RESEARCH PAPER

Implementing a Coastal Dune Vulnerability Index (CDVI) to support coastal management in different settings (Brazil and Italy)

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ABSTRACT

In this paper, the vulnerability of two dune fields located in southern Brazil (São Francisco do Sul Island) and western Italy (Tuscany) has been defined through the implementation of a Coastal Dune Vulnerability Index (CDVI). As the sites belonged to settings characterized by huge differences in terms of physical processes (Atlantic Ocean and Mediterranean Sea), the index has been adapted accordingly to minimize the influence of the dissimilarities in an attempt to define potential vulnerability parameters they might have in common. Five main groups of factors were taken into account in the design of the index: Geomorphological Condition of the Dune system (GCD), Marine Influence (MI), Aeolian Effect (AE), Vegetation Condition (VC), and Human Effect (HE) for a total of 51 variables. A total vulnerability index was calculated for each site. Cluster analysis and non-metric multidimensional scaling identified two main groups characterized by medium values of vulnerability (0.32 to 0.49): as a result, the vulnerability of both sites can be defined as “medium”. In more detail, GCD turned out to be the most influent factor on both settings; subordinately, marine influence also resulted relevant on the Oceanic site. The CDVI proved to be a flexible tool, as it was easily adjusted to work on such different sites. In this sense it will be of great support to increase the awareness of coastal managers and decision makers about the mutual interactions of many factors and processes that contribute to the evolution of coastal dunes regardless of the geographical setting.

1. INTRODUCTION

Coastal dunes are fundamental to the equilibrium of a coastal ecosystem (Hesp, 2002; Fenu et al., 2012), since they reduce the impact of the sea processes and their erosive effect on the coastline (Rocha et al*.,* 2003). Coastal dunes experienced severe stress in recent decades due to several human-related activities such as exploitation of natural resources, tourism, real estate and maritime activities (Carter, 1988; Martinez and Psuty, 2004; Maun, 2009; McLachlan et al., 2013; Botero et al*.,* 2015). Additionally, the natural processes add up to an even worse scenario thanks to sea level rise projections and increasing occurrence of high-energy events (Germani et al*.,* 2015). In Europe, 86 million people live less than 10 km from the coastline (ETC-CCA, 2011), with the result that coastal cities are densely populated and located within an extremely dynamic environment. The complexity of this environment justifies the worldwide concern about the rising sea level in the coming decades, which will intensify the impact of coastal erosion and flooding on coastal communities (Rao et al*.,* 2008; USAID, 2009; Özyurt and Ergin, 2010; IPCC, 2014; Germani et al*.,* 2015; Alsahli and AlHasem, 2016). Brazil is one example of the detrimental effects of the erosion process, and has been struggling to manage the effects all along its coasts (Mazzer, 2007; Mazzer and Dillenburg, 2009; Figueiredo, 2013; Ribeiro et al., 2013; Lima and Amaral, 2015; Alquini et al*.,* 2018). In Brazil, 50.7 million people occupy coastal areas or areas near the coast (IBGE, 2011). Developed countries such as United States, Nederland, England, Japan, Australia and Italy (Sathler,

2014) already incorporated climate policies in their urban planning and allocated part of the annual budget on improvements in urban infrastructure (*e.g.* construction of sea walls to contain the storm surges during high-energy events, underwater barriers that are raised in the event of flooding, wetlands restore, efficient alert systems, houseboats, waterways).

The technological improvement in image acquisition, in developing more efficient index-based tools and dynamic computational models has contributed to the rapid scientific growth of coastal monitoring methods (Bartolini et al., 2018). Devices such as drones provide a substantial boost to both terrestrial and underwater topography surveying; they are relatively cheap and easy to use compared to previous systems like LiDAR and multibeam, and are being utilized more and more for high-resolution data acquisition on the coastal environment (Scarelli et al., 2016; Scarelli et al., 2017; Garuglieri et al., 2019). The coastal vulnerability index proposed by Gornitz et al. (1994) for the USA coast is an example of an effective tool that provides useful indications about urban planning if integrated with the use of Geographic Information System (GIS) software (García-Mora et al*.,* 2001; Pereira and Coelho, 2013; Ribeiro et al*.,* 2013; Alexandrakis and Poulos, 2014). In addition, the index is easily upgradeable, and the outcome is quickly understood by coastal managers and practitioners (Satta et al*.,* 2016). There has been a significant increase over the last 15 years in the production of scientific papers involving the use of coastal vulnerability to classify the quality and the state of coastal areas. The vulnerability has been correlated to three main factors: i) rising sea level and flooding (Vafeidis et al*.,* 2008; Rao et al*.,* 2008; Özyurt and Ergin, 2009; Pendleton et al*.,* 2010; Kumar et al*.,* 2010; Thatcher et al*.,* 2013; Idier et al*.,* 2013; Germani et al*.,* 2015; Gaki-Papanastassiou et al*.,* 2015; Suganya et al*.,* 2015; Alsahli and AlHasem, 2016; Hereher, 2016); ii) erosion in the coastal zone (Menezes and Klein, 2006; Hegde and Reju, 2007; Boori, 2010; McLaughlin and Cooper, 2010; Palmer et al*.,* 2011; Kane et al*.,* 2012; Pereira and Coelho, 2013; Ribeiro et al*.,* 2013; Alexandrakis and Poulos, 2014); iii) vulnerability to natural and anthropogenic disturbances (Martínez and Psuty, 2004; Martínez et al*.,* 2006; Williams et al*.,* 2011; Tabajara et al*.,* 2013; Portz et al*.,* 2014; Ribeiro and Melo Jr., 2016; Ciccarelli et al*.,* 2017; da Costa

Cristiano et al., 2018). The vulnerability can be understood as, a) the result of an arrangement of different variables that are exposed to high-energy events and b) as the capacity of the system to recover from the effects of those conditions (Smit and Wandel, 2006; Ciccarelli et al*.,* 2017). Our research addressed the following questions: (1) Which parameters do affect the most the vulnerability of the dunes considering the different physical characteristics of the sites? (2) which actions should coastal managers take into consideration to develop appropriate strategies of conservation and management for these ecosystems in different parts of the world?

2. STUDY AREA

The study was carried out on two separate sites characterized by a well-developed coastal dune field (Figure 1), namely the São Francisco do Sul Island (Santa Catarina State, Brazil) and the Pisan coast (Tuscany, Italy). These areas were selected in order to compare the vulnerability index on two sites located in extremely different settings: the Atlantic Ocean and the Mediterranean Sea, respectively. Two stretches of beach of about 2 km in length were selected from both sites (A and B in Brazil; C and D in Italy) according to physical characteristics (accretion/erosion state), vegetation cover, and anthropogenic influence. On each sector 3 cross-shore transects were traced out from the shoreline to the woody vegetation, 12 transects as a whole. The plant communities of coastal sand dunes show different assemblages in different world regions because of climatic variability, geographic location, physiography of the dune system and other factors peculiar to each location (Maun, 2009).

São Francisco do Sul Island is located in the northern part of the Santa Catarina State (southern Brazil). The geological setting of the Brazilian coast is related to the opening of the Atlantic Ocean during the Mesozoic. In particular, the northern sector of the Santa Catarina State is considered part of a broad structural arc that extends from Cabo Frio (23°S) to Florianópolis (28°S). The Santos sedimentary basin is comprised within the arc and has been filled by sediments coming from the Serra do Mar range, which formed in the Upper Cretaceous (Angulo et al., 2009). São Francisco do

Sul Island is presently defined by a western sector where pre-Mesozoic metamorphics and igneous rocks outcrop in hills and headlands, and by an eastern sector mainly characterized by a sequence of two strandplain systems, Pleistocenic and Holocenic in age (Possamai et al., 2010). The two sectors (A and B) are located in the eastern coast along Grande beach, which is the island's longest beach (about 18 km long), facing the Atlantic Ocean. The northern sector (Figure 2A) is mainly defined by a series of NNE oriented parabolic dunes, with maximum frontal dune height of 6 m; the maximum backshore width is about 25 m. Conversely, the dune field in the southern sector is different than those to the north: it is characterized by transverse dunes with lower crest heights (Figure 2B). The vegetation is not characterized by the same association throughout the study area: Sector A shows lower species diversity, among which there are some exotic species, such as *Centella asiatica*, *Cyperus* sp, *Brachiaria* sp, and *Portulaca oleracea*. The exotic species are not present in Sector B. The vegetation cover is usually decreasing from the primary dunes to the secondary dunes, except for two transects (B1 and B2) in Sector B. The whole area is encompassed within the Acaraí State Park, which is a Conservation Unit established by State Decree 2005/3517 due to high naturalistic relevance (PROBIO, 2003; Melo Júnior and Boeger, 2015). In accordance with the classification of Köppen (1948) the climate is mesothermic (Cfa) with hot summer; the annual rain precipitation is comprised between 1600 and 1900 mm and the annual mean air temperature range between 20 and 22 °C (Alvares et al., 2013). The most frequent wind direction is from SW, subordinately from NE and S; the predominant wave directions are from SE and E. The strongest storms in terms of significant wave height most frequently occur from SSE, with typical values ranging from 1 to 3.5 m; the littoral drift is northwards trending (Alquini et al*.,* 2016b). Tidal range is mesotidal, on average between 1.3 and 1.9 m (Bogo et al*.,* 2015). The beaches are generally composed of medium sands (Abreu, 2011).

The Pisan coast is located in the central part of Tuscany (western Italy). It developed on two coastal plains (Viareggio and Pisa plains) that overlie the Viareggio extensional basin, which is a half-graben (active since late Miocene) roughly parallel to the NW-SE oriented Apennines chain

(Mariani and Prato, 1988). This formation is associated to the opening of the Tyrrhenian Sea back-arc basin (Malinverno and Ryan, 1986). In particular, the Pisa plain was formed by sediments supplied by the Arno and Serchio rivers: alternations of alluvial and nearshore deposits related to the last two glacial-interglacial cycles suggest the identification of several transgressive-regressive sequences (Amorosi et al., 2013; Sarti et al., 2017). The coastal dune field in this area is defined by a dune ridge system composed of transverse dunes, which can be identified up to 3 km inland. The northern sector is well developed (backshore width more than 50 m and frontal dune height of about 4 m) and shows no sign of coastal erosion effects (Figure 2C). Erosion processes are more active in the southern sector (Figure 2D), where the backshore is narrow (about 10 m wide) and the frontal dune quite high (9 m) but subjected to scouring at the toe (Bertoni et al., 2014). Plant communities follow a typical coast-to-inland zonation starting from the annual vegetation of the strandline zone of the beach, through the embryonic and mobile dunes, to the shrubby communities of the fixed dunes (Ciccarelli, 2014; Ciccarelli, 2015). The two sectors, C and D, are comprised within the northern Tuscany littoral cell (from Livorno to the River Magra's mouth, about 65 km long), facing the Ligurian Sea. The whole area is encompassed within the Migliarino – San Rossore – Massaciuccoli Regional Park, which is a Conservation Unit established by Region Tuscany (decree n.61, December 13th, 1979). It is characterized by a Mediterranean sub-humid climate according to Rapetti and Vittorini (2012). The mean annual temperature is about 15 °C and mean rainfall is 800-900 mm (Ruocco et al*.*, 2014). The prevailing winds in this region are southwesterly, while the average wave height is less than 0.5 m; tidal range is microtidal, hardly over 0.3 m (Bertoni et al*.*, 2012). Beach sediments are characterized by medium sand (Bertoni and Sarti, 2011). Ancient dune ridges extend along almost the entire length of the Park, whereas modern and active dunes are sometimes interrupted by man-made structures (Bertoni et al*.*, 2014). Littoral drift is northward-trending on the right side of the River Arno's delta (Pranzini, 2001).

3. MATERIALS AND METHODS

3.1. Coastal dune vulnerability index

The coastal dune vulnerability index (CDVI) developed for this research was based on protocols conceived by García-Mora et al. (2001) for the Spain coast (Gulf of Cadiz, Atlantic Ocean) and by Idier et al. (2013) for three different sectors along the France coast (Atlantic Ocean, English Channel and Mediterranean Sea), subsequently modified and adapted to other Mediterranean Sea sites by Ciccarelli et al. (2017). The index considers 51 variables (35 variables are related to the biotic and abiotic factors and 16 variables are related to human activities) distributed in five groups of parameters (Table 1): Geomorphological Condition of the Dune system – GCD; Marine Influence – MI; Aeolian Effect – AE; Vegetation Condition – VC; and Human Effect – HE. The index is based on a semi-quantitative approach (García-Mora et al., 2001; Williams et al., 2001; Judge et al., 2003), and was calculated by associating each value of the variables to a label categorized in a five-point scale, ranging from 0 (no vulnerability) to 4 (very high vulnerability). This range of categories is in accordance with the method of calculation firstly reported in Gornitz et al. (1991), and successively improved by Gornitz and White (1992). The sum of the variables within the above-mentioned groups was divided by the sum of the maximum achievable rating within each group, thus generating a partial index expressed as a percentage. The total CDVI was calculated on the unweighted average of the five partial indices through the algorithm:

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

Based on the different scale of the settings, two variables (namely the length of homogeneous active dune system and the width of intertidal zone) were adapted to the oceanic features in order to make the index applicable to the Brazilian coast by changing the unit of measure from meter to kilometer.

3.2. Data collection for the beach system

The geomorphological variables (Table 1) were defined through a series of topographic surveys using a Leica RTK-GPS instrument. The surveys were conducted recording a point with the GPS at each slope change along the cross-shore transect in order to reconstruct the beach profile while post-processing the raw data. The real-time differential correction allowed us to reach an accuracy of about 1 cm in all three dimensions. The differential correction was obtained connecting the GPS to fixed reference bases located close to the study areas (Estação Geodésica de Araquari for the Brazilian site and Madonna dell'Acqua base station for the Italian site). The collected data were then processed in QGIS 2.8.2 in order to obtain indications about the topographic parameters of the beaches (e.g., beach width and length, dune length and height, beach slope, etc.). The reference datum was South American Datum 69 (Universal Transverse Mercator, zone 22S) in São Francisco do Sul, and Roma 40 (Gauss-Boaga, zone 1) in Italy. The sedimentological characterization was carried out sampling the Brazilian beach in October 2015, while data about the Pisan coast were gathered from the literature (Bertoni and Sarti, 2011; Ruocco et al*.*, 2014). Sediment collection and grain-size analysis followed the procedure used in the Mediterranean site in the cited references: samples of about 0.5 kg were collected from the surface along cross-shore transects that started from the back-dune area up to the foreshore. Sampling points were chosen from geomorphological elements (foreshore, backshore, dune ridge, etc.) and vegetational features (frontal dune vegetation, back-dune vegetation, etc.). The samples were heated to 50°C for 24 hours to dry and to remove excess moisture, and then dry-sieved for 10 minutes using half-phi mesh interval sieves. The sedimentological characterization was carried out extracting the Folk and Ward (1957) parameters such as Mean (Mz) and Sorting (σ). The shoreline evolution was based on the evaluation of the coastlines traced out from orthophotographs spanning from 1938 to 2010 for the São Francisco do Sul Island (Alquini et al*.*, 2018) and from 1938 to 2014 for the Pisan coast (Bini et al*.*, 2008; Casarosa, 2016). Diretoria de Hidrografia e Navegação (DHN, available at the website http://www.mar.mil.br) and Servizio Idrologico Regionale (SIR, available at the website http://bit.ly/2cxGESt) provided data about the tidal range for the Brazilian and the Italian sites respectively. Wave data from the São Francisco do Sul Island were obtained from the literature (Alves, 1996). Wave data from the Pisan coast were also provided by Servizio Idrologico Regionale (http://bit.ly/2cxGESt). Wind data for the Brazilian site were gathered from Zular (2011), while those for the Italian site were provided by Consorzio LaMMA (available at the website http://www.lamma.rete.toscana.it/).

The vegetation characterization was carried out using plots of 2 x 2 m along the same transects that were traced out for topographic and sedimentologic analyses. The selection of the locations for the vegetation assessment was random. The percentage of vegetation coverage was estimated by a visual identification of the species (Causton, 1988; Ciccarelli et al., 2017). The taxonomic nomenclature of the Brazilian species followed Christenhusz et al. (2011) and APG IV (2016); species names and authors were in accordance with the Species List of the Botanical Garden of Brazil Flora of Rio de Janeiro (available at the website http://jbrj.gov.br/nosso-jardim/plantas). The taxonomic nomenclature of the Mediterranean species followed Conti et al. (2005) and Conti et al. (2007) for native species and Arrigoni and Viegi (2011) for alien species. The classification of plant functional types (PFT) were in accordance with the classification of García-Mora et al. (1999). Fieldwork on the Brazilian site was carried out in October, 2015, and on the Italian site in May, 2016.

A photo-interpretation of digital orthophotographs was carried out to obtain information about the variables related to human activities: the images were shot in 2010 for the Brazilian site (aerial orthophoto at 1:10000 scale, 3985 m flight altitude; survey commissioned by the municipality of São Francisco do Sul - Secretaria de Estado do Desenvolvimento Sustentável - and carried out with digital aerial cameras directly integrated in the georeferencing systems) and in 2013 for the Italian site (aerial orthophoto at 1:10000 scale, 4800 m flight altitude; survey commissioned by Regione Toscana and carried out with an ads40 camera). The percentage of natural origin waste, gravel cover and other variables was visually estimated on the field. All types of infrastructure (such as buildings, parking lots, resorts, lifesavers, streets, etc.) were considered in regards to the variable "visitor pressure".

3.3. Statistical analysis

A matrix of 51 variables x 12 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 optimizing 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 correlated the most to the NMDS axes. The nonparametric 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. Cluster analysis and NMDS was calculated with the software Primer 6.0 (Clarke and Warwick, 2001), the nonparametric test of Kruskal-Wallis with Bonferroni correction was performed using R statistical software (R Development Core Team, 2019) using the "vegan" package (Oksanen et al., 2012).

4. RESULTS

The results of the total CDVI ranged from 0.32 in C2 and C3 to 0.49 in A2 (Table 2). The average total CDVI was 0.46 for the Brazil sites and 0.35 for the Italian sites. The partial GCD showed high vulnerability values for the two countries, ranging from 0.71 (B2, B3 and D1) to 0.79 (D3). The cluster analysis revealed two groups (I and II) and four subgroups, with a Euclidean distance of ~13% (Figure 3). *Group I* was characterized by the Brazilian sites and can be further divided into two subgroups made of transects B1, B2 and B3 (Zone B) and transects A1, A2 and A3 (Zone A) respectively.

Group II is characterized by the Italian sites and can be further divided into two subgroups made of transects C1, C2 and C3 (Zone C) and transects D1, D2 and D3 (Zone D) respectively. This classification was supported by NMDS (Figure 4), which resulted in a distinct separation (the stress value of 0.04 corresponds to a very good ordination) between locations (Brazil and Italy) along the horizontal axis, and between the two sites within the locations (Zone A - Zone B; Zone C - Zone D) along the vertical axis. The Brazilian sites were dominated along the horizontal axis by marine influence (MI3-4, MI6-8) and geomorphological factors (GCD1), while along the vertical axis transects A1-A3 were particularly influenced by human effect (HE1, HE2, HE7, HE14). The Italian sites resulted to be mainly affected by, a) human effect (HE16), b) aeolian effect (AE6) and c) geomorphological factors (GCD2) along the horizontal axis. Similarly to Brazilian Zone A, the Italian transects C1, C2 and C3 were influenced by human effect (HE1, HE2, HE7, HE14) along the vertical axis.

The analysis of the average CDVI of Zone B (B1, B2 and B3) showed high values of GCD (0.73), and low values of HE (0.14) in the Brazilian sites (Table 3 and Figure 5). In contrast, Zone A (A1, A2 and A3) showed high values of GCD (0.74), medium values of MI (0.53), and moderate value of AE (0.27). The analysis of the average CDVI in the Italian sites (Table 3 and Figure 6) revealed that Zone C (C1, C2 and C3) was characterized by medium values of GCD (0.59), moderate values of VC (0.45), and low values of MI (0.13), while Zone D (D1, D2 and D3) by high values of GCD (0.75) and low values of MI and HE (0.19).

The Kruskal-Wallis test (Table 3) revealed statistical differences in the partial vulnerability indices between Brazilian and Italian sites regarding MI and HE variables. No differences were found for the total dune vulnerability indices of each group or subgroup.

5. DISCUSSION

Based on all the analyses that have been carried out, the overall vulnerability for the two investigated sites can be classified as *medium*, which translates to the medium class in accordance with García-Mora et al. (2001), as the average values for the Brazilian site (A and B) and the Italian site (C and D) are 0.46 and 0.35 respectively (Table 2). In more detail, the resulting vulnerability of Zone A at the São Francisco do Sul Island is 0.47 ± 0.02 (Table 3). The group includes the sites localized in the northern sector of the São Francisco do Sul Island (A1, A2 and A3), which are characterized by parabolic dunes of NNE orientation. This system is seriously affected by erosion processes that lead to scouring at the base of the frontal dune, which generates a steep escarpment at the transition between backshore and dunes. The frequent occurrence of high-energy waves is a possible consequence of this process. Coastal erosion is a global problem, but it affects primarily sandy beaches (*e.g.*, Grande beach) because they are constituted by loose, fine sediments that can be easily entrained and transported elsewhere even under mild-energy wave conditions (Muehe, 2006; Neves and Muehe, 2008; Abreu, 2011). Though recent studies proved that also pebble-sized sediments can be significantly displaced by low-energy waves (e.g., Grottoli et al., 2019), gravel beaches are more stable and less susceptible to erosion processes (Masselink and Hughes, 2003). As sand beaches are usually characterized by lower steepness than gravel beaches, they are also more vulnerable to coastal submersion. Santa Catarina State has been subjected to harsh erosion processes that affected large portions of urbanized coastal areas. The collapse of the frontal dune wipes out the structure of the embryonic dune (Maun, 2009), causing loss of biodiversity and holding back the local biological succession (Ciccarelli, 2014). Vegetation Condition (VC) was classified with medium values of vulnerability (average of 0.44): as a matter of fact, Grande beach is characterized by a high dominance of *Scaevola plumieri* and *Spartina ciliata*, which are species known as dune builders (Miot da Silva, 2006; Ripley and Pammenter, 2004); in addition, they usually reduce the reproduction rate in stable environmental conditions (Maun, 1985). Because the proximity of this area to the beach resorts built on Grande beach produces high rates of human pressure, this critically affects the evolution of the dune field (HE: 0.35, medium vulnerability). The negative effects are represented by: *i*) destruction of vegetation due to trampling, which prevents other plants from growing and leads to weed invasion; *ii*) vehicle traffic/parking on blowouts areas and frontal dunes; *iii*) mechanical/manual cleaning of beaches, which is intensified during the summer period; and *iv*) litter eviction in the backdune area. This observation is in accordance with the concerns raised by other authors, who claim that in recent decades the degradation of the *restinga* vegetation, which is typical of Brazil, is mainly caused by human-related activities (Falkenberg, 1999; Rocha et al*.*, 2003; Thomazi et al*.*, 2013; Melo Júnior and Boeger, 2015).

On regards to Zone B (B1, B2 and B3) the resulting vulnerability is similar to that of Zone A, as it falls in the medium interval (0.45 ± 0.02, Table 3). The NMDS pointed out that visitor pressure, visitor frequency, and path network as percentage of the frontal dune were the most critical variables for this site. The most vulnerable parameters are GCD, MI, and AE, ranging from medium to high vulnerability. The coastal dunes in the southern sector are morphologically lower compared to those of the northern sites; they are constituted by transverse dunes with no hints of blowout occurrence. Likewise, the base of the foredunes is subjected to scouring processes: despite the erosion effects, the frontal and steady dune plant coverage is dense and characterized by rapid transition from shrubs to woody vegetation. Human pressure was defined by anthropogenic litter, especially in B4 site, and path network in the steady dune.

Moving to the Mediterranean location, Zone C (C1, C2 and C3) shows a vulnerability value of 0.33 ± 0.01 (Table 3). The results remarked that the variables that mostly affected the segregation of the transects were visitor pressure and visitor frequency (Figure 4). Zone C is constituted by a coastal dune ridge system (transverse dunes) that extends for about 1-3 km away inland (Bertoni and Sarti, 2011); it is characterized by a wide backshore and a large backdune area (Ruocco et al., 2014), which are currently in accretion (Casarosa, 2016) because of the northward-trending littoral drift (Aiello et al., 1975). The large backdune area (~160 m on average) creates micro-environments (Hesp et al., 2011) that favor the growth of different plant communities more or less tolerant to the abiotic variables (Ciccarelli et al., 2012; Ciccarelli, 2014; Ruocco et al., 2014). An example of abundant stress-tolerant species in the Mediterranean is the *Ammophila arenaria* (Acosta et al., 2007; Ciccarelli, 2015), mainly found on the mobile dunes. The anthropic pressure (HE1/HE2) was classified with medium values of vulnerability; the main disturbing factors to the dune field resulted to be path network, beach cleaning programs, beach resorts, and the relative surface (%) forested in the system (200 m inland from the foredune). This is in accordance with a recent report (ISPRA, 2014) that evaluated the main factors threatening the Mediterranean coast. Subordinate to the above-mentioned disturbing factors, erosion, presence of solid waste, trampling, expansion of agricultural areas, and fire, are all aspects affecting the vulnerability assessment in this site. As well as the other groups, the vulnerability of Zone D (sites D1, D2 and D3) falls in the medium class, as it resulted 0.40 ± 0.03 (Table 3). This site is characterized by significantly shorter profiles in comparison to Zone C; it is also highly variable in terms of morphological features (Bertoni and Sarti, 2011). The dune system can reach a height of about 9 m, sometimes interrupted by blowouts; in the most critical points the foredunes are practically nonexistent (*e.g.*, site D3). The narrow backshore exerts little wave energy dissipation during the extreme events: waves reach the base of the frontal dune, causing scour of the dune, and its collapse eventually (Alquini et al., 2016a). The result of this process is the formation of an extremely steep scarp. Even though the overall vulnerability for this stretch of coast was defined as medium, the values regarding the geomorphological variables were extremely high, especially in D3 site (GCD 0.79). The VC was classified as medium (average of 0.42). The low number of species sampled in this sector probably confirms the stress caused by rapid morphological changes in the dune field, which are not tolerated by all the species (Bertoni et al., 2014; Ruocco et al*.,* 2014). This result points out that the erosion can cause absence of plant communities in the embryonic dune (AE6), which is consistent with the findings described by Ciccarelli et al. (2012). Many authors claim that the distance to the coastline is a determining factor in the floristic composition of the Mediterranean dunes (Guara-Requena, 1989; Houle, 2008; Nordstrom et al*.,* 2009; Angiolini et al*.,* 2013). At last, the significance of MI and HE can be defined as low in terms of vulnerability.

The resulting data from the Atlantic and Mediterranean locations allowed us to respond to the two questions we posed as aims to the research. Concerning the first question, the present data shows that the most significant variables affecting the vulnerability of the coastal sites were the average height and length of active dune systems, the marine negative influence, the percentage of vegetated seaward dune, and human disturbance. In particular, the highest values of vulnerability were recorded in the geomorphological group, which includes the major differences in physical processes and characteristics between the Mediterranean and the Atlantic sites.

The morphology of coastal dunes is the result of the synergy between sand depositions, wind action and vegetation, which is alike on every coast on the globe in both temperate and cold climates. Plant species colonizing the dunes vary geographically, but often share the same adaptive responses to the environment (Maun, 2009). In this sense, beach and dune morphological characteristics such as active dune length and height are critical factors even though the physical processes acting on each setting are different. Increasing the awareness about these data allows us to answer to the second question, suggesting the need to improve the consideration of GCD factors when coastal managers are called to recommend the best practices in terms of protection and conservation schemes. Coastal managers should be encouraged to implement actions dedicated to improving the quality and the frequency of monitoring activities of GCD parameters using as many surveying systems as possible. Ground instruments such as RTK-DGPS devices should be used to validate subaerial topographic data acquired from remote sensing systems (e.g., LiDAR, satellite photogrammetry) in order to optimize time and resources while not decreasing the quality of the outcome. Underwater topography should also be addressed with single- or multi-beam equipment at least twice per year, as no survey can be considered thoroughly complete without merging terrestrial and subaqueous data. According to Ciccarelli et al. (2017), coastal managers are encouraged to minimize human pressure, particularly where vulnerability was due to this group of variables (i.e. A1, A2, A3). Moreover, all restorations actions should promote the natural dune forming processes with the reintroduction of native dune builder plants (Martínez et al., 2006). However, we reiterate that the predictive significance of a CVI is always dependent upon quality and homogeneity of data input. This aspect might severely affect data replicability and compromise comparisons between different sites. Currently there are no clear-cut guidelines about how to acquire/collect the data that will be used to calculate the CVI, for instance taking into consideration also the effects that instrument accuracy, survey frequency, etc. may have on CVI outcome. In this sense we are working on a standard, replicable protocol that should be followed by anyone who is willing to apply a CVI on a given site. Finally, a multidisciplinary approach must be implemented to exploit every surveying/analysis technique to match and compare all the data acquired from different sources (Bartolini et al., 2018). The index can also be used for different purposes, such as the prioritization of the factors that mostly affect shoreline evolution (Hegde and Reju, 2007; Alexandrakis and Poulos, 2014), human pressure (Coelho et al*.,* 2006) and spatial/temporal evolution of the vulnerability (Idier et al*.,* 2013).

6. CONCLUSIONS

The resulting data from the Atlantic and Mediterranean locations highlight that the most important parameter affecting the vulnerability is GDC. Vulnerability was also affected by MI and HE parameters with different weights depending on the different locations studied. It is essential for coastal managers to take this outcome into close consideration because especially GDC and MI factors are not easy to control. They should be encouraged to monitor the physical processes contributing to subaerial and underwater geomorphological changes in accordance with integrated approaches (Bartolini et al., 2018) and using modern techniques that provide continuous, low-cost data acquisition (e.g., Pozzebon et al., 2018), and remote sensing (e.g., Splinter et al., 2018). This prudent course of action will put the emphasis of the "problems-solutions" binomial on solutions. Though it will not be a definitive solution, it will lead to a substantial weakening of GDC vulnerability by raising the resilience of dune systems by increasing their adaptive capacity in response to disturbance conditions (e.g., storms, erosion, sea-level change, anthropogenic pressure). The promising results demonstrated by the present study encourage the widespread application of this approach, developing adjustments to different settings in order to contribute to the coastal management in an efficient and flexible way.

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Figure captions

Figure 1. Localization of the study sites. A: Brazil (background map LiDAR 2010 commissioned by Prefeitura de São Francisco do Sul); B: Italy (background map LiDAR 2016 commissioned by Regione Toscana). The black squares with the red dots point out the exact location of the transects.

Figure 2. Pictures of the four sites where the surveys have been carried out. A: Zone A, northern sector of the Brazilian site; B: Zone B, southern sector of the Brazilian site; C: Zone C, northern sector of the Italian site; D: Zone D, southern sector of the Italian site (see Figure 1 for exact locations).

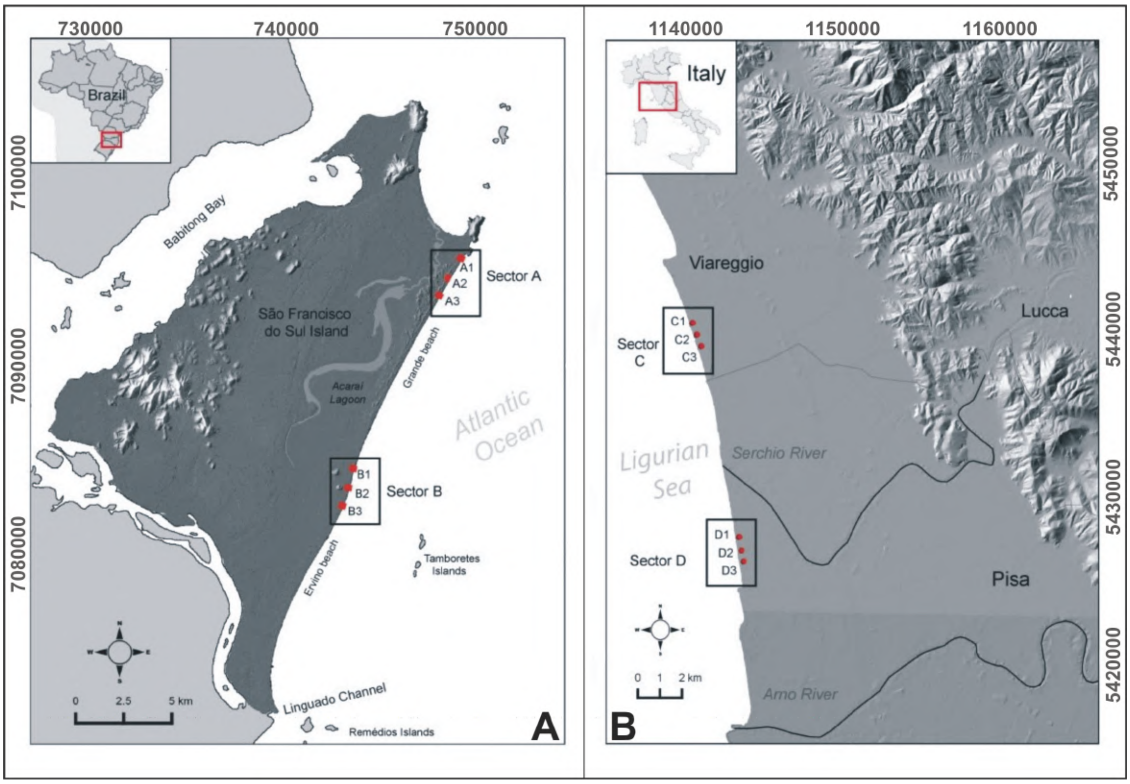
Figure 3. Dendrogram obtained by average-linkage cluster analysis (CA) based on the Euclidean distance of 12 Brazilian and Italian sites. The CA separated Brazilian coastal sites (Group I) from Italian ones (Group II) with a distance of ~13%. Sample abbreviations: B and A = Brazilian sites; C and D = Italian sites (see Figure 1 for exact locations).

Figure 4. NMDS diagram based on dissimilarity (measured by Euclidean distance) for 12 dune sites. All shown variables have a Spearman correlation coefficient > 0.8 with the two axes. Sample abbreviations: A and B = Brazilian sites; C and D = Italian sites (see Figure 1 for exact locations). Variable abbreviations: visitor pressure (HE1), visitor frequency (HE2), percentage of vegetated seaward dune (AE6), average height of second dunes (GCD2), percentage of relative surface forested in the system (200 m inland from the foredune) (HE14), grazing on the active dunes (HE16), particle size of the beach (MI8), width of the intertidal zone (MI3), width of the zone between HWSM and dune face (MI6), length of homogeneous active dune systems (GCD1), tidal range (MI4), breaches in the frontal dune (MI7), path network as percentage of the frontal dune (HE7).

Figure 5. Graphical representation of CDVI partial values for Zone B and A.

Figure 6. Graphical representation of CDVI partial values for Zone C and D.

Figure 1

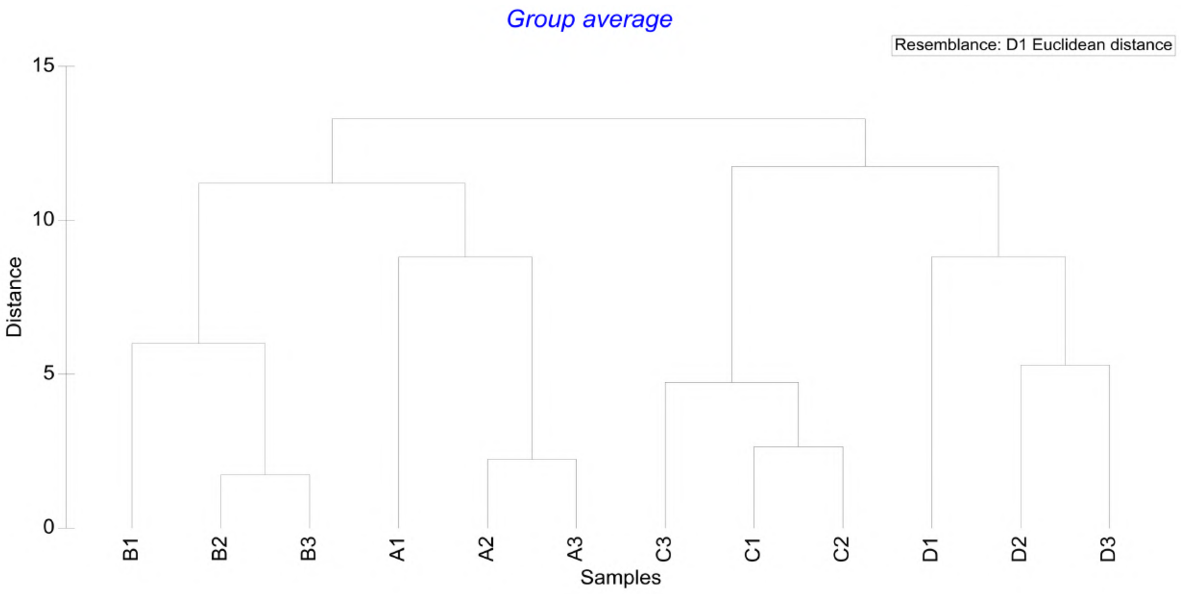

730000
740000
750000
7100000
7090000
7080000
Brazil
Babitong Bay
São Francisco do Sul Island
Sector A
A1
A2
A3
Grande beach
Acaraí Lagoon
Atlantic Ocean
Sector B
B1
B2
B3
Ervino beach
Tamboretes Islands
Linguado Channel
Remédios Islands
0
2.5
5 km
A
1140000
1150000
1160000
5450000
5440000
5430000
5420000
Italy
Viareggio
Lucca
Sector C
C1
C2
C3
Ligurian Sea
Serchio River
Sector D
D1
D2
D3
Pisa
0
1
2 km
Arno River
B

803 Figure 2

804

805

Figure 3


Group average
Resemblance: D1 Euclidean distance
Distance
15
10
5
0
B1
B2
B3
A1
A2
A3
C3
C1
C2
D1
D2
D3
Samples

809 Figure 4

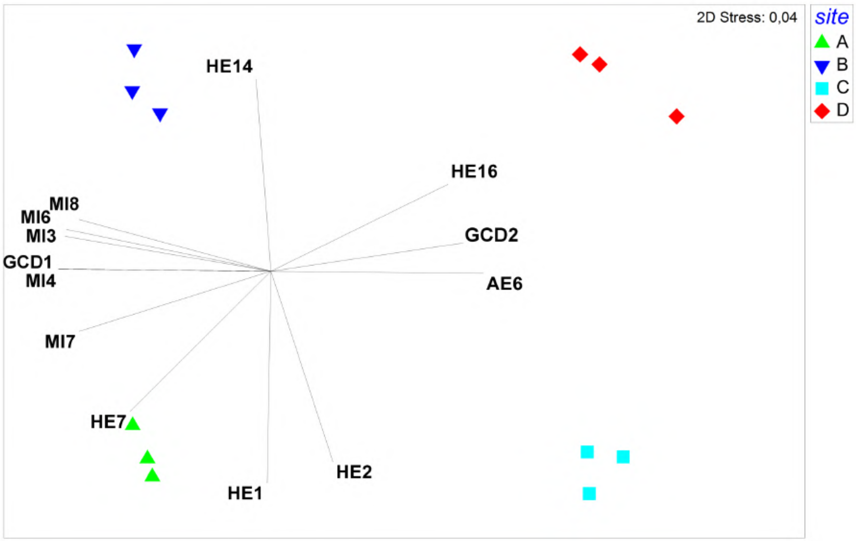


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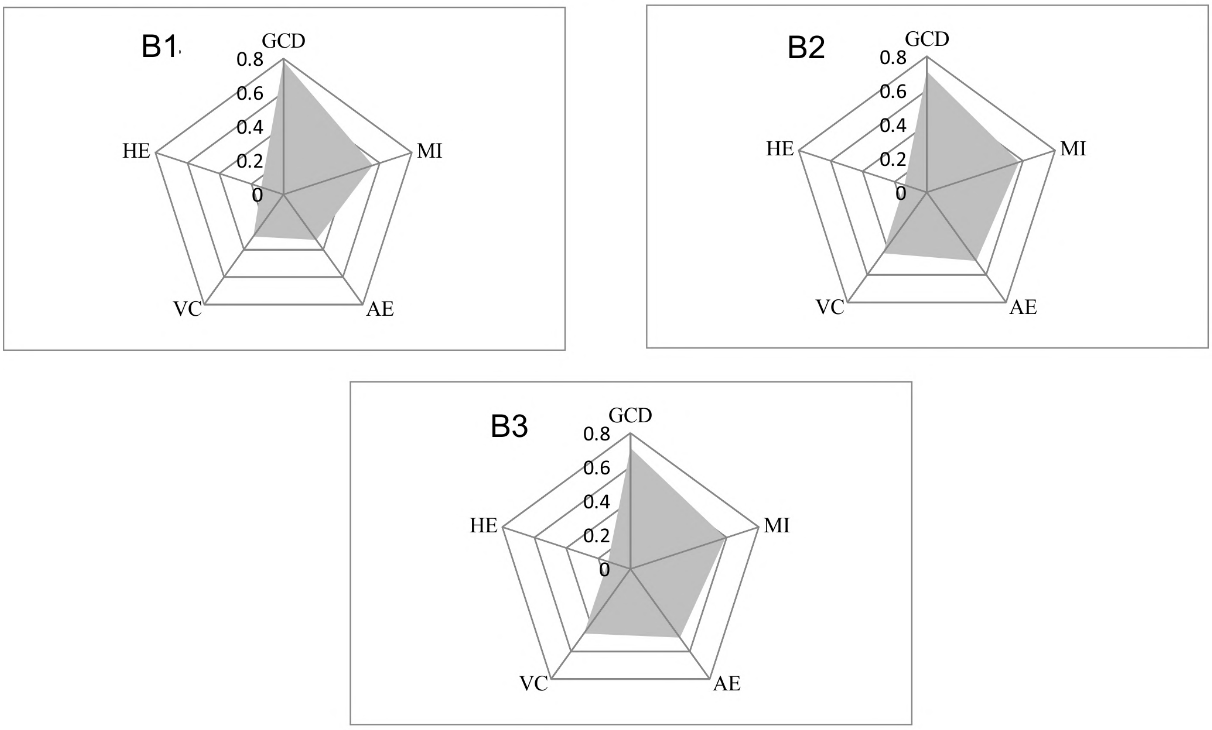
Figure 5

Zone B



Zone A

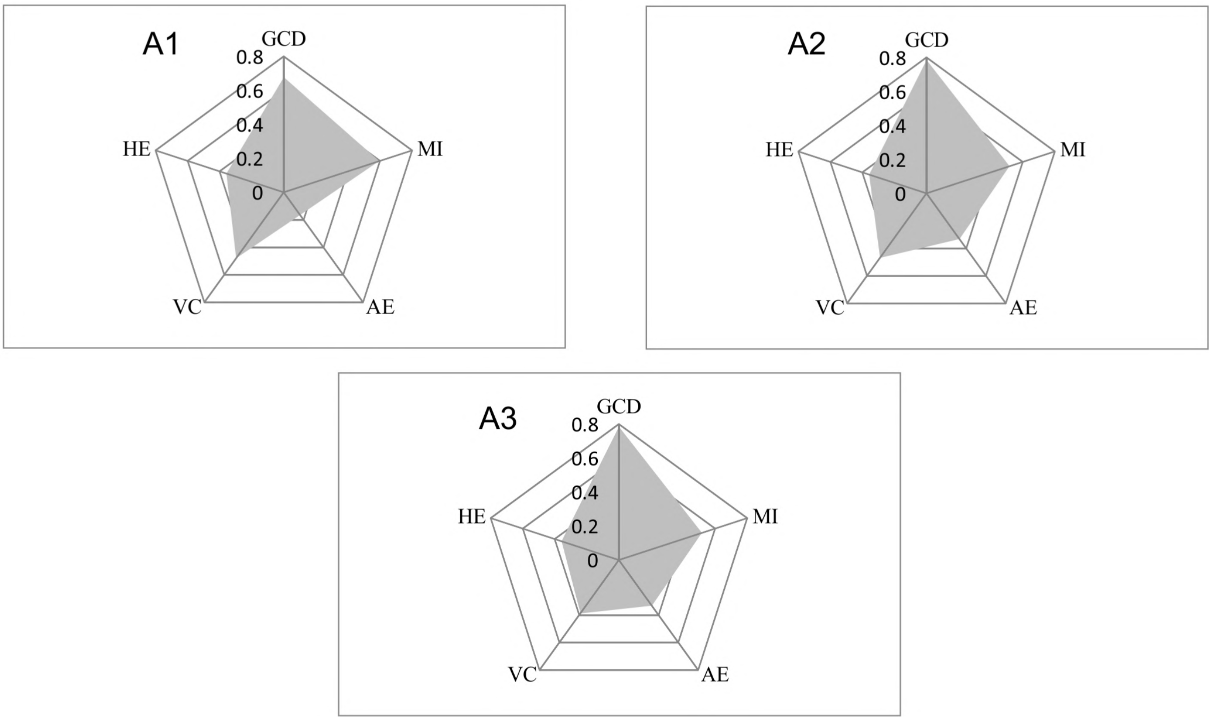
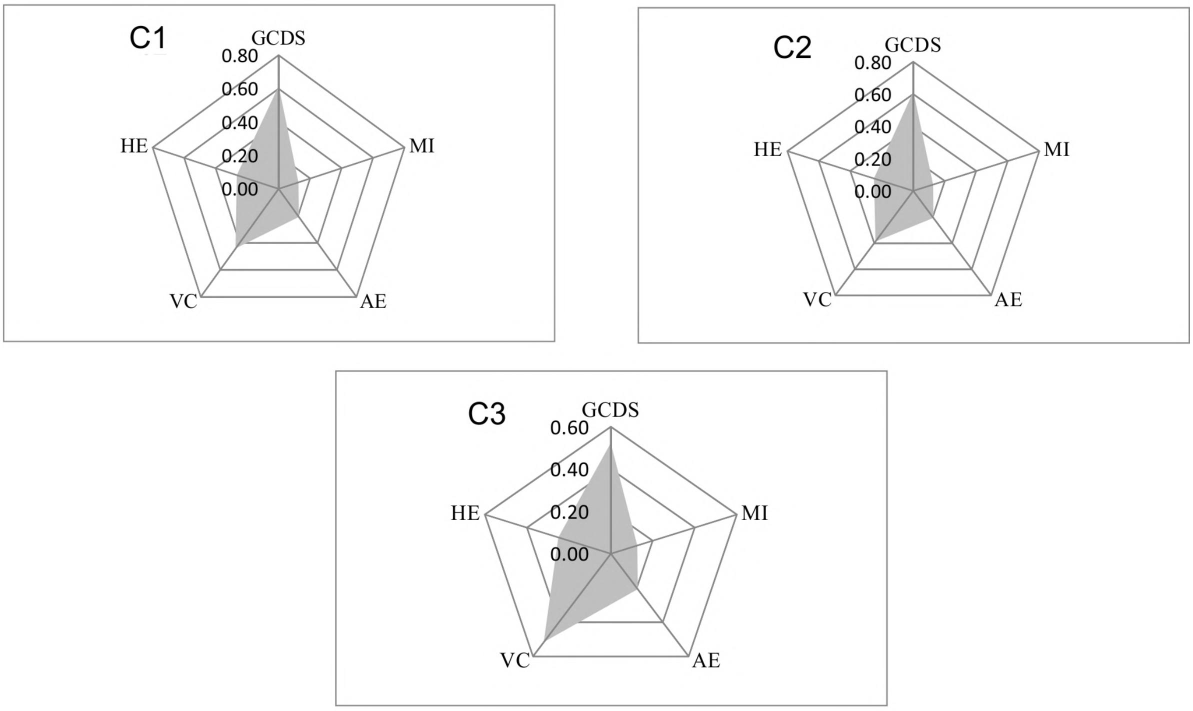


Figure 6

Zone C



Zone D

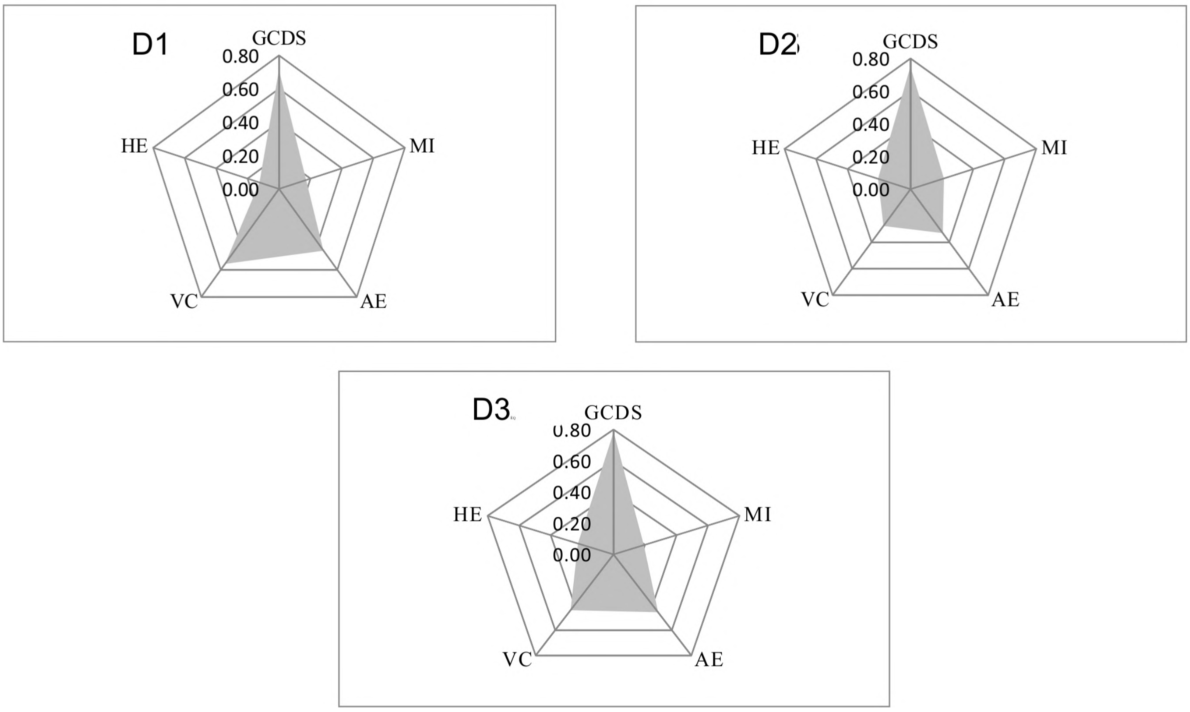


Table 1. Variables used to classify the vulnerability of coastal dunes; 0 = absence of vulnerability and 4 = very high vulnerability (modified after Ciccarelli *et al.*, 2017).

	Variable	**Class of Vulnerability**				
1. Geomorphological Condition of Dune system (GCD)		**0**	**1**	**2**	**3**	**4**
1	Length of homogeneous active dune system (km)	> 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)	< -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 (km)	> 0.5	> .2	> .1	> .05	< .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)	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 (degrees)	≤ 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	> 1		< 1		0

	transect (% cover)					
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

Table 2. Partial and total CDVI for each sampling site. Abbreviations: GCD: Geomorphological Condition of the Dune system; MI: Marine Influence; AE: Aeolian Effect; VC: Vegetation Condition; HE: Human Effect.

Dune Site	Location	Partial Vulnerability					Total CDVI
		GCD	MI	AE	VC	HE	
A1	Zone A	0.67	0.59	0.16	0.48	0.35	0.45
A2		0.78	0.51	0.33	0.47	0.35	0.49
A3		0.78	0.51	0.33	0.38	0.35	0.47
B1	Zone B	0.78	0.55	0.33	0.3	0.14	0.42
B2		0.71	0.57	0.5	0.44	0.14	0.47
B3		0.71	0.59	0.5	0.44	0.14	0.48
Average		*0.73*	*0.55*	*0.35*	*0.41*	*0.24*	*0.46*
C1	Zone C	0.62	0.13	0.21	0.44	0.27	0.33
C2		0.62	0.13	0.21	0.39	0.25	0.32
C3		0.52	0.13	0.21	0.52	0.25	0.32
D1	Zone D	0.71	0.17	0.46	0.56	0.13	0.40
D2		0.75	0.21	0.33	0.28	0.21	0.36
D3		0.79	0.19	0.46	0.44	0.23	0.42
Average		*0.66*	*0.16*	*0.31*	*0.43*	*0.22*	*0.35*

Table 3. Mean values (±SD) of partial and total coastal dune vulnerability index (CDVI) values calculated for each group defined by cluster analysis (indicated by roman letters - see Figure 3). 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	Zone B	Zone A	Zone C	Zone D
GCD	0.73 ± 0.04^{a}	0.74 ± 0.06^{a}	0.59 ± 0.06^{a}	0.75 ± 0.04^{a}
MI	0.57 ± 0.02^{a}	0.53 ± 0.05^{a}	0.13 ± 0.00^{b}	0.19 ± 0.02^{b}
AE	0.44 ± 0.09^{a}	0.27 ± 0.10^{a}	0.21 ± 0.00^{a}	0.42 ± 0.08^{a}
VC	0.39 ± 0.08^{a}	0.44 ± 0.06^{a}	0.45 ± 0.07^{a}	0.43 ± 0.14^{a}
HE	0.14 ± 0.00^{c}	0.35 ± 0.00^{a}	0.26 ± 0.01^{ab}	0.19 ± 0.05^{b}
CDVI	0.45 ± 0.03^{a}	0.47 ± 0.02^{a}	0.33 ± 0.01^{a}	0.40 ± 0.03^{a}

Abbreviations of the variables: GCD = Geomorphological Condition of the Dune system, MI = Marine Influence, AE = Aeolian Effect, VC = Vegetation Condition, HE = Human Effect.