Title:

Recognizing the relative effects of environmental versus human factors to understand the conservation of coastal dunes areas

Authors:

Giulia Calderisi[1], Donatella Cogoni[1], Maria Silvia Pinna[1]*, Giuseppe Fenu[1]

Affiliations:

1: Department of Life and Environmental Sciences (DiSVA), University of Cagliari, Viale Sant'Ignazio da Laconi 13, 09123 - Cagliari, Italy.

E-mail addresses:

Giulia Calderisi: giulia.calderisi@gmail.com

Donatella Cogoni: d.cogoni@unica.it

Maria Silvia Pinna: m.silviapinna@gmail.com

Giuseppe Fenu: gfenu@unica.it

Corresponding author:

* PhD Maria Silvia Pinna (m.silviapinna@gmail.com)

Department of Life and Environmental Sciences, University of Cagliari, Cagliari, Italy

CRediT authorship contribution statement

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

Abstract:

Coastal dunes are extremely complex sandy habitats and a place with considerable exchanges of mass and energy which support valuable biodiversity. During the last century, anthropogenic impact on coastal dunes has increased around the Mediterranean area leading to a decline of these ecosystems. However, it is not clear whether the status of a coastal dune system is more closely linked to the environmental dynamism or to the effects of the anthropogenic pressure. To explore this issue, the pocket-beach of Sa Mesa Longa (Sardinia), including two areas subjected to a different level of environmental and human pressures was selected as a study area. A total of 43 plots were randomly placed along nine transects orthogonal to the coastline; in each plot the presence and coverage of all vascular plants were measured to calculate a set of indices (i.e., Diversity index: H_{dune}; Evenness: E; Natural diversity index N; Endemicity index: EI) elaborated for the coastal dune systems.

Our results indicate a high degree of conservation for Sa Mesa Longa beach; both the diversity (H_{dune}) and Endemicity (EI) indices mean values increased moving away from the shoreline to inland with a similar trend in the two areas. Human-related factors did not seem significantly to influence the conservation status of a dune system; a clear effect of the factors linked to the natural dynamism of such environments seemed not even evident if the floristic diversity is analyzed. Although on a small scale human trampling does not seem to be able to have a significant impact, the conservation status of a Mediterranean coastal dunes seems instead to be linked to a complex interaction of the two categories of factors. However, further studies will be necessary to understand the effects of touristic activities on coastal dunes as key to planning management strategies for these fragile ecosystems.

Keywords:

Coastal dune system, Coastal vegetation, Environmental factors, Management plan, Plant diversity, Sardinia.

1. Introduction

Coastal dunes are extremely complex sandy habitats and a place with considerable exchanges of mass and energy which support valuable biodiversity. These ecosystems are ecologically complex and influenced by numerous factors that, on the one hand, determine their instability (i.e., the groundwater flow, the local hydrodynamics, the beach morphology, the prevailing winds and waves) and, on the other hand, stabilize the sand dunes such as the effects of the peculiarity flora and biotic communities (Martínez and Psuty, 2004; Maun, 2009; Fenu et al., 2013). In particular, the erosive or accreting action of wind and waves are the main factors to which coastal dunes are continuously subjected; the behavior of dunes under waves has been largely investigated (e.g., Tomasicchio et al., 2011; Sancho et al., 2011; D'Alessandro et al., 2012), also under the climate change influence in terms of sea level rise and increased sea storminess. However, the expected consequences of climate change are not unanimously accepted by the scientific community, in particular for the Mediterranean Basin (e.g., Lionello et al., 2017) and further research is needed to fully understand the evolution of such ecosystems in a future scenario.

Coastal dune systems are characterized by strong environmental gradients, which determine the coexistence of various plant communities in a relatively small area (Ranwell, 1972; Barbour et al., 1985; Wilson and Sykes, 1999; Frederiksen et al., 2006; Acosta et al., 2009; Fenu et al., 2013a). Among coastal systems, sand dune communities are characterized by high levels of complexity and originality at both the species and community levels; these unique ecological characteristics also make coastal dune systems particularly fragile environments (e.g., van der Meulen and Salman, 1996; Carboni et al., 2009; Prisco et al., 2021).

The stability of a coastal dune system (and the provision of most of the related ecosystem services) is mainly ensured by the integrity of the ecological and morpho-dynamic interactions between psammophilous plant communities and geomorphology, shaping the typical heterogeneous habitat mosaic along the sea–inland gradient (Acosta et al., 2009; Fenu et al., 2013; Sperandii et al. 2019; Bazzichetto et al., 2020). On one side, plant communities’ distribution and abundance depend on several geomorphology-related factors (e.g., wind and marine aerosol exposure, wave energy and flooding. The psammophilous plant communities are an essential functional component of coastal dune ecosystems because of the stabilizing effect on the substrate, which exerts major control over the development of the topographic features (e.g., substrate fixation and erosion prevention), mediating the same abiotic governing factors (Martínez and Psuty, 2004; Acosta et al., 2009;

Maun, 2009; Fenu et al., 2012, 2013a; Ciccarelli, 2014). Psammophilous plant communities occur in a typical zonation along the sea-inland environmental gradient (e.g., Maun, 2009; Frederiksen et al., 2006; Fenu et al., 2012, 2013a; Prisco et al., 2021). As a consequence, these dynamic environments host highly specialized vascular flora, characterized by plants with a wide range of adaptations and responses to the peculiar ecological conditions and the large-scale environmental stresses typical of coastal dunes (Maun, 2009; Fenu et al., 2012, 2013a; Pinna et al., 2015).

During the last century anthropogenic impact on coastal ecosystems has notably increased worldwide, and unregulated (or poorly-regulated) human-related activities (e.g., urbanization, intensive farming, an increase of the road infrastructures, massive tourism, etc.) have led to a general decline in the quantity and quality of coastal habitats (e.g., Del Vecchio et al., 2015; Nordhaus et al., 2018; Cooke et al., 2020). Human-related impacts were particularly relevant along the coastal systems of the Mediterranean Basin, which are currently considered among the most endangered environments in Europe (e.g., van der Meulen and Salman, 1996; Kutiel et al., 2001; van der Meulen et al., 2004; Carboni et al., 2009; Prisco et al., 2013, 2021; Pinna et al., 2015, 2019; Delbosc et al., 2021). Among others, touristic and recreational activities are considered the most influential factors in the coastal dunes (e.g., Davenport and Davenport, 2006; Northstrom, 2008; Kutiel et al., 2001; Santoro et al., 2012; Šilc et al., 2017; Ciccarelli et al., 2017; Cooke et al., 2020; Prisco et al., 2021; Prisco et al., 2013; Delbosc et al., 2021). These recreational activities caused a plethora of alterations in the coastal dune systems, resulting in the strong simplification of the typical spatial pattern of well-preserved dune mosaics, with an associated loss of ecological integrity (e.g., Carboni et al., 2009; Fenu et al., 2012, 2013a; Drius et al., 2019).

However, to date it is not entirely clear whether the status of a coastal dune system is more closely linked to the intrinsic environmental dynamism described above (natural stressors) or to the current results of anthropogenic pressure (human-related stressors). Because the Mediterranean sandy coastal systems are considered particularly endangered or, sometimes, extremely threatened, understanding how stressors (environmental versus anthropogenic) influence conservation status is crucial in planning adequate management strategies.

Several approaches to assessing the conservation status of coastal sand dunes have been developed focusing on a plethora of approaches/variables: single species or plant communities as bioindicators or parameters, such as species composition, richness, diversity and cover (e.g., Kutiel, 2001; Provoost et al., 2004; Acosta et al., 2007; Lomba et al., 2008; Attorre et al., 2013;

Pinna et al., 2015, 2019), landscape cover types and related structural indices (e.g., Carboni et al., 2009; Malavasi et al., 2013; Bazzichetto et al., 2020), or more complex indices integrating several factors, such as geomorphological condition, marine influence, aeolian factor, vegetation characteristics and human-related factors (e.g., García-Mora et al., 2001; Muñoz Vallés et al., 2011; Ciccarelli et al., 2017; Garcia-Lozano et al., 2020).

A specific index obtained via the modification of the Shannon diversity index and elaborated for coastal dunes has been developed (Grunewald and Schubert, 2007). The H_{dune} index manages to capture the fragmentation typical of coastal dune systems by considering qualitative or quantitative species measures concerning the extent of the habitat. The H_{dune} index uses the abundance of species (as cover percentage) in relation to a constant sampling area, and it can detect changes in both plant species richness and total cover (e.g., Attorre et al., 2013; Ciccarelli, 2014; Pinna et al., 2015, 2019). By adopting this approach, previously tested on numerous coastal dunes in Sardinia, the main aim of our research was to investigate whether the conservation status of sandy coastal dunes is more closely linked to intrinsic environmental dynamism (natural stressors) or the effects of anthropogenic pressure (human-related stressors). To explore this issue, we selected a small pocket-beach, clearly composed of two parts subjected to different conditions: one part was protected from the main weather-marine effects and more exploited by tourists, and the second was more exposed to natural factors but less frequented by tourists. In this context, the specific aims of this study are as follow: (1) to assess the overall conservation status of the coastal dune system by using a specific set of indices, (2) to analyze the variation pattern of these indices starting from the shoreline to the back-dune and (3) to compare two different areas of the coastal dune system in order to determine which drivers (natural versus human-related) principally affect the conservation status of coastal dunes.

2. Materials and Methods

2.1. Site description

Our study focused on the small pocket-beach of Sa Mesa Longa (CW Sardinia). The geological context consists of a volcanic basement covered by various formations of marine sediments (Upper Miocene period), covered by Quaternary deposits (Wurmian aeolian formations) composed of well-cemented sandstone with interspersed red-brown clayey paleosols. The upper limit of the succession is made up of sandy and coastal deposits along the coast.

In this context, Sa Mesa Longa is a small pocket-beach extending for approximately 1,200 m between two headlands and it is characterized, in its central part, by a salient shape due to a reef located approximately 100 m from the baseline/shoreline (Figure 1). A very small long-shore variation in grain size was observed; the beach sands are rather coarse-grained and well-sorted due to wind deflation (Sulis and Annis, 2014).

This site shows a western aspect, representing the main exposure to the mistral and west winds, considered among the two most important winds of the W-Mediterranean Basin (Ruti et al., 2008). In front of the pocket-beach, approximately in the middle part and a few tens of meters from the shore, there is the small island of Sa Mesa Longa, connected in the northern part with the mainland by a submerged reef; such shore-parallel structures are the most common protective structures in term of limiting shoreline erosion, representing a physical barrier against the most intense storms and reducing their effects in the relative portion of the beach (Figure 1). Accordingly, the pocket-beach of Sa Mesa Longa could be divided into two areas of similar surface area (North and South, respectively), characterized by various conditions and anthropogenic disturbances (Figure 1). The North area, with a cover area of c. 31,500 m^2, is protected from the above-described shore-parallel structure, less affected by extreme climatic phenomena and, for this reason, more frequented by tourists in summer. Conversely, the South area, covering a surface of c. 33,000 m^2, is affected by extreme climatic phenomena and, hence, less frequented by tourists in summer.

The study area includes the entire sandy dune system occupied by the typical psammophilous vegetation up to the retro-dunal temporary ponds characterized by halo-nitrophilous plant communities.

The vegetation zonation follows a typical Mediterranean Sea-inland ecological gradient, spanning from annual-dominated plant communities on the strandline zone of the beach to shrubby or forest communities on the stabilized dunes (Fenu et al., 2012, 2013a). In this context, some habitats of European interest, identified through the presence of the diagnostic species according to the Italian Interpretation Manual of EU Habitats (Biondi et al., 2009), are recorded (Appendix A).

2.2. Data collection

Plant diversity has been analyzed using transects and plots that were randomly placed in the dune system; during the sampling activities, each plot was assigned to a specific EU habitat considering the presence and abundance of the diagnostic plant species (Appendix A). A total of nine transects (five in the north area and four in the South) orthogonal to the shoreline, always starting from the coastline to the fixed dunes, have been randomly placed. Along the transects, a total of 43 plots have been placed, each with a surface of 4 m^2 (Figure 1). In each plot, the total plant coverage and the relative coverage of each vascular plant have been visually estimated. The plant taxonomy has been updated following the recent Italian checklist of native flora (Bartolucci et al., 2018).

As a proxy with which to estimate the anthropogenic disturbance in the pocket beach, the length of the footpaths present in the study area have been measured using aerial photographs, obtained from the Autonomous Region of Sardinia website (http://www.sardegnageoportale.it) related to the years 2003, 2006, 2013 and 2018. The footpaths have been divided into three categories related to their mean width: T1 (< 1m), T2 (1-1.5m) and T3 (> 1.5m).

2.3. Data analysis

To measure the overall plant species diversity, the H_{dune} index (Grunewald and Schubert, 2007) was used following the formula:

$$H_{dune} = - \sum P_i \times \ln P_i$$

Where P_i indicates the percentage coverage of each plant. The H_{dune} value increases as diversity in the community increases (Pinna et al., 2015). Starting from H_{dune} it is possible to calculate a second index, $H_{dune\text{-}max}$. The $H_{dune\text{-}max}$ index was calculated following the formula:

$$H_{dune\text{-}max} = - s \times [(\sum P_i) / s] \times \ln [(\sum P_i) / s]$$

where s represents the number of plant species.

Evenness (E) is an index often used as a parameter for community structure, being independent of species richness (Grunewald and Schubert, 2007). Grunewald and Schubert (2007) modified E (E_{dune}) and calculated it as a ratio between H_{dune} and $H_{dune\text{-}max}$. This index ranges from 0 to 1, where 0 indicates that the community is dominated by one species and the other species present diverse but lower abundances, and 1 indicates that all species in the community have the same abundance (Pinna et al., 2015).

In addition, to calculate the coverage of endemic plants, considered a bioindicator of the sound conservation status of a beach, an additional index was used (Pinna et al., 2019), calculated according to the formula:

$$EI = H_{dune} \text{ (considering only endemic plant species)} / H_{dune}$$

The index ranges from 0 to 1, where 0 indicates the null coverage of endemic plant species in the coastal dune, and 1 indicates that the plant cover is composed exclusively of endemic species. The increase in the EI value corresponds to a greater conservation status for a coastal dune system (Pinna et al., 2019).

The indices were calculated for the overall beach and separately for the Northern and Southern areas.

According to the protocol in Grunewald and Schubert (2007) and Pinna et al. (2015), the Mann-Whitney U inferential statistical test was applied to evaluate differences of the indices between sites (North and South), while the Kruskal-Wallis One-way Analysis of Variance on Ranks, followed by all pairwise multiple comparison tests, were applied to evaluate significant differences between habitats/morphologies.

All statistical analyses were carried out using the Statistica 8.0 software (Statsoft, USA).

3. Results

The analysis of the aerial images showed that the anthropogenic disturbance (in terms of the lengths of the footpaths on the dune system) had an oscillatory trend, with peaks in 2006 and 2018 and lower values in 2013 (Table 1). It is important to note that the cumulative length of the three types of footpaths has changed in various ways over time: the widest footpaths (T3), mainly due to vehicular traffic, significantly increased in length over time since 2006, doubling in 2018; the intermediate-sized footpaths (T2) maintained almost the same length values over time, and the narrower footpaths (T1), exclusively linked to human trampling, significantly increased, affecting the total values recorded for the entire dune system (Table 1).

Our data show that, while, in the southern part, the total values remained similar after 2006, in the northern part, the main changes, which affected the general oscillatory trend of the dune system, were observed (Table 1).

A total of 61 vascular plant species (45 species, 15 subspecies and 1 variety), belonging to 27 families and 53 genera were recorded in the dune system. Among them, not one alien plant species was present (see Appendix B for details). The mean values (± standard error) of the H_{dune}, $H_{dune\text{-}max}$, E and EI indices obtained for the Sa Mesa Longa dune system and for the two areas studied are reported in Table 2; because no alien plant species were detected, the value of N was always equal to 1.

Considering the overall pocket-beach (Figure 2A), H_{dune} had the lowest value in the upper beach (0.407 ± 0.147) and then gradually increased up to the Mobile Dunes (1.527 ± 0.114); slightly lower average values were recorded for the Fixed Dunes (1.289 ± 0.122). The Kruskal-Wallis One-way Analysis of Variance on Ranks (Kruskal-Wallis test: $H_{(3,\ N=43)}$ =17.473; p =0.0006) confirms that there were only significant differences among the Upper beach and the other habitats, while no significant differences existed among the foredunes, mobile dunes and fixed dunes (Table 3).

The EI followed the same trend showed by H_{dune} (Figure 2B), with the lowest values being observed in the Upper beach (0.054 ± 0.054) and the highest values in the Mobile dunes (0.184 ± 0.033). The Kruskal-Wallis One-way Analysis of Variance on Ranks (Kruskal-Wallis test: $H_{(3,\ N=43)}$ =16.72089; p =0.0008) confirmed that there were significant differences between Upper beach and Mobile and Fixed dunes (Table 3), but no significant differences from the foredunes were recorded.

Both indices are positively correlated to the distance of the shoreline (H_{dune}: r^2=0.129, $p < 0.05$; EI: r^2=0.141, $p<0.05$); in addition, H_{dune} and EI are positively correlated ($r^2 = 0.275$, $p<0.001$; Figure 3).

3.1. Comparison of the two areas within the pocket-beach

Separately considering the two areas identified in the dune system we can observe some important differences. The values of the two indices H_{dune} and EI had an opposite trend between the two areas. Specifically, in the South area, there was a higher average value of H_{dune} (1.233 ± 0.143) than in the North area (1.157 ± 0.104), while in the latter, there was a higher average value of the EI (0.153 ± 0.026) as compared to the South area (0.122 ± 0.021; Table 3). However, no statistically significant differences between the two sites were found for either index ($p > 0.05$ by Mann-Whitney U test).

In both areas, the lower value of H_{dune} is recorded in the Upper beach (North: 0.473 ± 0.242; South: 0.341 ± 0.198), and the highest value is recorded in the Mobile dunes (North: 1.364 ± 0.168; South: 1.643 ± 0.148; Figure 4). However, the values of H_{dune} showed a different trend along the sea-inland gradient (different habitats) in the two areas. While, in the South area, the trend of the index followed the pattern already observed for the entire beach (Figure 2), in the North area, some differences were found, with the values of Mobile dunes being similar to those of Fixed dunes. The statistical analysis showed that the H_{dune} values of the Mobile dunes in the South area were significantly different from those of the other habitats, while no significant differences were observed in the North area (Table 3).

The EI values related to each area showed different trends in the different habitats. In the North area the index follows the same trend as the pocket-beach, with the highest mean value of the index being recorded for the Mobile dunes (0.268 ± 0.039), while in the South area, the highest value of EI was recorded in the Fixed dunes (0.151 ± 0.044; Figure 4). The statistical analysis showed that the EI values of the Mobile dunes in the North area were significantly different from those of the other habitats, while no significant differences were observed among values for habitats in the south area (Table 3).

In both areas the two indices were positively correlated with one another, and an increase in H_{dune} values corresponds to an increase in EI values (North: $r^2 = 0.383$, $p < 0.001$; South: $r^2 = 0.289$; $p < 0.05$). In addition, in both areas, the two indices were positively correlated with the distance to the shoreline, except for EI values in the North area, for which the correlation to the distance of the shoreline was not statistically significant (Figure 5).

4. Discussion

Coastal dunes are particularly fragile sandy habitats (van der Meulen and Salman, 1996; Carboni et al., 2009; Pinna et al., 2019; Delbosc et al., 2021), highly threatened by human-related activities, especially in the Mediterranean area (e.g., Kutiel et al., 2001; Prisco et a., 2021; Delbosc et al., 2021). In fact, over the last decades, tourism and related recreational activities have grown quickly along the Sardinian coastal dune systems, which are among the most visited tourist sites in the Mediterranean area (Pungetti et al., 2008), causing severe impacts on plant populations and communities (e.g., Fenu et al., 2013b; Ciccarelli, 2014; Pinna et al., 2015, 2019), such as the disappearance of native species with substantial ecological value, including endemic and keystone plant species. However, it has not yet been fully demonstrated whether the state of conservation of a dune system is more influenced by the natural dynamism of the system or by the negative effects of tourist activities; understanding which factors are primarily responsible for the conservation status of a coastal dune system is essential in preserving these vulnerable environments through appropriate management strategies (Pinna et al., 2019).

To explore this issue, our study focused on a peculiar small pocket-beach by using a set of specific diversity indices (H_{dune}, N and EI). Sa Mesa Longa beach was a representative study case composed of two distinct sections with various levels of environmental and anthropogenic impact; specifically, within the same dune system, the Southern area is more exposed to natural impact while in the Northern area, there is a greater anthropogenic impact.

The mean H_{dune} value obtained for Sa Mesa Longa beach was higher than all Sardinia beaches previously analyzed using the same approach; in particular, such a value is comparable to that of S. Giovanni Sinis, which represented the best-preserved coastal system among all Sardinian coastal sites analyzed (Pinna et al., 2019). As regards the N index value, Sa Mesa Longa coastal dune showed a high value of naturalness, like the Sardinian coastal systems previously analyzed (Pinna et al., 2019), deviating significantly from the predictions regarding the spread of alien species on the coastal dune systems (e.g., Giulio et al., 2021).

The EI value calculated for Sa Mesa Longa beach indicated a high level of endemicity, with EI values comparable to the highest ones calculated among the Sardinian coastal dune systems (e.g., Chia, Funtanamare, Le Saline, Piscinas and Villasimius; see Pinna et al., 2019 for details). This result, associated with the highest values of N, suggests a generally high degree of conservation for Sa Mesa Longa beach and supports the observation that the presence (and relative abundance) of endemic species in the dune systems *per se* indicates a low level of human exploitation (Fenu et al., 2012).

As expected, both H_{dune} and EI values increased moving away from the shoreline to the inland. In addition, they increase moving from the upper beach towards inland (Foredune, Mobile dune and Fixed dunes). In particular, significant differences in H_{dune} values were observed only for the upper beach, probably due to the natural fragmentation of this habitat. In fact, it is well known that only a few pioneer species that grow near to the sea are adapted to the strong natural disturbance to which they are usually exposed (Kutiel et al., 2001; Fenu et al., 2012; Prisco et al., 2021). Conversely, EI index differences between the Upper beach and more stabilized dunes (Mobile dune and Fixed dunes) were found, with these latter ecological conditions generally being less selective. In addition, the effects of trampling, as well as changes in species cover or richness, strongly depend on the plant community in which species are included. The typical plant communities of Mediterranean mobile and fixed dunes can tolerate human trampling and usually show a very rapid recovery when this disturbance ends (Santoro et al., 2012). These habitats are usually less affected by the direct exploitation of seaside tourism than those of the Upper beach. In our study system, H_{dune} showed similar values in the two areas (North and South), and no statistically significant differences were found; in the Southern area, where a lower level of human trampling is present, the H_{dune} value is slightly higher than that in the Northern zone, where, on the contrary, the degree of disturbance is greater. Conversely, the mean EI values are higher in the North zone although no statistically significant differences between areas were observed. This result suggests that, at a small scale, neither natural factors nor human trampling intensity are capable of decisively influencing the floristic composition of the beach. In addition, the EI values indicate that the endemic plant species can tolerate a certain level of human trampling.

Comparing the trend for the two indices recorded for the habitats, small differences between the North and South areas were observed. Both indices, H_{dune} and EI showed a positive correlation with the distance from the shoreline; hence, the greater the distance from the shoreline to inland, the higher the mean values of the indices. In both areas, the H_{dune} index has higher values in the Mobile dunes, but in the North area, the values are similar. This pattern can be justified by the presence in the Northern area of more structured and species-rich scrub formations, which are more sporadic in the Southern area. Moreover, these data are also consistent with the mean values of H_{dune} obtained for the Mobile dune of the South area, which were significantly different from those of all the other habitats. These values support the results obtained by Pérez-Maqueo et al. (2017) for oceanic beaches, which showed non-significant differences in H_{dune} values among various localities and levels of tourism activity, while differing from what has been observed in other studies both in the Mediterranean and oceanic coastal dune systems (e.g., Grunewald and Schubert, 2007; Pinna et al., 2019). A different pattern among habitats was detected for the EI: the mean values in the North area showed their peak in Mobile dunes, with significant differences as compared to the other habitats, following the same trend observed for the entire beach, while in the South area, higher values were recorded in the Fixed dunes.

Based on these results, it could be argued that human-related factors do not significantly influence the H_{dune} and EI indices and, consequently, do not significantly affect the conservation status of the analyzed dune system. Similarly, it could be highlighted that a clear effect on the part of the factors linked to the natural dynamism of such environments is not even evident. As a consequence, it is more plausible that the conservation status of a coastal dune system is linked to a complex interaction of these two macro-categories of factors. This is an interaction in which, at small scale, human trampling is not, however, capable of causing the significant worsening of the conservation status of a coastal dune system. This statement is strongly supported by the pattern of the indices in relation to the distance from the shoreline: the mean values of both indices increase as the distance from the sea increases and the effects of marine events decrease in magnitude. In other words, this pattern follows the well-known ecological sea-inland gradient typical of the coastal sand dune. However, this does not mean that human trampling should not necessarily be regulated, because several coastal plants, particularly endemics, are highly sensitive to this threat as also detected in this study. Within the frame of correct beach management, the typical resilience of dune vegetation could be exploited. This resilience often manifests as a rapid short-term recovery as soon as the disturbance is interrupted or mitigated through simple management options, such as the use of fences or walkways (e.g., Kutiel et al., 2001; Santoro et al., 2012; Fenu et al., 2013b; Šilc et al., 2017; Pinna et al., 2019).

Finally, the DESCR framework considering "Drivers"-"Exchanges"-"State of the environment" and "Consequences"- "Responses" factors (Silva et al., 2020; Chacón Abarca et al., 2021) was elaborated to assess the “coastal squeeze” phenomenon in Sa Mesa Longa beach (Figure 6). The interaction of natural and anthropogenic factors, through energy and matter exchanges, may induce a "coastal squeeze" that concerns the reduction in space available for the natural functioning of coastal ecosystems, due to physic and human-related phenomena, which may lead to the disappearance of some species, ecosystems and, consequently, ecosystem services (Silva et al., 2020; Chacón Abarca et al., 2021). Compared to specific studies focused on this methodology, our results should be considered as a basis on which further scientific-based quantitative analysis is needed to implement the DESCR framework.

Our study highlighted the fact that we cannot *a priori* assume that the conservation status of a coastal dune system is more closely linked to the natural environmental dynamism or anthropogenic pressure level, because the effect of the different variables can vary considerably and, at local scale, notably deviate from the general models; as a consequence, because the Mediterranean sandy coastal systems are considered particularly threatened by humans, further studies will be necessary to understand the effects of touristic activities on coastal dunes as a crucial key to planning adequate management strategies for these fragile ecosystems. In addition, considering the potential future effects of ongoing climate change, the assessments on the tourist exploitation of sandy coasts will have to be framed in a broader and more complex scenario.

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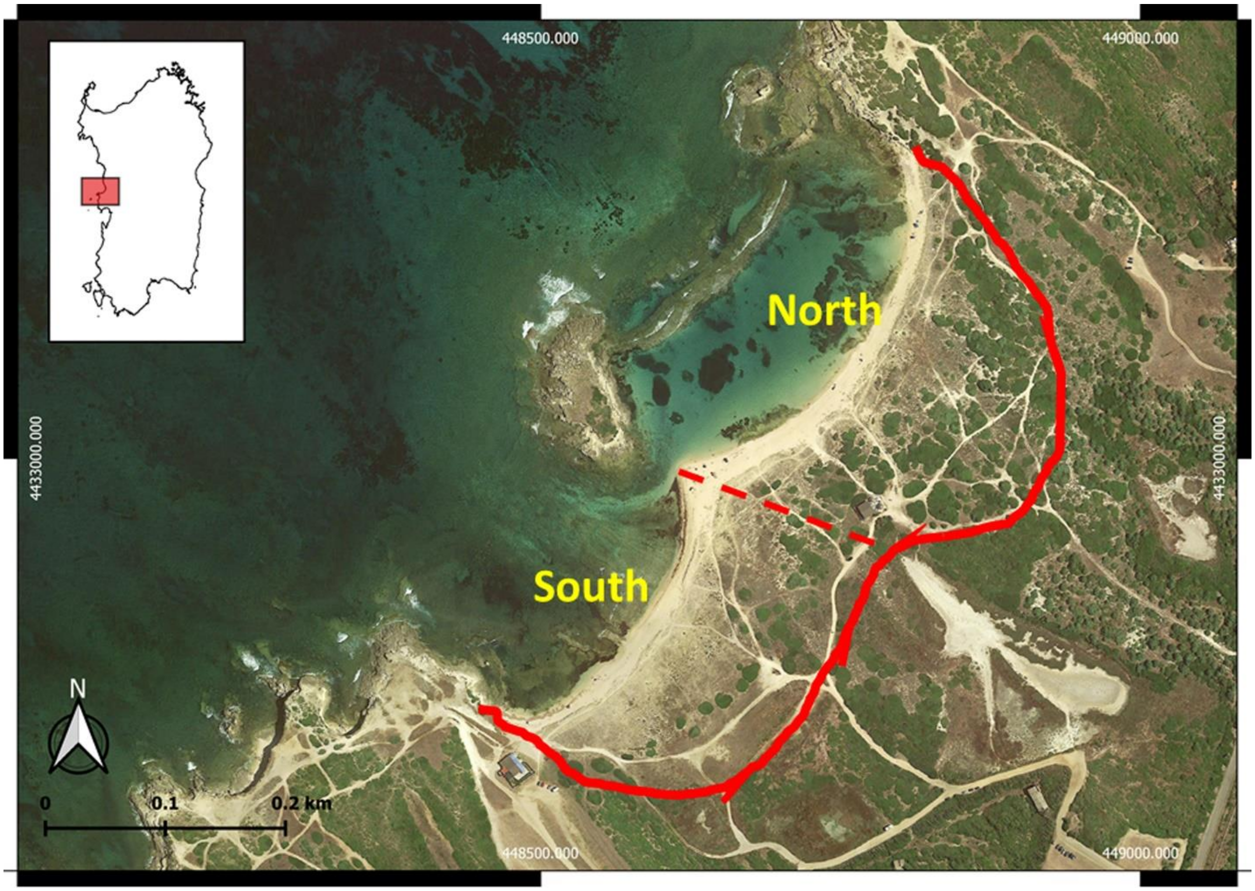

Figure 1. Location of the Sa Mesa Longa pocket-beach in Sardinia. The dashed line separates the two different areas (North and South) showing different level of environmental and anthropogenic pressure.

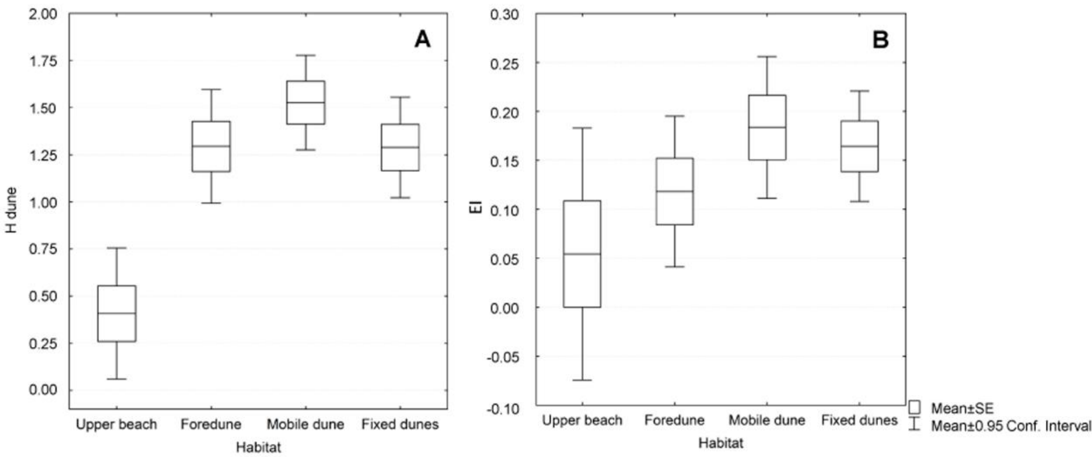

Figure 1. Overall H_{dune} and EI mean values related to the different habitats along the coastal dune system of Sa Mesa Longa.

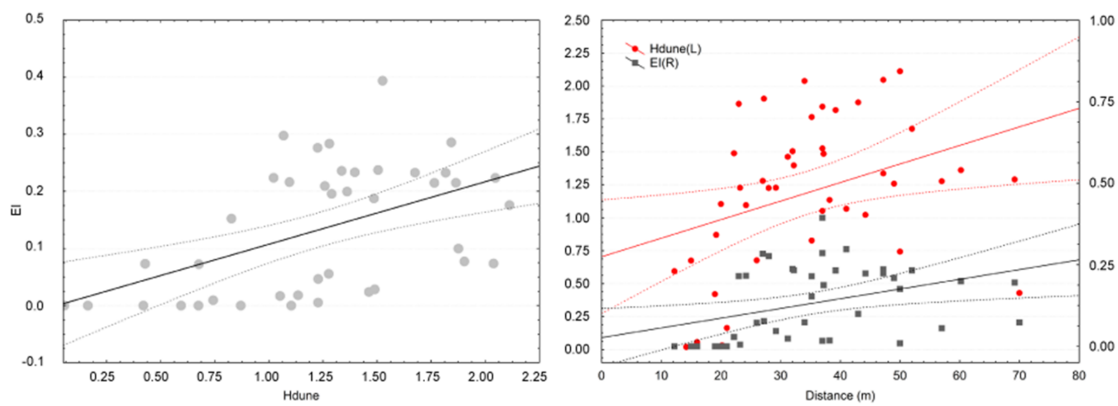

Figure 3. Correlation between the indices (H_{dune} and EI) and the distance from the shoreline.

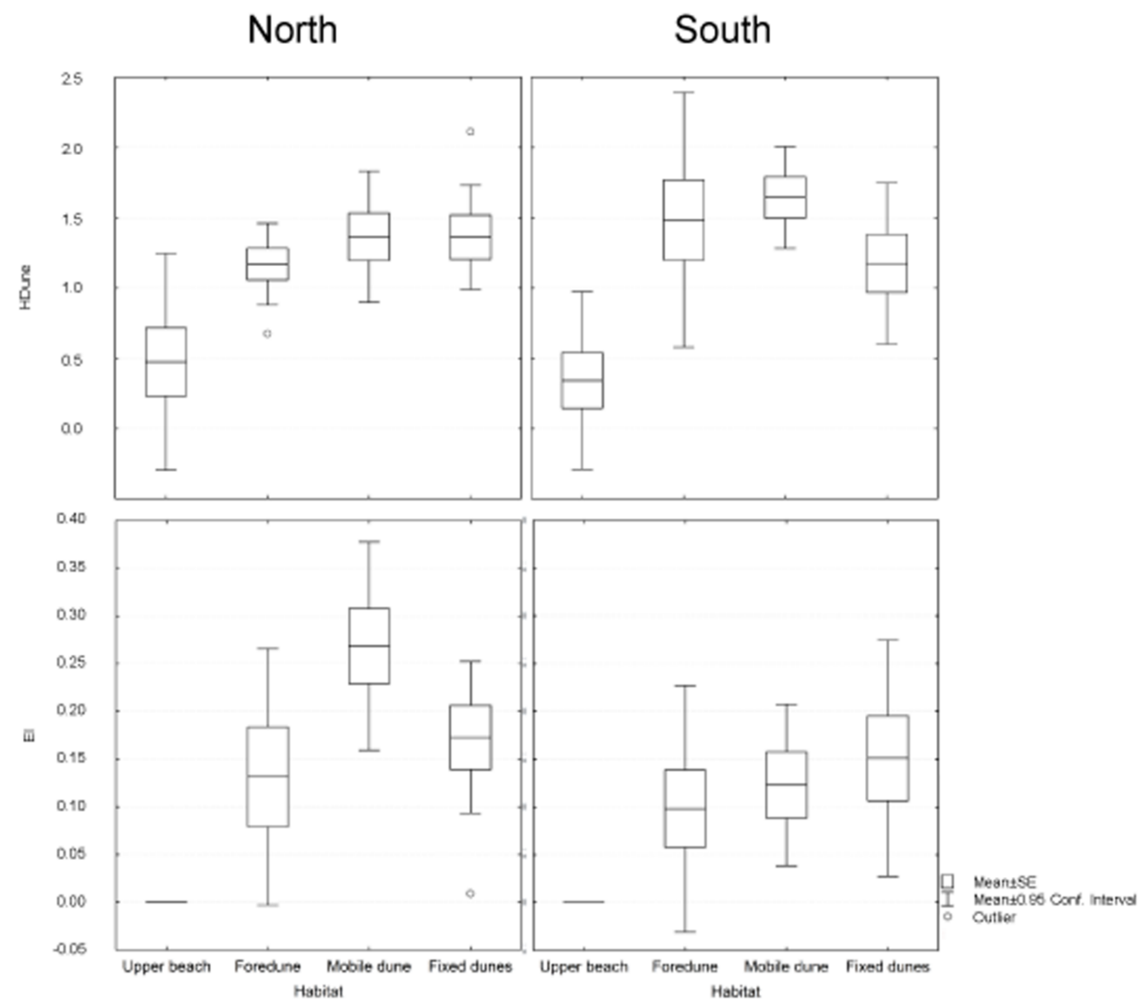

Figure 4. Pattern of Hdune and EI along the different habitats in the two areas of the dune system of Sa Mesa Longa: North (left) and South (right).

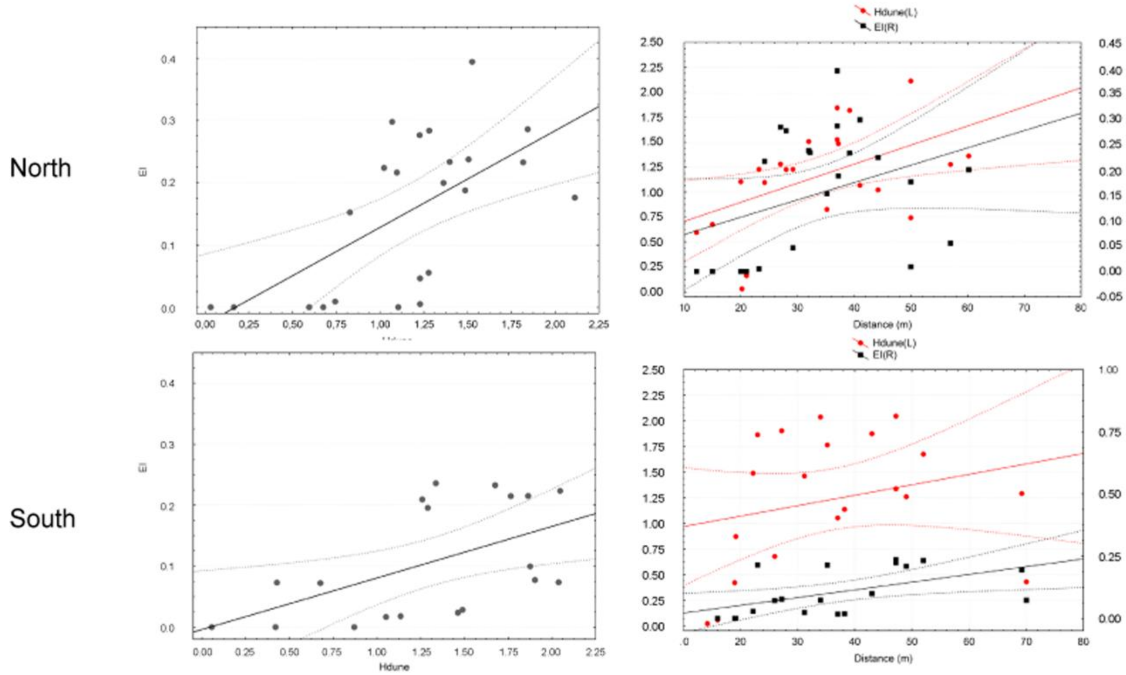

Figure 5. Correlation between the indices (H_{dune} and EI) and the distance from the shoreline in the two areas: North (top) and South (bottom).

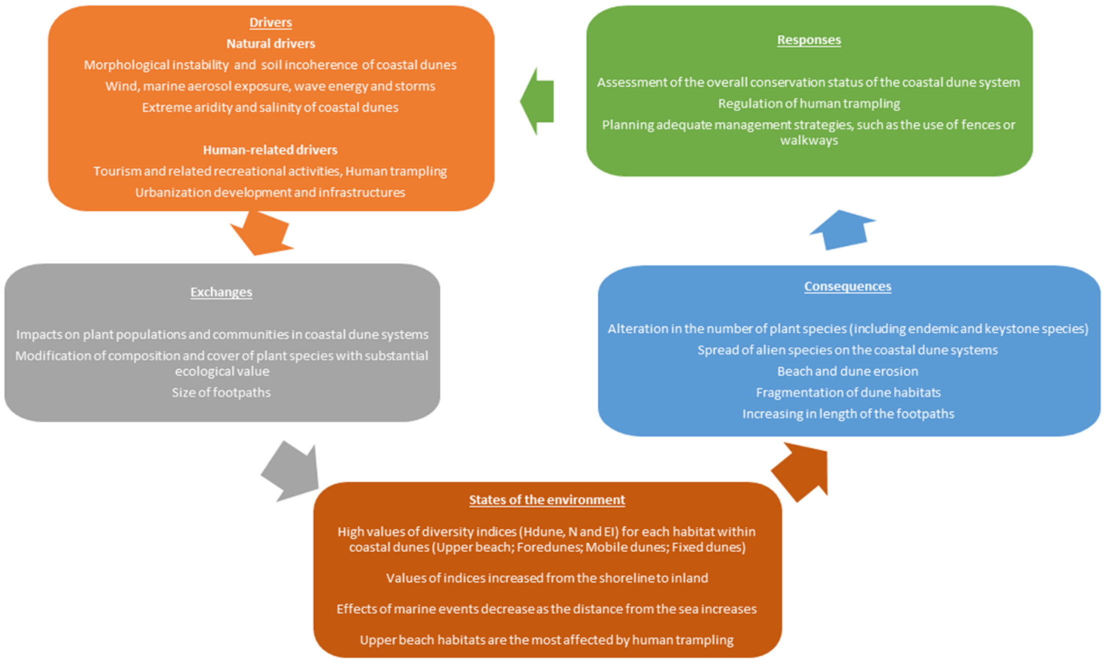

Figure 6. The DESCR (drivers, exchanges, state of the environment, consequences, and responses) framework applied to Sa Mesa Longa beach.

Tables

Table 1. Length (in meters) of the footpaths present in the study area, in both the North and the South sites and the total length of the T1, T2 and T3 footpaths, relating to the years 2006, 2013 and 2018.

Year	Total	T1	T2	T3	North	South
2006	3742.59	2460.25	912.53	369.81	2692.26	1050.33
2013	3091.21	1980.11	532.10	579.00	2085.91	1005.30
2018	3692.97	2344.89	575.83	772.25	2655.44	1037.53

Table 2. Mean values (± standard error) of H_{dune}, $H_{dune-max}$, E and EI indices of Sa Mesa Longa dune system and of the North and South areas.

	H_{dune}	$H_{dune-max}$	E	N	EI
Sa Mesa Longa Beach	1.192 ± 0.086	2.145 ± 0.086	0.527 ± 0.033	1	0.138 ± 0.017
North area	1.157 ± 0.104	2.148 ± 0.118	0.514 ± 0.038	1	0.153 ± 0.026
South area	1.233 ± 0.143	2.142 ± 0.128	0.543 ± 0.058	1	0.122 ± 0.021

Table 3 - Multiple Comparisons z' values for H_{dune} and EI calculated for the total beach and separately from the North and South areas. Significant values are in bold.

	H_{dune}				**Endemicity Index**			
Total beach	UB	F	MD	FD	UB	F	MD	FD
Upper beach (UB)		**2.9424**	**3.9767**	**3.0419**		2.0378	**3.1298**	**2.8485**
Foredunes (F)			0.9796	0.0684			1.0788	0.7450
Mobile dunes (MD)				1.1197				0.3711
Fixed dunes (FD)								
North								
Upper beach (UB)		1.8273	2.4617	2.1078		1.9415	**3.2969**	2.4378
Foredunes (F)			0.7792	0.5460			1.5827	0.4436
Mobile dunes (MD)				0.3103				1.2608
Fixed dunes (FD)								
South								
Upper beach (UB)		2.3905	**3.0050**	1.6126		1.9777	2.3544	2.6280
Foredunes (F)			0.3082	0.9071			0.1823	0.6093
Mobile dunes (MD)				1.3691				0.5029
Fixed dunes (FD)								

Kruskal-Wallis test for the total beach: $H_{dune} = H_{(3, N= 43)} =17.473$; $p =0.0006$; $EI = H_{(3, N= 43)} =16.721$; $p =0.0008$.

Kruskal-Wallis test for the North area: $H_{dune} = H_{(3, N= 23)} =7.374$; $p =0.0609$; $EI = H_{(3, N= 23)} =11.321$; $p =0.0101$.

Kruskal-Wallis test for the South area: $H_{dune} = H_{(3, N= 20)} =9.969$; $p =0.0188$; $H_{(3, N= 19)} =7.648$; $p =0.0539$.