish and Miller, 2010; Nicholls and Cazenave, 2010). In fact, plant communities are one of the most important stabilising factors for coastal dunes (Duran and Moore, 2013; Fenu et al., 2012). In particular, García-Mora et al. (1999, 2000) evidenced the importance of pioneer species typical of the foredune habitats (called type-III plants), which are able to tolerate soil mobility, salt spray, and sand abrasion. Reducing the populations of type-III plants from large coastal sectors could cause a risk of local extinction with dramatic consequences for coastal dune stabilisation. Finally, human pressure has been confirmed as a negative factor that dramatically influences coastal vulnerability: trampling, path network, beach cleaning, and permanent and ephemeral bathing settlements can decrease plant diversity and cover, particularly with regard to the endemic and threatened plant species (Davenport and Davenport, 2006; Fenu et al., 2013b; Ciccarelli, 2014, 2015).

To answer the second question, the vulnerability indices calculated for each coastal site may underline the main sources of local disturbances, providing relevant information to stakeholders on the adequate management strategies for each location. From our results, it is obvious that high vulnerability sites might need restoration actions in order to ameliorate the ecosystem quality. Coastal managers are encouraged to minimise human pressure, particularly where vulnerability was due to this group of variables (i.e. T8, S1, S2, S6). In particular, trampling can be reduced by the installation of footbridges and the use of appropriate fences to allow aeolian sand transport and drift (Doody, 2013). Disturbance caused by human activities (i.e. cleaning of the beach during summer, the presence of bathing settlements, etc.) can be avoided by soft management actions (Fenu et al., 2013b; Pinna et al., 2015b).

Coastal sites characterised by high values of geomorphological condition or marine influence vulnerability are relatively more complex to manage. Geomorphology and sedimentary characteristics are intrinsic to the dune system, and they are not modifiable by soft actions that do not alter the ecosystem. Moreover, marine variables such as storms, tidal phenomena, and partly shoreline erosion are processes that are not under human control and are, therefore, unpredictable. As far as possible, all restoration actions should promote natural dune formation with the reintroduction of native species, particularly type-III plants, which are the natural dune builders (Martínez et al., 2006).

In conclusion, this paper was the first example of the application of MDVI at the Mediterranean level. This index was useful for well discriminating between the peninsular and the island sites. In fact, the Italian coasts showed a modest vulnerability mainly attributed to the geomorphological factors and the marine and vegetational variables. In particular, both the GCD and the MI parameters are connected to the wave and sea processes, which are slightly different between the peninsular and the island sites. However, natural factors such as environmental backgrounds are integral parts of coastal vulnerability and should be considered simultaneously with human or other pressures to estimate the vulnerability of a dune system because of the multidisciplinary nature of our index. These findings highlighted that the MDVI index provides an easy-to-use tool for assessing dune vulnerability and then planning appropriate management actions for each dune system. In future, the MDVI index could be applied periodically to check the evolution of coastal areas on a regular basis.

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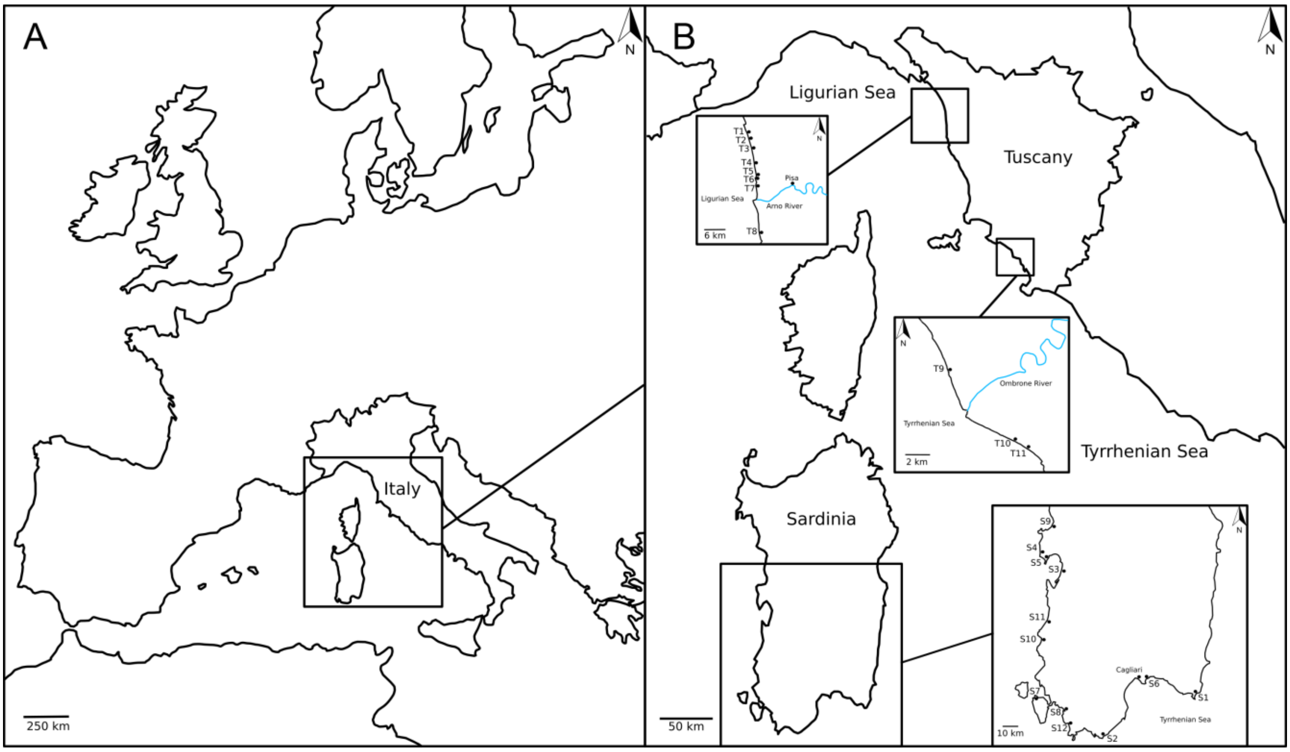

Fig. 1A. Map of Europe. **B.** Map of Italian coastal sites analysed in the study. Abbreviations: T, Tuscan sites and S, Sardinian sites. Coastal areas considered in this study: T1: Viareggio; T2: Torre del Lago; T3: Marina di Vecchiano; T4: San Rossore; T5: San Rossore; T6: San Rossore; T7: San Rossore; T8: Calambrone; T9: Principina; T10: Maremma; T11: Maremma; S1: Villasimius; S2: Chia; S3: S'Ena Arrubia-Abbarossa; S4; Maimoni; S5: San Giovanni; S6: Poetto; S7: Le Saline - Sant'Antioco; S8: Porto Botte-Is Solinas; S9: Is Arenas_Oristano; S10: Buggerru; S11: Piscinas; S12: Porto Pino.

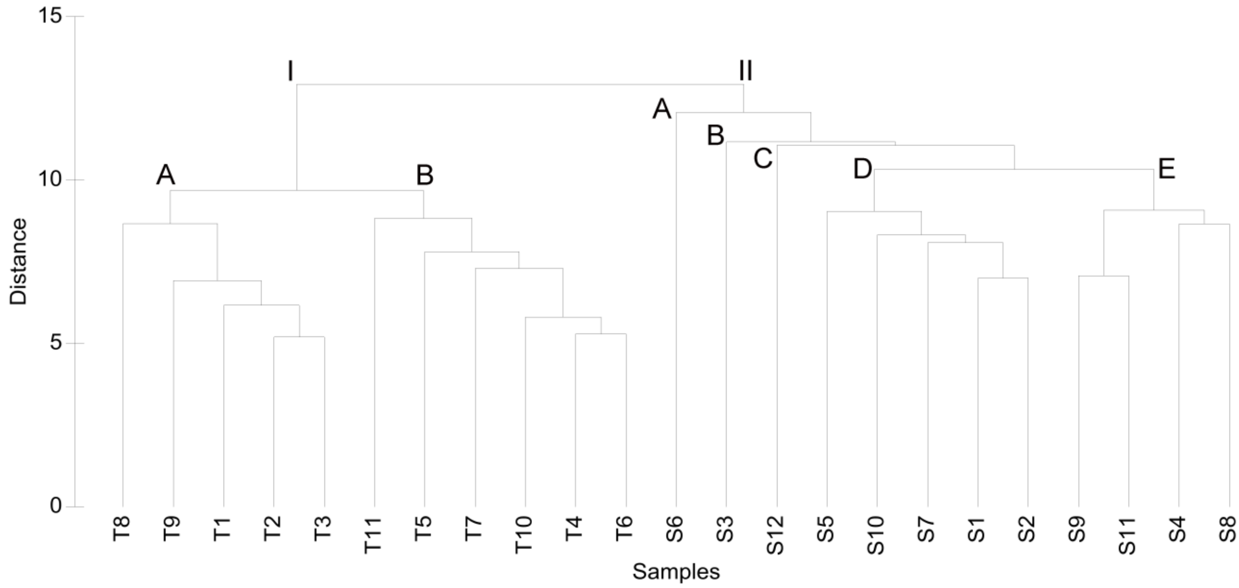

Fig. 2. Dendrogram obtained by average-linkage cluster analysis (CA) based on the Euclidean distance of 23 Italian sites. The CA separated Tuscan coastal sites (Group I) from Sardinian ones with a distance of ~ 13%. Sample abbreviations: S = Sardinia (Italy), T = Tuscany (Italy).

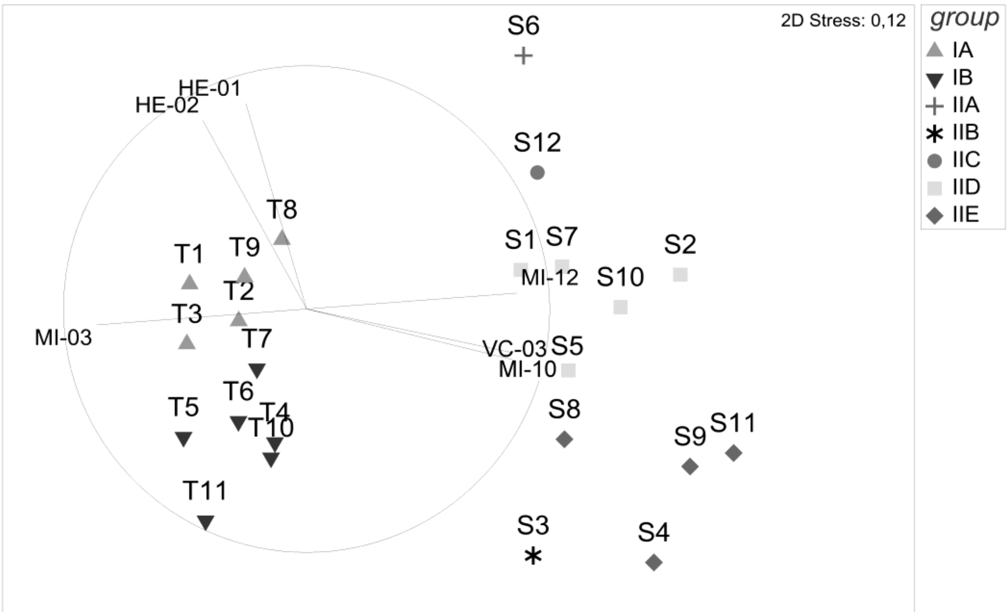

Fig. 3. NMDS diagram based on the dissimilarity (measured by the Euclidean distance) occurring in 23 Italian sites. All shown variables have a Spearman correlation coefficient > 0.8 with the two axes. Sample abbreviations: S = Sardinia, T = Tuscany. Variable abbreviations: HE-01 = visitor pressure, HE-02 = visitor frequency, MI-03 = width of intertidal zone, MI-10 = mean wave height, MI-12 = storm frequency, VC-03 = relative proportion of type II plants in the seaside of the frontal dune.

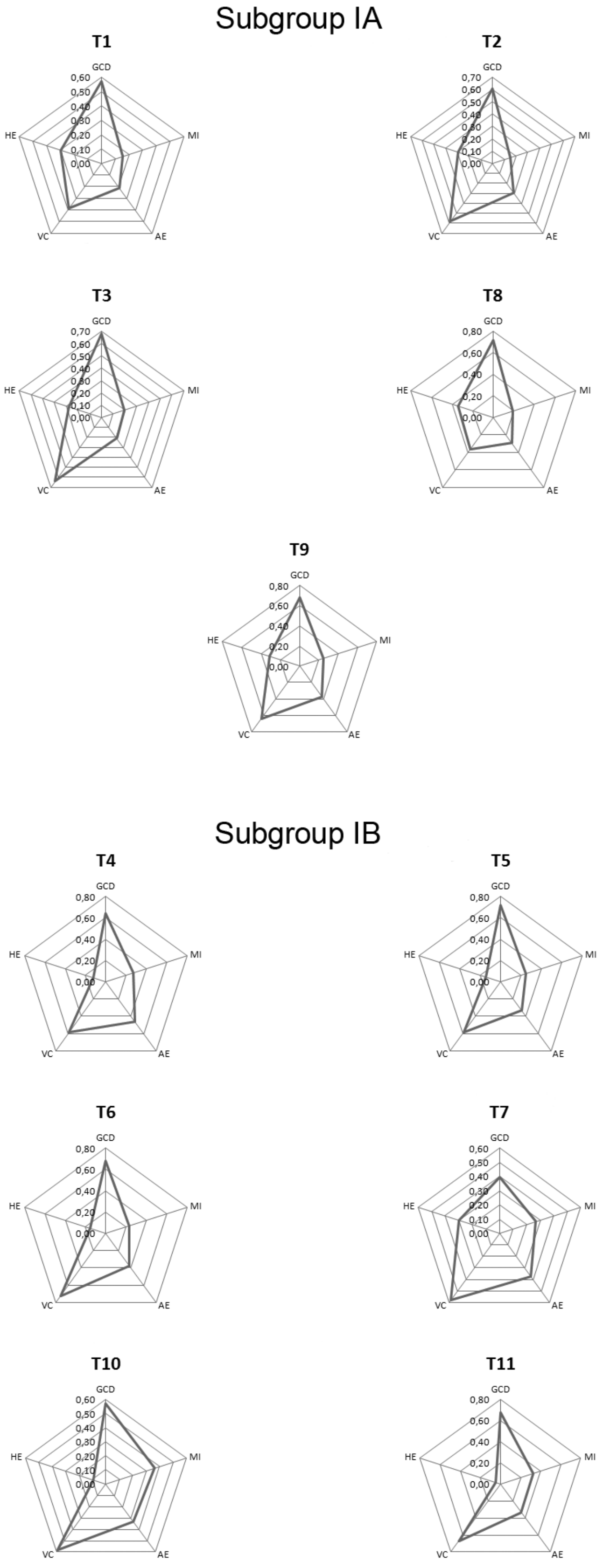

Fig. 4. Graphic representation of partial coastal dune vulnerability index of subgroup IA and IB sites.

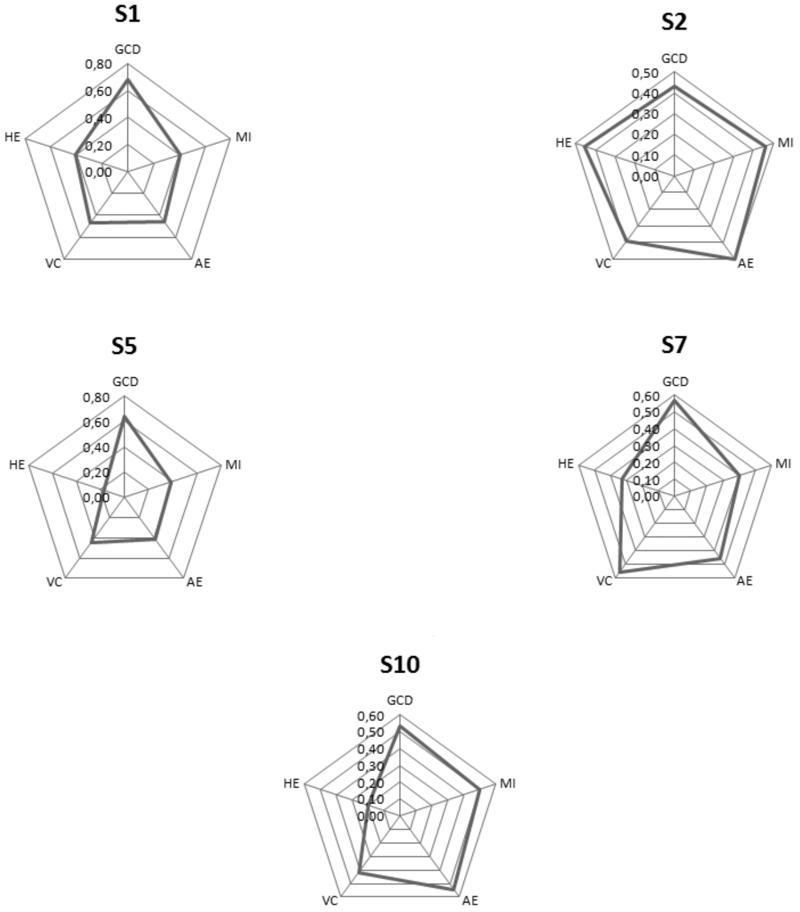

Fig. 5. Graphic representation of partial coastal dune vulnerability index of subgroup IID sites.

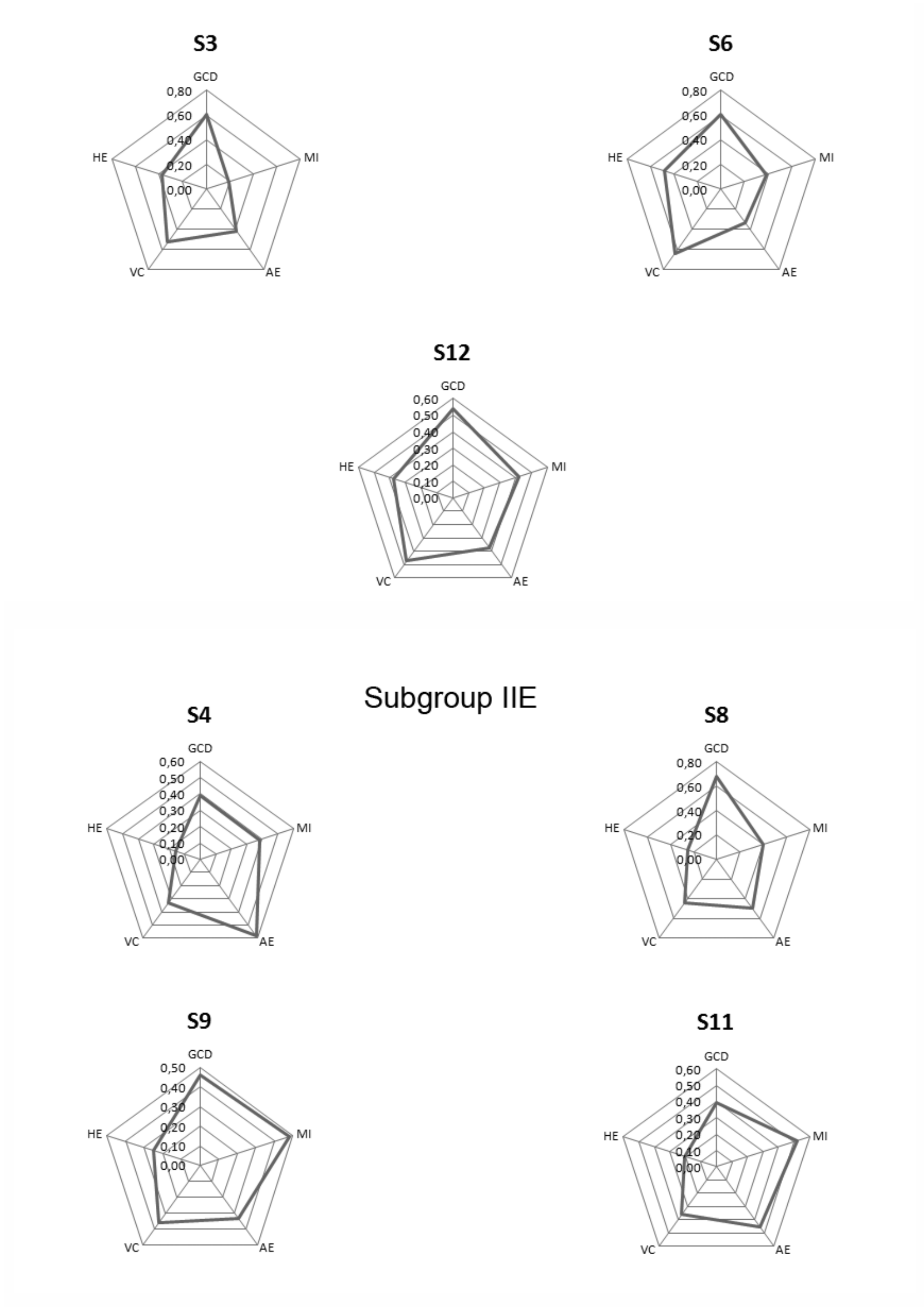

Fig. 6. Graphic representation of partial coastal dune vulnerability index of subgroup IIA-C and IIE sites.

Table 1

Variables considered in the coastal dune vulnerability classification procedure (adapted from García-Mora et al., 2001 and integrated with Idier et al., 2013). Class of vulnerability of each variable ranged from 0 (absence of vulnerability) to 4 (very high vulnerability).

	Variables	**Vulnerability class**				
	1. Geomorphological Condition of the Dune System (GCD)	**0**	**1**	**2**	**3**	**4**
1	Length of homogeneous active dune system (m)***	> 20	> 10	> 5	> 1	> 0.1
2	Average height of secondary dunes (m)***	> 25	> 10	> 5	> 1	< 1
3	Average height of frontal dunes (m)*	> 25	> 15	> 10	> 5	< 5
4	Foredune, slope steepness***	Moderate		Gentle		Steep
5	Relative area of wet slacks measured from map (%)*	Moderate		Small		None
6	Degree of dunes system fragmentation*	Low		Medium		High
7	Particle size of the frontal dune-Phi sizes*	< -1	0	1	2	3
	2. Marine Influence (MI)	**0**	**1**	**2**	**3**	**4**
1	Orthogonal fetch (km)*	< 25	< 100	< 250	> 500	> 1000
2	Berm slope (degrees)*	Moderate		Gentle		Steep
3	Width of intertidal zone (m)***	> 0.5	> 0.2	> 0.1	> 0.05	< 0.05
4	Tidal range (cm)***	< 2		2-4		> 4
5	Coastal orientation to wave direction (degrees)*	10-45°		0-10°		0°
6	Width of the zone between HWSM and dune face (m)*	> 75	< 75	< 25	< 10	0
7	Breaches in the frontal dune due to wash over, relative total area*	0	< 5%	< 25%	< 50%	> 50%
8	Particle size of the beach-Phi sizes*	0		0-2		> 2
9	Shoreline changes since 1980***	No retreating				Retreating
10	Mean wave height - MWH (m)**	≤ 0.5	0.5-1	1-1.25	1.25-1.4	> 1.4
11	Mean wave incident angle - MWA (°)**	≤ 10	10-15	15-25	24-40	> 40
12	Storm frequency - SF (event yr^{-1})**	≤ 5	5-15	15-25	25-35	> 35
13	Storm duration - SD (d)**	≤ 1	1-2	2-3	3-4	> 4
	3. Aeolian Effect (AE)	**0**	**1**	**2**	**3**	**4**
1	Sand supply input*	High		Moderate		Low
2	Blowouts: % of the system*	< 5%	< 10%	< 25%	< 50%	> 50%
3	If breaches-depth as % of dune height*	< 5%	< 10%	< 25%	< 50%	> 50%
4	Natural litter drift cover as % surface*	0	< 5%	> 5%	> 25%	> 50%
5	Pebble cover as % surface*	0	< 5%	> 5%	> 25%	> 50%
6	% seaward dune vegetated*	> 90	> 60	> 30	> 10	< 10
	4. Vegetation Condition (VC)	**0**	**1**	**2**	**3**	**4**
1	% cover of Type III plants in the beach*	> 50	> 25	> 15	> 5	< 5
2	% cover of Type III plants in the seaside of the frontal dune*	> 90	> 60	> 30	> 15	< 15
3	Relative proportion of Type II plants in the seaside of the frontal dune (% cover)*	< 5	< 15	< 30	< 60	> 60

4	Relative proportion of Type I plants in the seaside of the frontal dune (% cover)*	< 1	> 1	> 5	> 10	> 30
5	Relative proportion of alien species in the seaside of the frontal dune (% cover)*	0	< 1	< 5	< 15	> 15
6	Relative proportion of alien species along the transect (% cover)***	0	< 1	< 5	< 15	> 15
7	Relative proportion of endemics in the seaside of the frontal dune (% cover)***	> 1		< 1		0
8	Relative proportion of endemics along the transect (% cover)***	> 1		< 1		0
9	Number of associations along the transect***	≥ 5	4	3	2	1

	5. Human effect (HE)	**0**	**1**	**2**	**3**	**4**
1	Visitor pressure*	Low		Moderate		High
2	Visitor frequency*	Low	Moderate	High		
3	Access difficulty*	High		Moderate		Low
4	On dune driving*	None		Some		Much
5	On beach driving *	None		Some		Much
6	Trampling by animals***	None		Some		Much
7	Path network as percent of the frontal dune	0%	< 5%	> 5%	> 25%	> 50%
8	Anthropogenic litter: cover as % surface cover*	0%	< 5%	> 5%	> 25%	> 50%
9	Amount of sand (%) extracted for building etc. *	0%	< 5%	> 5%	> 25%	> 50%
10	Summer beach cleaning frequency (High is twice a day; medium, daily)*	Low		Moderate		High
11	% upper beach cleaned*	0	< 25	< 50	< 75	> 75
12	% permanent infrastructure replacing active dunes (roads, houses, etc.)*	0	< 25	< 50	< 75	> 75
13	% ephemeral infrastructure replacing active dunes (outdoor facilities, camping, etc.)*	0	< 25	< 50	< 75	> 75
14	Relative surface (%) forested in the system (200 m inland from the foredune)*	0	< 25	< 50	< 75	> 75
15	Relative surface (%) of agriculture in the system (200 m inland from the foredune)*	0	< 25	< 50	< 75	> 75
16	Grazing on the active system***	None	Low	Moderate	High	Intensive

Legend: (*) Parameters from García-Mora et al. (2001); (**) Parameters from Idier et al. (2013); (***) transformed or new parameters.

Table 2

Partial and total Mediterranean dune vulnerability index (MDVI) values for Tuscan (T) and Sardinian (S) sites.

Site	Location	GCD	MI	AE	VC	HE	MDVI
T1	Viareggio	0.57	0.15	0.21	0.39	0.30	0.32
T2	Torre del Lago	0.61	0.15	0.29	0.58	0.30	0.39
T3	Marina di Vecchiano	0.68	0.19	0.21	0.64	0.28	0.40
T4	San Rossore	0.64	0.27	0.46	0.58	0.13	0.42
T5	San Rossore	**0.71**	0.25	0.33	0.58	0.14	0.40
T6	San Rossore	0.68	0.23	0.38	**0.72**	0.16	0.43
T7	San Rossore	0.39	0.27	0.38	0.58	0.30	0.38
T8	Calambrone	**0.71**	0.19	0.29	0.36	0.34	0.38
T9	Principina	0.68	0.25	0.38	0.64	0.31	0.45
T10	Maremma	0.57	0.37	0.33	0.58	0.09	0.39
T11	Maremma	0.68	0.33	0.33	0.67	0.05	0.41
S1	Villasimius	0.68	0.40	0.46	0.47	0.41	0.48
S2	Chia	0.43	0.46	0.50	0.39	0.45	0.45
S3	S'Ena Arrubia-Abbarossa	0.61	0.19	0.42	0.53	0.38	0.42
S4	Maimoni	0.39	0.38	0.58	0.33	0.16	0.37
S5	San Giovanni	0.64	0.38	0.42	0.44	0.17	0.41
S6	Poetto	0.61	0.38	0.33	0.64	**0.48**	**0.49**
S7	Le Saline - Sant'Antioco	0.57	0.40	0.46	0.56	0.33	0.46
S8	Porto Botte-Is Solinas	0.68	0.40	0.50	0.44	0.25	0.46
S9	Is Arenas_Oristano	0.46	0.48	0.33	0.36	0.25	0.38
S10	Buggerru	0.54	0.50	**0.54**	0.42	0.20	0.44
S11	Piscinas	0.39	**0.52**	0.46	0.36	0.20	0.39
S12	Porto Pino	0.54	0.42	0.38	0.47	0.38	0.44

Abbreviations of five group of variables: GCD = Geomorphological condition, MI = marine influence, AE = aeolian effect, VC = vegetation condition, HE = human effect.

Table 3

Mean values (±SD) of partial and total Mediterranean dune vulnerability index (MDVI) values calculated for each group defined by cluster analysis (indicated by roman letters – see Fig. 4). Means followed by the same letters are not significantly different at 5% according to the non-parametric Kruskal-Wallis test after the Bonferroni correction for multiple comparisons.

Group	IA	IB	IID	IIE
GCD	0.65 ± 0.06^{a}	0.61 ± 0.12^{a}	0.57 ± 0.10^{b}	0.48 ± 0.14^{b}
MI	0.19 ± 0.04^{c}	0.29 ± 0.05^{b}	0.43 ± 0.05^{a}	0.45 ± 0.06^{a}
AE	0.28 ± 0.07^{b}	0.37 ± 0.05^{ab}	0.48 ± 0.05^{a}	0.47 ± 0.10^{a}
VC	0.52 ± 0.14^{ab}	0.62 ± 0.06^{a}	0.46 ± 0.06^{b}	0.38 ± 0.05^{b}
HE	0.31 ± 0.02^{a}	0.14 ± 0.08^{b}	0.31 ± 0.12^{a}	0.21 ± 0.04^{ab}
MDVI	0.39 ± 0.05^{a}	0.41 ± 0.02^{a}	0.45 ± 0.03^{a}	0.40 ± 0.04^{a}

Abbreviations of five group of variables: GCD = Geomorphological condition, MI = marine influence, AE = aeolian effect, VC = vegetation condition, HE = human effect.