Ocean and Coastal Management 252 (2024) 107105

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Implementing a vegetation-based risk index to support management actions in Mediterranean coastal dunes

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ARTICLE INFO

Keywords:
Coastal management
Hazard
Risk
Tuscany
Vegetation
Vulnerability

ABSTRACT

Coastal dunes play a crucial role in mitigating sea-related impacts and safeguarding coastlines. However, increasing human influence and natural factors such as sea-level rise underscore the need for effective coastal risk assessment methodologies. This study introduces a comprehensive coastal risk index covering 24 km of the Italian coastline within the protected area of San Rossore Park (Tuscany, Italy). The study area, distinguished by its notable coastal dune ecosystems, holds naturalistic, cultural, and economic importance. Nevertheless, diverse uses, zoning, and human impact variables pose challenges.

By incorporating geological, socioeconomic, cultural, and ecological parameters, the index integrates a range of data sources and field observations. This research focused on developing and applying a vegetation-based risk index (VRI) within a geographic information system (GIS) framework, recognizing the ecological importance of dune vegetation in mitigating coastal erosion.

Analysis: revealed varying risk levels within the study area. Half of the San Rossore Park coastline exhibited low risk values, 37.5% had moderate risk values, and 12.5% had high risk values. The publicly accessible northernmost section displays excellent preservation of dune habitats but faces heightened risk due to anthropogenic impacts. Conversely, the central-southern portion, inaccessible to the public, registers high-risk levels linked to variables associated with coastal erosion.

Furthermore, the results highlight areas with heightened cultural and ecological vulnerabilities aligned with elevated risk levels. The index facilitates clear and intuitive cartographic representations of coastal risk, identifying variable categories that substantially influence on risk determination. Tailored strategies, including mitigating human pressure in the northern sector and implementing erosion management in the central-southern region, are recommended.

In summary, this study not only provides a practical tool for assessing and managing coastal areas and directing attention to specific threats but also supports stakeholders in informed decision-making. The VRI enhances global sustainable coastal conservation, deepening our understanding of coastal risks and providing valuable insights for effective management strategies.

1. Introduction

Coastal dunes serve as transitional ecosystems at the land–sea interface and are known as the Coastal Transition Zone (CTZ). They play a crucial role in shoreline preservation, mitigating the impacts of sea processes and coastal erosion (Maun, 2009). These ecosystems support specialized flora and fauna adapted to coastal environments, making them unique and vital for conservation (IUCN, 2022). Coastal dunes provide diverse ecosystem services, including coastal protection, groundwater retention and purification, and habitat provision for plants and animals (Maun, 2009). They also contribute to climate regulation and recreational and tourism opportunities and offer cultural and educational value (Pérez-Maqueo et al., 2013).

The evolution and conservation of coastal dunes stem from the complex interactions between natural processes and human activities. Natural factors include sedimentary budget, marine and aeolian

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https://doi.org/10.1016/j.ocecoaman.2024.107105
Received 14 December 2023; Received in revised form 1 February 2024; Accepted 19 March 2024

influences, beach morphodynamics, and psammophilous vegetation succession (Doody, 2013). However, these ecosystems face significant threats from human-induced activities such as resource exploitation, tourism development, urbanization, maritime operations, invasive species, and littering (Heslenfeld et al., 2004; McLachlan et al., 2013; Mo et al., 2021; Ciccarelli et al., 2023). Moreover, increasing coastal flooding and erosion, linked to rising sea levels and more frequent high-energy events, pose additional hazards to these unique ecosystems (Oppenheimer et al., 2022).

Managing coastal dunes requires a comprehensive understanding that extends beyond the physical environment to encompass geological and marine dynamics and wind influences. Biological aspects, especially vegetation, are crucial for dune formation and stabilization (Maun, 2009). Coastal dune management aims to balance habitat preservation with sustainable resource use (Rangel-Buitrago et al., 2020). This approach should consider natural, socioeconomic, and cultural dimensions; enhance territorial understanding; and develop focused, effective strategies (Rangel-Buitrago and Anfuso, 2015).

Mapping is a fundamental tool in coastal area management. Coastal dune management begins with assessing and mapping coastal risks, prioritizing interventions. Risk is the product of event probability and associated consequences and arises from hazard and vulnerability interplay (IPCC, 2019). Various methodologies calculate coastal risk indices, focusing on physical, geological, and, to a lesser extent, socioeconomic, ecological, and cultural factors (Nguyen et al., 2016; Rocha et al., 2023). The coastal risk index (CRI), proposed by Rangel-Buitrago and Anfuso (2015) and modified by Rangel-Buitrago et al. (2020), integrates geomorphological, socioeconomic, cultural, and ecological parameters. This study applied the CRI to a Mediterranean sandy coastline region in Italy, emphasizing vegetation-related variables. Traditional risk indices often generalize coastal vegetation, overlooking the specific characteristics of individual plant communities (Abuodha and Woodroffe, 2006; Nguyen et al., 2016; Bukvic et al., 2020). Generally, these indices evaluate the presence of vegetation by collectively considering green areas along beaches and dunes (e.g., Raji et al., 2013; Pantusa et al., 2018). However, certain indices provide a more nuanced analysis by examining coastal vegetation through the examination of plant community structure and diversity, calculation of naturalness values, or consideration of plant functional types (e.g., García-Mora et al., 2001; Ciccarelli et al., 2017; Malavasi et al., 2018; Pinna et al., 2019).

For a comprehensive understanding of the variables encompassed in coastal vulnerability and risk indices, one can refer to Nguyen et al. (2016), Bukvic et al. (2020), Anfuso et al. (2021), and Rocha et al. (2023). Crafting an informative index requires a delicate balance of information, aiming to introduce variables linked to vegetation that are accessible not only to experts. In our study, we addressed this issue by incorporating variables that specifically focus on the presence and abundance of typical sandy coastal habitats but are easily obtainable in the field.

Coastal vegetation is threatened by varying salinity levels, water retention conditions, soil temperature and moisture, nutrient availability, wind intensity, and marine aerosols (Doing, 1985; Torca et al., 2019). These factors influence habitat spatial organization, favoring species adapted to extreme conditions, especially on Mediterranean sandy coasts (Acosta and Ercole, 2015). The vegetation-based risk index (VRI) presented in this work combines three subindices in a geographic information system (GIS) environment.

- **Forcing Variables:** Indicating stress levels from physical agents.
- **Dynamic Variables:** Describe sandy coastline resilience or susceptibility to erosion.
- **Vulnerable Targets:** Covering socioeconomic, cultural, and ecological aspects.

These components form two primary indices: the hazard index (combining forcing and susceptibility components) and the vulnerability index, which together constitute the VRI. The VRI was enhanced with additional data on coastal dune plant communities, affecting both susceptibility and ecological vulnerability variables. The final goal is to determine the role of vegetation in coastal resilience and address the loss of valuable habitats.

The primary objective of this research is to establish a vegetation-based risk index as a management tool. This index provides specific recommendations for coastal managers to develop sustainable conservation and management strategies. Due to similarities in environmental and climate aspects between the Mediterranean Sea and other coastal regions, the methodology presented is applicable in various global contexts.

2. Study area

The study was conducted in Migliarino-San Rossore-Massaciuccoli Park (henceforth referred to as San Rossore), which is situated along the Tuscany coast in western Italy (Fig. 1). This protected area is positioned at the mouth of the Arno River, which, over the centuries, has given rise to cuspate deltas (Pranzini, 2001). The southern boundary of San Rossore Park aligns with the mouth of the Arno River.

San Rossore, distinguished by its notable coastal dune ecosystems, holds naturalistic, cultural, and economic importance. Nevertheless, diverse uses, zoning, and human impact variables pose challenges. The park extends 24 km along the northern Tuscany coast, from Viareggio to Marina di Pisa (Fig. 1). San Rossore encompasses wide strips of natural, protected beaches with minimal human activity, while the edges near Viareggio and Marina di Pisa experience greater human pressure. This area is a strandplain formed by sediments from the Arno and, to a lesser extent, the Serchio River (Sarti et al., 2022). The delta, resulting from lagoon filling and subsequent progradation due to the Arno River's solid discharge over the last 2500 years, experienced significant growth between the 17th and 19th centuries. This was due to river waterworks, which led to the delta's current asymmetrical shape and erosion (Della Rocca et al., 1987; Pranzini, 2001; Cappucci et al., 2020). Presently, the area near the Arno River mouth is retreating, while accretion occurs toward the northern end (Bini et al., 2021). The delta cusp marks the start of two diverging longshore drifts. This Ligurian Sea sector is characterized by a significant wave height of 0.54 m, a dominant SW wave direction, and a microtidal tidal regime with a range of less than 30 cm (Cipriani et al., 2001). The backshore zone primarily consists of medium sand (0.3 mm; Bertoni and Sarti, 2011).

In the coastal dunes of San Rossore Park, plant communities exhibit a typical shoreline-to-inland zonation pattern, corresponding to an ecological gradient that extends from the annual vegetation of the strandline zone on the beach to the shrubby communities found on the stabilized dunes (Ciccarelli, 2014). Many of these plant communities align with the habitat types identified in the EUNIS classification (Chytrý et al., 2020).

The vegetation on sand beaches and shifting dunes, situated in close proximity to the shoreline, is predominantly colonized by annual and perennial herbaceous plants known for their resistance to sand burial and wind exposure. Examples include *Cakile maritima* Scop. subsp. *maritima*, *Thinopyrum junceum* (L.) Á. Löve, and *Calamagrostis arenaria* (L.) Roth subsp. *arundinacea* (Husn.) Banfi, Galasso & Bartolucci. Moving beyond the shifting dunes, interdunal spaces are characterized by a mosaic of annual dune grasslands (e.g., *Festuca fasciculata* Forssk. and *Silene canescens* Ten.) and perennial dune scrubs (e.g., *Lomelosia rutifolia* (Vahl) Avino & P. Caputo, *Seseli tortuosum* L., and *Helichrysum stoechas* (L.) Moench subsp. *stoechas*).

Further inland, discontinuous dune thickets are dominant for various species within the *Juniperus* genus. Along this ecological gradient, there is a transition from arid and low-nutrient soils characterized by high substrate instability in sandy beaches and shifting dunes to more stable, nutrient-rich soils in dune thickets (Ciccarelli and Bona, 2022).

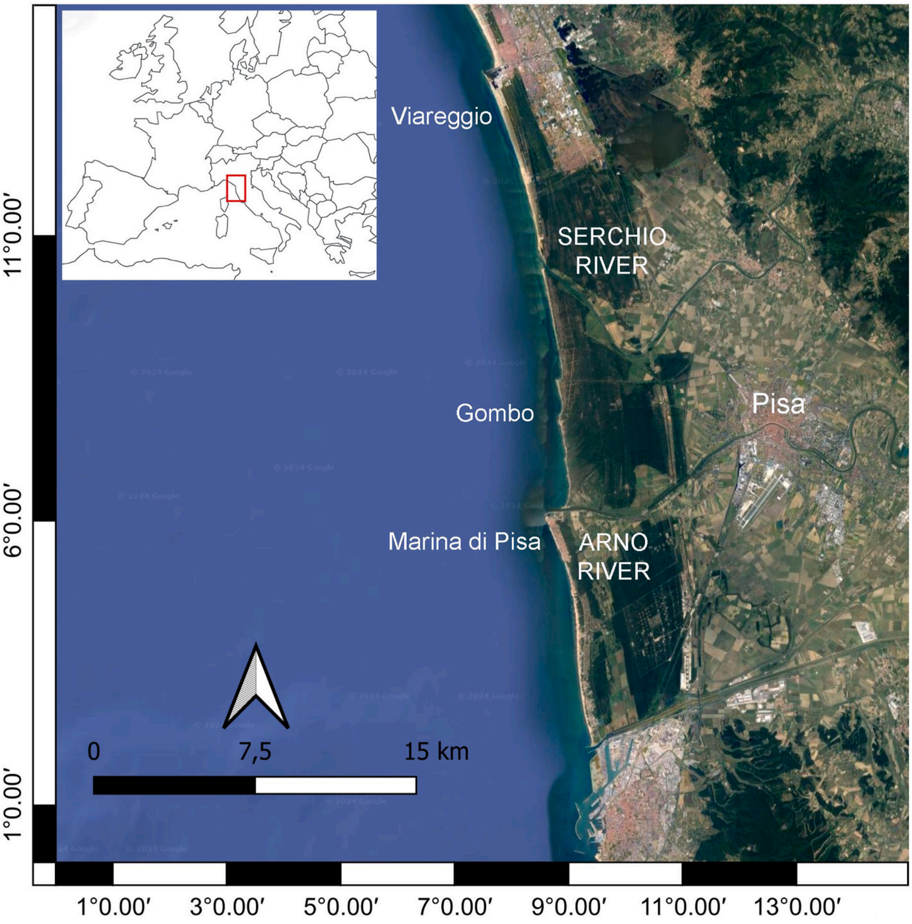

Fig. 1. Map illustrating the shoreline study area, highlighting key localities and rivers. The map was modified from Google Satellite to provide a clear representation of the geographic features under investigation. The upper left inset features a map of Europe highlighting the specific location of Italy. The study area is delimited by a red rectangle.

3. Materials and methods

3.1. Coastal risk assessment

The study area was divided into 24 contiguous units, each measuring 1000 m in length and 500 m in width. Additionally, two buffer zones were included outside the northern and southern boundaries of the park to facilitate a comparison of risk indices both inside and outside the protected area. For each unit, a vegetation-based risk index (VRI) was computed following the methodology proposed by Rangel-Buitrago et al. (2020), initially designed for the Atlantic Ocean coast. This methodology was adapted to account for the unique characteristics of the Mediterranean region, which, unlike the Atlantic, is a closed basin surrounded by complex topography that significantly influences the local climate. The Mediterranean is characterized by high water temperature and salinity and limited tidal and wave dynamics compared to those of the Atlantic (Weyl, 1970; King, 1975; D'Ortenzio et al., 2005). The adaptations presented in this work included various vegetation variables to characterize the ecological conditions of the dune systems.

The coastal risk index comprises two main subindices: the hazard index, which combines the forcing and susceptibility indices (10 variables in total), and the vulnerability index, which considers socioeconomic (5 variables), cultural (2 variables), and ecological aspects (7 variables). The coastal risk index quantifies the probability and consequences of coastal erosion events within socioeconomic, ecological, and cultural contexts, as defined by UNISDR (2009). The hazard index, in this context, is a numerical value indicating the potential for an area to incur damage due to coastal erosion.

The coastal forcing index (Table 1) measures the energy level of physical processes involved in coastal erosion, providing insights into the stress exerted by physical agents. In designing the risk index, this study aimed for simplicity and ease of application, streamlining some challenging variables. For instance, “Significant wave height at a specific coastal sector” was simplified to “Mean wave height.” The variable “Storm Surge at a specific coastal sector” was omitted because it is not representative of the Mediterranean. A new variable, “coastal dynamism,” was introduced to evaluate whether coastal units are experiencing erosion, stability, or accretion; this variable is crucial for risk assessment on sandy coasts (Ciccarelli et al., 2017; Bertoni et al., 2019).

The coastal susceptibility index assesses the resilience and susceptibility of sandy coasts to erosion processes, considering various factors based on typology, including geological and geomorphological features (Table 2). The role of vegetation was emphasized by introducing the variable “ecosystem and habitat cover” into the susceptibility index. Vegetation plays a crucial role in dune formation and consolidation, reducing shoreline erosion susceptibility (Maun, 2009). We simplified the variable “dry beach width as a multiple of the ICZ” to “dry beach width.”

The vulnerability index quantifies the coastal system's ability to withstand and recover from erosion events, evaluating potential consequences within socioeconomic, ecological, and cultural dimensions. These aspects are considered inherent attributes of coastlines, and vulnerability is acknowledged as an intrinsic characteristic (Tables 3–5).

The socioeconomic aspect of the vulnerability index includes variables representing social, economic, and human activities impacted by coastal erosion. In the case of the “roads” variable, we adopted a binary

Table 1
Variables contributing to **coastal forcing**.

Variable	Null/Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Mean wave height (Rangel-Buitrago et al., 2020)	0–1 m	1.5–2 m	2.5–3 m	3.5–4 m	>4 m
Degree of littoral exposure to wave fronts (García-Mora et al., 2001)	10–45° Oblique	x	0–10° Subparallel	x	0° Parallel
Tidal Range (McLaughlin and Cooper, 2010)	Macrotidal	x	Mesotidal	x	Microtidal
Dynamism (Bertoni et al., 2019)	>-25 m Maximum erosion	Between −6 and −25 m Erosion	Between −5 and +5 m Stable	Between 6 and 25 m Progradation	>25 m Maximum progradation

Table 2
Variables contributing to **coastal susceptibility** on sandy coasts.

Variable	Null/Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Dune height (Gracia et al., 2009)	≥6	≥3	≥2	≥1	<1
Percentage of washovers (García Mora et al., 2001)	0	≤5%	≤25%	≤50%	≥50%
Dry beach width (Rangel-Buitrago et al., 2020)	>35 m	35–25.5 m	25–15.5 m	15-5 m	<5 m
Beach slope/morphodynamic state, Foreshore slope (Anfuso, 2002)	Dissipative ($\tan\beta \leq 0.02$)	x	Intermediate ($0.02 < \tan\beta < 0.08$)	x	Reflective ($\tan\beta \geq 0.08$)
K Index (Aybulatov and Artyukhin, 1993)	Extreme ($K > 1$)	Maximum ($K =$ from 0.51 to 1)	Average ($K =$ from 0.11 to 0.5)	Minimum ($K =$ from 0.0001 to 0.1)	No structures ($K = 0$)
Ecosystem and habitat cover (Li and Li, 2011)	Strategic ecosystems: psammophilous vegetation communities, wetlands	x	Bushes, stubble, grassland, bare rocks	x	Unvegetated area

Table 3
Variables associated with the **socioeconomic vulnerability** index.

Variable	Null/Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Land uses (Rangel-Buitrago et al., 2020)	Bushes and scrubs	Pastures (dense grass cover), Pastures (grass, crop), Pastures (grass, trees)	Swamp area, Salt marsh, Coastal lagoon, Wet area, Gallery forest	Agricultural pond, Cropland Complex, cultivation area	Recreational structures, Airports, Industrial-Commercial area, Urban area, Mining area
Percentage of urbanized area (Li and Li, 2011)	Lower than 20%	20–40%	40–60%	60–80%	Larger than 80%
Population density (Li and Li, 2011)	Lower than 10 inhabitants per square kilometer	11–75	76–300	301–999	Greater than 1000 inhabitants per square kilometer
Conservation designation (Contreras and Kienberger, 2011)	International	National	Regional	Local	Absent
Roads (Drejza et al., 2019)	Absent	x	x	x	Present

Table 4
Variables associated with the **cultural vulnerability** index.

Variable	Null/Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Cultural heritage (McLaughlin and Cooper, 2010)	Absent	Local interest	Regional interest	National interest	International interest, UNESCO World Heritage Site
Cultural built environment (Rangel-Buitrago, 2019)	Heavy industry	Heavy tourism/urban	Light tourism/sensitive industry	Sensitive tourism	Historic

Table 5
Variables associated with the **ecological vulnerability** index.

Variable	Null/Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Protected areas	Absent	x	Protected area	x	SIC
Level of human intervention (Li and Li, 2011)	Very High (more than 80% of the area)	High (80%–60%)	Medium (60%–40%)	Low (40%–20%)	Very low (Lower than 20%)
Litter presence (Rangel-Buitrago, 2019)	Continuous accumulations	Full strand line	Local or discontinuous accumulation	Few scattered items	Virtually absent
Number of coastal habitats	0–1	x	2–3	x	≥4
Sand beach & shifting dune vegetation	0%	1–15%	16–30%	31–50%	>50%
Dune grasslands	0%	1–20%	21–40%	41–60%	>60%
Dune scrubs & thickets	0%	1–15%	16–30%	31–50%	>50%

classification (presence/absence) to align with the relatively uncomplicated road system within the initial 500 m inland of the park. In contrast, the "land uses" variable encompasses various anthropization levels, extending beyond the simplicity of roads. Consequently, we have made a clear distinction between these variables to better capture the intricate nature of our study area. Furthermore, certain variables, such as "number of infrastructure services," "tourism," and "economic activities," were removed due to their broad or intricate nature (Table 3).

The cultural aspect focuses on preserving significant cultural elements, including archaeological and historical sites. The variables "ethnographic interest" and "ethnic communities" were eliminated because they did not align with the cultural context of the local study area. The final cultural vulnerability index employs two variables: "cultural heritage" and the "cultural built environment" (Table 4).

The ecological aspect emphasizes conserving natural habitats, inherently offering protection against coastal erosion. New variables related to the number and percentage of different dune habitats present in the study area were introduced (Table 5), and the species were assigned high ecological vulnerability when the number of habitats was greater and the psammophilous habitat cover was at its maximum (Table 5).

Variables for both the hazard and vulnerability indices were assessed and ranked on a scale from 1 to 5, with 1 indicating a low contribution and 5 indicating a high contribution. These classes were categorized on an ordinal scale.

The following equation was used to calculate the total score for each variable:

$$Coastal\ Forcing\ Index = \frac{\left(\sum_{Cf\ an=1}^{nCf} Cf\ an\right) - nCf}{nCf \times 4} \times 100 \tag{1}$$

$$Coastal\ Susceptibility\ Index = \frac{\left(\sum_{S\ an=1}^{nS} S\ an\right) - nS}{nS \times 4} \times 100 \tag{2}$$

$$Hazard = \frac{(Coastal\ Forcing\ index \times nCf) + (Coastal\ susceptibility\ index \times nS)}{nCf + nS} \tag{3}$$

$$Vulnerability\ Index = \frac{\left(\sum_{V\ an=1}^{nV} V\ an\right) - nV}{nV \times 4} \times 100 \tag{4}$$

Here, "an" represents each of the individual variables within the respective subindex (forcing: Cf, susceptibility: S, and vulnerability: V), and "n" denotes the total number of variables included in each subindex. Consequently, each subindex can assume values within the range of 1–100.

The risk index (RI) was then calculated as a numerical value emerging from the combination of the hazard and vulnerability indices, normalized as detailed by McLaughlin et al. (2002).

$$Risk\ Index = \frac{[Hazard \times (nCf + nS)] \times [Vulnerability \times (nV \times 4)]}{(nCf + nS) + (nV \times 4)} \tag{5}$$

The total risk index, ranging from 0 to 100, is determined by the weighted average of the socioeconomic, cultural, and ecological risk indices, considering the number of variables in each subindex. After calculating the final indices for each unit, the cells were categorized into five risk classes, from very low to very high: 0–19.5 = class 1; 20–39.5 = class 2; 40–59.5 = class 3; 60–79.5 = class 4; and 80–100 = class 5.

All indices were visually represented through hazard, vulnerability, susceptibility, and risk maps using QGIS 3.22 (QGIS.org, QGIS Geographic Information System. QGIS Association. http://www.qgis.org).

3.2. Data collection and analysis

The risk index for each unit was computed using distinct sets of information (Tables S1–S5 in the supplementary materials). The data sources included the Hydrogeological Service of the Tuscany Region, which provided variables such as "mean wave height" and "degree of littoral exposure to wave fronts" for coastal forcing (Tables 1 and S1) [https://www.cfr.toscana.it/index.php? IDS = 8&IDSS = 50]; the National Environmental Information System for "land uses" [https://www.isprambiente.gov.it/it/attivita/reti-e-sistemi-informativi-ambientali/sistema-informativo-nazionale-ambientale-sina]; and ISTAT for "population density", which contributes to socioeconomic vulnerability data (Tables 3 and S3) [https://www.istat.it/archivio/104317]. Additional information, including "dune height", "percentage of washovers", "dry beach width", "K index", and "ecosystem and habitat cover" for coastal susceptibility (Tables 2 and S2) and "percentage of urbanized area" and "roads" for socioeconomic vulnerability (Tables 3 and S3), was obtained using Google Earth (https://www.google.com/intl/it/earth/about/). The "level of human intervention" for the ecological vulnerability index (Tables 4 and S4) was also determined through Google Earth. Data from the literature were incorporated into these analyses (Tables S1–S5).

For variables such as "litter presence", "number of habitats", and habitat coverage within the ecological vulnerability index, field sampling was conducted (Tables 4 and S4). Litter assessment covered the entire length of the units. To quantify the presence and cover of coastal habitats, randomly placed perpendicular transects were used within each unit, stretching from the annual vegetation of drift lines to fixed dunes dominated by scrubs and thickets. Along each transect, the presence of dune habitats, classified into sand beach and shifting dune vegetation, dune grasslands, and dune scrubs and thickets (see Table S6 for a detailed description of habitats and target species) following the EUNIS classification (Chytrý et al., 2020), was recorded in contiguous 2 × 2 m plots. Vegetation sampling occurred between April and June 2021 and 2022.

All the data were processed using RStudio March 1, 2023 (R Core Team, 2022) and QGIS 3.22 (QGIS.org, QGIS Geographic Information System. QGIS Association. http://www.qgis.org). A matrix comprising 24 variables and 37 units was then compiled and subjected to multivariate analyses to examine the relationships between sites and the influence of variables on site variation. For the cluster analysis, average-linkage clustering was used with the Euclidean distance as the dissimilarity index. The same resemblance matrix supported nonmetric multidimensional scaling (NMDS), a technique that represents samples in two-dimensional space by optimizing the correspondence between original dissimilarities and distances in the ordination (Økland, 1996). Additionally, Pearson correlation coefficients were computed between variables and NMDS axes. Both cluster analysis and NMDS were conducted using PRIMER 7.0 software (Clarke and Gorley, 2015).

4. Results and discussion

4.1. Spatial distribution of hazards, vulnerability, and risk

The hazard index is a quantitative metric designed to assess potential damage from coastal erosion in each region. This index includes two main subindices: coastal forcing and coastal susceptibility. Coastal forcing evaluates the physical stress magnitude a coastal segment might undergo during erosion, while coastal susceptibility quantifies both the exposure level and intrinsic coastline characteristics.

Along the San Rossore coastline, 29.2% of the region exhibited a low coastal forcing index, whereas 45.8% and 25% were characterized by medium and high coastal forcing indices, respectively (Table 6, Fig. 2). These values indicate the factors influencing the wave energy distribution along the San Rossore coast. The predominance of medium to high coastal forcing indices is attributed to the region's microtidal nature, which has been linked to coastal flooding and erosion (Gornitz et al.,

Table 6

Distributions of forcings, susceptibilities and hazards calculated for San Rossore Park (24 km in length).

		Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Forcing	Length (km)	0	7	11	6	0
	Percentage (%)	0	29.2	45.8	25	0
Susceptibility		0	10	14	0	0
		0	41.7	58.3	0	0
Hazard		0	11	12	1	0
		0	45.8	50	4.2	0

1994; Costas et al., 2015), and the dynamics of wavefronts, particularly in the southern half of the study area.

In terms of coastal susceptibility, 41.7% of the coastal stretches had low susceptibility values, while the remaining 58.3% had medium susceptibility values (Table 6, Fig. 2). These susceptibility values are related to the predominant characteristics of the coastline, which are mainly reflective of urban beaches with low dune heights. In certain San Rossore areas, "induced susceptibility" arises from the use of hard structures (e.g., seawalls, detached breakwaters, and groins) for erosion management. Examples include Viareggio, Gombo, and Marina di Pisa, where these structures have altered the natural shoreline, increasing susceptibility values. The extensive armoring of the coastline, especially at Gombo and the Arno River mouth, reshapes the natural susceptibility of the San Rossore shoreline (Pranzini et al., 2018).

Coastal erosion, considered a hazard when it threatens a specific area, is a natural geological process. Problems arise when urban development encroaches on the shoreline, known as the “coastal squeeze” (Pontee, 2013). In this study, low hazard values were found for 45.8% of the coastline, with medium and high hazard values identified for 50% and 4.2%, respectively (Table 6, Fig. 2). The central-southern region of San Rossore exhibited medium and high hazard values, which correlated with significant erosion in these areas.

The vulnerability index evaluates the potential consequences of coastal erosion within socioeconomic, ecological, and cultural contexts. San Rossore Park, bordered by the densely populated areas of Viareggio and Marina di Pisa, had a high socioeconomic vulnerability of more than 12.2%. The northern section, with high tourism and infrastructure, exhibited medium vulnerability across 20.8% of the coastline, while regions with limited public access exhibited very low and low socioeconomic vulnerability, accounting for 29.2% and 37.5%, respectively (Table 7, Fig. 3). Socioeconomic vulnerability is influenced by factors such as population density, urbanization, and land use patterns, as highlighted in the literature (McLaughlin et al., 2002; Del Rio and Gracia, 2009).

Culturally, 66.7% of the park exhibited very high vulnerability, with high and medium vulnerability levels observed for 8.3% and 4.2%, respectively, of the coastline. Areas outside the park boundaries displayed lower cultural vulnerability (Table 7, Fig. 3).

Ecologically, an inverse relationship with socioeconomic vulnerability is observed. Urbanized areas outside and in the southern part of the park exhibited very low ecological vulnerability (16.7%) and low vulnerability (41.7%) (Table 7, Fig. 3). The southern part, which is experiencing severe erosion and loss of dune habitats, exhibited lower ecological vulnerability. Conversely, the central-northern region within the park exhibited medium to high ecological vulnerability due to preserved dune systems (Table 7, Fig. 3).

The integration of these vulnerability indices provided a comprehensive assessment of San Rossore’s overall vulnerability, ranging from low (58.3% of the coastline) to medium (33.3%) and high vulnerability (8.3%) (Table 7, Fig. 3).

Hazard and vulnerability were combined into the vegetation-based

Table 7

Distribution of vulnerability calculated for San Rossore Park (24 km in length).

		Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Socioeconomic	Length (km)	7	9	5	3	0
	Percentage (%)	29.2	37.5	20.8	12.5	0
Cultural		2	3	1	2	16
		8.3	12.5	4.2	8.3	66.7
Ecological		4	10	6	4	0
		16.7	41.7	25	16.7	0
Total		0	14	8	2	0
		0	58.3	33.3	8.3	0

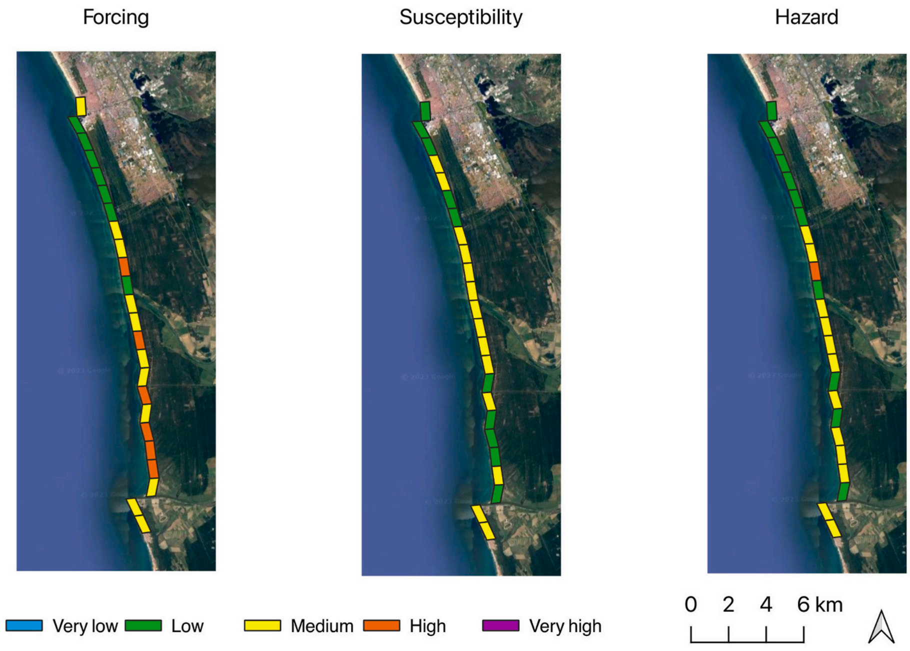

Fig. 2. Distributions of forcings, susceptibilities, and hazards calculated for San Rossore Park.

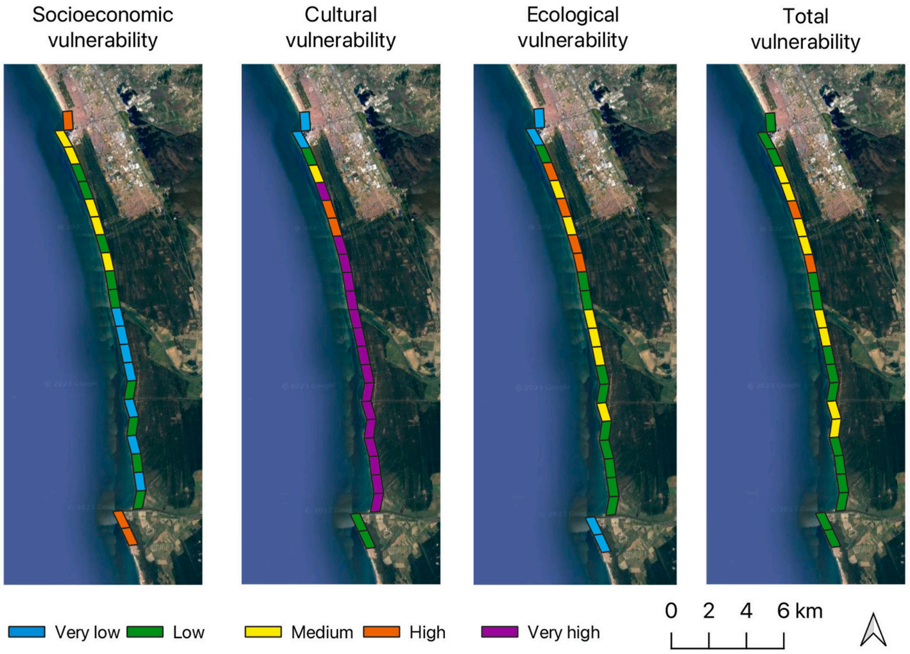

Fig. 3. Distribution of vulnerability calculated for San Rossore Park.

coastal risk index. This index quantifies the probability and adverse outcomes of coastal erosion events. Socioeconomically, high- and medium-risk areas were concentrated within urbanized regions, covering 8.3% and 12.5%, respectively. Low-risk areas (50%) were found within publicly accessible sites, and very low-risk areas (29.2%) were found in regions with stricter regulations. Cultural heritage risk assessment revealed the highest risk areas, primarily within the park, with 20.8% moderate risk, 41.7% high risk, and 4.2% very high risk (Table 8, Fig. 4). Ecologically, high risk values, including very high risk (12.5%) and high risk (29.2%), were concentrated in the park's central region (Table 8, Fig. 4).

Overall, the study revealed that 50% of the San Rossore Park had low risk values, 37.5% had moderate risk values, and 12.5% had high risk values (Table 8, Fig. 4).

4.2. *Multivariate analyses*

NMDS analysis revealed distinct separations, primarily along the first axis, among the two groups of units, confirming that similar segregation was observed in the cluster analysis (see Fig. S1 in the supplementary materials). The first, smaller group, positioned to the right of NMDS1 in Fig. 5, consisted of units located outside or near the boundaries of the park. This group exhibited high percentages of urbanized area (SEV2 within the socioeconomic vulnerability variables).

Conversely, the second group, situated to the left of NMDS1 in Fig. 5, comprised the majority of units. This group was distinguished by elevated scores in the "cultural built environment" (specifically CV2 within the cultural vulnerability variables) and in the "conservation designation" (SEV4 within the socioeconomic vulnerability variables). Additionally, there were high values for "protected areas" and low values for "level of human intervention" (EV1 and EV2 within the ecological vulnerability variables).

Table 8
Distribution of risk calculated for San Rossore Park (24 km in length).

		Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Socioeconomic	Length (km)	7	12	3	2	0
	Percentage (%)	29.2	50	12.5	8.3	0
Cultural		3	5	5	10	1
		12.5	20.8	20.8	41.7	4.2
Ecological		3	6	6	7	2
		12.5	25	25	29.2	8.3
Total		0	12	9	3	0
		0	50	37.5	12.5	0

Moving to the second axis of NMDS (Fig. 5), several units in the upper part of the axis stood out with high scores in the "number of coastal habitats" and in "dune grasslands" (specifically, EV4 and EV6 within the ecological vulnerability variables). In contrast, a larger group, situated in the lower part of NMDS2 (Fig. 5), exhibited high percentages of washovers (specifically, CS2) within the coastal susceptibility variables.

Extensive human intervention, coupled with social activities, leads to increased levels of socioeconomic vulnerability. This often results in the disruption or absence of characteristic coastal dune vegetation. Within protected areas, cultural and ecological vulnerability indices influence the assignment of medium to high values of coastal risk. Notably, units characterized by intense erosional processes tend to exhibit low values of coastal risk, primarily due to the loss of most coastal dune habitats.

4.3. *Methodological considerations*

Coastal risk mapping plays a crucial role in coastal management and planning. A comprehensive map encompasses essential information for evaluating optimal management strategies and serves both as technical and legal support for decision-making and in the formulation of development policies. Currently, policies and initiatives are increasingly adopting an integrated and holistic perspective to address and mitigate the growing threats faced by coastal regions. In this context, there is an urgent and imperative need to prioritize coastal risk mapping in all coastal nations (Rangel-Buitrago et al., 2020).

Given the frequent oversight of the distinct characteristics of sandy coastal plant communities in existing risk index methodologies, as highlighted by previous studies (Abuodha and Woodroffe, 2006; Nguyen et al., 2016; Bukvic et al., 2020), this work recognized the need to fill this gap by integrating vegetation data. Specifically, additional ecological information concerning the presence and abundance of plant

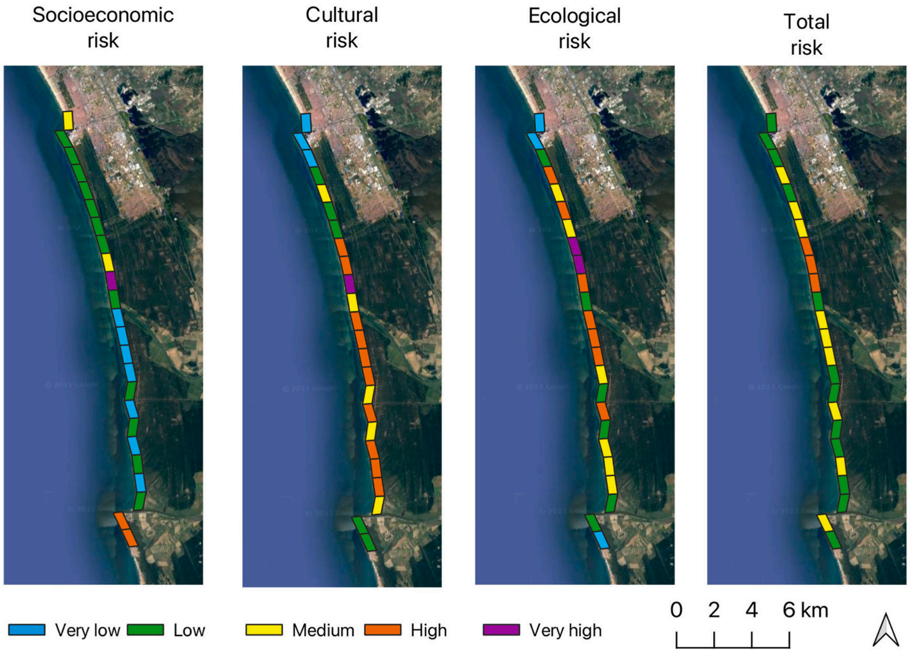

Fig. 4. Risk indices calculated for San Rossore Park.

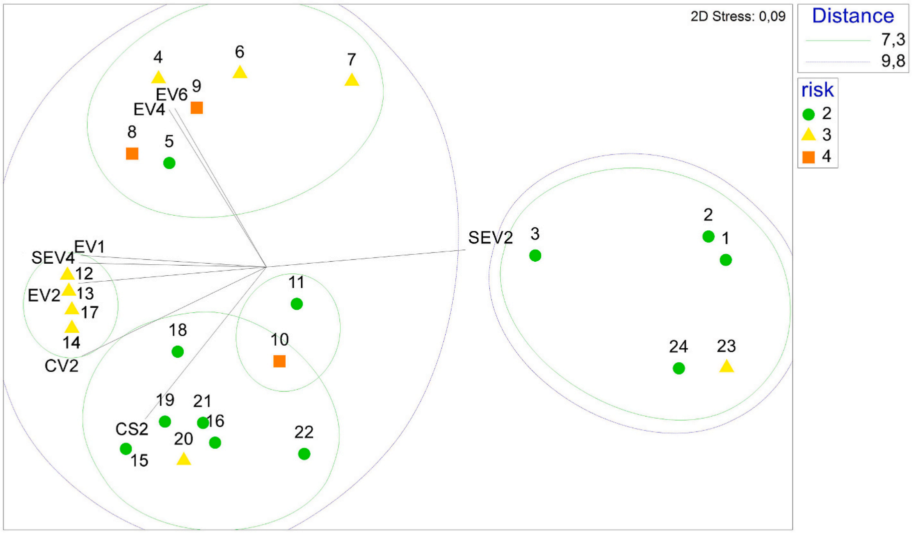

Fig. 5. NMDS diagram based on dissimilarity (measured by Euclidean distance) for 24 coastal cells. The groups obtained via cluster analysis were superimposed into the diagram and are circumscribed by a green line (distance = 7.3) or by a blue line (distance = 9.8). All the variables shown had a Pearson correlation coefficient >0.8 with the two axes. Variable abbreviations: CS2 = "percentage of washovers" (within susceptibility variables); CV2 = "culturally built environment" (within cultural vulnerability variables); EV1 = "protected areas", EV2 = "level of human intervention", EV4 = "number of coastal habitats", and EV6 = "dune grasslands" (within ecological vulnerability variables); SEV2 = "percentage of urbanized area", and SEV4 = "conservation designation" (within socioeconomic vulnerability).

communities typically found in coastal dunes is introduced. These data have been integrated into both susceptibility and ecological vulnerability variables, serving the dual purpose of recognizing the positive influence of vegetation on coastal resilience and addressing the detrimental consequences associated with the loss of these unique and strategically important habitats. Indeed, natural coastal habitats play a pivotal role in mitigating coastal erosion, thereby reducing susceptibility. The specific function of these systems in stabilizing coastal dunes provides more valuable insights than does a generalized consideration of vegetation.

The foundational step in this coastal risk assessment involved comprehensive data collection. The data sources included the Hydrogeological Service of the Tuscany Region for coastal forcing variables such as the "mean wave height" and the National Environmental Information System for socioeconomic factors such as "land use". Field sampling was crucial for determining ecological variables, particularly "litter presence" and "number of habitats" (Abuodha and Woodroffe, 2006; Nguyen et al., 2016; Bukvic et al., 2020). The preprocessing phase involved standardizing and normalizing the data to maintain consistency across metrics, a critical step that ensures accurate representation of each site's unique characteristics and enhances the robustness of subsequent analyses.

The integration of socioeconomic, cultural, and ecological vulnerability indices was key in assessing overall vulnerability. Computed using relevant variables, this integration created a comprehensive vulnerability profile (Rangel-Buitrago et al., 2020). This approach helps to understand how different aspects of vulnerability interact and contribute to the overall risk level.

Cluster analysis and NMDS were employed for data analysis. Average-linkage clustering with the Euclidean distance was utilized in the cluster analysis to identify groups based on coastal risk factors. NMDS efficiently reduced multidimensional data into two dimensions, validating patterns among units identified by the cluster analysis. Furthermore, NMDS offered insights into the factors contributing to the risk profile of each unit.

The methodology employed offers the distinct advantage of being amenable to graphical representation, thereby facilitating intuitive comprehension of the risk levels along the analyzed coastal stretch. Additionally, the results enable a dissection of the risk into distinct components, encompassing socioeconomic, cultural, and ecological dimensions. This approach aids in discerning the pivotal variables influencing overall risk. However, it is important to acknowledge certain limitations inherent in this methodology. While the index used in this study is presented as a user-friendly tool (Rangel-Buitrago and Anfuso, 2015; Rangel-Buitrago et al., 2020), its practical application requires specialized expertise across the diverse categories of variables encompassed, coupled with the procurement of requisite datasets. Often, the necessary information for index compilation is not readily available and requires significant data manipulation before utilization. Despite these challenges, this methodology remains one of the most intuitive and readily applicable approaches compared to alternatives in the literature (Nguyen et al., 2016).

4.4. Management considerations

Coastal risk mapping is a critical tool in coastal management strategies. Maps provide a comprehensive visual representation of the potential risks associated with coastal erosion, flooding, and other environmental factors. This mapping approach is invaluable for decision makers because it offers an integrated perspective that combines geological, ecological, and socioeconomic data. Understanding the spatial distribution of risks enables policymakers and planners to allocate resources effectively, prioritize conservation efforts, and implement protective measures in areas most susceptible to coastal hazards.

The integration of ecological data, particularly coastal plant community data, into coastal risk assessments represents a significant advancement in coastal management practices. By acknowledging the role of natural habitats in stabilizing coastlines and mitigating erosion, this approach promotes sustainable and environmentally sensitive coastal development. This approach encourages the preservation of natural dune systems and the use of green infrastructure rather than traditional hard engineering solutions, which usually have adverse ecological impacts.

Coastal risk assessment and mapping serve multiple purposes: they contribute to spatial and temporal knowledge of an area, assist in creating indicators and indices, support socioeconomic development decisions, and integrate various aspects, such as socioeconomic, ecological, and cultural factors.

Currently, policies and actions are increasingly taking an integrated and holistic approach to address and counteract increased coastal hazards (UNEP 2009; Jones and Phillips 2011). In this sense, prioritizing coastal risk mapping in all coastal countries is urgent. With respect to humans, we can achieve a sustainable global civilization if we evaluate the past from a broad perspective and emphasize planning for the future using mapping. Worldwide, coastal countries, especially the most vulnerable nations, can manage coastal erosion with new and innovative strategies that must begin with coastal risk mapping. These countries must also plan to replace old and less efficient management processes, particularly those known to generate more problems such as shore-hardening.

Coastal risk assessment and mapping can also be performed as follows.

- A tool to be incorporated into the spatial and temporal knowledge of an area.
- Materials for creating indicators and indices.
- A decision support tool for social and economic development.
- An integrative system for all aspects involved (i.e., socioeconomic, ecological, and cultural).

Effective coastal management requires a balance between adaptation and mitigation strategies. Adaptation involves adjusting existing practices and infrastructure to better withstand coastal hazards, while mitigation focuses on reducing the severity of these hazards through proactive measures. Our methodology underscores the importance of both approaches, suggesting that areas with high ecological value should prioritize conservation and natural buffer creation, whereas urbanized or highly developed areas might focus more on adaptive infrastructure and emergency response planning.

The findings from this work have significant implications for coastal policy and development regulations. These authors highlighted the need for stringent building codes in high-risk areas, promoting sustainable development practices that minimize the ecological footprint and enhance the resilience of coastal communities. The data also support the argument for restricting development in areas with high ecological vulnerability, preserving these zones as natural buffers against coastal hazards. Planning should allow for the landward migration of such zones in light of sea-level rise and increased coastal flooding.

Public awareness and community involvement are essential components of effective coastal management. Educating local communities about the risks associated with coastal erosion and the importance of preserving natural habitats can lead to more community-led conservation initiatives. Involving communities in decision-making processes ensures that management strategies are not only scientifically sound but also socially acceptable and aligned with the community's needs and values. In the same way, continuous monitoring and future research are vital for ensuring the effectiveness of coastal management strategies. Environmental conditions and coastal dynamics are constantly changing, necessitating regular updates to risk assessments and management plans. Future research should focus on refining risk assessment methodologies, exploring the impacts of climate change on coastal systems, and developing innovative management solutions that are both environmentally sustainable and economically feasible.

Effective management strategies for protected areas such as San Rossore Park are imperative. This park, distinguished by its unique ecological and cultural attributes, faces growing vulnerability to the influences of both human activities and natural processes such as erosion. The following strategies are designed to address general and specific issues across various sectors of the park, with a focus on achieving a harmonious balance between ecological preservation and responsible human use.

4.4.1. General strategies

4.4.1.1. Risk index analysis.

- We conducted detailed studies to analyze the components of the risk index, identifying specific factors contributing to cultural and ecological vulnerabilities.

- The findings can be used to prioritize areas for intervention and to tailor conservation strategies to the specific needs and challenges of parks.

- The continuous monitoring and evaluation of risk factors should be ensured to adapt management strategies to changing conditions and new scientific insights.

4.4.1.2. *Stakeholder Engagement and education.*

- Engage with local communities, tourists, and other stakeholders to foster a culture of conservation and responsible park use.
- To develop educational materials and programs that highlight the unique features and conservation needs of parks.

4.4.1.3. *Collaboration and research.*

- Foster collaboration with research institutions, NGOs, and other conservation organizations can benefit from a wide range of expertise and resources.
- Ongoing research within parks should be encouraged to gain a deeper understanding of their ecosystems and to inform management decisions.

4.4.2. *Specific strategies*

4.4.2.1. *Conservation in the northern sector.*

- Stringent regulations should be implemented to control tourism and human activities, especially in dune habitats.
- Surveillance and enforcement should be enhanced to prevent unauthorized activities that may harm the ecosystem.
- To develop educational programs to raise awareness among visitors about the ecological significance of the area and the importance of conservation.
- Encourage inclusive public participation in conservation actions (e.g., beach/dune litter clean-ups, removal of alien species, and replanting native dune plants such as *Calamagrostis arenaria* and *Thinopyrum junceum*).

4.4.2.2. *Erosion management in the central-south region.*

- Explore and invest in alternative erosion control measures that do not involve hard structures, such as soft engineering and natural solutions such as beach nourishment or dune restoration (e.g., sand fencing, replanting native vegetation, particularly on sand beaches and shifting dunes).
- Shoreline changes should be regularly monitored and assessed to identify areas of concern, and management strategies should be adjusted accordingly.
- Coastal engineers and scientists should collaborate to develop and implement sustainable shoreline protection methods.

These structured strategies aim to preserve the ecological integrity and cultural significance of the park, ensuring its sustainable management for future generations.

5. Conclusions

This study underscores the critical ecological and management importance of coastal dunes, particularly on the Mediterranean sandy coastline. These transitional ecosystems serve as pivotal components in preserving shorelines and providing habitats. This research highlights the delicate balance between natural processes and human impacts on these ecosystems, emphasizing the need for comprehensive management strategies that integrate physical, biological, and socio-economic aspects.

The chosen study area, the protected area of San Rossore Park in Tuscany (Italy), stands out for its noteworthy coastal dune ecosystems, which hold naturalistic, cultural, and economic importance. However, challenges arise from diverse land uses, zoning, and human impact variables.

At the core of this research is the development and application of the vegetation-based risk index (VRI) within a geographic information system (GIS) framework. This innovative index, which incorporates geological, socioeconomic, cultural, and ecological parameters along with unique variables related to coastal dune vegetation, integrates a variety of data sources and field observations, providing a valuable tool for assessing coastal resilience. Indeed, the VRI recognizes the ecological significance of vegetation in mitigating coastal erosion, thereby contributing to sustainable coastal conservation efforts on a global scale.

The index facilitates clear and intuitive cartographic representations of coastal risk, identifying variable categories that substantially influence risk determination. Assessing risk factors in this region provides valuable insights into the diverse factors influencing coastal erosion risks in such environments and should be applied throughout the Mediterranean as well as similar global coasts.

The analysis revealed varying risk levels within the study area. Half of San Rossore Park's coastline exhibited low risk values, 37.5% had moderate risk values, and 12.5% had high risk values. The publicly accessible northernmost section, despite excellent preservation of dune habitats, faces heightened risk due to anthropogenic impacts. Conversely, the central-southern portion, inaccessible to the public, registers high-risk levels linked to variables associated with coastal erosion. Tailored strategies, including mitigating human pressure in the northern sector through tourism control, educational programs, and conservation actions, are recommended. Additionally, erosion management strategies are proposed for the central-southern region, exploring measures such as beach nourishment or dune restoration and promoting collaboration between coastal engineers and scientists.

Finally, this research emphasizes the role of vegetation in enhancing coastal resilience and advocates for holistic, integrated approaches in policy-making, community involvement, and continuous monitoring. The proposed strategies for San Rossore Park underscore the importance of balancing conservation with responsible park use for sustainable management.

In summary, this study not only provides a practical tool for assessing and managing coastal areas and directing attention to specific threats but also supports stakeholders in informed decision-making. The VRI enhances global sustainable coastal conservation, deepening our understanding of coastal risks and providing valuable insights for effective management strategies.

CRediT authorship contribution statement

Viola Alessandrini: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Duccio Bertoni:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology. **Nelson Rangel-Buitrago:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Daniela Ciccarelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors express their gratitude to the Migliarino-San Rossore-Massaciuccoli Regional Park for granting permission to access the protected area and collect the research data. Appreciation is also expressed to the Hydrogeological Service of the Tuscany Region for providing meteo-marine data. Special acknowledgment is extended to Gianni Bedini and Monica Bini from the University of Pisa, who provided valuable assistance to Viola Alessandrini in enhancing her master's degree thesis. Additionally, sincere thanks are owed to David Dolci for his technical support in manipulating certain data used in the index. Finally, the authors are grateful to four anonymous reviewers whose insightful comments and suggestions significantly contributed to the refinement of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107105.

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