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MULTIDISCIPLINARY STUDY OF THE COASTAL DUNE SYSTEM STABILITY THROUGH THE ANALYSIS OF ABIOTIC AND BIOTIC FACTORS: A COMPARISON BETWEEN THE MEDITERRANEAN (ITALY) AND ATLANTIC OCEAN (BRAZIL)

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This Work is dedicated to my parents,

Celso e Julieta

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Abstract

In this thesis, was development out on two separate sites characterized by a well-developed coastal dune field, namely the: São Francisco do Sul Island (Santa Catarina State, Brazil) and the Pisan coast (Tuscany, Italy). The settings were chosen due to the ecological relevance of the dune fields and according to physical characteristics (accretion/retreat state), vegetation cover and anthropization. The research was based on the hypothesis that multidisciplinary analysis enrich scientific research and contribute to improve knowledge about the factors that drive the evolution of beach dune systems in both the oceanic and Mediterranean climates. The methodology used includes: data collected in the field (topographic survey, sediment sampling, vegetation coverage and anthropic pressure), measurement of the aeolian transport of sediment in coastal dunes, through the development of a wireless sensor network (vertical sand trap, sensors based on photoresistor and anemometer/anemoscope stations), dataset digital (lithologic and geological elements mapping, photo-interpretation and build photo-mosaic) and statistical analysis (sediment volume, plant functional types classification, coastal dune vulnerability index development). The results obtained for the coast of São Francisco do Sul indicate a tendency to retraction of the coastline, mainly in the northern sector of the island. The dune system is continuous along the N-S direction and is composed by an interconnection of frontal and semi-mobile dunes, backed by steady dunes. There is one spatial separation of parabolic (NNE orientation are located on the north sector of the beach) and transverse dunes (covered by dense shrub vegetation, are prevalent in the southern sector). The width of the backshore was higher in the northern sector; the gran-size is comprised within the medium sand interval. The north sector has a higher biodiversity compared to the south sector. The results obtained for the Pisano coast showed a strong retraction of the coast line in the south sector (between Arno and Serchio Rivers) and an accretion in the north sector (Torre del Lago and Viareggio). The frontal dunes showed a great decrease in the last nine years. In some points in the south sector they are completely inexistent. The difference of vegetal coverage between the two sectors is visually remarkable. The north sector is composed of a well-structure vegetation succession distributed in more than 300 m wide between sea-inland. On the other side, in the south sector, the succession of vegetation is threatened by severe erosion that reaches this stretch of beach. The sensors system architecture proposed for monitoring the sand dynamics proved its effectiveness in the collection of physical parameters, but needs to be tested at longer sampling times in order to provide more accurate results. The index developed for the sandy beaches has classified, for both countries, the total vulnerability as moderate. The geomorphological condition was the parameter most significant for all the sites analyzed, besides the marine influence to Oceanic sites and vegetation condition to Mediterranean sites. The vulnerability index proved to be an effective tool in the analysis of a large number of multidisciplinary variables and as a ready-to-use instrument for anybody who manages coastal areas.

Keywords: coastal dune, multidisciplinary, abiotic and biotic variables, vulnerability, Italy, Brazil.

Riassunto

Lo studio è stato sviluppato in due siti separati caratterizzati da un campo di dune costiere ben sviluppato: l'isola di São Francisco do Sul (Stato di Santa Catarina, Brasile) e il litorale Pisano (Toscana, Italia). I siti sono stati scelti per via della rilevanza ecologica dei campi di dune, per le caratteristiche fisiche (accrescimento/arretramento), copertura vegetale e antropizzazione. La ricerca si è basata sull'assunzione che le analisi multidisciplinari arricchiscono la ricerca scientifica e contribuiscono a migliorare le conoscenze sui fattori che guidano l'evoluzione dei sistemi duna-spiaggia in entrambi i climi, Oceanico e Mediterraneo. La metodologia utilizzata comprende: raccolta dei dati sul campo (rilievo topografico, campionamento dei sedimenti, rilievo della copertura della vegetazione e pressione antropica); misurazione del trasporto eolico dei sedimenti sulle dune costiere attraverso lo sviluppo di una rete di sensori wireless (trappola di sabbia verticale, sensori basati su fotoresistore e stazioni anemometro/anemoscopio); set di dati digitali (mappatura di elementi litologici e geologici, fotointerpretazione e costruzione di foto-mosaici); analisi statistica dei dati (volume di sedimenti, classificazione di tipi funzionali delle piante, sviluppo di un indice di vulnerabilità delle dune costiere). I risultati ottenuti per la costa di São Francisco do Sul indicano una tendenza all'arretramento della costa, soprattutto nel settore nord dell'isola. Il sistema di dune è continuo lungo la direzione N-S ed è composto da una interconnessione tra dune frontali e semi-mobili, sostenute da dune fisse. Vi è una separazione spaziale delle dune paraboliche (orientamento NNE, si trovano settore nord della spiaggia) dalle dune trasversali (coperte da una densa vegetazione arbustiva, sono prevalenti nel settore sud). La larghezza della spiaggia emersa è maggiore nel settore nord; la granulometria dei sedimenti rientra nella classe della sabbia media . Il settore nord presenta una diversità specifica maggiore rispetto al settore sud. I risultati ottenuti per il litorale Pisano hanno mostrato un forte arretramento della linea di costa nel settore sud (tra i fiumi Arno e il Serchio) e un accrescimento nel settore nord (Torre del Lago e Viareggio). Le dune frontali hanno mostrato una forte diminuzione negli ultimi nove anni, e in alcuni punti del settore sud sono completamente inesistenti. La differenza di copertura vegetale tra i due settori è visivamente notevole. Il settore nord è ben strutturato per quanto riguarda la sucessione della vegetazione, distribuita in più di 300 m di larghezza tra mare e spiaggia. Nel settore sud la successione della vegetazione è minacciata dalla severa erosione che colpisce questo tratto di spiaggia. Per quanto riguarda l'architettura del sistema proposto per i sensori di monitoraggio delle dinamiche del trasporto della sabbia, questa ha dimostrato la sua efficacia nella raccolta dei parametri fisici, ma il campionamento dovrà essere testato più a lungo per fornire risultati più accurati. Grazie all'indice sviluppato per le spiagge sabbiose, la vulnerabilità delle spiagge è stata classificata moderata per entrambe i paesi. La condizione geomorfologica è il parametro più significativo per tutti i siti analizzati, oltre all'influenza marina per i siti Oceanici e alla condizione della vegetazione per i siti del Mediterraneo. L'indice di vulnerabilità ha dimostrato di essere uno strumento efficace per l'analisi di un gran numero di variabili multidisciplinari e uno strumento adatto per chi gestisce il territorio costiero.

Parole chiave: dune costiere, studio multidisciplinare, variabili abiotiche e biotiche, vulnerabilità, Italia, Brasile.

PART I – SYNTHESIS

1. Introduction

Coastal environments consist of complex interactions between marine, continental and atmospheric elements. According to the Intergovernmental Panel on Climate Change (IPCC 2001), coastal environments support some of the most diverse and productive habitats, including mangroves, wetlands, coral reefs, dunes and beach field. Despite its importance as regulators of water (land and sea) and chemical composition and distribution of sediments, storage and recycling of nutrients, they also provide an important portion of socio-economic activities (tourism, shipping, fishing, ports, real estate, another). However, the significant and increasing urbanization, industrialization and tourism activities in the coastal zone, put in risk the balance of these environments. It is estimated that 40% of the world's population lives less than 100 km from the coast (UNEP Arendal, 2007). European countries such as Denmark, Holland, Italy, Germany and England are considered lowlying and have densely populated coastal areas (EEA, 2010), making them particularly vulnerable to sea level rise and changes in the intensity and frequency of floods (ETC-CCA, 2011). Vulnerabilities for sea Mediterranean resulting from climate changes are mainly correlated with flooding, salt water intrusion and erosion (Table 1).

Erosion is already a global reality (Souza, 1997; IPCC, 2014), 70% of the sandy beaches around world are experiencing strong erosions (Brunelli, 2008). In Europe, erosion is of longstanding, affecting more than 40% of the beaches in France, Italy and Spain (Gómez-Pina et al., 2002; Ferretti et al., 2003a; Alexandrakis & Poulos, 2014). Among the countries of Latin America and the Caribbean, Brazil is ranked as one of the most vulnerable to retrogradation of the coastline, along with Argentina, Mexico, Cuba and the Bahamas (Muehe, 2006; ECLAC, 2012; Martins, 2015). The case of erosion is seen as the result of two phenomena: increasing in the sea level and a negative balance of sediment (Muehe, 2006; Mazzer & Dillenburg, 2009). In addition, changes in upstream activities and engineering works (dams, sand mining in rivers, straightening watercourses, paving the coastline, among others) contribute to changing the budget of sediment that reaches the coast. In Italy, almost 80% of the beaches (ARPA, 2007) have defense works (transverse, longitudinal or adherent), creating physical obstacles for the exchange of sediment between the submerged beach and emerged one, and consequently inhibit the interaction with adjacent domains (Ferretti et al., 2003b; Brunelli, 2008).

Table 1. Main hazards and vulnerabilities for Mediterranean Sea facing the climatic changes (adapted and modified from ETC-CCA, 2011).

Main hazards and vulnerabilities	Western Mediterrenean Sea	Adriatic Sea, Ionian Sea and Central Mediterranean Sea	Aegean – Levantine Sea
Coastal flooding	x	x	x
Coastal erosion	x	x	x
Altered salinity	x		
Salt water intrusion	x	x	x
Freshwater scarity	x		
Loss of marine habitats, ecosystems and biodiversity	x	x	
Socio-economic vulnerabilities (fisheries, tourism, health)	x		
Socio-economic vulnerabilities (agriculture, tourism)			
Socio-economic vulnerabilities (heritage, tourism, health)		x	
Introduction of alien species			x

In this scenario the study of coastal dunes, which will be the focus of our research, are characterized as natural defenses against backdune space sea entry during extreme events, balancing the retreat of the shoreline with sediment from entering the beach system (Sarti, 2006). This is a deposit of aeolian type, which migrates in time and space, made up of loose sand that is taken by the wind (land back), carried by deflation and deposited in neighboring regions (Brunelli, 2008; Martínez & Psuty, 2004). Such interactions favor the formation of a profile for the beach-dune system. Due to the dynamism of the dunes, geomorphologically they have low probability to preserve its internal structure, in the form of geologic-stratigraphic column (Brunelli, 2008). The density and distribution of the community of plant also influence the morphological development dunes (Hesp, 2002). Coastal-to-inland complex have a notable and rapidly changing environmental gradient, which determines the coexistence of diverse flora and fauna communities (Ciccarelli, 2014; Ruocco et al., 2014). Dunes are important barrier against the action of the marine aerosol, freshwater reserves and protection of adjacent areas (field, wetlands, stream). Moreover, they rapidly respond to climate change (action of the tide cycle, waves, wind regime and biological seasonality) and anthropogenic interference (Lopez y Royo et al., 2009).

Coastal dune habitats are important ecosystems in Europe, but during the last century has been estimated a reduction of about 70% (McLachlan & Brown, 2006; Ruocco et al., 2014). In Italy, in late of the century the process of degradation of the dune was 45.000 ha in 1900 to 9000 ha (Feola et al. 2011; Ciccarelli, 2014). Among these 55% of the remaining has lost its natural quality, with 85% of these dunes currently in jeopardy (Heslenfeld et al., 2004; Muñoz-Valléz et al., 2011). However, international concern about the integrity of the coastal zone gained visibility with Agenda 21 (1992) and World Coastal Conference in 1993 (Brunelli, 2008) which examined actions to strengthen sustainable development and Integrated Coastal Zone Management (ICZM) (http://bit.ly/iczmconf). In Europe a Habitats Directive 92/43/CEE (European Commission, 1992) created the network Nature 2000 with objectives to contribute to the protection of highly biodiverse environments (*e.g.*, coastal dune system), through conservation and monitoring activities reported at every six years (art.17) (http://bit.ly/ministamb). However, the recent report ISPRA 194/2014 (Genovesi et al., 2014) presented the results of evaluation of the conservation status of Italian maritime and internal dunes as bad (http://bit.ly/habitatpdf) also highlighting key risk factors for each type of dune environment (Table 2).

Due to the undeniable importance of these environments, many studies have been conducted over correlated abiotic or biotic factors: grain size characterization of modern and ancient dunes (Bertoni & Sarti, 2011), sediment transport calculation using traps (Nordstrom et al., 2009; Jackson & Nordstrom, 2011; Jackson et al., 2011), topographic survey of the dune field (Bate & Ferguson, 1996; Hesp, 2002; Armaroli et al., 2013; Bertoni et al., 2014a; Corbau et al., 2015), geophysical approaches used to inspect the subsoil of dune systems (Bakker et al., 2012), ground penetrating radar (Buynevich et al., 2007), development trends erosion and/or accretion (Anfuso et al., 2009; De Falco et al., 2014; Pinna et al., 2015), vegetation coverage (García-Mora et al., 2000; Martínez & Psuty, 2004; Martínez et al., 2006; Acosta et al., 2007; Miot da Silva et al., 2008; Ciccarelli et al., 2012; Fenu et al., 2012; Duran & Moore, 2013; Drius et al., 2013; Malavasi et al., 2013, Malavasi et al., 2016), usage of different digital technologies such as laser scanning (Nield et al., 2011) and video/photo-monitoring in order to study the evolution of the beach dune morphology (Bini et al., 2008; Delgado-Fernandez et al., 2009; Casarosa, 2016). However, increased knowledge about how these factors interact is necessary and provides the basis for better management of coastal dune systems (Fenu et al., 2013; McLachlan et al., 2013; Ruocco et al., 2014; Bertoni et al., 2014b).

Table 2. Conservation state and trend evolutionary of the dune field in Italy localized in Mediterranean (MED) and Continental zone (CON): FA: favorable; IN: inadequate; BA: bad; IC: increased; DE: decreased; and ST: stable (Adapted from ISPRA, 2014). * Priority habitats.

Code	Habitat	Conservation state/ trend evolutionary				Factors threat
		MED		CON		
1210	Sand beach annual communities	FA	IC	IN	DE	Erosion, mechanical cleaning, recreational tourist, the presence of exotic species.
2110	Embryonic shifting dunes	BA	DE	BA	DE	Beach recreation, trampling, sand away for bathing purposes, mechanical cleaning, erosion, presence of solid waste, invasion of exotic species.
2120	Shifting dunes along the shoreline with *A. arenaria* (white dunes)	BA	DE	BA	DE	Trampling, beach tourism, erosion.
2210	Fixed beach dunes (*Crucianellion maritimae*)	BA	DE	-	-	Erosion, limiting the development of dune ridges, trampling, tourism, presence of ruderal species and exotic.
2230	Dune grasslands (*Malcolmietalia)*	IN	DE	BA	DE	Trampling, presence of ruderal species, areas enriched in nitrogen and subject to seaside attendance.
2250	Coastal dunes with *Juniperus* spp.*	BA	DE	BA	IC	Fragmented and altered due to urbanization and use of the dune for tourist, fires, excessive grazing, expansion of agricultural areas and coastal erosion.
2260	Dune sclerophyllos scrubs (*Cisto-Lavanduletalia)*	BA	DE	BA	DE	Expansion of agricultural areas and urbanization.
2270	Wooded dunes with *P. pinea* and/or *P. pinaster* *	IN	DE	FA	ST	Fires, camping, urbanization and contamination.

Finally, the issues which will be addressed in this thesis intends to provide a scientific contribution to the knowledge of the coastal environment as well as its reaction to events of natural or anthropogenic order.

1.1 Objectives

This thesis presents a comprehensive, multidisciplinary assessment for the vulnerability of the coastal dunes systems, through the analysis of abiotic and biotic factors applied in two different contexts: Mediterranean climate (Italy) and Atlantic Oceanic (Brazil). The overall aim of the thesis is to contribute to an enhanced understanding of the elements governing each environment through the use of traditional survey analyses integrated with state-of-the-art technologies, which would serve as an auxiliary tool for decision making to current coastal management models. The specific objectives of this thesis are:

i. create a data basis for both fields of study obtained through the multidisciplinary method;
ii. identify the factors that drive the evolution of beach dune systems;
iii. distinguish which are the most important factors in the evolution for the Oceanic beaches and for the Mediterranean;
iv. classify the vulnerability for all analyzed settings;
v. verify the reliability and advantages of the methodologies innovative as an alternative tool for the monitoring and support of coastal zones.

1.2 Structure of the thesis

The thesis is structured in two parts: i) the first part entitled "Part I – Synthesis" consists of a general introduction about the coastal environment, its peculiarities and problems; general and specific objectives of the thesis; methodology used and/or developed and the results and discussions; ii) the second part entitled "Part II – Papers I to VIII" is divided into 8 articles developed during this PhD.

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 the Mediterranean Sea. The first application of the CDVI occurred simultaneously in two Italian regions, Tuscany and Sardinia (Ciccarelli et al., 2016): the sites were characterized by different contexts, peninsular and insular respectively. There were also similarities about several aspects: microtidal regime, geomorphology (accretion, equilibrium, erosion), ecology (presence of plant communities) and anthropogenic (human pressure). Later, the index was tested in a macrotidal context, in Santa Catarina, Brazil (Alquini et al., 2016), after the necessary adjustments to the ocean conditions (e.g., length and distance measurements were expressed in kilometers rather than meters). At last, the results from both settings, Italy (Mediterranean Sea) and Brazil (Atlantic Ocean), were compared in order to verify which factors mostly affect the evolution of a beach-dune system in the Oceanic and the Mediterranean climates.

The physical and biological data, along with assessments about human pressure, that were acquired during the activities realized in both countries within this PhD provided the creation of a database that will be continuously implemented in the future. In addition, these data enabled the preparation of four scientific manuscripts that were included in this dissertation, as they clearly support a better definition of the health state of the beaches under investigation and their evolution over time, serving as a basis for the development of the vulnerability index.

This summary described below aims to highlight the main findings of **Paper I** to **VIII** (Figure 1), which are then put in a larger context (see **Part II – Papers**). For detailed descriptions of the methods and discussions of the results, please see the individual papers. Moreover, each of the above mentioned objectives were to a different extent considered in the individual papers.

In **Paper I** we perform a multidisciplinary analysis of the dune field in Grande beach, São Francisco do Sul (Brazil). We investigate its morphological, sedimentological, geological and vegetation characteristics. The scope is to increase the knowledge of the local characteristics and produce a multi-thematic map at 1:50000 scale (**Appendix I**). We provide in this way new insights into the physical processes, the points to be monitored in relation to coastal erosion and the sediment distribution coarsening-northwards trend.

The **Paper II** describes the current situation of a stretch of coast in the Tuscany, impacted by coastal erosion. In this work, multiple surveys were carried out along a 5 km long sector of coast located within the boundaries of the Migliarino-San Rossore-Massaciuccoli Regional Park (Italy), in order to evaluate the evolution state of the area within a 9-months timespan (January 2016-September 2016). The results emphasize the importance of increase the knowledge about the morphodynamics processes acting on this area based on the significant retreat in the crests of the dunes observed during this monitoring.

The **Paper III** was written in 2013 and published in 2014, being the first article produced during the PhD. The objective was to apply a multidisciplinary approach to understand the evolution of the coastal dune field in a more in-depth and integrated way. The proposal is to create a complementary database (parameters biotic and abiotic) economically and easily reproduced in other sandy coasts, integrating traditional survey analyses and state-of-the-art technologies (network of wireless sensors).

The aim of **Paper IV** was to describe the development and construction of the technological solution that enabled to overcome the difficulties related to the real-time acquisition of physical data about aeolian-driven sediment transport. The proposal for the acquisition of physical parameters in real time involves the use of traditional methods (digital database and terrain analysis) with the development of a prototype projected in partnership with the Department of Information Engineering and Mathematical Sciences, University of Siena**.** The development of the prototype complemented the acquisition of local scale wind data, data absent in literature. Therefore, the prototype consists of a wireless sensors network (WSN) measuring parameters speed, wind direction and variation of volume of sand transported by the wind, which would require frequent and lengthy field operations. The proposal creates a complementary methodology at low cost and could be applied to any type of coastal dunes.

In **Paper V**, we formulate a Coastal Dune Vulnerability Index (CDVI) adapted to the climatic conditions of the Mediterranean, which assists in determining the sensitivity level of the dune field on 23 sites in Italy. We use 51 variables divided into five groups of factors: Geomorphological Condition of the Dune system (GCD), Marine Influence (MI), Aeolian Effect (AE), Vegetation Condition (VC) and Human Effect (HE) (supporting information Table 1 in **Paper V** to **VIII**).

In **Paper VI** we extend our studies to adapted oceanic climatic conditions, analyzing now 6 coastal dunes in Brazil. This work resulted in a publication of a chapter in a brazilian book in order to disseminate the result for a broader public, as well as a full text in the conference entitled World Multidisciplinary Earth Science Symposium – WMESS occurred in Prague, Czech (see **Paper VII)**.

In **Paper VIII** we apply the CDVI in 12 contexts of sand dunes: 6 in Italy and 6 in Brazil. The confrontation shows which variables determine the evolution of each type of environment and which one are important for only one type of environment, proving to be a valuable guiding tool for management policy.

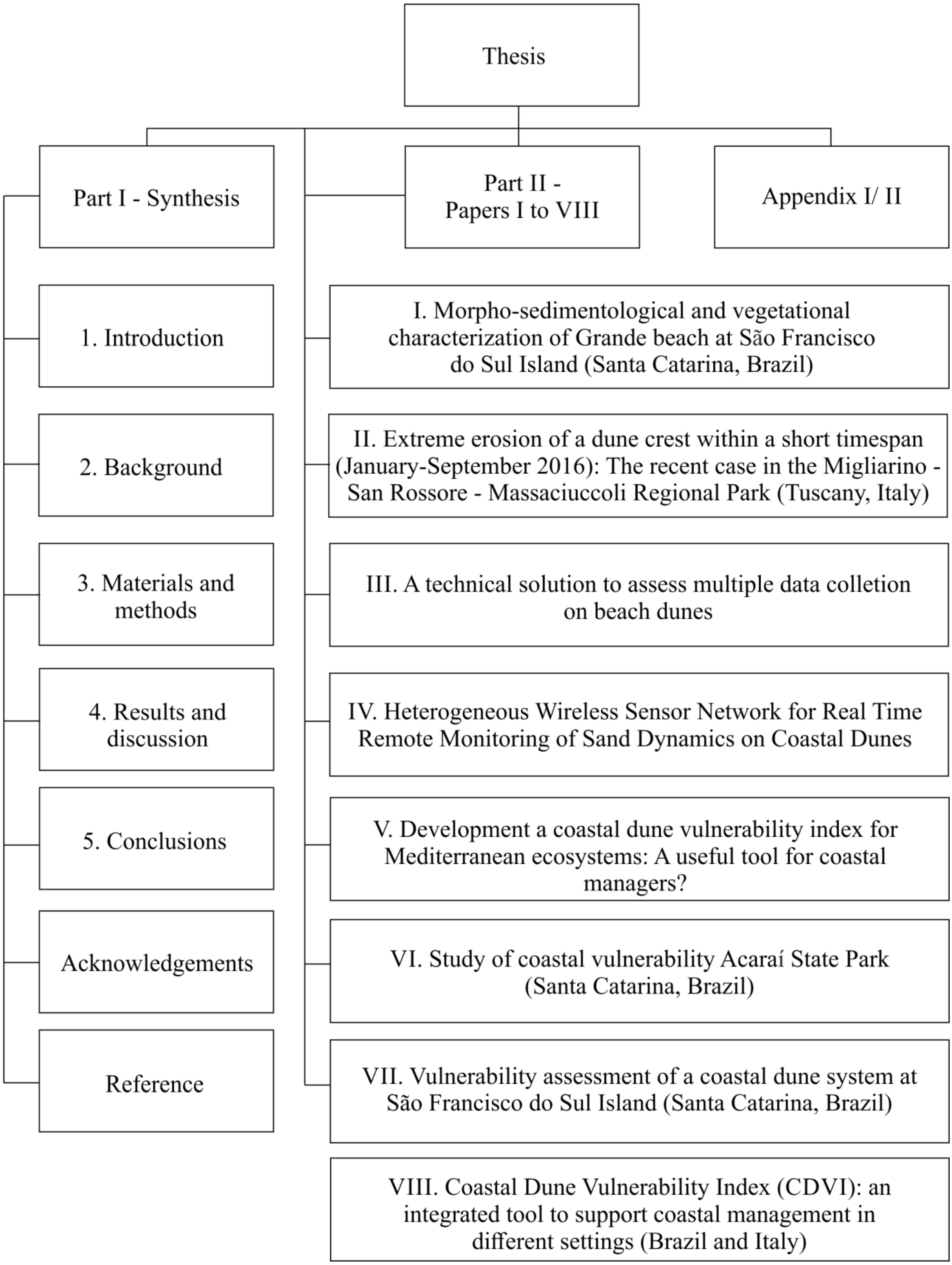

Figure 1. Layout of the thesis.

2. Background

2.1 Study area - Italy

The Italian 8.130 km long marine territory is morphologically extremely diverse, consisting of 59% rocky beaches and 41% of sandy beaches (Barsanti et al., 2011). Tidal exposures are characteristic of the so called micro-tidal coasts and reach a maximum of about 90 cm asl in the north Adriatic. The Italian coast is composed of a north-south trending peninsula, three major islands (Sicily, Sardinia and Elba), and 68 minor islands (Barsanti et al., 2011). The Mediterranean is characterized by a sub-humid climate with arid summers and mild winters (Rapetti and Vittorini, 2012), with mean annual temperature over 15°C and a mean rainfall of 800 mm (Rapetti, 2003).

The physiographic unit of the Pisan coast is compressed in the southern part of northern Tuscany, between Livorno and Bocca di Magra, containing two main water courses, the Arno and Serchio Rivers (Aielo et al., 1976; Casarosa, 2016). Behind the current beach deposits the coastal plain has several dune ridges, which are humanized and partially demolished to the south, while they are preserved in the northern (Sarti et al., 2010; Casarosa, 2016). In this coast, the dominant waves are of the sector 240°- 270° (Cipriani et al., 2001). The calm waves (Hs < 0,5 m) represent 35% incidence of the Pisan coast (monitoring between 2008 to 2012 conducted by the Province of Pisa) and the higher waves that 0,5 m corresponding to 64% coming the sector 220°- 260° N. This same sector were registered the major incidents of storms, in mean 48 events/year (Casarosa, 2016). Littoral drift is northward-trending on the side of the Arno River (Aiello et al., 1975; Pranzini, 2001; Ciampalini et al., 2015). Pisan littoral is characterized by a mesotidal, that rarely exceeding 30 cm (see **Paper II**). The wind regime is dominant belong to the III quadrant, with maxim for directions OSO and SO (Rapetti e Vittorini, 2012, Rapetti, 2003). Beaches are composed of well-sorted sands (quartz content ca. 50 vol %) of mean diameter about 0.3 mm (Gandolfi & Paganelli, 1975, Bertoni & Sarti, 2011).

This ecosystem has an ensemble of the dunes of high biodiversity value (European Directive 92/43/CEE; European Commission, 1992; Bertoni et al., 2014b; Ciccarelli, 2014; Ruocco et al., 2014) inserted within the limits of natural reserve Migliarino-San Rossore Massaciuccoli Regional Park (Tuscany Region n.61 of 13/12/1979) (Figure 2). However, the intense erosion that achieves this stretch of coastline from the late '800, created two beach systems: of the northern portion of the Arno River to the mouth of Serchio River is characterized by strong erosion (-1.99 m/a), of the Serchio River to Torre del Lago results in progradation (+6.63 m/a) (Casarosa, 2016). Engineering works were carried out in order to contain the erosion process, such as: rock groynes and breakwater parallel. All these works caused slight expansion of the beach, but with time unleashed the erosion of the traits further north (Noli & Franco, 1989). Even with the implementation of all protection structures, the delta of the Arno River continues regressing, creating new alignments beach, requiring the construction of other structures protection to contain the problems in Northern coast.

Finally, this site was chosen because of a variety of physical features, geographic position and vegetation content that made it an appropriate place to test the methodology (Figure 2).

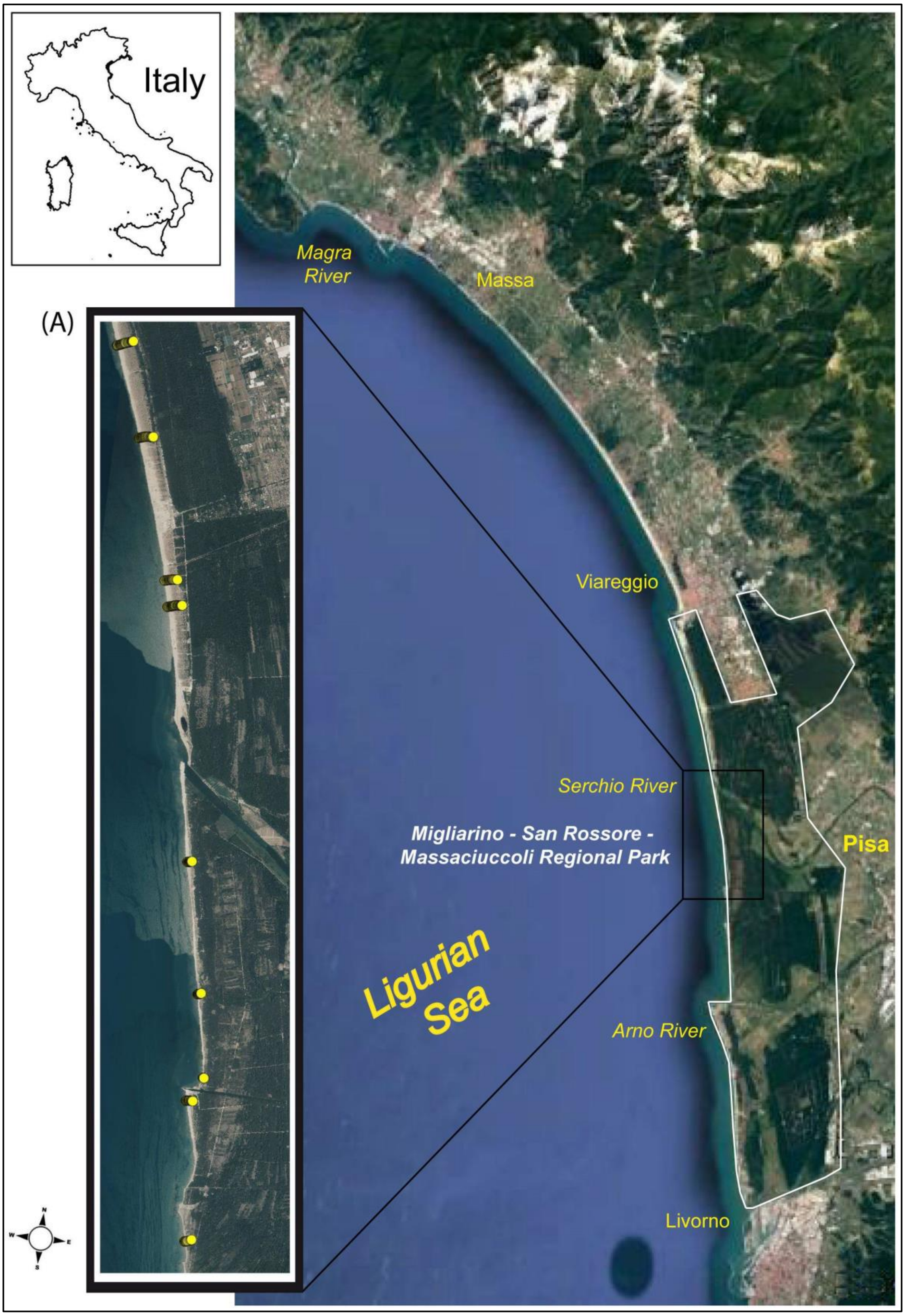

Figure 2. The rectangle (A) represents the studied area, localized between Arno River to Viareggio. The yellow points represent the locations monitored (Adapted from **paper II**, Figure 1).

2.2 Study area - Brazil

Brazil has a coastline of 7367 km, covering an area of 442,000 km^2 which corresponds to 5% of the national territory (Horn Filho & Simo, 2008), facing the Atlantic Ocean. State of Santa Catarina located in the southern part of Brazil has 538 km of coastline by compounds sand beaches with intense human occupation. The climate is mesothermic (Cfa), with humid temperatures and warm summers (Köppen, 1948), controlled by two oceanic air masses of synoptic character: South Atlantic tropical cyclone or Subtropical High Atlantic (AAS) and the Anticyclone Migratory Polar (AMP), which favors the occurrence of cold winter fronts and variations in atmospheric pressure (Bogo et al., 2015). The average annual rainfall is around 1000 to 1500 mm/year and an average temperature between 16° to 20 °C (Horn Filho, 1997).

The island of São Francisco do Sul (Figure 3), formed during the upper Pleistocene period (see **Paper I** for further details), has prevailing winds from the southeast quadrant (22%), followed by NE quarters (18%) and S (13%) (Truccolo, 2011; Bogo et al., 2015). Features macrotidal regime, semidiurnal, with maximum amplitude less than 2 m (Vieira, et al., 2008) (see **Paper I**), predominantly ripple swell – southeast and east, due to the orientation of the coastline (Alves, 1996; Abreu, 2011). The island has 12 beaches: the longest one, about 25 km, is named Grande beach and is located on the eastern side of the island, is characterized by a large variability of morphological and sedimentological features, and of vegetation species.

This site has great importance conservationist, because it covers the largest remaining area in continuous *restinga* vegetation in the state of Santa Catarina (PROBIO, 2003, Melo Júnior & Boeger, 2015). Recently, the Environment Foundation (FATMA) created a Conservation Unit (State Decree 2005/3517), to protect this natural heritage established by the Acaraí State Park (see **Paper VI**). Despite the efforts of researchers, the region is still very lacking in coastal dynamics related information (incidence waves in times of storms, bathymetry data, sediment transport, another). This work contributes to the knowledge of the morphodynamics of the dune field of São Francisco do Sul region, supporting the objectives proposed in the Management Plan of the Acaraí State Park.

Further details on the morpho-sedimentology and biological characteristics can be seen in **Paper I**, **VI, VII** and **VIII**.

Figure 3. Location of the study area in Brazil. The yellow points represent the locations monitored in this thesis. In orange the limit of the Acaraí State Park (Adapted from **Paper VI**, Figure 1).

3. Materials and methods

To achieve the above mentioned objectives, different methods and statistical analysis were used to quantify the dune field evolution. Precisely, we have used:

- ✓ Data collected in the field;
- ✓ Measurement of the aeolian transport of sediment in coastal dunes, through the development of a wireless sensor network;
- ✓ Dataset digital;
- ✓ Statistical analysis.

3.1 Data collected in the field

The topographic survey was performed using a Leica RTK-GPS (Figure 4) for 29 transects. The points were recorded at any break-in slope along the cross-shore profile; the accuracy of about 1 cm was obtained post-processing the raw data. Each transect started at the shoreline and ended at the transition to the woody vegetation. Data were processed in QGIS 2.8.2 system. The field work was conducted in 2015 and 2016. A short description of the general conditions for the dune fields of the two sites are described in **Paper I** and **II**.

Sediment sampling was carried out together with the topographic survey in Brazil. Field work was conducted in October 2015. Samples were collected from the surface by means of a small shovel, in specific spots: the beachface, the dune crest, the dune back-toe, and the steady dune. As no grain-size variability between the beachface and the berm was reported in previous observations of the site (medium sand; Abreu, 2011), we elected to sample only the beachface in order to optimize the surveying time. The grain-size analysis was then performed on all the samples collected on the beach. Prior to the sieving procedures, they were accurately treated according to Bertoni et al. (2014a). Sieves from 0.75 mm to 0.063 mm were used, with mesh interval of 0.5 phi (Figure 4). The sediment retained on each sieve was weighed by means of a digital scale (instrument error of 0.01 g). The ensuing data were processed by SYSGRAN 3.0 software (Camargo, 2006), which provided the most important textural parameters such as the Mean (Mz) (Folk & Ward, 1957) (see **Paper I**). For Italy, the data were processed from a database, collected in 2006, following the methodology Bertoni et al. (2014a).

The vegetation 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 (accretional, stable, or erosional), ecological (presence of plant communities) and anthropogenic (different human pressures). On each sector 3 cross-shore transects were traced out from the shoreline to the woody vegetation, 12 transects as a whole. The percentage of vegetation coverage of each vascular plant was visually estimated in plots of 2 x 2 m along the transects. Classification of the plant functional types followed the approach of García-Mora et al. (1999), whose field work was conducted in spring of 2015 and 2016 (Figure 4).

The taxonomic nomenclature followed the checklist of the Italian vascular flora (Conti et al., 2005, 2007) for native species, whereas for alien plants, the checklists of Arrigoni & Viegi (2011) and Podda et al. (2012) for Tuscany and Sardinia respectively were adopted (**Paper V**). In Brazil the classification of the species followed Christenhusz et al. (2011) and APG VI (2016). The flora identification was based in the *restinga* vegetation list of the PEA proposed by Melo Júnior & Boeger (2015). Species names and authors were in accordance with the Species List of the Botanical Garden of Brazil Flora of Rio de Janeiro (http://floradobrasil. jbrj.gov.br) (supporting information Table 5 **Paper VI**).

3.2 Measurement of the aeolian transport of sediment

The physics sampling, correlated with the erosion-transport-deposition of the sand, was tested integrating three typology of sensors (Figure 4): vertical sand traps equipped with an automatic rotation mechanism enabling the system to react to wind direction variations; sensors based on photoresistor (LDR) arrays to measure dune height variations; anemometer/anemoscope stations positioned at three different heights (40 cm, 120 cm and 200 cm) from the beach surface.

Each sensor node is made up at least of a ZigBee radio module that is able to transmit the data collected by the sensor at a distance of about 100 meters. While the sand level sensor and the sand collector are provided only with this transmission module, the anemometric station also integrates a microprocessor board in charge of data processing. A Gateway node provided with a GSM connection for remote data transmission and a Zigbee radio module for Local Area communication has also been developed. This node is in charge of collecting all the data packets sent by the Sensor Nodes and transmits them to a remote server through GPRS connection. A Web server has been set up to collect these packets and stores them in a database.

The proposed system can provide both a static and a dynamic framework of sand transport processes acting on coastal dunes. The field work was conducted in Mach 2016 (Figure 4) for a period of 24 hours (**Paper IV**).

3.3 Dataset digital

The lithologic of São Francisco do Sul (Brazil) was rendered on a hillshade with the use of a DTM (SDS, 2010) that emphasize the relief. The geological elements were mapped according to Possamai et al. (2010) and Vieira (2015), and re-interpreted on the basis of new insights. The systematic tracing of the coastline was carried out analyzing aerial photographs and ortho-photographs. The images were properly georeferenced and used to build photo-mosaics of the entire coast for each year of aerial coverage. For each mosaic the shoreline was traced out using QGIS 2.8.2 vectorization tools at 1:2000 scale. The shoreline is defined by the mean high water line, which is represented by the wet/dry line (Crowell et al., 1991; Leatherman, 2003; Mazzer & Dillenburg, 2009). Coastal dunes were identified by photo-interpretation of both the 2010 and 2013 ortho-photograph mosaic and the DTM (SDS, 2010). The photo-interpretation was realized mapping the features at 1:3000 scale. Dunes were classified according to Bertoni & Sarti (2011). In detail, there have been recognized:

- *Embryonic dunes* (consist in incipient foredunes ridges, formed in correspondence of the tempest berm);
- *Frontal dunes* (still subjected to physical processes, covered with typical dune vegetation);
- *Semi-mobile dunes* (might experience physical processes, characterized by shrubbery and by blowouts);
- *Steady dunes* (no more subjected to physical processes, covered by arboreous vegetation).

In addition, parabolic and transverse dunes crest were traced out following the classification of Hesp (2002). Backshore and blowouts have also been mapped. For details of these results see **Appendix I** – Map at 1:50000 scale.

For Pisa (Italy), the geological elements were mapped according to Sarti et al. (2006) and re-interpreted on the basis of new insights:

- *Undifferentiated anthropogenic: deposits* accumulations of heterogeneous materials, (aggregates, coastal defenses stone blocks, mouths and armed banks);

- *Reclaimed areas:* light brown clay and clay-silty, vegetal debris bioclast and few scattered pebbles;
- *Clay silt palustrine deposits:* black and dark brown organic rich silt and silt-clay;
- *Beach ridge sandy deposits:* fine and well-sorted sand;
- *Inter aeolian ridge deposits:* very fine sand and well-sorted;
- *Sandy beach deposits*: medium to coarse sand and well-sorted.

The cartographic elements used was firstly digitalized and georeferenced (Table 3) by each deposit. Coastal dunes were identified by photo-interpretation of 2006 to 2017 (Regione Toscana and Provincia di Pisa) and were classified using the same classification used in Brazil (Bertoni & Sarti, 2011). For details of these results see **Appendix II -** Map at 1:25000 scale. All mapping was realized at 1:2000 scale using QGIS 2.8.2.

Table 3. List of cartographic elements used for remote sensing.

Cartographic elements	*Description*	*Scale*
272044	Mouth Serchio River	1:5000
272043	San Rossore Forest	1:5000
272083	Gombo	1:5000
272084	*Pinus* forest of San Rossore Park	1:5000
272124	Mouth Arno River	1:5000
Ortophoto (year)	*Description*	*Film*
2006	Consortium with Provincia di Pisa	colorful
2007	Regione Toscana	colorful
2010		
2013		
2017	Google Earth	colorful

3.4 Statistical analysis

The monitoring of the topographic profiles obtained in the field allowed to calculate the rate of loss and/or gain in the sediment volume for each transect/month. The data was released in an Excel table for graphing, subarea profile volume calculation and volume comparison between months. The calculations were performed using basic rules of geometry.

The value of the plant functional types - PFT classification was obtained using cluster analysis and Euclidean distance as the dissimilarity index following García-Mora et al. (1999).

Two separate matrices, one for the Brazilian site and one for the Italian site, with seven plant traits were arranged including all the species occurring on each site (**Paper V to VIII**).

The coastal dune vulnerability index (CDVI) was applied in the 29 sandy beaches to Mediterranean (Italy) and Atlantic Oceanic (Brazil). The index takes into account 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 (supporting information **Paper V**, Table 1): Geomorphological Condition of the Dune system – GCD; Marine Influence – MI; Aeolian Effect – AE; Vegetation Condition – VC; and Human Effect – HE. The index was calculated associating each variable to a five point scale, ranging from 0 (no vulnerability) to 4 (very high vulnerability). 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 final CDVI was calculated on the unweighted average of the five partial indices through the algorithm:

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

CDVI ranging between 0 and 1, as the index increases, the ability of a dune system to withstand further intervention decreases. The vulnerabilidade index has produced a matrix with the number of sites x 51 variable and submitted a cluster analysis using Euclidean distance as the dissimilarity index. The outcome was subjected to a Non-metric Multidimensional Scaling (NMDS) (Økland, 1996) with a Spearman correlation coefficient calculated (> 0.8) in order to indicate the variable that was more correlated to the NMDS axes. The non-parametric test of Kruskal Wallis with Bonferroni correction for multiple comparisons was applied to compare the partial and total vulnerability values in the groups defined by cluster analysis. Statistical analyses were performed in PRIMER 6.0 (Clarke & Gorley, 2006) (**Paper V to VIII**).

In Table 4, one overview the main methods, location, sources and acquisition period.

Table 4. Overview of the material and method used in this thesis. Abbreviation: B – Brazil, I – Italy.

Variable	**Material or method**	**Year or period**	**Unit**	**Source**
Length of active dune system	GPS monitoring, QGis 2.8.2	2015 and 2016	m	-
Height of frontal and secondary dune	GPS monitoring, QGis 2.8.2	2015 and 2016	m	-
Berm slope	GPS monitoring, QGis 2.8.2	2015 and 2016	°	-
Relative area of wet slacks	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana.
Width intertidal zone	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	m	
Dune system fragmentation	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	
Mean grain diameter	Gran-size analysis, software SYSGRAN 3.0 and use of database for Italy.	2015 (B), 2006 (I)	phi	Bertoni & Sarti (2011)
Orthogonal fetch	Literature	-	km	Nemes & Marone (2013); APAT (2004)
Tidal range	Literature	-	cm	Vieira (2008); Pranzini (2001)
Fragmentation dune system	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana.
Shoreline variation	Aerial photo-interpretation (build photo-mosaics, vectorization at 1:2000 scale) and Literature.	1938 to 2010 (B); 1938 to 2004 (I)	m	Serviço Aerofotogramétrico Cruzeiro do Sul S/A. Bini et al. (2008)
Dune classification	Aerial photo-interpretation and DTM	2010 (B), 2006 to 2017 (I)		Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana and Provincia di Pisa.
Coastal orientation to wave direction	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	°	Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana.
Width of the zone between HWSM and dune face	GPS monitoring, QGis 2.8.2	2015 and 2016	m	-
Breaches-depth	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana.

Variable	Material or method	Year or period	Unit	Source
Blowouts	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	Serviço Aerofotogramétrico Cruzeiro do Sul S/A, Regione Toscana.
Mean wave height	Data base	2015 (B), 2013-2015 (I)	m	Centro de Hidrografia da Marinha – CHM; Servizio Idrologico Regionale – SIR.
Mean wave incidente angle	Data base, literature	2015 (B), 2013-2015 (I)	°	
Storm frequency	Data base, literature	2015 (B), 2013-2015 (I)	yr^{-1}	Servizio Idrologico Regionale SIR, APAT (2004).
Storm duration	Data base, literature	2015 (B), 2013-2015 (I)	d	
Tide conditions during field collections	Data base	2015 and 2016 (B, I)	cm	Diretoria de Hidrografia e Navegação – DHN, Consorzio LaMMA.
Input sediment	GPS monitoring, QGis 2.8.2, Estimate Excel,	2015 and 2016 (B, I)	%	-
Pebble cover as surface	Field	2015 and 2016 (B, I)	%	-
Seaward dune vegetated	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	SDS, 2010 S/A, Regione Toscana.
Direction wind	Database, Anemometric station	2004 – 2014, 2015 - 2016	°	Diretoria de Hidrografia e Navegação – DHN, Consorzio LaMMA
Wind speed	Database, Anemometric station	2004 – 2014, 2015 - 2016	m/s	
Vegetazione coverage, relative proportion of endemics and endemic plant species	Field	Spring: October 2015 (B) and May 2016 (I)	m^2	Christenhusz et al. (2011), APG III (2009), Conti et al. (2005, 2007), Arrigoni & Viegi (2011), Podda et al. (2012).
Visitor pressure and frequency, access difficulty, dune driving, beach driving, trampling by animals	Field	2015 and 2016 (B, I)	%	-
Path network of the frontal dune	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	SDS, 2010 S/A, Regione Toscana.
Natural litter and anthropogenic cover as surface	Field	2015 and 2016 (B, I)	%	-

Variable	Material or method	Year or period	Unit	Source
Sand extracted for building	Field	2015 and 2016 (B, I)	%	-
Summer beach cleaning frequency	Field	2015 and 2016 (B, I)	d	-
Permanent and ephemeral infrastructure replacing active dunes	Field	2015 and 2016 (B, I)	%	-
Relative surface forested and agriculture	Aerial photo-interpretation, QGis 2.8.2	2010 (B), 2013 (I)	%	SDS, 2010 S/A, Regione Toscana.
Sediment transport by aeolian process	Sand traps by Wireless Sensor Network	2016	g	-
Sand dune level	Wireless Sensor Network	2016	cm	-
Volume calculation (profile)	GPS monitoring, QGis 2.8.2, Excel	2016	m^3/m	-

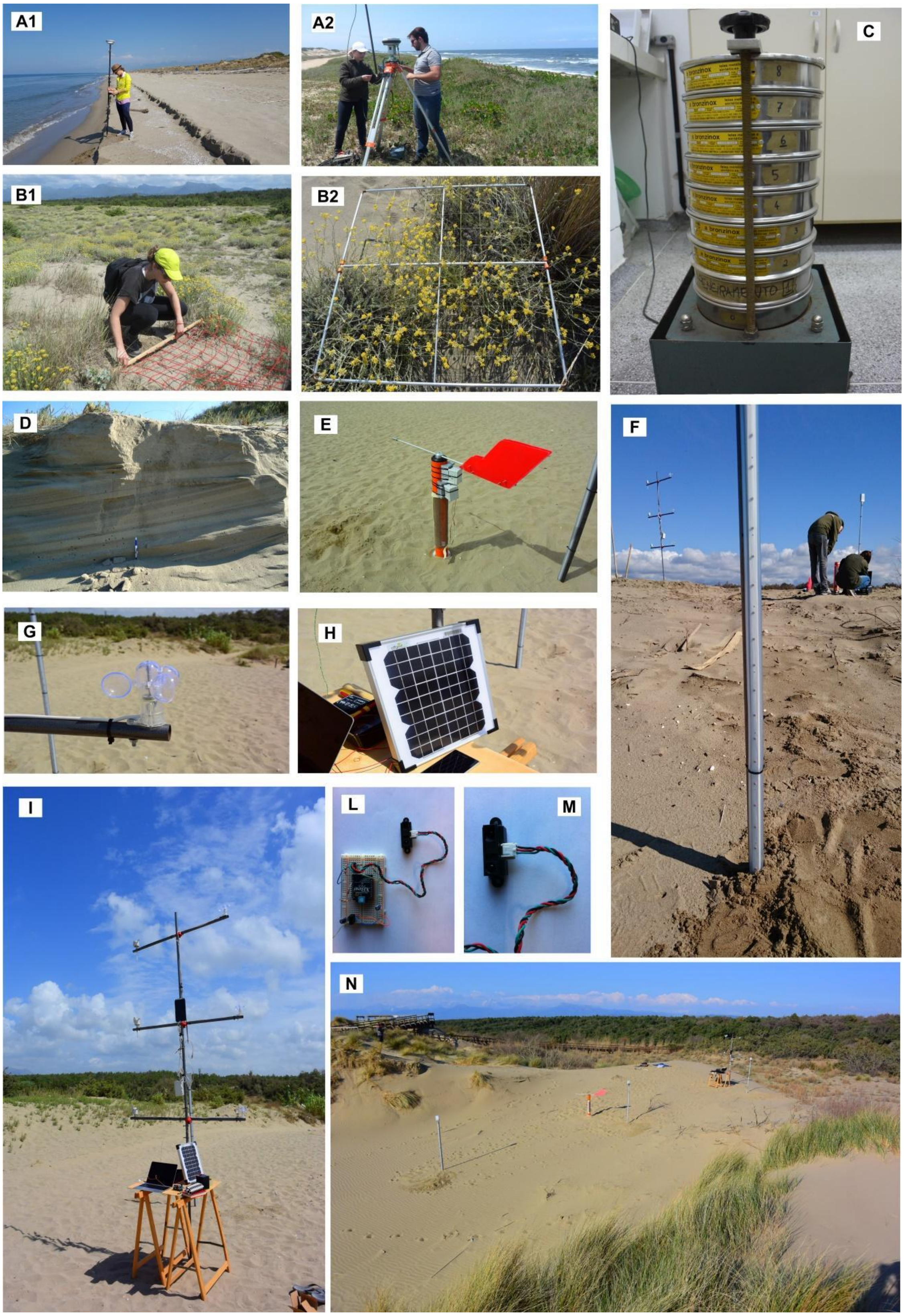

Figure 4. A1-A2: topographic survey; B1-B2: vegetation coverage estimated in plots of 2 x 2 m; C: sieves from 0.75 mm to 0.063 mm; D: stratigraphic analysis in field; E: sand trap; F: sand level node; G: anemoscope couples; H: solar cell; I: anemometric station; L-M: ZigBee radio module; N: transport aeolian sand traps arrangement.

4. Results and discussion

4.1 The case Brazil

The study of geological units and deposition systems in São Francisco do Sul Island allowed a reconstruction of the evolution of this environment (more details **Appendix I**) in nine types of deposits (Table 5). The pre-Mesozoic metamorphic and igneous units (São Francisco do Sul Complex and Suíte Morro Inglês) outcrop prevalently on the hills on the western side of the island; metamorphic outcrops are also located on isolated elevations, promontories and islands on the eastern side.

Table 5. Geological elements mapped for São Francisco do Sul Island.

Age	Grain size	Depositional environmental
Holocene	silt and fine sand	coastal paludal deposits
	fine and medium sand	active aeolian deposits
	silty sand	lagoon fill deposits
	fine to coarse sand	strand plain deposits
Pleistocene	silty sand	lagoon fill deposits
	very fine to fine sand	strand plain deposits
Undifferentiated Quaternary	sand, silt and clay	alluvial colluvial deposits
Cambrian-Ordovician	Suíte Morro Inglês	Igneous unit
Paleo-Proterozoic	São Francisco do Sul Complex	Metamorphic unit

During the Quaternary streams flowing down the slopes, formed colluvial and alluvial deposits at the foot of the hills, which are typical of continental systems. The most important feature that strongly characterized the evolution of the São Francisco do Sul Island is related to relative sea level oscillations, which led to consecutive landward and seaward migrations of a barrier/lagoon system during Pleistocene and Holocene (Horn & Simo, 2008; Possamai et al., 2010; Abreu, 2011; Bogo et al., 2015). Two strand plain systems can be observed in the central and in the eastern portion of the island: the former is Pleistocene, the latter Holocene. The Acaraí Lagoon formed on the back of the Holocene beach ridges; currently it is a distributary channel flowing to the northeast direction. Paludal deposits can be recognized along several sectors of the present course of the channel and along the Linguado Channel. Large aeolian deposits formed in the north-eastern sector, producing high parabolic dunes that covered the Holocene beach ridges in that portion of the island (see **Paper I** for further details).

The variation of the coastline was analyzed based on the preparation of series of photographs of mosaics of the years: 1938, 1957, 1978 and 2010. Through the use of digital mapping techniques were extracted coastlines by defined the mean high water line (Table 6). The shoreline evolution showed that between 1938 and 1957 the coast was subjected to a predominant progradation of the system, with peaks of more than 60 m in the northern and southern sectors. The central portion of the coast was characterized by negative values in that same timespan: a retreat of almost 40 m. During the next timespan (1957 to 1978) the trend was significantly different as the erosion processes begun to hit the coast seriously. Retreat peaks of almost 70 m were calculated along the northern sectors of Grande beach during that timespan. The central sector was basically the only portion of the coast that recorded accretion (almost 40 m) as opposed to the previous time interval, during which it was characterized by a relevant retreat. During the last timespan (1978 to 2010) the tendency to a progressive retreat of the system continued, in particular in the southern sector of the coast: retreat of about 30 m was generally calculated along that portion. Conversely, the northern sector experienced accretion of more than 10 m in that same time period (see **Paper I**).

Table 6. Shoreline evolution expressed in annual rates during three different intervals (from 1938-2010) calculated along the 8 transects traced out for the topographic surveys (+: accretion; -: retreat) (Adapted from **Paper I**, Table 2).

Transect	Time intervals		
	1938-1957	1957-1978	1978-2010
1	+ 67 m	- 10 m	- 22 m
2	+ 44 m	- 9 m	+ 4 m
3	-	-	- 43 m
4	- 38 m	+ 37 m	- 25 m
5	+ 39 m	- 13 m	- 3 m
6	+ 79 m	- 74 m	+ 17 m
7	+ 31 m	- 4 m	+ 15 m
8	+ 4 m	+ 7 m	- 12 m

The photo-interpretation of ortho-photographs allowed to describe the dunes on the eastern side of the Island of São Francisco do Sul. The results showed that the dune field is continuous along the N-S direction and is composed by an interconnection of frontal and semi-mobile dunes, backed by steady dunes. The semi-mobile dunes are not present in the southern sector of Grande beach, where transverse dunes are predominant. The dune field reaches its maximum width in the northern portion of the beach (just over 1000 m). The narrowest portion is located towards the central sector of the coast (about 500 m). The mobile dunes are largest where the steady dunes have been wiped out by human activities. The photo-interpretation confirmed the spatial separation of parabolic and transverse dunes: parabolic dunes of NNE orientation are located towards the northern sector of the beach, where they are characterized by several large blowouts; conversely, the transverse dunes, covered by dense shrub vegetation, are prevalent in the southern sector (**Paper I**).

The topographic profiles showed that the backshore width was higher in the northern sector of Grande beach (Table 7), being consistently over 20 m with the exception of the sector northernmost, located towards Grande beach village. To the south the backshore was generally narrower. The topographic survey also highlighted great variability in terms of width and height of the frontal dunes: the width was higher to the south and lower in the central and northern portions of the beach. Again, sector north was an exception, showing a frontal dune width of more than 50 m. In terms of height the whole dune field showed a clear trend to increase northwards. All the coast showed evidence of ongoing erosion process: this is particularly relevant along the transects showing a steeper scarp relative to the backshore slope (see **Paper I**).

Table 7. Analytical data about geomorphological (backshore width, frontal dune width and height, and maximum dune height) and sedimentological features (mean grain size) of Grande beach, São Francisco do Sul Island (Adapted from **Paper I**, Table 4).

Transect	Backshore width (m)	Frontal dune width (m)	Frontal dune height (m)	Maximum height (m)	Mean grain size (phi)
1	15	23	4	4	2.20
2	11	50	4	6	2.08
3	25	59	5	6	1.63
4	11	14	5	5	2.05
5	30	14	6	6	1.48
6	34	22	8	8	1.32
7	26	13	6	8	1.19
8	13	57	7	7	1.75

The grain-size analysis carried out on the sediment samples collected at Grande beach showed that the average grain-size is comprised within the medium sand interval (Table 7; Figure 5). The grain-size decreases landward along each transect: the Mean (Mz) values also evidenced a clear decreasing trend to the north. The grain-size decreases landward along each transect, as already pointed out by many authors on different coastal dune settings (Anthony et al., 2006; Bertoni & Sarti, 2011; Fenu et al., 2012). In addition, the Mean (Mz) values evidenced a clear decreasing trend to the north, which is not in accordance with the northward direction of the littoral drift. This tendency was already observed by Abreu (2011). Considering that the coarsening-northward trend is confirmed in each sampling points along the transects (beachface, dune crest, dune back-toe, steady dune), it implies that the grain-size distribution has not changed in time. The shoreline evolution did not highlight any preferential volume shift able to determine sediment accretion or erosion, which is also confirmed by visual observation of the promontories that bound Grande beach at both edges, which lack any clue of accumulation. These factors might point in the direction that the longshore sediment transport at Grande beach is not particularly intense, which is further corroborated by the fact that the beach does not show the typical logarithmic spiral configuration (Hsu et al., 1987) (**Paper I**).

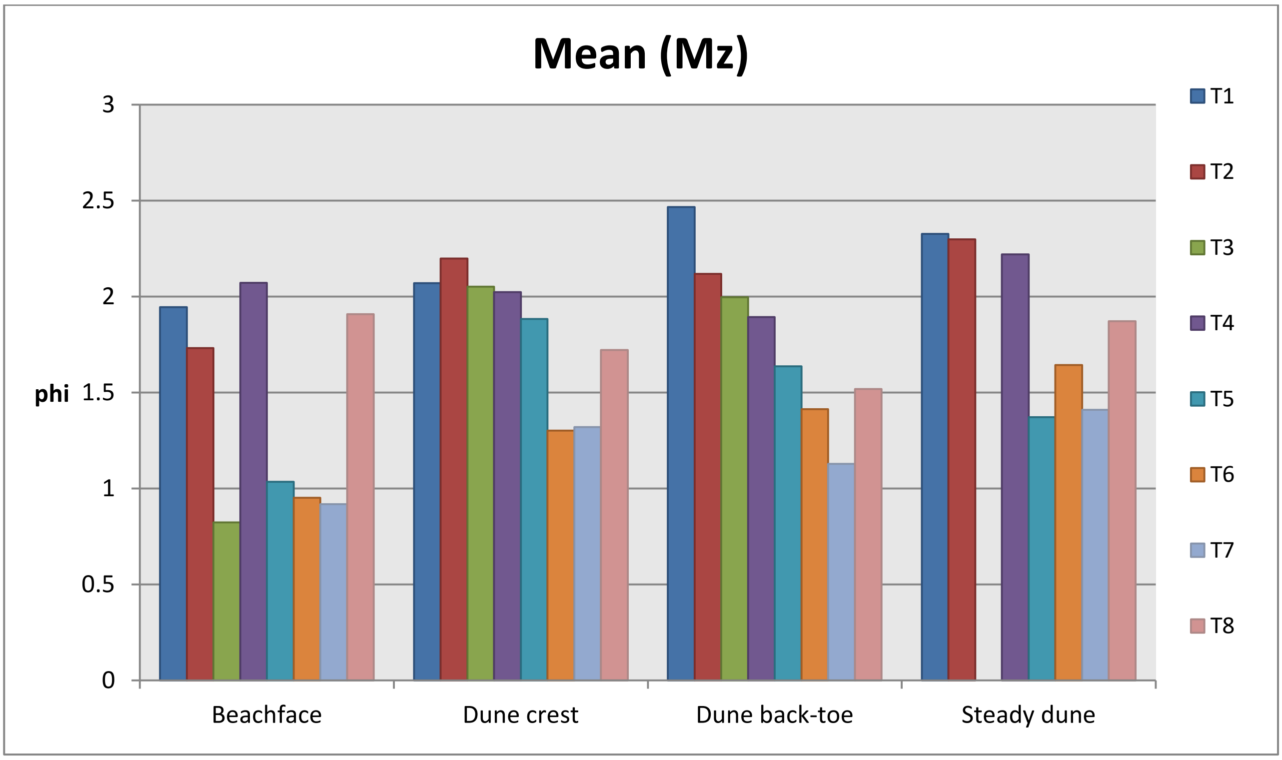

Figure 5. Grain-size distribution (Mean, Mz) sorted by the spots where sediment samplings were carried out along each transect: beachface, dune crest, dune back-toe, steady dune (Adapted from **Paper I**, Figure 3).

For vegetation were showed 53 species and 33 families, the families with the highest number of recorded species were Poaceae (6 species), Fabaceae (5 species), Asteraceae (4 species), Cyperaceae (4 species) and Malvaceae (3 species). The most frequent species in the community structure were *Scaevola plumieri*, *Ipomoea imperati*, *Spartina ciliata*, *Hydrocotyle bonariensis*, *Remiera maritima*, *Smilax campestris*, *Aechmea ornata*, *Guapira opposita*, *Varronia curassavica* and *Myrcia pulchra* (Table 8). Zone A is characterized by lower species diversity compared with the Zone B and by the presence of exotic species (*Centella asiatica*, *Cyperus* sp, *Brachiaria* sp and *Portulaca oleracea*), which are not detected in Zone B. Another factor separating the two sites was the coverage: in Zone A, every transect has higher percentage values in the frontal dune rather than in the semi-mobile dune; in Zone B, the vegetation coverage increases from the frontal dune towards the steady dune. The result of the PTF divided of the species in three functional groups being classified as A (Type II), B1 (Type III) and BII (Type I) (Table 8). The result is the division of vascular plants in groups with characteristics to the degree of exposure in coastal environments (see **Paper I, VI, VII** and **VIII**).

Table 8. Species found along transects on the Acaraí State Park. Legend: Zone: A (north) and B (south). Plant functional types (PFT): I, II and III (Adapted from **Paper VI**, Table 5).

Families	Species	Zone	PFT
Aizoaceae	*Sesuvium portulacastrum* (L.) L.	B	II
Anacardiaceae	*Schinus terebinthifolius* Raddi	B	I
Apiaceae	*Centella asiatica* (L.) Urb.	A	II
Araliaceae	*Hydrocotyle bonariensis*	A, B	II
Apocynaceae	*Oxypetalum tomentosum* Wight ex Hook. & Arn.	A, B	III
Asteraceae	*Pterocaulon purpurascens* Malme	A	I
Asteraceae	*Cyrtocymura scorpioides* (Lam.) H.Rob.	A, B	III
Asteraceae	*Gamochaeta americana* (Mill.) Wedd.	A, B	III
Asteraceae	*Symphyopappus casarettoi* B.L. Rob.	A	I
Boraginaceae	*Varronia curassavica* (Jacq.) Roem & Schult.	B	I
Bromeliaceae	*Aechmea ornata* Baker	B	I
Cactaceae	*Opuntia monacantha* Haw.	B	II
Calyceraceae	*Calycera crassifolia* (Miers.) Hicken	A	II
Clusiaceae	*Clusia criuva* Cambess.	B	I
Convolvulaceae	*Ipomoea imperati* (Vahl) Griseb.	A, B	II
Convolvulaceae	*Ipomoea pes-caprae* (L.) R. Br.	A	II
Cyperaceae	*Cyperus ligularis* L.	A	III
Cyperaceae	*Cyperus sp*	A	II
Cyperaceae	*Remiera maritima* Aubl.	A, B	II
Cyperaceae	*Scleria hirtella* Sw.	B	I

Families	Species	Zone	PFT
Dryopteridaceae	*Rumohra adiantiformis*	B	I
Euphorbiaceae	*Microstachys corniculata* (Vahl) Griseb.	B	III
Fabaceae	*Canavalia rosea* (Sw.) DC.	A	II
Fabaceae	*Chamaecrista flexuosa* (L.) Greene	A	I
Fabaceae	*Centrosema virginianum* (L.) Benth	A	I
Fabaceae	*Desmodium adscendens* (Sw.) DC.	A	III
Fabaceae	*Stylosanthes viscosa* (L.) Sw.	A	I
Goodeniaceae	*Scaevola plumieri* (L.) Vahl	A	II
Malvaceae	*Pavonia sp*	A	I
Malvaceae	*Pavonia alnifolia*	A	I
Malvaceae	*Sida carpinifolia* L.	A	I
Marcgraviaceae	*Norantea brasiliensis* Choisy	B	I
Myrtaceae	*Myrcia pulchra* (O.Berg) Kiaersk.	B	I
Myrtaceae	*Psidium cattleianum* Sabine	A	I
Nyctaginaceae	*Guapira opposita* (Vell.) Reitz	B	I
Orchidaceae	*Epidendrum fulgens* Brongn.	B	II
Peraceae	*Pera glabrata* Poepp. Ex Baill.	B	I
Piperaceae	*Peperomia pereskiaefolia* (Jacq.) Kunth	B	III
Plantaginaceae	*Plantago tomentosa* Lam.	A	III
Poaceae	*Andropogon arenarius Hack.*	A	III
Poaceae	*Brachiaria sp*	A	III
Poaceae	*Paspalum vaginatum* Sw.	B	III
Poaceae	*Spartina ciliata* Brongn.	A, B	III
Poaceae	*Sporobolus virginicus* (L.) Kunth	B	III
Poaceae	*Stenotaphrum secundatum* (Walter) Kuntze	A, B	III
Polypodiaceae	*Polypodium sp*	B	III
Portulacaceae	*Portulaca oleracea* L.	A	II
Primulaceae	*Myrsine venosa* A.DC.	B	I
Rubiaceae	*Diodella apiculata*	B	I
Rubiaceae	*Diodella radula* (Willd. Ex Roem. & Schult.) Delprete	B	I
Smilacaceae	*Smilax campestris* Griseb.	A, B	II
Solanaceae	*Solanum* sp	B	I
Verbenaceae	*Lantana camara* L.	B	I

4.2 The case Italy

The use of photo-interpretation of ortho-photographs and digital mapping process by Sarti et al. (2006) enabled the reinterpretation of a map to scale 1:50000 containing the main coastal deposits, the definition of the total area and old alignments and coastlines (see **Appendix II**). Six types of deposits were identified: Undifferentiated anthropogenic deposits, Reclaimed areas, Clay silt palustrine deposits, Beach ridge sandy deposits Inter aeolian ridge deposits and Sandy beach deposits.

The geomorphological evolution of the Pisano coastline in recent centuries is closely correlated with the evolution of the Arno River delta and the variation of the amount of sediment transported. The result is a very morphologically variable dune field along the northern portion of the study area (between Viareggio and the mouth of the River Serchio, about 6.5 km extension) and the southern portion (between the River Serchio the Arno River, about 6.0 km extension). The northern section consists of a dune field in accretion and the southern sector is under severe erosion, as also observed in other studies (Toniolo, 1910; Toniolo, 1927; Albani, 1940; Borghi, 1970; Vittorini, 1977; Carli et al., 2004; Cipriani et al., 2004; Bini et al., 2008; Casarosa, 2016) (**Paper III**).

The topographic profiles showed that the northern sector consists of well-established transverse dunes, with an average width of 245 meters in between the inland and sea, with a gradual transition between mobile dune field and fixed dune (Table 9). The average width of backshore is 64 m, average length of the frontal dune is 43 meters and average frontal dune height is 3 m on the crest. The southern sector is characterized by transverse dunes interspersed by blowouts of up to 40 m length which area burying the vegetation backdune. The maximum width of the dune field corresponds to 74 meters average width of backshore is 15 meters average width of the frontal dune is about 20 meters and average a front height is 4 meters.

In some places erosion causes a total loss of the frontal dune and mobile dune, consequently, retracting the process of vegetation succession and interfering in the stability of the dunes, as also observed in other studies (Gornish & Miller, 2010; Ciccarelli et al., 2012; Ciccarelli, 2014, 2015; Ruocco et al., 2014) (**Paper V** and **VIII**).

For the calculation of sediment volume were used only 3 transect (5, 6 and 7) localized between Serchio River to Morto Nuovo River, during the nine months-long investigation. In general terms too short a time frame to evaluate the evolution state of a coastal area, did not prevent to observe some major modifications to the beach and the dune field along this sector of the Migliarino – San Rossore – Massaciuccoli Regional Park (see **Paper II**).

The comparison between the four surveys for each transect also raised some concerns (unfortunately the January survey for transects 06 and 07 was recorded along a different trace relative to the next three: the variation was necessary because the operator could not reach the previous location due to collapse of the dune). The northern sector virtually showed no differences throughout the time frame of the investigation. Beach width, embryonic dune position and frontal dune height did not change considerably. Major variations occurred along Transect 06, where a huge retreat can be easily observed: within just 4 months (from March 2016 to June 2016) the backshore profile shifted landward of almost 10 m. The retreat is far more impressive on regards to the dune profile: as a matter of fact, the dune crest moved landward of about 6 m in that same time span, along with a crest height decrease of almost 1 m (Figure 6). The southern sector did not experience considerable modifications in terms of beach width and dune height: the only difference is a decrease of the steepness of the eroding dune, from 0.85 in March 2016 to 0.57 in June 2016 and September 2016 (see **Paper II**).

Table 9. Analytical data about geomorphological (maximum width transects, backshore width, frontal dune width and frontal dune height) of Migliarino-San Rossore Massaciuccoli Regional Park.

Sector	Transects	Maximum width transects (m)	Backshore width (m)	Frontal dune width (m)	Frontal dune height (m)
North	1	291	74	55	3
	2	243	57	38	3
	3	209	58	40	3
	4	240	68	41	4
Average		*245*	*64*	*43*	*3*
South	5	78	30	43	7
	6	58	14	35	8
	7	17	10	6	3
	8	114	12	12	2
	9	105	11	8	2
Average		*74*	*15*	*20*	*4*

Volume computation (expressed as m^3/m) basically confirmed the tendencies that were already brought out by the analysis of the topographic surveys (Table 10). Transect 05 did not experience any significant difference neither in sediment volume nor in the average volume along the profile. As expected based on the retreat pointed out by the topographic surveys, a harsh volume decrease occurred between March 2016 and June 2016 along Transect 06; during the summer, a little increase is observed (about 5 m^3/m). The marginal difference in beach profile evolution that was evidenced by the topographic surveys along Transect 07 transpires also in volume computation: just a modest volume increase is reported between March 2016 and June 2016, which was expected based on the presence of an accumulation at the toe of the eroding dune (Figure 7). Volumes do not vary during the summer months.

Table 10. Volume computation for each transect within the time frame of the investigation (January 2016 to September 2016). *Length* refers to the extension (m) of the beach profile along which the volume has been calculated; *volume* refers to the volume of sediments above 0 m elevation expressed as m^3/m; *average* refers to the average volume per linear meter (expressed in m^3/m).

	Transect 05			Transect 06			Transect 07		
	Length	Volume	Average	Length	Volume	Average	Length	Volume	Average
January 2016	80	254	3.2	-	-	-	-	-	-
March 2016	78	255	3.3	52	273	5.3	14	24	1.7
June 2016	81	252	3.1	44	187	4.3	16	27	1.7
September 2016	80	257	3.2	43	192	4.5	16	28	1.8

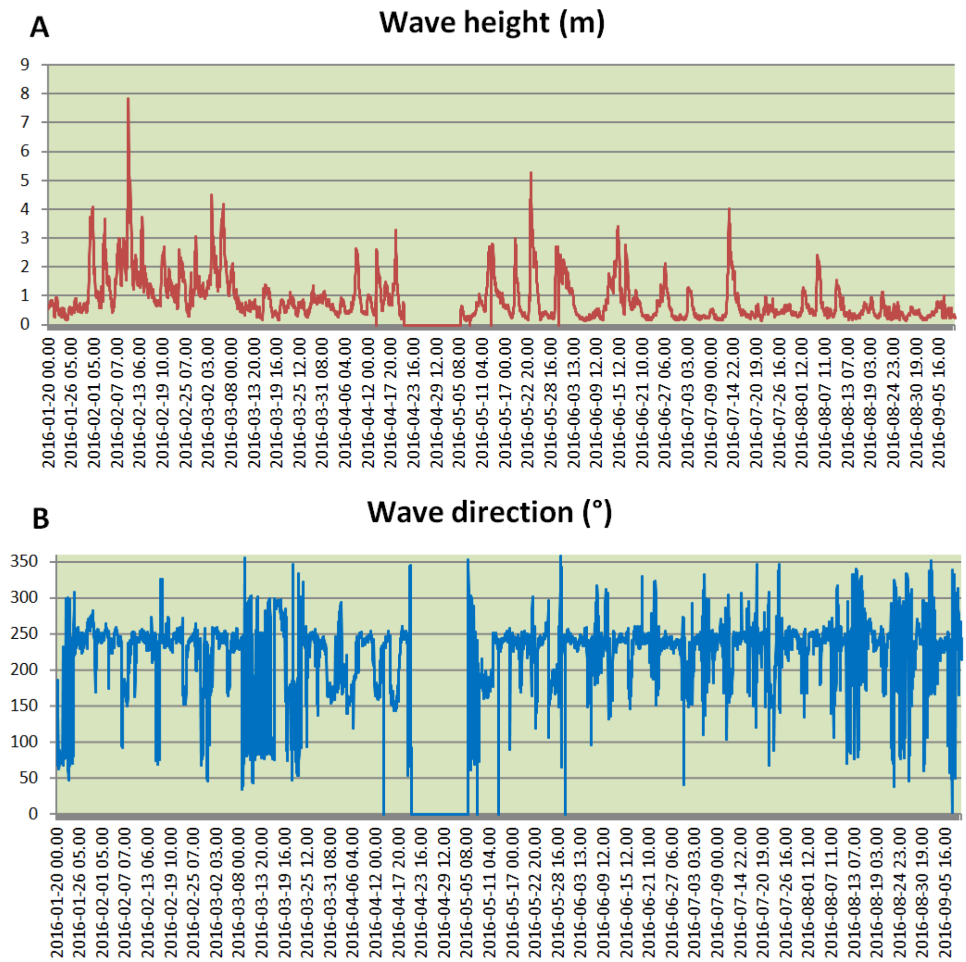

Figure 6. Sea-weather characterization within the time frame of the investigation. A) Wave height (expressed in m) recorded between January and September 2016; B) Wave direction (expressed in °) recorded between January and September 2016. The data were measured by the wave gauge located offshore the Gorgona Island; the gap between April 21 and May 5, 2016 is

due to technical maintenance of the device. Wave data were provided by Servizio Idrologico Regionale (Adapted from **Paper II**, Table 3).

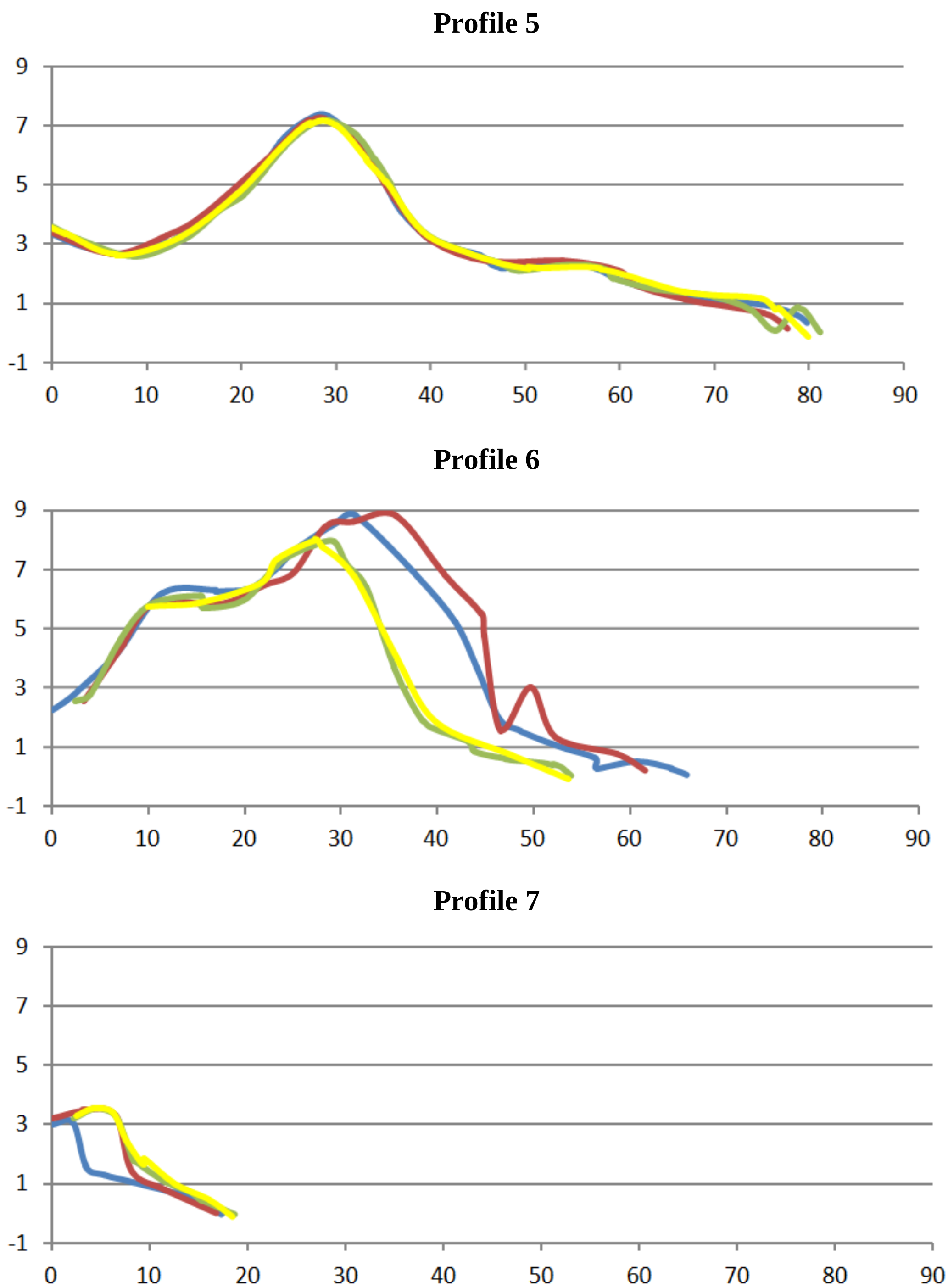

Figure 7. Beach profiles for each transect measured during the topographic surveys. Blue line: January 2016 survey; red line: March 2016 survey; green line: June 2016; yellow line: September 2016 survey (Adapted from **Paper II**, Table 4).

For the analysis the evolution of dune field it was used the stretch of coast between the Arno River and the Serchio River. The photo-interpretation was used to delimitate the seven types of land coverage: as Embryonic dune, Frontal dune, Semi-mobile dune and Steady dune, and other elements of the environmental (see **Appendix II**).

For vegetation were found 43 species and 21 families (Table 11). The families with the highest number of recorded species were: Poaceae (9 species), Asteraceae (5 species), Fabaceae (3 species), Apiaceae (3 species), Euphorbiaceae (3 species) and Caryophyllaceae (3 species). The most frequent species in the community structure were: *Ammophila arenaria*, *Cerastium semidecandrum, Chamaesyce peplis, Daphne gnidium, Elymus farctus, Euphorbia paralias, Helichrysum stoechas, Phleum arenarium, Polygonum maritimum, Silene canescens* and *Vulpia fasciculate*. The exotic species found were: *Chamaesyce maculata, Oenothera biennis* and *Xanthium orientale*. The two sectors were nearly the same diversity, zone D with 28 species and zone C with 27 species. The result of the PTF divided the species in three functional groups being classified as A (Type II), B1 (Type III) and BII (Type I) (Table 11). The result is the division of vascular plants in groups with characteristics to the degree of exposure in coastal environments. The difference in vegetation structure between the C and D sectors is visually noticeable. The C sector is composed of a well-structured vegetation succession, comprising a dune field composed of embryonic dunes, mobile and fixed ones, distributed in more than 300 m wide between sea-inland. The D sector in the succession of vegetation is threatened by severe erosion that reaches this stretch of beach. The D2 sector in the frontal dunes form large vertical walls because of wave action that erodes the base of the frontal dune. In the D3 sector the frontal dunes are practically nonexistent. Finally, can be noticed that the distance to the coastline determined the composition of sand dune communities, corroborating the observed in other studies in the Mediterranean and Atlantic Ocean (Miot da Silva et al., 2008; Nordstrom et al., 2009; Angiolini et al., 2013; Ruocco et al., 2014) (**Paper IV** and **VII**).

Table 11. Species found along transects on the Migliarino-San Rossore Massaciuccoli Regional Park. Legend: Zone: C (north sector) and D (south sector). Plant functional types (PFT): I, II and III.

Families	Species	Zone	PFT
Amaranthaceae	*Salsola kali* L.	D	III
Apiaceae	*Echinophora spinosa* L.	C	III
Apiaceae	*Eryngium maritimum* L.	C	III
Apiaceae	*Seseli tortuosum* L.	C	II
Asteracea	*Crepis bellidifolia* Loisel.	D	III

Asteraceae	*Achillea maritima* (L.) Ehrend. & Y.P.Guo subsp. *maritima*	C	III
Asteraceae	*Helichrysum stoechas* (L.) Moench	C, D	II
Asteraceae	*Hypochaeris radicata* L.	C	II
Asteraceae	*Xanthium orientale subsp. italicum*	C	III
Brassicaceae	*Cakile maritima* Scop. Subp. *maritima*	C, D	III
Brassicaceae	*Malcolmia ramosissima* (Desf.) Gennari	C	I
Caprifoliaceae	*Pycnocomon rutifolium* (Vahl) Hoffmanns. & Link	C	II
Caryophyllaceae	*Cerastium semidecandrum*	C, D	I
Caryophyllaceae	*Silene canescens* Ten.	C, D	I
Caryophyllaceae	*Silene otites* (L.) Wibel s.l.	C	II
Chenopodiaceae	*Atriplex spp.*	D	III
Convolvulaceae	*Calamintha nepeta* (L.) Savi	D	III
Convolvulaceae	*Calystegia soldanella* (L.) Roem. & Schult.	C	III
Cupressaceae	*Juniperus oxycedrus* L. subsp. macrocarpa *Sibth. & Sm.*	C	II
Euphorbiaceae	*Chamaesyce peplis (L.) Prokh.*	C, D	III
Euphorbiaceae	*Chamaesyce maculata*	D	I
Euphorbiaceae	*Euphorbia paralias* L.	C, D	III
Fabaceae	*Dorycnium hirsutum* (L.) Ser.	D	III
Fabaceae	*Lotus hirsutus* L.	D	II
Fabaceae	*Medicago littoralis* Loisel.	C	I
Geraniaceae	*Geranium purpureum* Vill.	D	III
Lamiaceae	*Teucrium chamaedrys* L.	D	II
Onagraceae	*Oenothera biennis* L.	C	II
Orobanchaceae	*Orobanche* spp.	C	I
Pinaceae	*Pinus pinaster* Aiton	D	II
Plantaginaceae	*Plantago arenaria* Waldst. & Kit.	C	I
Poaceae	*Ammophila arenaria* (L.) Link subsp. *australis* (Mabille)	C, D	III
Poaceae	*Arundo donax*	D	II
Poaceae	*Bromus sterilis* L.	D	I
Poaceae	*Cutandia maritima* (L.) Barbey	D	I
Poaceae	*Elymus farctus* (Viv.) Runemark ex Melderis subsp. *farctus*	C, D	III
Poaceae	*Lagurus ovatus* L.	D	I
Poaceae	*Phleum arenarium* L. subsp. *caesium* H. Scholz	C, D	I
Poaceae	*Phragmites australis* (Cav.) Trin.	D	II
Poaceae	*Vulpia fasciculata* (Forssk.) Fritsch	C, D	I
Polygonaceae	*Polygonum maritimum* L.	C, D	III
Rosaceae	*Rubus spp.*	D	II
Thymelaeaceae	*Daphne gnidium* L.	C, D	I

4.3 The instrumentation ad hoc

The instrumentation was built for the purpose of calculating wind sediment transport in the dune field. The tests were conducted on actual ambient conditions for a period of 24 hours within the dune system Migliarino-San Rossore Massaciuccoli Regional Park (Italy). For the tests five types of sensors were used: three sand level nodes, one sand collector node and one anemometric station node. All sensors were positioned in line, perpendicular to the coast, about 10 meters away from each other. Data acquisition by anemometric station was recorded every 20 minutes (three speeds and three directions) (Table 12). The direction and wind speed was calculated by an Arduino Uno board, and then sent to a gateway. The sand level node collected information once an hour. Three data packets were sent every time each packet by reading 8 LDRs (Table 13). The amount of sand accumulation was calculated on the gateway and then transmitted to the remote server Glassfish. The sand collector was sampled once per hour (Table 14). The weight of the sand was calculated by Gateway and then transmitted the values for the remote server. All data received by the five sensors were stored in MySQL database.

The WSN architecture proposed for monitoring the sand dynamics in coastal dunes has been successfully tested, proving its effectiveness in the collection of physical parameters. Although the aim of the first test was the proof the technology infrastructure, are required acquisitions more prolonged because the 24 hour time interval has proved too short to allow the collection of a set of meaningful data. Furthermore, the first tests were conducted on a small scale, integrating only five sensors. Additional sensors are being developed to expand the layout of the system architecture in online field for a grid format. System expansion will provide a better interpretation of the dune surface dynamics.

Table 12. Preliminary data acquired by anemometric station.

1-Height 0.40 m	Direction	2-Height 1.20 m	Direction	3-Height 2.00 m	Direction	Date	Time
19	WSW	16	W	16	SW	10/08/2016	13:34
14	SW	15	SW	15	SW	10/08/2016	13.29
4	SW	11	SW	11	SW	10/08/2016	13.24
18	WSW	19	W	16	S	10/08/2016	13.19
7	SW	20	SW	22	SW	10/08/2016	13.14
9	SW	14	SW	18	SW	10/08/2016	12.57
13	SW	16	SW	19	S	10/08/2016	12.52
5	SW	13	W	17	SW	10/08/2016	12.47
8	SW	17	SW	15	S	10/08/2016	12.37

11	SW	11	S	11	S	10/08/2016	12.32
11	SW	13	SW	13	SW	10/08/2016	12.27
14	SW	12	SW	15	S	10/08/2016	12.22
12	SW	11	SW	14	S	10/08/2016	12.17
5	S	7	SW	10	S	10/08/2016	12.12
10	SW	11	SW	13	S	10/08/2016	12.07
2	SW	10	S	10	S	10/08/2016	12.02

Table 13. Preliminary data acquired by sand level node (1, 2 and 3).

1-Height in relation surface	Date	Time
-60	10/08/2016	13.30
-60	10/08/2016	13.10
-60	10/08/2016	12.51
-60	10/08/2016	12.12

2-Height in relation surface	Date	Time
-60	10/08/2016	13.21
-60	10/08/2016	12.22
-60	10/08/2016	12.02

3-Height in relation surface	Date	Time
-60	10/08/2016	13.32
-60	10/08/2016	13.13
-60	10/08/2016	12.53
-60	10/08/2016	12.34
-60	10/08/2016	12.14

Table 14. Preliminary data acquired by sand collector.

Weight (g)	Date	Time
121	10/08/2016	12.06

Finally, the system architecture is designed to be easily expanded, used in any type of sandy beach and is an alternative instrument for rapid acquisition of physical data at low-cost (**Paper II** and **III**).

4.4 Coastal Dune Vulnerability Index - CDVI

The index developed for the sandy beaches of Italy and Brazil aimed to make the analysis of multidisciplinary parameters a feasible task. The result confirmed that the index is a useful tool with upgradable and applicable characteristic for both countries. The results of the total CDVI ranged from 0.32 in C2 and C3 to 0.49 in A2 (Table 15). The average total CDVI was 0.46 for the Brazil site, while 0.35 for the Italian site, for both country the total vulnerability was classified with moderate (García-Mora et al., 2001). In particular, the geomorphological condition of the dune system was the most significant for all sites (ranging from 0.52 to 0.79), besides the marine influence to Oceanic sites (medium 0.55) and vegetation condition to Mediterranean sites (medium 0.43). The cluster analysis revealed two groups of environments (I and II) and four subgroups (IA, IB, IIA and IIB), with a Euclidean distance of ~14% (Figure 8). Two separate groups can be pointed out: *Group I*, characterized by the Brazilian sites (A1 – B3) and further divided into two subgroups IA (B1, B2 and B3) and IB (A1, A2 and A3); *Group II*, characterized by the Italian sites (C1 – D3) and further divided into two subgroups IIA (C1, C2 and C3) and IIB (D1, D2 and D3) (**Paper VII**).

The NMDS computation (Figure 9) resulted in a distinct separation (horizontal axis) between Mediterranean and Oceanic sites (stress value of 0.04) and between Zone A and Zone B (vertical axis). Both cluster analysis as the NMDS showed a clear separation between the characteristics that drive the evolution of the sandy beaches of the Mediterranean and the Atlantic Ocean. For the Oceanic sites were dominated along the horizontal axis by human effect (HE7), marine influence (MI4, MI7) and geomorphological factors (GCD1), while the vertical axis was particularly influenced by marine influence (MI6, MI3, MI8, MI2). The analysis cluster showed that the variables with higher values for the vulnerability are: berm slope, particle size of beach, width of intertidal zone, length of homogeneous active dune systems, tidal range, breaches in the frontal dune and path percent of the frontal dune.

For Mediterranean sites resulted to be mainly affected by human effect (HE1, HE2) and vegetation conditions (VC6) along the horizontal axis, and by aeolian effect (AE6), geomorphological factors (GCD2) and human effect (HE16) along the vertical axis. The variables most vulnerable are: visitor pressure, visitor frequency, percent of alien species along the transect, the percent de seaward dune vegetated, height of secondary dunes and grazing on the active system.

Table 15. Partial and total CDVI for each sampling site (Adapted from **Paper VII**, Table 2).

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*

Abbreviations: GCD - Geomorphological Condition of Dune system, MI – Marine influence, AE – Aeolian effect, VC – Vegetation condition, HE – Human effect.

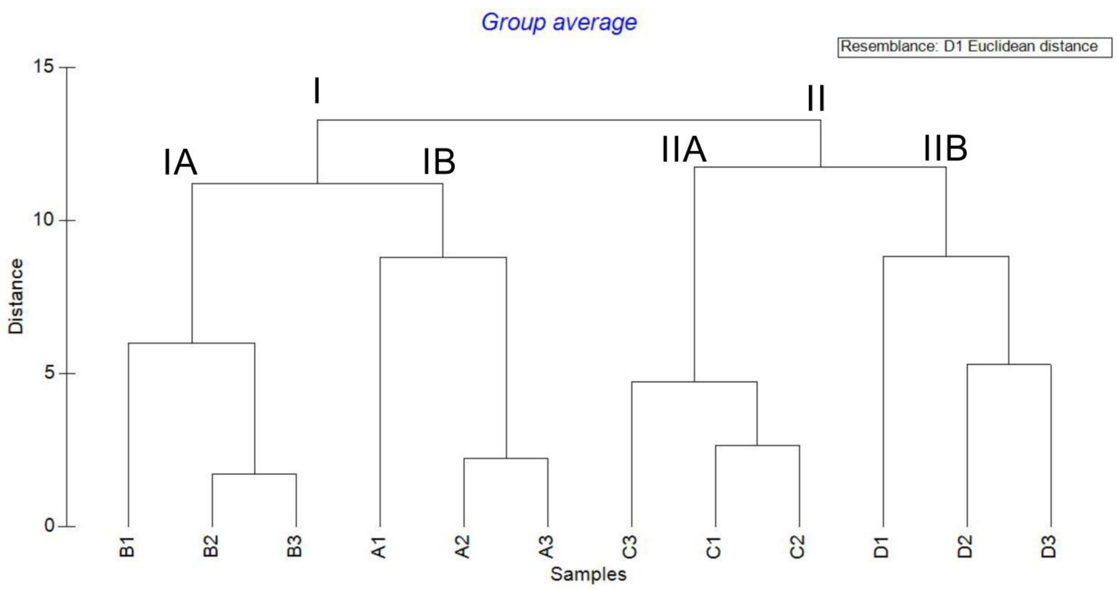

Figure 8. Dendrogram of 12 costal dune sites according to partial CDVI (Adapted from **Paper VII**, Figure 2).

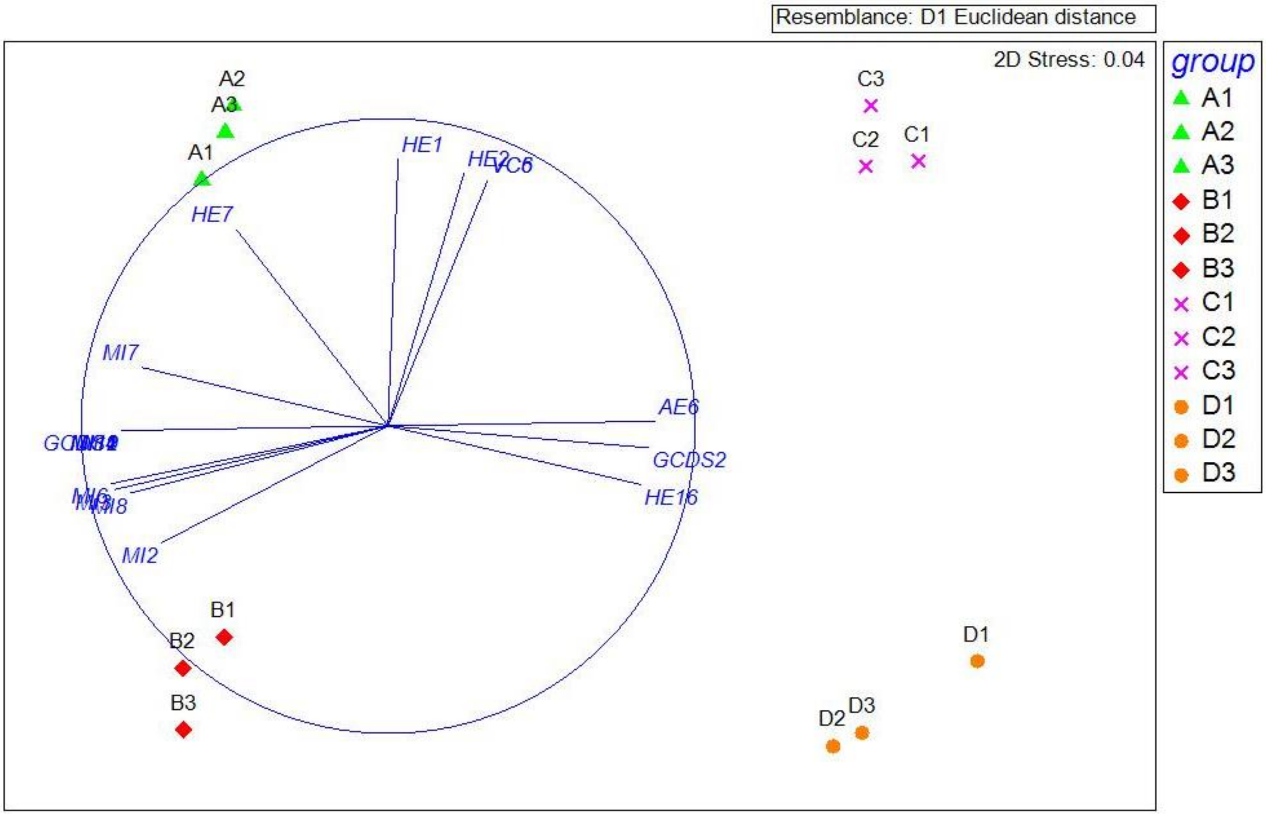

Figure 9. NMDS diagram based on dissimilarity (measured by Euclidean distance) for 12 dune sites. Abbreviations: visitor pressure (HE1), visitor frequency (HE2), relative proportion of alien species in the seaside of the frontal dune (VC6), percentage of vegetated seaward dune (AE6), average height of second dunes (GCD2), grazing on the active dunes (HE16), berm slope (MI2), 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) (Adapted from **Paper VII**, Figure 3).

This work contributes to a holistic view of the Tuscany coast, and in particular to better define the processes that control this environment. It may provide an increased awareness about conservation interventions, risk assessment and impact mitigation. The integration of 51 variables reduces the subjectivity of each multidisciplinary analysis and provides a quantitative assessment of the significance of each variable to the evolution of the dune field. Moreover, the index can be applied with a definite frequency, adding additional variables (e.g., numerical modeling) and on different scales (regional/local). This approach may serve as a reference for other Italian regions characterized by different physical and geographical settings. Finally, the index proved to bean useful tool to support coastal zone management, as it facilitates the identification of coastal sectors in need of either short term or long term interventions.

5. Conclusions

The results of this research confirmed that for a deeper understanding of the factors (abiotic and biotic) determining the evolution of coastal dunes, a multidisciplinary approach is necessary. This approach allows one to enlarge the view of the relevant issues of this system, which are not only restricted to the physical and biological components, but also the ecological, economic and social components. A wide view of all these components determines greater assertiveness in the responses of public front managers to local interests and hydrodynamic processes that influence this environment.

The supporting coastal management tools produced in this work, such as improved local database, alternative methods of acquiring information field and the development of a Coastal Dune Vulnerability Index - CDVI (Vafeidis et al., 2004); provide insights to a better definition of the processes acting at Grande beach at San Francisco South Island (Santa Catarina, Brazil) and Pisan coast (Italy).

Applying vulnerability indexes with frequency may improve significantly the management of specific coastal areas, as they are an easy-to-use, constantly updating tool. However, being an expression of a synthesis of so different parameters, these indexes can hide or reduce the extent of the differences between specific environments. Thus, the classification of vulnerability should not be assessed from arbitrarily chosen variables and/or automatically, or rather on the basis of the mere availability of data. It has to be a conscious choice and provide a reliable assessment of the environment. The correct selection of the parameters for a coastal vulnerability assessment is crucial such methodological approach, but not always a larger number of variables leads to a better analysis (Cooper & McLaughin, 1998; Mazzer et al., 2008), because many have similar and/or irrelevant effect.

The creation of an updated and reliable database is essential for any environmental analysis, especially for highly dynamic environments such as the coastal zone. To check the reliability and consistency of data collected through the ad hoc methodology, new tests should be performed, particularly with higher monitoring periods. The tool, however, proved useful and readily applicable to other types of sandy dunes.

The vulnerability index also proved an effective alternative in the analysis of a large number of quantitative variables. Among the variables that most interfere in both contexts analyzed (Mediterranean and Atlantic Ocean) were those related to the geomorphological conditions.

The morphology of the sand dunes is the result of synergy between the sand deposits, the wind and the distribution and height of vegetation (Hesp, 2002; Acosta et al., 2007; 2009; Fenu et al., 2012). Plant species that colonize the dunes vary geographically, but often share the same adaptive responses to the environment (Maun, 2009). In our opinion, the CDVI is a good tool to help the decision-making process. The study used a muldisciplinary approach, developed at a local scale, establishing links between the prior knowledge of the environments studied with the acquisition of new information. This index can be used for different necessities, such as the prioritization of factors related to erosion or shoreline evolution (Alexandrakis & Poulos, 2014), human intervention (Coelho et al., 2006) and evolution vulnerability of space-time (Idier et al., 2013). Aiming to continue this type of approach, we encourage adaptations to the method developed for the use in other sandy beaches in order to contribute to coastal management in an efficient and flexible way.

We encourage the use of this index as a way to support coastal zone management only after a careful analysis of the variables, as some parameters may be applied to any type of coastal dune system, while some others may only be applied to specific sites. Further improvements of this approach would basically consist of constant monitoring and update of the variables over time. In addition, this alternative methodology would contribute in filling the gap of information transfer between the scientific community and local authorities, stakeholders and the population, which would lead to a synergy between each social position that of course would determine a more integrated management of the coastal systems.

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PART II – PAPERS I TO VIII

PAPER I

MORPHO-SEDIMENTOLOGICAL AND VEGETATIONAL CHARACTERIZATION OF GRANDE BEACH AT SÃO FRANCISCO DO SUL ISLAND (SANTA CATARINA, BRAZIL)

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ABSTRACT

A multidisciplinary study based on several digital (geology, lithology, shoreline evolution, photo-interpretation of aerial and ortho-photographs) and field (topographic and vegetational surveys, grain-size analysis) datasets prompted new insights to a better definition of the processes acting at Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil). The resulting data enabled to produce a multi-thematic map at 1:50000 scale that might be useful to assist decision-makers manage the coastal system taking into account every factor involved at once and not separately; in addition, the map may be implemented and integrated with new information when available, since the database is provided in geographical information system (GIS). The results confirmed the importance to address coastal systems with a multi-faceted approach that can be applied everywhere and not only on settings similar to São Francisco do Sul Island.

Keywords: multi-thematic map; beach erosion; sediment grain-size; vegetation; barrier/lagoon system; São Francisco do Sul Island.

1. INTRODUCTION

The coast is a dynamic environment characterized by a complex interaction between internal and external factors (García-Mora, Gallego-Fernández, & García-Novo, 1999; Andrews, Gares, & Colby, 2002; Ruocco, Bertoni, Sarti, & Ciccarelli, 2014). Local tectonics, topography, vegetation, and soil are the main internal factors driving the evolution of a coastal system, while processes related to wind and wave action, and to a larger scale the eustatism, concur to influence the evolution as external factors. Usually all these processes are addressed individually, which is useful to increase the understanding of each (e.g., Gallego-Fernández & Martínez, 2011; Devi et al., 2013, Hesp et al., 2015). Nonetheless that does not necessarily add up to the overall comprehension of coastal system dynamics because of the mutual influence these factors have on each other (Bertoni et al., 2014). A lack of knowledge about how these factors interact often leads to wrong decisions about coastal planning: therefore, a better definition of the relationships between internal and external processes is mandatory for a conscious management of the naturalistic and administrative facets of littoral areas.

Multi-thematic maps are progressively gaining more reliability as a tool that might help decision makers taking the right choices about several aspects involving the management of coastal systems (Ghosh, Kumarb, & Roya, 2015; Sabatakakis, Nikolakopoulos, Papatheodorou, & Kelasidis, 2016). In addition, they can be easily queried to obtain lots of different data and can be continuously implemented and integrated with further information as soon as they are collected, which is instrumental to enable instant comparisons and matches between every dataset. Mapping might support critical planning decisions about the potential land use, the reduction of areas subjected to any kind of risk related to coastal processes (Coelho, Silva, Veloso-Gomes, & Taveira-Pinto, 2006) and to vulnerability to beach erosion (García-Mora, Gallego-Fernández, Williams, & García-Novo, 2001; Alexandrakis & Poulos, 2014), the identification of areas designated to protection and conservation (Fernandes & Amaral, 2013; De Jong, Keijsers, Riksen, Krol, & Slim, 2014), and to recreation (Araujo & Costa, 2008; Botero, Pereira, Tosic, & Manjarrez, 2015).

The aim of this work is to increase the understanding of the morpho-sedimentological and vegetational characteristics of Grande beach along with the backing field dune at the Island of São Francisco do Sul (Santa Catarina, Brazil), also providing a multi-thematic map that needs to be referred to when decisions must be taken about how to manage the coastal area of the Island of São Francisco do Sul.

2. STUDY AREA

2.1. Physical setting

The Island of São Francisco do Sul is located in the northern portion of the State of Santa Catarina, in the southernmost sector of Brazil (Figure 1). The eastern side faces the Atlantic Ocean, whereas Babitonga Bay borders the Island to the W and to the N. To the S, the Linguado Channel separates the Island from the continent, even though the mouth was silted up artificially in the Thirties to allow the construction of a the access road to the municipality of São Francisco do Sul (Cremer, Morales, & Oliveira, 2006). A series of 4 small islands, the Tamboretes Islands, are located almost 5 km offshore of the central sector of the Island of São Francisco do Sul (Figure 1). The sea floor is gently sloping, being about 0.01% (Zular, 2011). Only three villages are present on the island: the most important, São Francisco do Sul, is on the western side; the other two settlements, Praia Grande to the north and Praia do Ervino to the south, are on the eastern side. The Acaraí Lagoon occupies the inner portion of the island, whereas a series of hills (about 300 m high) characterizes the western side. São Francisco do Sul Island is comprised within the Acaraí State Park: the decision to protect this site establishing the Park was made because of the presence of the “restinga” vegetation, which is a particular plant association typical of the Brazilian coast. Due to its great relevance to the environment, the “restinga” vegetation required immediate protection and conservation actions (Melo Júnior & Boeger, 2015).

São Francisco do Sul Island includes 12 beaches: the longest one, about 25 km, is named Grande and is located on the eastern side of the island. This is the beach where the study has been focused on, because it is characterized by a large variability of morphological and sedimentological features, and of vegetation species. The rest of the beaches are mostly pocket beaches, not even comparable to Grande beach in terms of extension (the second longest being about 4 km). Medium sand is the typical grain-size of the sediments that constitute most beaches at São Francisco do Sul (Abreu, 2011). Grande beach width is quite constant throughout the entire length of the beach: the average width is about 20 m. The beach is subjected to erosion processes that at times produced the demolition of the foredune and the generation of a steep scarp at the transition between the backshore and the dunes. The erosion is uniform throughout the length of the beach, therefore no particular accumulation or retreat areas are detectable. The littoral drift is northwards trending (Zular, 2011). Parabolic dunes up to 15 m high characterize the northern sector of Grande beach, they are well-developed, but wide blowouts interrupt their regularity (Figure 2(a)). In addition, human interference is significant in this portion of the beach. In the central sector of the beach the dunes are transverse (Figure 2(b)): they are characterized by lower height (hardly over 7 m) and less human impact, likely due to their major distance from the villages. Close to Praia do Ervino village the human interference increases back again.

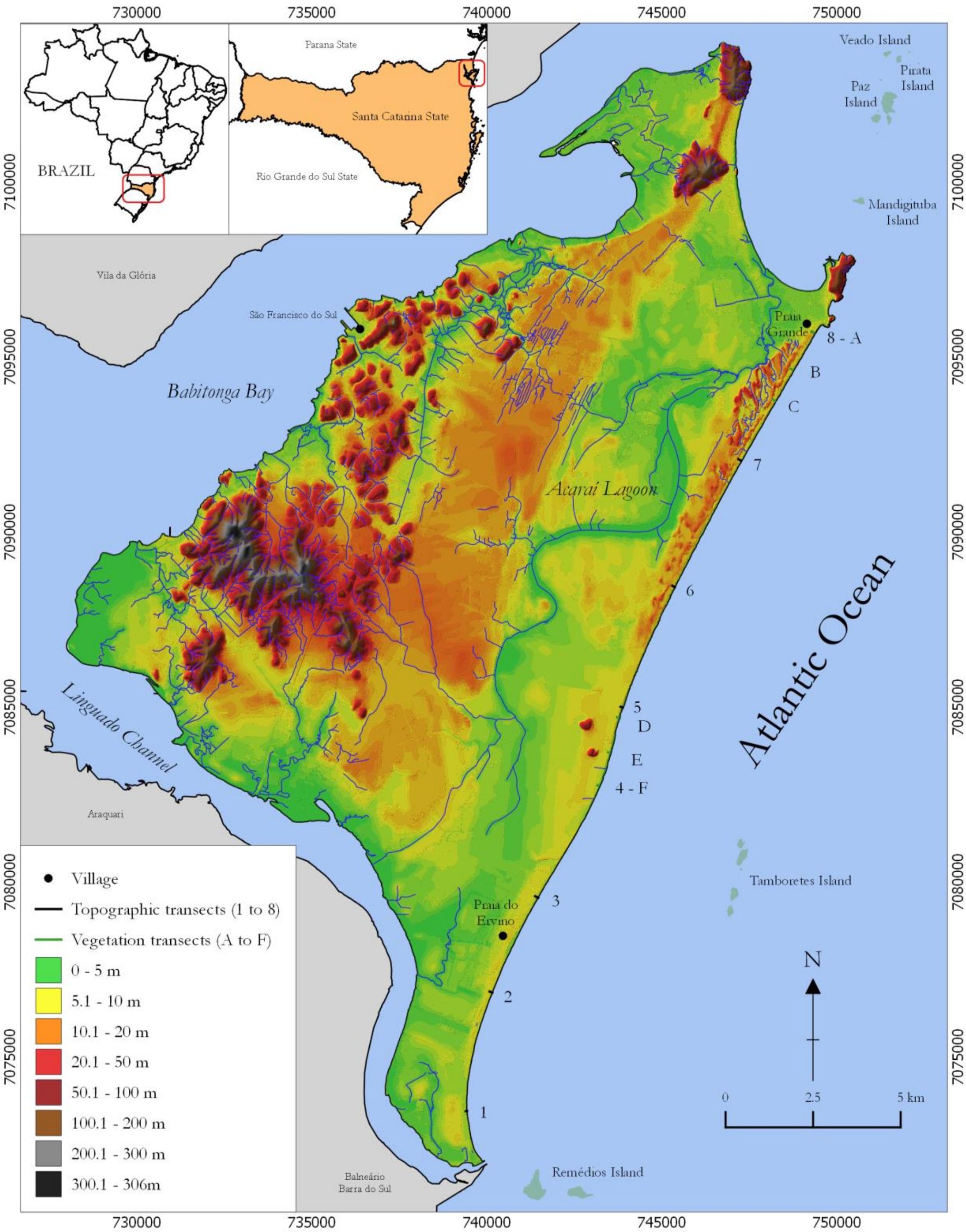

Figure 1. Location of the São Francisco do Sul Island (Santa Catarina, Brazil); the map is derived from a digital elevation model at 1:10000 scale. The progressive numbers point out the position of the transects where the topographic survey was carried out. The letters represent the position of the transects where the vegetation sampling was carried out. Two transects (4 and 8 and A and D respectively) have both notation because the topographic survey overlapped the vegetation sampling.

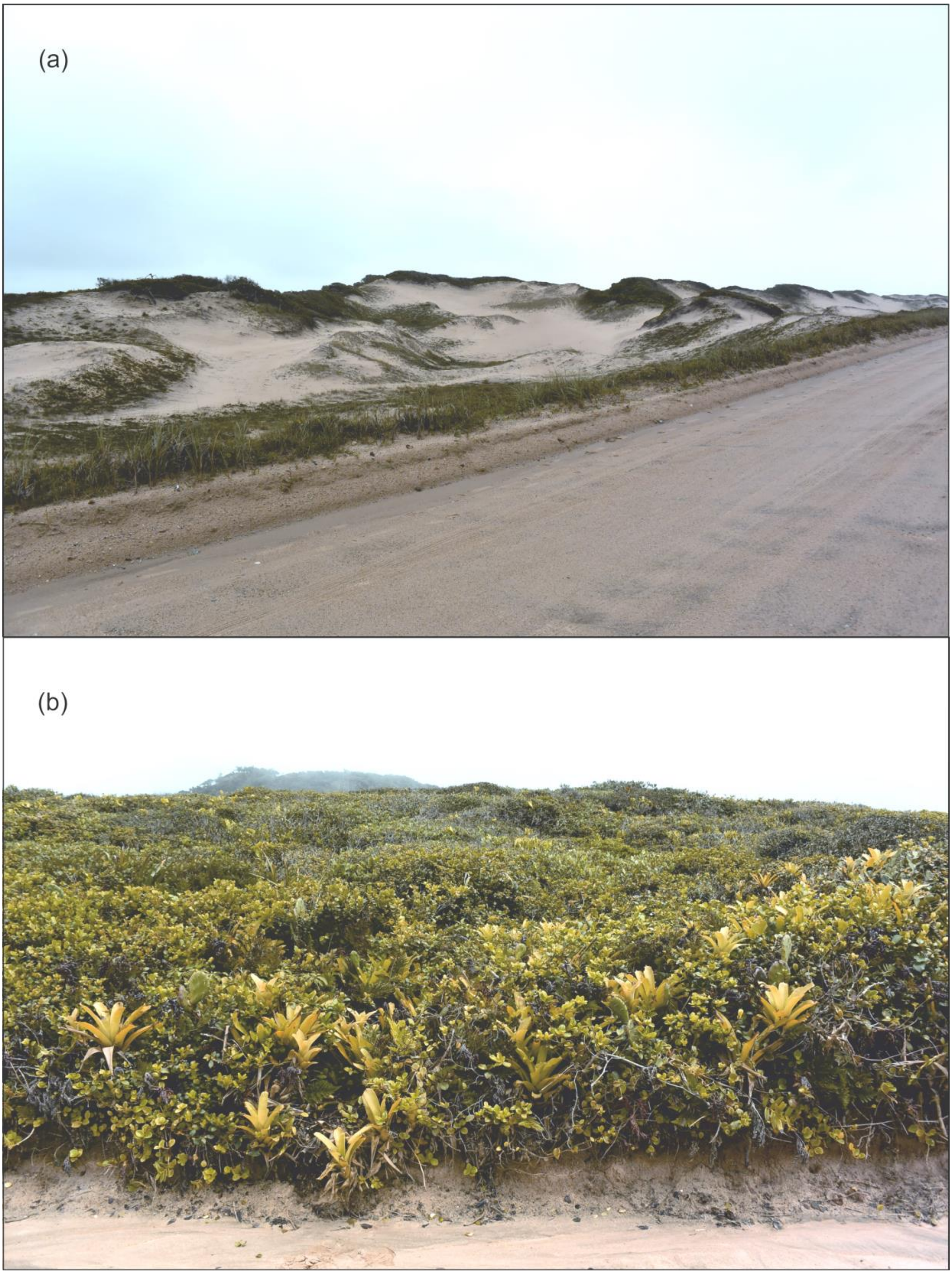

Figure 2: Pictures of parabolic dunes (a) and transverse dunes (b) at Grande beach, São Francisco do Sul Island. The recognition of large blowouts on parabolic dunes is easily appreciable, as is the difference in vegetation coverage between the two dune types.

2.2. Geological setting

The geological elements that characterize the São Francisco do Sul Island were pointed out in accordance with Possamai, Vieira, Oliveira, & Horn Filho (2010) and Vieira (2015). The units were identified on the basis of lithological characteristics, fossil content, absolute dating, and genesis; sorted by age:

Paleo-Proterozoic

- São Francisco do Sul Complex (metamorphic unit of the crystalline system) is composed of gneisses with bands defined by intercalations of felsic and mafic minerals characterized by different shades of grey.

Cambrian-Ordovician

- Suíte Morro Inglês (igneous unit of the crystalline system) is composed of porphyritic granitoides with predominant monzogranites, sienogranites, and granodiorites.

Quaternary (undifferentiated)

- Poorly-sorted sediments with predominant sand, silt and clay, and variable content of gravel and pebbles; usually the sediments are immature and angular, and can be associated with colluvium deposits (interpreted as colluvial, alluvial deposits).

Pleistocene

- Deposits composed of very fine to fine sand, well-sorted sediments, low-angle plane-parallel stratification and characterized by series of beach ridges at an elevation of 8-20 m above present mean sea level (interpreted as beach deposits).
- Deposits composed of silty sand sediments, plane-parallel stratification with laminations and lenses of finer sediments; they are usually located at an elevation of 8-12 m above present mean sea level (interpreted as lagoon deposits).

Holocene

- Deposits composed of fine to coarse sand, moderately sorted, low-angle plane-parallel stratification and characterized by series of beach ridges at an elevation up to 6 m above present mean sea level (interpreted as beach deposits).
- Deposits composed of silty sand sediments, moderately to well sorted with organic matter and bioturbation; they are usually located at an elevation of about 4 m above present mean sea level (interpreted as lagoon deposits).
- Deposits composed of fine to medium sands, well sorted; they usually form parabolic dunes, which are active or fixed by vegetation (interpreted as aeolian deposits).

- Deposits composed of silt and fine sand, well sorted sediments; they exhibit flat, elongated surface terraces located along the Acaraí Lagoon (interpreted as lagoon-paludal deposits).
- Deposits composed of silt to fine sand sediments located along the Babitonga Bay and the mouth of the Linguado Channel (interpreted as estuarine-paludal deposits).

3. MATERIALS AND METHODS

The data used in this study consist of digital data (aerial photographs and digital terrain models, DTM; SDS, 2010) and field data collected during topographic and sampling surveys. These data were also used to generate a multi-thematic map (1:50000 scale) that describes the morphological, sedimentological and vegetational characteristics of Grande beach. The map can be queried to obtain information about geomorphology (beach profile topography, type of dune, presence of morphological elements such as blowouts), sedimentology (sediment grain-size), geology (type of deposit), shoreline evolution, and vegetation coverage. The data about geomorphology (with the exception of beach profile topography), geology and shoreline evolution are spatial, since they cover the whole Grande beach and the backing dune field; the data about beach profile topography are linear along cross-shore transects, those about sediment grain-size and vegetation coverage are punctual.

3.1. Digital data

3.1.1. Geological map

The lithological map was rendered on a hillshade generated model from a DTM (SDS, 2010) to emphasize the relief. The geological elements were mapped according to Possamai et al. (2010) and Vieira (2015), and re-interpreted on the basis of new insights. The units are represented in different colours on the map: for São Francisco do Sul Complex, Suíte Morro Inglês, and alluvial/colluvial deposits the RGB colour code is in accordance with the Commission for the Geological Map of the World (CGMW); specific colours were assigned to the units of the same age.

3.1.2. Shoreline analysis

The systematic tracing of the coastline was carried out analyzing aerial photographs and ortho-photographs, spanning from 1938 to 2010 (72 years). The images were properly georeferenced and used to build photo-mosaics of the entire coast for each year of aerial coverage (1938, 1957, 1978, 2010). For each mosaic the shoreline was traced out using QGIS vectorization tools at 1:2000 scale. The shoreline is defined by the mean high water line, which is represented by the wet/dry line (Crowell, Leatherman, & Buckley, 1991; Leatherman, 2003; Mazzer & Dillenburg, 2009). The lines were traced in different colours to ease direct comparisons (Table 1).

Table 1. List of aerial photographs and ortho-photographs used to set up the shoreline evolution during a 72 year timespan.

Product	Year	Scale	Source	Line colour
Aerial photo	1938	1:20000	North American Marine	Red
Aerial photo	1957	1:12000	Aerophotogrammetric services Cruzeiro do Sul S/A	Blue
Aerial photo	1978	1:25000	Aerophotogrammetric services Cruzeiro do Sul S/A	Green
Ortho-photo	2010	1:10000	Municipality of São Francisco do Sul	Yellow

3.1.3. Dune classification

Coastal dunes were identified by photo-interpretation of both the 2010 ortho-photograph mosaic and the DTM. The photo-interpretation was realized mapping the features at 1:3000 scale. Dunes were classified according to Bertoni & Sarti (2011), modified after Hellemaa (1998): in detail, there have been recognized i) frontal dunes (still subjected to physical processes, covered with typical dune vegetation); ii) semi-mobile dunes (might experience physical processes, characterized by shrubbery and by blowouts); iii) steady dunes (no more subjected to physical processes, covered by arboreous vegetation). In addition, parabolic and transverse dunes were traced out following the classification of Hesp (2002). Backshore and blowouts have also been mapped; the backshore seaward limit is represented by the 2010 shoreline.

3.2. Field data

3.2.1. Topographic surveys

The topographic survey was carried out in October 2015 along 8 cross-shore transects (Figure 1). The profiles were about 3 km spaced: even though they were uniformly spaced, either the anthropized and the natural portions of the beach were surveyed. Each transect started at the shoreline and ended at the transition to the woody vegetation. The survey was performed using a Leica RTK-GPS (Universal Transverse Mercator projection, Zone 22 S, Datum SAD69); points were recorded at any break-in slope along the cross-shore profile. The instrument accuracy of about 1 cm was obtained post-processing the raw data using the information provided by the nearest fixed station (Araquari Station - SAT 96171). Sea-weather information during the survey were provided by DHN (http://www.mar.mil.br): mean wave height was 1.65 m, with a peak of 1.84 m; the average tide condition was 0.7 m, while the tidal range was about 1.7 m.

3.2.2. Sediment sampling and grain-size analysis

Sediment sampling was carried out together with the topographic survey along the same 8 transects (Figure 1). Samples of about 1 kg each were collected from the surface by means of a small shovel. The sediment was sampled in specific spots, that is the beachface, the dune crest, the dune back-toe, and the steady dune. Grain-size analysis was then performed on all the 31 samples collected on the beach. Prior to the sieving procedures, they were accurately treated according to Bertoni, Biagioni, Sarti, Ciccarelli, & Ruocco (2014). Once dried and reduced to a quantity still representative of the whole sample (about 100 g), the samples were sieved for ten minutes using a mechanic sieve shaker. Sieves from 0.75 mm to 0.063 mm were used, with mesh interval of 0.5 phi. The sediment retained on each sieve was weighed by means of a digital scale (instrument error of 0.01 g). The ensuing data were processed by SYSGRAN 3.0 software (Camargo, 2006), which provided the most important Folk & Ward (1957) textural parameters such as the Mean (Mz). Each grain-size class was then represented along the transects with dots of different colours: blue (fine sand), orange (medium sand) and green (coarse sand).

3.2.3. Vegetation sampling

The percentage of vegetation coverage was estimated in 2 x 2 m plots along 6 cross-shore transects (Figure 1). The transects were located in two sectors of Grande beach characterized by a different configuration in order to enable comparison between plant association on the parabolic dunes to the north (Zone A) and on the transverse dunes to the south (Zone B). The plots were placed on specific spots on the front dune, on the backdune area and on the fixed dune. The vegetation coverage was visually estimated according to the Causton (1988) scale. The phytosociological parameters of absolute and relative coverage, absolute and relative frequencies, and level of significance of the indicator value were calculated according to Munhoz & Araújo (2011).

The classification of the species followed Christenhusz, Zhang, & Schneider (2011) and APG III (2009). The flora identification was based in the “restinga” vegetation list of the PEA proposed by Melo Júnior (2015). Species names and Authors were in accordance with the Species List of the Botanical Garden of Brazil Flora of Rio de Janeiro (http://floradobrasil. jbrj.gov.br).

4. RESULTS

4.1. Digital data

The recognition of the geological units and the depositional systems allowed to provide a reconstruction of the evolution of the São Francisco do Sul Island since the Pleistocene. The pre-Mesozoic metamorphic and igneous units (São Francisco do Sul Complex and Suíte Morro Inglês) outcrop prevalently on the hills on the western side of the island; metamorphic outcrops are also located on isolated elevations, promontories and islands on the eastern side. During the Quaternary streams flowing down the slopes formed colluvial and alluvial deposits at the foot of the hills, which are typical of continental systems. The most important feature that strongly characterized the evolution of the São Francisco do Sul Island is related to relative sea level oscillations, which led to consecutive landward and seaward migrations of a barrier/lagoon system during Pleistocene and Holocene. Two strand plain systems can be observed in the central and in the eastern portion of the island: the former is Pleistocenic, the latter Holocenic. The Acaraí Lagoon formed on the back of the Holocenic beach ridges; currently it is a distributary channel flowing to the northeast direction. Paludal deposits can be recognized along several sectors of the present course of the channel and along the Linguado Channel. Large aeolian deposits formed in the north-eastern sector, producing high parabolic dunes that covered the Holocene beach ridges in that portion of the island.

The shoreline evolution showed that between 1938 and 1957 the coast was subjected to a predominant progradation of the system (Table 2), with peaks of more than 60 m in the northern and southern sectors. The central portion of the coast was characterized by negative values in that same timespan: a retreat of almost 40 m. During the next timespan (1957 to 1978) the trend was significantly different as the erosion processes begun to hit the coast seriously.

Table 2. Shoreline evolution expressed in annual rates during three different intervals (from 1938-2010) calculated along the 8 transects traced out for the topographic surveys (+: accretion; -: retreat).

Transect	Time intervals		
	1938-1957	1957-1978	1978-2010
1	+ 67 m	- 10 m	- 22 m
2	+ 44 m	- 9 m	+ 4 m
3	-	-	- 43 m
4	- 38 m	+ 37 m	- 25 m
5	+ 39 m	- 13 m	- 3 m
6	+ 79 m	- 74 m	+ 17 m
7	+ 31 m	- 4 m	+ 15 m
8	+ 4 m	+ 7 m	- 12 m

Retreat peaks of almost 70 m were calculated along the northern sectors of Grande beach during that timespan. The central sector was basically the only portion of the coast that recorded accretion (almost 40 m) as opposed to the previous time interval, during which it was characterized by a relevant retreat. During the last timespan (1978 to 2010) the tendency to a progressive retreat of the system continued, in particular in the southern sector of the coast: retreat of about 30 m was generally calculated along that portion. Conversely, the northern sector experienced accretion of more than 10 m in that same time period.

The photo-interpretation of ortho-photographs allowed to describe the dunes on the eastern side of the Island of São Francisco do Sul. The dune field is continuous along the N-S direction and is composed by an interconnection of frontal and semi-mobile dunes, backed by steady dunes. The semi-mobile dunes are not present in the southern sector of Grande beach, where transverse dunes are predominant. The dune field reaches its maximum width along transect 7 (Table 3), in the northern portion of the beach (just over 1000 m). Aside from the transects where human activities replaced the steady dunes with buildings and structures (transects 2, 3 and 8), the narrowest portion is located towards the central sector of the coast (about 500 m). The mobile dunes are largest where the steady dunes have been wiped out by human activities.

The photo-interpretation confirmed the spatial separation of parabolic and transverse dunes: parabolic dunes of NNE orientation are located towards the northern sector of the beach, where they are characterized by several large blowouts; conversely, the transverse dunes, covered by dense shrub vegetation, are prevalent in the southern sector.

Table 3. Foredune and steady dune width along each transect calculated by photo-interpretation of the 2010 ortho-photograph. Transects 2, 3 and 8 have no value for the steady dunes because they were almost completely replaced by urbanized areas.

Transect	Foredune width (m)	Steady dune width (m)
1	26	838
2	60	-
3	59	-
4	18	442
5	15	455
6	24	774
7	15	1049
8	60	-

4.2. Field data

The topographic profiles showed that the backshore width was higher in the northern sector of Grande beach, being consistently over 20 m with the exception of the northernmost transect (Profile 8), which is located towards Praia Grande village (Table 4). To the south the backshore was generally narrower: the wider transect (Profile 3) was just as wide as the narrowest among those in the northern portion of the beach (about 25 m). The topographic survey also highlighted great variability in terms of width and height of the frontal dunes: the width was higher to the south and lower in the central and northern portions of the beach (Table 4). Again, Profile 8 was an exception, showing a frontal dune width of more than 50 m.

In terms of height, the frontal dunes showed a clear trend to increase northwards; the same tendency was pointed out taking into account the whole dune field, not only the frontal dunes (Table 4). It is worth to note that most transects were characterized by a direct correlation between backshore width and frontal dune height, except for Profile 8, where the frontal dune height was high (7 m) and the backshore was narrow (13 m). Each profile showed evidence of ongoing erosion process: this is particularly relevant along the transects showing a steeper scarp relative to the backshore slope.

Table 4. Analytical data about geomorphological (backshore width, frontal dune width and height, and maximum dune height) and sedimentological features (mean grain size) of Grande beach, São Francisco do Sul Island.

Transect	Backshore width (m)	Frontal dune width (m)	Frontal dune height (m)	Maximum height (m)	Mean grain size (phi)
1	15	23	4	4	2.20
2	11	50	4	6	2.08
3	25	59	5	6	1.63
4	11	14	5	5	2.05
5	30	14	6	6	1.48
6	34	22	8	8	1.32
7	26	13	6	8	1.19
8	13	57	7	7	1.75

The grain-size analysis carried out on the sediment samples collected at Grande beach showed that the average grain-size is comprised within the medium sand interval (Figure 3). The grain-size decreases landward along each transect: the Mean (Mz) values also evidenced a clear decreasing trend to the north (Table 4). The only exceptions are represented by transects 3, 4 and 8.

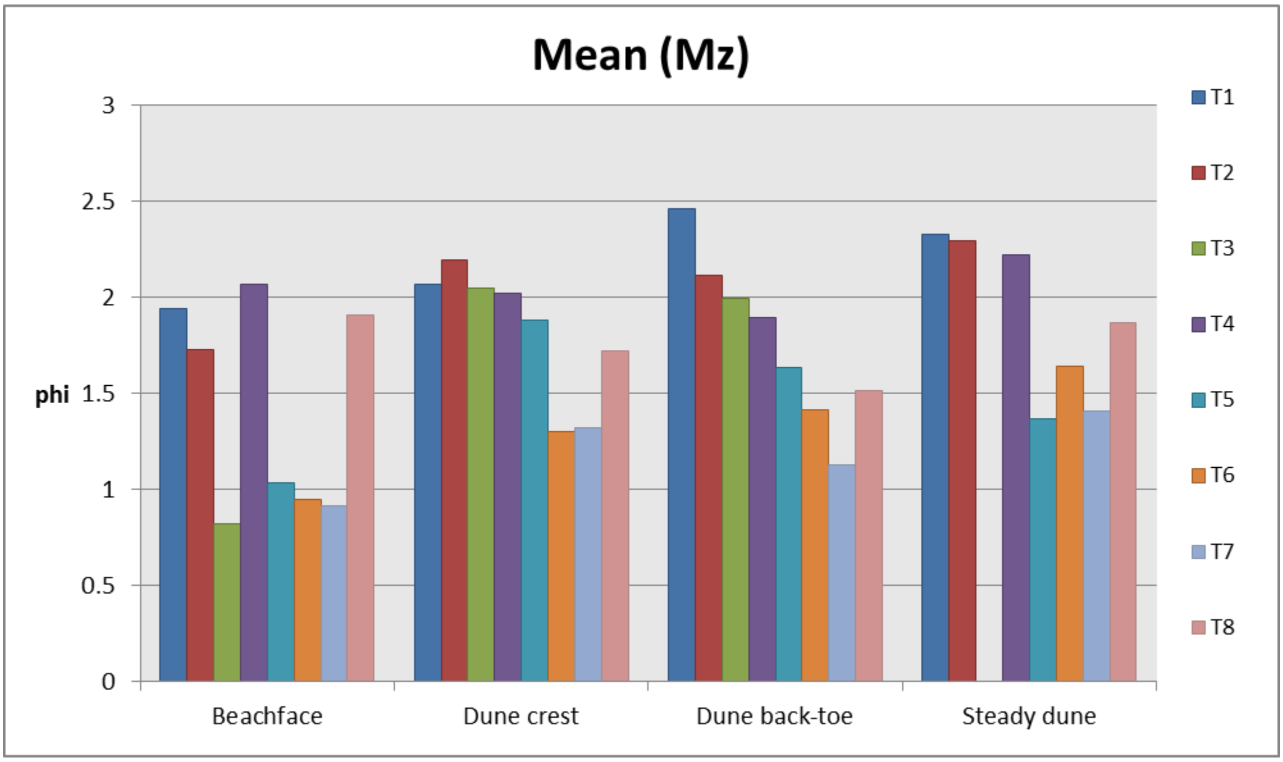

Figure 3. Grain-size distribution (Mean, Mz) sorted by the spots where sediment samplings were carried out along each transect: beachface, dune crest, dune back-toe, steady dune.

On regard to the vegetation, 53 species and 33 families were recorded in the two sites (Zone A and Zone B) where vegetation sampling was carried out. The families with the highest number of recorded species were Poaceae (6 species), Fabaceae (5 species), Asteraceae (4 species), Cyperaceae (4 species) and Malvaceae (3 species). The most frequent species in the community structure were *Scaevola plumieri*, *Ipomoea imperati*, *Spartina ciliata*, *Hydrocotyle bonariensis*, *Remiera maritima*, *Smilax campestris*, *Aechmea ornata*, *Guapira opposita*, *Varronia curassavica* and *Myrcia pulchra.*

Zone A is characterized by lower species diversity compared with the Zone B and by the presence of exotic species (*Centella asiatica*, *Cyperus sp*, *Brachiaria sp* and *Portulaca oleracea*), which are not detected in Zone B. Another factor separating the two sites was the coverage: in Zone A, every transect has higher percentage values in the frontal dune rather than in the semi-mobile dune; in Zone B, the vegetation coverage increases from the frontal dune towards the steady dune, with the exception of transect F that shows a major coverage on the frontal dune.

5. CONCLUSION

The data obtained from the morpho-sedimentological and vegetational analyses carried out during this study provided new insights about the processes acting at Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil) and about the recent evolution of this barrier/lagoon system. In addition, the datasets allowed to produce a multi-thematic map that includes all the sensible information collected from field and laboratory activities. The map provides a quick overview of the geology and of the deposits that presently outcrop on the entire island, along with an indication about aspects related to the coastal morphodynamics. As a matter of fact, the focus on Grande beach prompts the identification of peculiar tendencies in the evolution of beach profile, sediment grain-size, and vegetation.

This study confirms that a wise management of coastal systems is reached when multiple factors are taken into account all at once. The multidisciplinary approach is often successful because it allows to look at the same aspect from different perspectives and scales, which usually leads to a better, all-around product. As a result, mapping is a valid instrument that is useful for research purposes and as a tool to aid coastal management. The multi-thematic map generated using all the datasets acquired from digital analyses and field surveys might be a reference to gather quick information about morpho-sedimentological and vegetational aspects of Grande beach at São Francisco do Sul Island and a legitimate contributor to a conscious planning of the site. Besides, this approach can be easily replicated elsewhere because it is not strictly related to specific characteristics of the local area.

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PAPER II

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EXTREME EROSION OF A DUNE CREST WITHIN A SHORT TIMESPAN (JANUARY – SEPTEMBER 2016): THE RECENT CASE IN THE MIGLIARINO – SAN ROSSORE – MASSACIUCCOLI REGIONAL PARK (TUSCANY, ITALY)

Abstract - *Extreme erosion of a dune crest within a short timespan (January – September 2016): the recent case in the Migliarino – San Rossore – Massaciuccoli Regional Park (Tuscany, Italy).* Beach erosion is a process that in the last decades is affecting several coastal areas around the world. Unfortunately the Tuscany coast makes no exception. The factors responsible of this phenomenon are different: some are natural, some other are related to human activities. Usually the latter determine drastic hastening of ongoing processes, mainly because they act over temporal scales much smaller than those typical of the natural factors. In this paper, multiple topographic surveys were carried out along a 5 km long sector of coast located within the boundaries of the Migliarino – San Rossore – Massaciuccoli Regional Park in order to evaluate the evolution state of the area within a 9-months timespan (January 2016 – September 2016). The results emphasize the importance to increase the knowledge about the morphodynamics processes acting on this area based on the resulting retreat that was observed analyzing the data: in just 4 months the crest of a 9 m high dune retreated of about 6 m, which resulted in a volume loss of about 80 m^3/m along the selected transect. This worrying outcome implies the need to manage this sector of coast applying a rather different approach relative to those used thus far. It is paramount to consider each sector of coast as a whole and not separately, that is in accordance with the physiographic unit rather than territorial and administrative limits. In addition, this new approach must also take care of the coastal environment in the direction orthogonal to the coastline, adding into the equation rivers and catchment areas, which are the main source of sediments feeding the beaches.

Keywords - Beach erosion, coastal dune, topographic survey, volume shift, Migliarino – San Rossore – Massaciuccoli Regional Park

Riassunto - *Erosione molto accentuata della cresta di una duna frontale in un breve periodo di tempo (gennaio – settembre 2016): il recente caso nel Parco Regionale di Migliarino – San Rossore – Massaciuccoli (Toscana, Italia).* L'erosione costiera è un fenomeno che da diverse decine di anni affligge tante aree costiere in tutto il mondo, e purtroppo la costa settentrionale della Toscana non fa eccezione. Tante sono le cause alla base dei processi erosivi, alcune ovviamente naturali, altre legate alle attività antropiche: queste ultime generalmente sono responsabili di brusche accelerazioni dei fenomeni già in atto, proprio perché agiscono su scale temporali molto più piccole rispetto alle cause naturali. Nel presente lavoro, realizzato in un tratto di litorale di circa 5 km di estensione compreso all'interno del Parco Regionale di Migliarino – San Rossore – Massaciuccoli, è stato evidenziato la stato evolutivo dell'area attraverso l'esecuzione di 4 rilievi topografici in un periodo di tempo di 9 mesi (gennaio 2016 – settembre 2016) allo scopo di sottolineare quanto

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importante sia aumentare le conoscenze legate ai processi morfodinamici di questa area dal momento che in soli 4 mesi si è avuto un arretramento di circa 6 m della cresta di una duna alta quasi 9 m, con una perdita volumetrica stimata in circa 80 m^3/m. Questi preoccupanti valori implicano la necessità di gestire questo tratto di litorale nel modo più efficace possibile, utilizzando approcci significativamente diversi rispetto a quelli utilizzati sinora. Risulta quindi fondamentale considerare i vari settori di costa non più in maniera separata e distinta tra loro, magari in base ai limiti amministrativi, bensì in termini di unità fisiografica. Inoltre, è indispensabile approcciare la gestione e lo studio delle aree costiere anche in senso trasversale alla linea di riva, coinvolgendo quindi anche i fiumi e i bacini idrografici, sorgente primaria dei sedimenti che alimentano le spiagge. Solo in questo modo è possibile raggiungere un sistema di gestione delle aree costiere che sia efficace e consapevole.

Parole chiave - Erosione costiera, dune costiere, rilievi topografici, spostamento di volume, Parco Regionale di Migliarino – San Rossore – Massaciuccoli

1. INTRODUCTION

Erosion is a natural process that defines the evolution of coastlines everywhere, it is significantly influenced by natural conditions such as wave and tide processes, sea weather (storms), coastal area geology and morphology, and climate change (Thatcher et al., 2013; Idier et al., 2013; IPCC, 2014). In addition to the natural factors, erosion is also strongly affected by human-related activities such as changes in land use in the hinterland, dam and armored bank construction along the course of the rivers, wetland reclamation, the readjustment and reforestation of mountain slopes to reduce hydrological hazard, and river bed quarrying (Masselink & Hughes, 2003). Sometimes the erosion processes are also augmented and intensified by the construction of piers and seawalls to permit harbor activities, and of groynes and breakwaters that are built to protect specific sectors of the coast (French, 2001). The major difference between natural and anthropogenic factors is the timescale at which they influence the coast: the human impact is usually fast, at times immediate, while the natural processes typically produce long-term modifications.

As previously mentioned, beach erosion is a worldwide issue that causes significant losses such as economic setbacks (infrastructure, port, agriculture and tourism), environmental damage (loss of biodiversity, change in plant succession) and social problems (loss of property and territory, different land use) (Gómez-Pina et al., 2002; Boruff et al., 2005; Muñoz-Valles et al., 2011). The Tuscany coast makes no exception: about 73 km out of the 207 km of sandy coasts are currently subjected to erosion processes (Cipriani, 2014). In more detail, an area that experienced exceptional retreat over the last 200 years is located around the River Arno’s mouth, where the coastline retreated more than 1 km on the right side and 300 m on the left side (Pranzini, 2001; Bertoni & Sarti, 2011a). The intense erosion of the Pisan coast began in the middle of the XIX century (Pranzini & Sagliocco, 1994): based on the significance of this region, a large number of technical reports and scientific papers were published in order to understand the dynamics of this sector of the Tuscany coast. Several studies attempted to define the evolution of the coastline since the early XX century, with the result of acknowledging and reaffirming a recurrent tendency to a landward retreat of the system (Toniolo, 1910; Toniolo, 1927; Albani, 1940; Borghi, 1970; Vittorini, 1977; Cipriani et al., 2001; Carli et al., 2004; Bini et al., 2008; Casarosa, 2016). The complexity of the issue was also addressed with the support of geological and geomorphological studies (Gandolfi & Paganelli, 1975; Mazzanti, 1983; Della Rocca et al., 1987; Pranzini, 2001; Cammelli et al., 2004; Bertoni & Sarti, 2011a) and sedimentological analyses (Aiello et al., 1975; Cipriani et al., 2001; Bertoni & Sarti, 2011b); up-to-date tracing technologies (Radio Frequency Identification, RFID) were used to track coarse sediments in order to define transport trends (Bertoni et al., 2012a; Bertoni et al., 2013) and sediment abrasion rates (Bertoni et al., 2012b; Bertoni et al.; 2016); mathematical models (Noli & Franco, 1989) and modern multi-spectral techniques were employed as well (Ciampalini et al., 2015); at last, consideration was given to an in-depth characterization of the climate state (Rapetti & Vittorini, 1974).

Despite this massive production, the erosion problem of the Pisan coast has not been fully understood yet. Besides, the lack of a true governance able to manage all the information provided by every source either academic or private, which usually work with different methods and timescales, makes it hard to define the actual factors that interfere on the coast. For instance, the inability to cross administrative borders when discussing about longshore sediment distribution is another aspect that concurs to exploit the major deficiency: the lack of sediment budget measurements, which is directly related to the concept of physiographic unit. The paradigm shift that needs to be stressed is that the physiographic unit not only must be considered in the traditional longshore sense, but also cross-shore, starting from the river basins to the alluvial plains and finally to the open sea.

Amid all this confusion the erosion processes are far from slowing down: the aim of this paper is to raise concerns about the state of the coast within River Arno's and River Serchio's mouths providing the immediate results obtained from a series of topographic surveys carried out since January 2016. This dataset may be crucial to understand that the erosion problem needs to be addressed quickly, but with a different approach than before.

2. Study Area

The area where the fieldwork were carried out is comprised between the mouth of River Serchio to the north and River Morto Nuovo to the south, within the Migliarino – San Rossore – Massaciuccoli Regional Park (Figure 1). The stretch of coast is about 5 km long: although the above mentioned rivers define the extension of the area, the most important sediment source is the River Arno, whose mouth is located about 6 km south of the River Morto Nuovo. The River Serchio is about 126 km long and its sediment discharge is only subordinate to that of the River Arno; the River Morto Nuovo is just 20 km long and it does not contribute to the littoral sediment budget. This area is characterized by a Mediterranean sub-humid climate with arid summers and mild winters (Rapetti & Vittorini, 2012). The mean annual temperature is over 15°C, while the mean rainfall is about 800 mm (Rapetti, 2003). The typical wave direction is from the southwest: major storms also comes from this sector, 240°- 270° N (Cipriani et al., 2001). Based on the data recorded by a wave gauge located offshore the Gorgona Island between 2008 and 2012, calm periods ($H_s < 0.5$ m) resulted to occur 35% of the time, while waves with height comprised between 0,5 and 2 m occurred 57% of the time; wave height higher than 2 m occurred for the remaining 8% (Casarosa, 2016). The littoral drift is northward-trending on the right side of the River Arno (Aiello et al., 1975; Pranzini, 2001). The Pisan coast is defined as microtidal on regards to the tide regime: the tidal range rarely exceeds 30 cm.

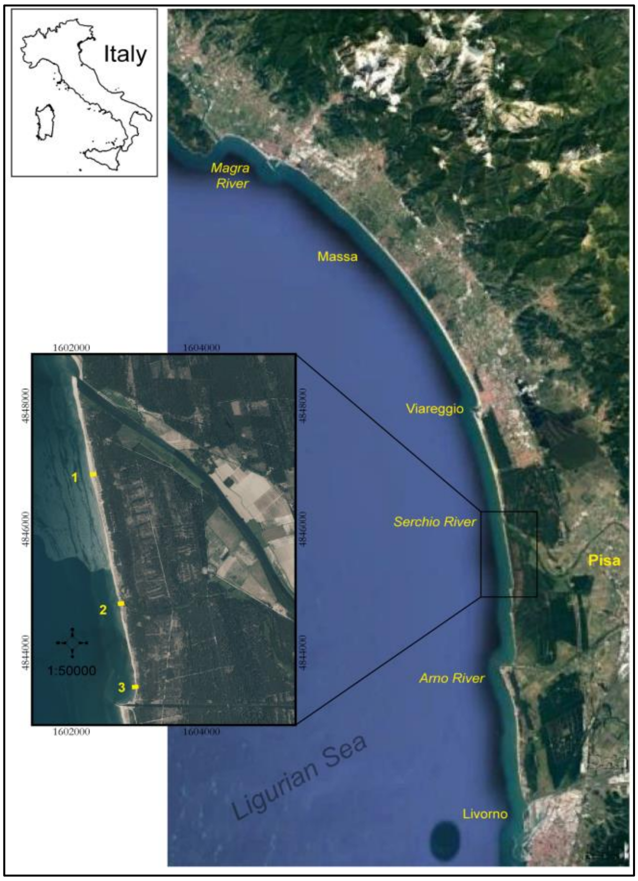

Fig. 1 - Geographic localization of the Migliarino – San Rossore – Massaciuccoli Regional Park. The zoom-in points out the study area; the yellow numbered dots trace the exact site of the transects where the topographic surveys were carried out.

The wind regime is in accordance with the typical wave direction within this sector of Tuscany: dominant winds come from SW, so as the extreme events (Rapetti & Vittorini, 1978; Rapetti, 2003). Beaches are typically composed of well-sorted medium sands (Bertoni & Sarti, 2011b); on regards to the composition, quartz content is on average 50% of the total (Gandolfi & Paganelli, 1975).

As a whole, the dune field in this sector of the Migliarino – San Rossore – Massaciuccoli Regional Park is characterized by transverse dunes. South of the River Serchio the dunes are well structured morphologically, being constituted by frontal dunes, semi-mobile dunes and steady dunes (Bertoni & Sarti, 2011b), with maximum dune height of about 4.5 m (Figure 2a). The vegetation is continuous and covers the whole dune field. Seaward of the frontal dunes, sparse vegetation often buried by wood and waste material brought by river floods define the presence of the embryonic dunes, which are still preserved in this sector. To the south the situation changes dramatically: the dunes are up to 9 m high, but they are subjected to strong erosion processes (Figure 2b).

Fig. 2 - The study area can be subdivided into 3 sectors characterized by different morphologies and evolution state: A) the northern sector; B) the central sector; and C) the southern sector.

In some places wave action led to a complete loss of the frontal dune and part of the mobile dune especially during storms (Figure 2c), thus hampering the formation of the typical vegetation succession and interfering in the stability of the dunes (Ciccarelli et al., 2012; Ciccarelli, 2014; Ciccarelli, 2015; Bertoni et al., 2014a; Ruocco et al., 2014). Large blowouts (up to 40 m wide) also punctuate this sector of the dune field: here vegetation is almost completely absent. No tourist infrastructures nor human activities are reported within the investigated area, with the exception of a concrete groin built to protect the mouth of the River Morto Nuovo and of a wood walkway built to reduce pedestrian trampling over the dune crest.

3. METHODOLOGY

Three sectors were selected within the area under investigation in order to cover as much as possible the different configurations of the dune field, especially in terms of geomorphological characteristics and evolution state (Figure 2): in detail, the northern sector, about 1.5 km south of the River Serchio's mouth, is currently in accretion or in equilibrium (Sector 01); the central sector, located midway through the area just across the wood walkway, is experiencing erosion processes that are eroding the high mobile dunes (Sector 02); at last, the southern sector, about 200 m north of the River Morto Nuovo's mouth, is subjected to erosion processes that already wiped out the mobile dunes and are now striking the steady dunes (Sector 03). A transect was traced out in each sector to serve as a reference to assess the topographic evolution within the time frame of the research, which spanned nine months, from January 2016 to September 2016. In particular, four topographic surveys were carried out: January 2016, March 2016, June 2016 and September 2016 (Table 1). The transects covered the area comprised within the transition between steady dunes to semi-mobile dunes and the shoreline. The survey was performed using a Leica RTK-GPS 500, 1 mm of instrument error (reference: Universal Transverse Mercator projection, Datum WGS 84). A point was recorded at each significant slope variation along the beach profile. The resulting data were processed by Q-GIS software, profile rendering was realized using Profiler 2.3, a *macro* for Microsoft Excel developed by Mouncef Sedrati of the Université de Bretagne-Sud (Lorient, France). Sea-weather characterization was gathered by a wave gauge located offshore the Gorgona Island (Table 1). Wave condition plots indicate that 6 storms with wave height over 4 m occurred within the time frame of the research, all coming from southwest (Figure 3), which confirms that major high-energy events are expected from that direction in this sector of the Tuscany coast. Additional minor storms (3 m > maximum wave height > 4 m) occurred mainly in winter (January and February), while in the rest of the time just twice (mid-April and mid-June) an event reached the threshold of 3 m as maximum wave height.

Tab. 1 - Sea-weather characterization during the topographic surveys: *wave* refers to the average wave height during the duration of the survey; *max height* refers to the maximum wave height recorded during the duration of the survey (data provided by Servizio Idrologico Regionale). Based on the modest tidal range that characterizes this sector of the Ligurian Sea, tide influence is negligible and not taken into account.

Survey	Wave (cm)	Max height (cm)
January 25, 2016	40	60
March 10, 2016	48	54
June 23, 2016	23	25
September 09, 2016	34	39

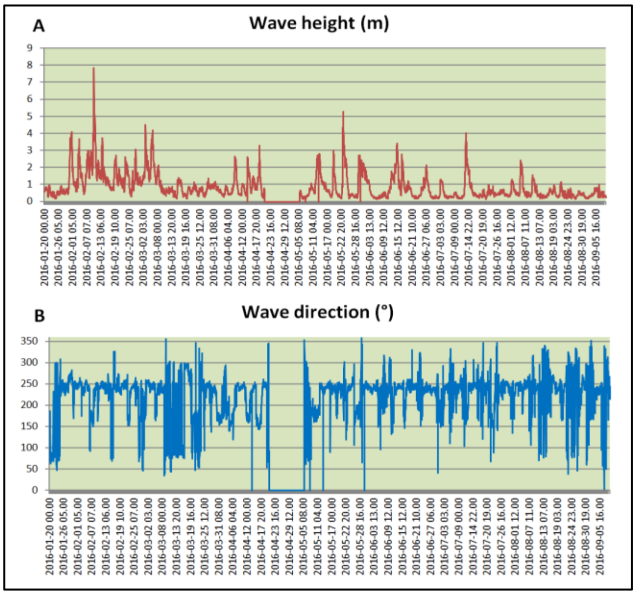

Fig. 3 - Sea-weather characterization within the time frame of the investigation. A) Wave height (expressed in m) recorded between January and September 2016; B) Wave direction (expressed in °) recorded between January and September 2016. The data were measured by the wave gauge located offshore the Gorgona Island; the gap between April 21 and May 5, 2016 is due to technical maintenance of the device. Wave data were provided by Servizio Idrologico Regionale.

To further discuss the data obtained by the topographic surveys, a simple but effective way to assess volume shifts during the time frame of the fieldwork is the method that defines the volume as cubic meter per linear meter (m^3/m). Intuitively, this method is not extremely accurate, but it still provides an approximation of sediment displacement on the investigated sectors of the coast, which is useful to highlight the evolution state of the area.

4. Results

A 9-months-long investigation, which is in general terms too short a time frame to evaluate the evolution state of a coastal area, did not prevent to observe some major modifications to the beach and the dune field along this sector of the Migliarino – San Rossore – Massaciuccoli Regional Park. A quick glance over the three transects enables to point out a few general trends. To the north the beach is wider (about 80 m) and gets narrower southwards: in the central sector is almost 70 m wide, whereas it is just less than 20 m in the southern sector (Figure 4). Transect 01 is characterized by the presence of embryonic dunes at an elevation of about 2 m; dune crest height is just over 7 m. No embryonic dunes are reported along Transect 02; the dune is significantly higher, reaching almost 9 m. Again, transect 03 is completely different based on the absence of the frontal dune – embryonic dune system: here surface elevation is just 3.5 m.

The comparison between the four surveys for each transect also raised some concerns (unfortunately the January survey for transects 02 and 03 was recorded along a different trace relative to the next three: the variation was necessary because the operator could not reach the previous location due to collapse of the dune). The northern sector virtually showed no differences throughout the time frame of the investigation. Beach width, embryonic dune position and frontal dune height did not change considerably. Major variations occurred along Transect 02, where a huge retreat can be easily observed: within just 4 months (from March 2016 to June 2016) the backshore profile shifted landward of almost 10 m. The retreat is far more impressive on regards to the dune profile: as a matter of fact, the dune crest moved landward of about 6 m in that same time span, along with a crest height decrease of almost 1 m (Figure 4). The southern sector did not experience considerable modifications in terms of beach width and dune height: the only difference is a decrease of the steepness of the eroding dune, from 0.85 in March 2016 to 0.57 in June 2016 and September 2016.

Volume computation (expressed as m^3/m) basically confirmed the tendencies that were already brought out by the analysis of the topographic surveys (Table 2).

Tab. 2 - Volume computation for each transect within the time frame of the investigation (January 2016 to September 2016). *Length* refers to the extension (m) of the beach profile along which the volume has been calculated; *volume* refers to the volume of sediments above 0 m elevation expressed as m³/m; *average* refers to the average volume per linear meter (expressed in m³/m).

Months	Transect 01			Transect 02			Transect 03		
	Length	Volme	Average	Length	Volume	Average	Length	Volume	Average
January 2016	80	254	3.2	-	-	-	-	-	-
March 2016	78	255	3.3	52	273	5.3	14	24	1.7
June 2016	81	252	3.1	44	187	4.3	16	27	1.7
September 2016	80	257	3.2	43	192	4.5	16	28	1.8

Transect 01 did not experience any significant difference neither in sediment volume nor in the average volume along the profile. As expected based on the retreat pointed out by the topographic surveys, a harsh volume decrease occurred between March 2016 and June 2016 along Transect 02; during the summer, a little increase is observed (about 5 m³/m).

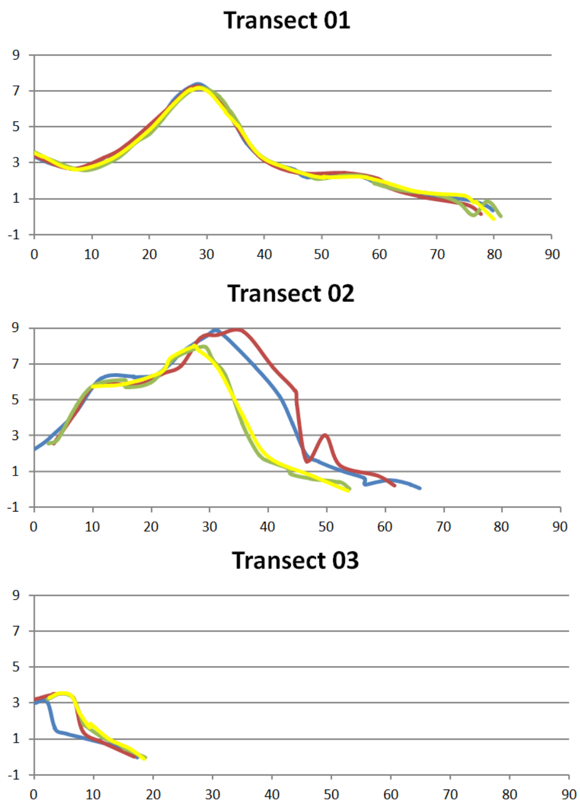

Fig. 4 – Beach profiles for each transect measured during the topographic surveys. Blue line: January 2016 survey; red line: March 2016 survey; green line: June 2016; yellow line: September 2016 survey.

The marginal difference in beach profile evolution that was evidenced by the topographic surveys along Transect 03 transpires also in volume computation: just a modest volume increase is reported between March 2016 and June 2016, which was expected based on the presence of an accumulation at the toe of the eroding dune (Figure 4). Volumes do not vary during the summer months.

5. Discussion

As previously mentioned, the erosion processes in this sector of the Pisan coast have been thoroughly reported and discussed (e.g., Vittorini, 1977; Pranzini, 2001; Bini et al., 2008), therefore nothing apparently new occurred along the shoreline in the first ten months of 2016. Regardless, serious concerns raised because of the extreme retreat observed on the frontal dune in the central portion of the investigated area (Transect 02), which is something not so frequent even in a site where the coastline is receding significantly. As a matter of fact, within a 3-months timespan a 9 m high frontal dune retreated about 6 m, with an estimated volume loss of about 80 m³/m along the transect (Figure 5). In this case the observed retreat is even more concerning because the sediments wiped out during the storms were not moved backwards on the backdune area, where a huge accumulation should be expected (Figure 4), rather they were transported either northwards in accordance with longshore drift direction and offshore. The former case is serious for the site, but at least the sediments that were removed there are going to accumulate and eventually benefit other sectors of the coast; conversely, the latter is worse because sediments lost offshore cannot be naturally brought back onto the shore and must be considered out of the system. Therefore, a huge retreat occurred along Transect 02, but it led to a massive erosion of the seaward side of the high frontal dune rather than an actual landward shift of the coastline, which can be estimated in just less than 10 m. The ensuing concerns are quite obvious because while coastline shifts are dynamic and frequent over time in both directions, the collapse of a portion of a coastal dune is an irreversible process.

In the other sectors the situation is rather different (Figure 4). To the north (Transect 01) there were virtually no modifications along beach profiles, which might be explained with an apparent equilibrium state. This does not mean that the erosion processes are not active or their influence is lessened in the area. Rather, it means that this is a sediment transfer zone, where sand does not accumulate and moves through this sector of coast northwards according to the direction of the littoral drift. As a matter of fact, the length of each profile is constant during the time frame of the observations. Beach width is not constant along the coast though. Southwards it gets significantly narrower (Table 2): the decrease can be ascribed to the landward shift of the coastline because the position of the frontal dunes does not change. Further to the south (Transect 03) the backshore is just 5 m wide and the frontal dunes are not even present anymore: erosion processes are already consuming portions of the semi-mobile and steady dunes, which formed the steep, 2 m high scarp at the back-end of the backshore (Figure 2c). As well as Transect 01, no major differences can be observed along Transect 03 analyzing the comparison between the surveys that were carried out within the time frame of the investigation. The reduction of scarp steepness is the only appreciable variation, which was likely determined either by the collapse of sediments from the top of the dune and by the accumulation of eroded sand coming from the upflow direction; beach recovery during fair-weather periods might contribute to that small accumulation as well.

Fig. 5 –The configuration of the dune along Transect 02 in February 2016 (A) and in June 2016 (B). The extreme erosion of the frontal portion of the dune is clearly appreciable. The red dots point out the position of the same object in each picture.

As previously mentioned, the volume decrease along Transect 02 is brutal: even though the beach profile is shorter by almost 10 m, which would apparently explain the reported volume loss, the average values are decreasing as well, which means that volume actually decreased regardless of beach profile length (Table 2). The strong storm occurred in early May

2016 might be responsible of this huge retreat (Figure 3a). Prior to the March 2016 survey a few major storms did strike the Pisan coast, but they did not affect the dune profile significantly; the effect of the series of high-energy events occurred in winter 2016 might be felt on the system as a follow-up, that is the weakening of the frontal dune in terms of stability due to intense scouring at the toe. Beach recovery after storms cannot be feasible on such a frontal dune, which led to its collapse after the following strong storm (early May 2016). The slight volume increase recorded after the summer months along each transect is likely determined by wave action during extended fair-weather periods, which is usually responsible of a modest accretion on the beachface. As a matter of fact, just one major storm (barely reaching 4 m of maximum wave height) occurred after the June 2016 survey (Figure 3a).

6. CONCLUSIONS

The present paper highlights the serious health state of the coastal dune system within the Migliarino – San Rossore – Massaciuccoli Regional Park. Even though the erosion processes along this sector of the Pisan coast have already been described, an actual episode of collapse of a portion of the frontal dune was never recorded and measured before. Topographic surveys evidenced a 6 m retreat of the dune crest in the central sector of the investigated area, which was located between River Serchio's and River Morto Nuovo's mouths. Such a retreat is impressive because it occurred on a 9 m high frontal dune in just less than 3 months (March – June 2016): a quick assessment of the volumes involved provided an estimation of about 80 m^3/m lost along Transect 02. Basically, volume computation reflects the evolution of the beach profile within the time frame of the surveys.

This dataset confirms the retreating trend of this stretch of the Pisan coast, but it also implies a novel notion about its evolution: based on the massive collapse measured on the frontal dune, the system is likely getting more unstable over time. Since the approach used to manage this coastal area did not provide a definite outcome so far, it would be beneficial a paradigm shift that involves the use of a different approach, which would be integrated with all the components (territory, local authorities, scientific community) and multidisciplinary (geology, biology, engineering, economy). Employing low-cost, integrated engineering devices to collect extensive, real-time datasets may be the first step to an up to date monitoring system (Bertoni et al., 2014b; Pozzebon et al., 2016). Along with innovative technical solutions, it will be crucial to manage the coast as an environment influenced by processes acting along the shoreline as well as on the drainage basin and along river courses. The transversal scale must be taken into account as much as the longitudinal scale, which must be always considered in terms of physiographic unit, as opposed to the local site approach too often used in the past. Future interventions should reduce the use of hard structures (breakwaters, groynes) and look to viable options such as sediment by-passing or back-passing, where city limits or territory boundaries do not factor in the decision-making process. Anyhow, a wise management of the sand is paramount for a better management of the coastal area as a whole: even taking into consideration the *managed retreat*, which claims that the system should be allowed to evolve without human interference and the efforts should be moved to a conscious landward re-alignment of the shoreline especially on natural settings such as the Migliarino – San Rossore – Massaciuccoli Regional Park (Nordstrom et al., 2015; Nordstrom et al., 2016), sand redistribution needs to be properly managed.

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PAPER III

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A TECHNICAL SOLUTION TO ASSESS MULTIPLE DATA COLLECTION ON BEACH DUNES: THE PILOT SITE OF MIGLIARINO SAN ROSSORE REGIONAL PARK (TUSCANY, ITALY)

Abstract - *A technical solution to assess multiple data collection on beach dunes: the pilot site of Migliarino San Rossore Regional Park (Tuscany, Italy).* Coastal dunes are a complex environment characterized by several biotic and abiotic factors that concur to their evolution and development. A whole comprehension of the interplay between those factors is paramount to a wider definition of dune systems: in some cases focusing on a factor at once is not suffice to get satisfying insights. Here is proposed an integrated solution involving different disciplines in order to collect in-depth datasets within a short span of time on a selected site located in the Migliarino – San Rossore – Massaciuccoli Regional Park (Tuscany, Italy). Geological (geomorphology, sedimentology, and geophysics) and biological aspects of the coastal dunes will be assessed using traditional survey analyses and integrated with state-of-the-art technologies (UAV flights, wireless sensors) to get an all-around characterization of the ecosystem. A Wireless Sensor Network will be set up on the selected site to measure in real-time physical parameters such as wind speed and direction, soil moisture and sand dune volume and height variations. The ensuing data will be stored to create a database that might be used for management purposes. The aim of the paper is to provide a modern, inexpensive, and easy to reproduce system to monitor the evolution of any coastal dune field.

Keywords - beach dune; grain size; geomorphology; vegetation; GPR; aerophotogrammetry; wireless sensor, Tuscany, Italy.

Riassunto - *Una soluzione metodologica per acquisire un dataset multiplo sulle dune costiere: il sito pilota del Parco Migliarino - San Rossore (Toscana, Italia).* Le dune costiere sono un ambiente complesso caratterizzato da diversi fattori biotici e abiotici che determinano la loro evoluzione e sviluppo. La comprensione dell'interazione tra questi fattori è fondamentale per una caratterizzazione più profonda dei sistemi dunali. Approcci eccessivamente puntuali, seppur molto dettagliati, non sono sempre sufficienti a garantire un quadro conoscitivo adeguato ad una corretta gestione. È qui proposta una soluzione integrata che coinvolgendo diverse discipline permette di acquisire più dataset complementari, in modo economico e facili da essere riprodotti per il monitoraggio di qualsiasi sistema costiero dunale.
Il sito pilota scelto per testare questo nuovo approccio è situato nel Parco Regionale Migliarino - San Rossore - Massaciuccoli (Toscana, Italia). Gli aspetti geologici (geomorfologia, sedimentologia e geofisica) e biologici (copertura vegetale) delle dune costiere sono stati affrontati attraverso metodologie tradizionali di terreno integrate con approcci tecnologici specifici (voli UAV) o innovativi (rete sensori wireless). La misura dei parametri fisici, come velocità e direzione del vento, umidità del terreno, variazioni del volume di sabbia delle altezze delle dune è stata misurata in tempo reale tramite una rete di sensori wireless. I dati memorizzati da remoto sono implementati in un database utile anche a fini di gestione e monitoraggio dell'area di studio.

Parole chiave - dune costiere; granulometria; geomorfologia; vegetazione; GPR; aerofotogrammetria; sensori wireless; Toscana.

1. Introduction

Coastal dune systems are arguably one of the most dynamic environments because their evolution is controlled by many factors, either natural (river sedimentary supply, wave motion, longshore currents, wind action, type and density of vegetation cover) and anthropogenic (proliferation of protection structures, anthropization of backdune areas, poor management). The interaction between all these aspects makes coastal dunes vulnerable to any minimal change, which easily leads to alterations of such an instable equilibrium (Hesp, 2002). The variations often have a negative impact on the environment, ultimately triggering erosion processes that constitute a major threat to the development of coastal dunes (Masselink & Hughes, 2003). Since this ecosystem has a high value in terms of biodiversity (several habitats are included in the European Habitats Directive 92/43/EEC; European Commission, 1992) and economy (dunes serve as a form of natural protection also where human activities are present inland; Masselink & Hughes, 2003), the need to preserve each aspect is usually considered as one of the most important element when dealing with coastal zone management (Martinez *et al*., 2013): as a matter of fact, 85% of protected areas in Europe are currently endangered (Muñoz Valles *et al*., 2011), while according to recent estimates dune fields recorded a reduction of about 70% during the last century (McLachlan & Brown, 2006).
In this regard, an exhaustive understanding of the pro-

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cesses that concur to steer coastal dune evolution is paramount to better define the environment. Therefore, coastal dunes have been extensively studied in the last decades using a large variety of analyses and approaches. Traditional investigations such as grain-size analysis (e.g. Hesp *et al.*, 2007; Bertoni & Sarti, 2011; Ruocco *et al.*, 2014) and topographic surveys (e.g. Hesp, 2002; Armaroli *et al.*, 2013; Bertoni *et al.*, 2014) have been widely applied to characterize dune sedimentology and geomorphology. These conventional analyses have been recently backed by modern techniques characterized by high level of technology, such as video-monitoring (Delgado-Fernandez *et al.*, 2009), laser scanning (Nield *et al.*, 2011), and spectroscopy (Ciampalini *et al.*, 2015). Sediment transport on coastal dunes has been addressed using sediment traps (e.g. Jackson & Nordstrom, 2013), miniphones (Ellis *et al.*, 2009) and laser techniques (Bauer *et al.*, 2012; Davidson-Arnott *et al.*, 2012). Geophysical approaches has also been used to inspect the subsoil of dune systems (e.g. Jol *et al.*, 1996; Bakker *et al.*, 2012), in particular by means of ground penetrating radar (GPR) instruments (Bristow *et al.*, 2000; Jol *et al.*, 2002; Buynevich *et al.*, 2007). In addition, the evolution of beach dunes has been modeled in order to reproduce their development: XBeach is the process-based model most frequently used to predict erosion or accretion tendencies (Roelvink *et al.*, 2009; Splinter & Palmsten, 2012; Armaroli *et al.*, 2013). Since the vegetation is among the major factors driving the evolution of coastal dunes by trapping and stabilizing sand grains, a lot of works have been done to assess aspects on that regard (e.g. Martinez & Psuty, 2004; Maun, 2009; Ciccarelli *et al.*, 2012; Bitton & Hesp, 2013; Ciccarelli, 2014). Aerial photography is a reliable technique to investigate the evolution of beach dune morphology (Bini *et al.*, 2008), but it has also been used as a valuable tool to carry out vegetation assessment in remote, at least to recognize plant communities (Drius *et al.*, 2013; Malavasi *et al.*, 2013).

Most recent studies emphasized the notion that an all-round definition of this environment needs an approach that systematically involves several disciplines, merging every data collected from any individual analyses (Bertoni *et al.*, 2014; Ruocco *et al.*, 2014). Investigations addressing a physical or biological factor at once still are essential, but increasing the knowledge about how they interact is the basis for a better management of coastal dune systems. The best way to achieve this target is to collect as many data obtained from different disciplines as possible in the shortest span of time in order to minimize the negative effects of comparing datasets that are not simultaneous. Therefore, a new multidisciplinary approach to study coastal dunes has been conceived in order to integrate geology, biology, and modern wireless technologies. This method combines traditional analyses (topography, sedimentology, plant ecology) with state of the art survey techniques (unmanned aerial vehicles, ground-penetrating radar): the Wireless Sensor Network enables to gather discrete amounts of data at the same time by remote, without the need to directly go to the beach except for routine activities such as retrieving the stored data. Meanwhile topographic and geophysical surveys, along with vegetation sampling, can be carried out without affecting data collection of the remote network. Considering its activation and maintenance low cost and the ease to replicate elsewhere, this system might become a valid instrument to improve the understanding about coastal dunes, in particular the interactions between biotic and abiotic factors, which are instrumental for a successful evolution of this environment. It might also provide insights to optimize their management, which is imperative since several issues stem from lack of knowledge and awareness.

2. The multidisciplinary solution

The approach to the study of coastal dune systems here presented is based on the notion that a better definition of a multifaceted environment such as beach dunes is achieved by the integration of datasets provided by different analyses and collected within short spans of time. Such an accomplishment can be reached coupling the traditional surveys that need fieldwork activities (grain-size analysis, topographic and ground penetrating radar surveys) and the conventional remote sensing analyses to the implementation of a network of wireless sensors able to measure other physical parameters (dune height and volume variations, soil moisture, wind speed and direction) that would require frequent and time-consuming field operations. Systems involving remote sensing techniques applied to dune characterization have been already conceived. These solutions proved to be able to collect a wide range of different parameters, mainly dealing with sediment transport, wind speed and surface moisture detection. While these solutions are ideal for short-term monitoring (Delgado-Fernandez *et al.*, 2012), the system here presented could be much more useful in case of long term monitoring. The solution proposed by Delgado-Fernandez *et al.* (2012) is mainly based on the use of cameras: in this case no remote data collection is available. Moreover, being the data acquisition structure unique, its malfunctioning totally invalidates the data collection. The solution proposed in this paper allows the direct transfer of the data collected by the sensors through the use of a GPRS gateway: this means that datasets are received in real-time in laboratory, without the need to reach the sensors to collect them. At the same time this feature allows the real time detection of a possible sensor node malfunctioning when data transfer is interrupted. Furthermore, the proposed solution relies on the use of sensors: data are directly collected and made available, and not obtained as a result of image processing techniques. This means that data collection is straightforward and then notably easier. At last, the solution is totally modular: the addiction of new sensors and sensor nodes can be made without modifying the overall architecture of the system.

2.1. Topography

Topographic surveys will be carried out within the site that will be chosen for the implementation of the Wireless Sensor Network. Transects orthogonal to the coastline will be traced out on the beach, and every significant change in slope will be recorded with a DGPS-RTK instrument. The accuracy of the equipment is about 2 cm on regards to latitude and longitude, increasing to 5 cm on regards to the elevation. The surveys will be repeated after any relevant storm to monitor modifications on the beach profile. The spacing of the transects is strictly dependent on the width of the area where the Wireless Sensor Network will be set up: in this case the profiles will be traced out every 50 m. The topographic surveys will involve the backshore and the foreshore: in particular, the landward limit of the surveyed area is represented by the first steady dune ridge, whereas the seaward limit corresponds to the beach step crest. The resulting data will be processed with GIS-based software.

2.2. Grain-size analysis

A traditional sediment sampling will be completed to characterize the textural parameters of the sediments that constitute the beach where the Wireless Sensor Network will be realized. Samples will be collected from specific points along the transects traced out for the topographic surveys. These points will be selected taking into account the shape of the topographic profile and the plant communities, according to the protocol previously used by Ruocco et al. (2014): each relevant geomorphologic element will be sampled (step zone, swash zone, backshore, foredune front toe, foredune crest, foredune back toe, semi-mobile dune) along with the most significant vegetation features (annual vegetation of drift lines, embryonic shifting dune vegetation, vegetation of the shifting dunes, and vegetation of the fixed beach dunes). The samples, about 500 g each, will be heated to 100°C for 24 hours before being dry-sieved mechanically for 10 minutes. The sieves used for the analysis has a 0.5 phi mesh: the last sieve will be the 0.063 mm to discriminate the fine fraction from the sand. Further definition of the fine fraction is not functional to the sedimentological characterization of the beach sediments. The resulting data will be processed to obtain textural parameters such as Mean (Mz) and Sorting (σ) according to Folk & Ward (1957) formulae.

2.3. Aerophotogrammetry

The recent introduction of Unmanned Aerial Vehicles (UAV) greatly improved the traditional techniques of multi-temporal and high-resolution mapping of landforms (e.g. Bisson & Bini, 2012). Aerophotogrammetric surveys using a helicopter drone flying at 40 m of elevation above the surface will be implemented to analyze the topography of coastal dunes. Several ground control points (GCP) will be arranged on the beach and recorded with the RTK-DGPS instrument to enable the comparison of the results with those provided by the topographic surveys carried out by means of the RTK-DGPS instrument in order to prevent errors due to wrong calibration of the system mounted on the UAV. Nadir images will be collected by a Sony NEX5 camera (focal 16 mm) and eventually processed to obtain 3D visions and orthophotomaps.

2.4. Subsurface stratigraphy

Ground-Penetrating Radar (GPR) is a fast and cost-effective electromagnetic (EM) method providing relevant information on the shallow subsurface stratigraphy. Aeolian dunes are frequently prospected using GPR because of the low conductivity of sandy sediments and high EM velocity, which limits the attenuation effects of GPR signals and increases the investigation depth. A GPR survey will be carried out on the pilot site using a Radar System device of IDS Company© (www.ids-spa.it), equipped with an antenna of 400 MHz of nominal peak frequency. The data will be captured in continuous mode, checking the step size by means of an odometer wheel. Topographic data will be acquired along the GPR survey line. After the fieldwork, a standard processing sequence will be applied to the raw data to filter out the noisy data, to gain attenuated GPR signals and to convert the time-to-depth data. Given the expected rapidly variable shape of the dune layering, an accurate sampling of EM signal returned to the receiver should be adopted to avoid the occurrence of spatial aliasing effects. Particular care will be paid to avoid to filter out sub-horizontal reflectors by the use of spatial median filter operators. The EM scattering by discrete object in the subsurface will allow to estimate EM velocity using the method of synthetic hyperbola fitting. The existence of shallow trenches in the dune profile with identifiable scattering points will consent a calibration of the velocity model. A static topographic correction is necessary at the end of the process to adapt the radar image to the dune profile. This last point needs particular care because, due to the stoss and lee topography of dunes, an additional correction for the tilting effect of the antenna will be required. Fences of vertical radargrams and 3D cubes of GPR data will be used to interpret the subsurface stratigraphic bedding.

2.5. Vegetation sampling

Coastal dune vegetation assessment will be carried out by the analysis of digital images collected by a helicopter drone (UAV), and validated as a confirmation by field campaigns during the spring and the autumn. The study site will be divided into sectors of an appropriate width. Each sector will be divided into three layers from the coastline to inland: upper beach with pioneer annual vegetation (BPV); herbaceous dune vegetation (HDV), which includes embryonic and mobile dunes; shrub and woody dune vegetation of fixed dunes (WDV). Distribution and coverage of the different plant communities will be detected in each sector.

2.6. Wireless Sensor Network

Wireless Sensor Networks (WSN) are becoming a key technology for low cost pervasive monitoring solutions (Mainwaring *et al*., 2002; Werner-Allen *et al*., 2006; Ramesh *et al*., 2009; Grindvoll *et al*., 2012). The term WSN encompasses all the monitoring systems composed by a set of autonomous sensing nodes provided with Short Range communication capabilities (Akyildiz *et al*., 2002): WSN can be then composed by tens or even hundreds or thousands of nodes, they can be structured according to different network topologies and communication protocols and they can be employed virtually in a infinite array of different scenarios. Each sensor node is usually composed by at least the following items: *i*) a microprocessor managing data acquisition and transmission; *ii*) a communication module; *iii*) a set of sensors; *iv*) a battery or any other source of energy. A sensor node can be developed basing a simple microcontroller provided with low level data acquisition functions but also with more complex devices with data analysis and storage capabilities. At the same time it can be equipped with a single sensor monitoring ordinary parameters like temperature or humidity or it can be provided with a wide array of sensors monitoring complex parameters like for example water or air quality. It can be powered with common 9V batteries or even with photocells or other green power sources.

One of the key features of every WSN is the networking technology: the choice of the right communication protocols notably affects the performances of the monitoring system, both in terms of power consumptions and of reliability. In the last ten years several standard protocols have been proposed for WSNs: the most important are the IEEE 802.15.4 standard, specifying the physical layer and media access control for low-rate wireless personal area networks (LR-WPANs) and the ZigBee standard, a set of high level communication protocols for low-power wireless mesh networking. ZigBee standard has been thought for the definition of low cost, general purpose networks to be employed in several monitoring scenarios: ZigBee communication platforms are small, cheap and they can be easily integrated with microcontrollers and sensing devices. The most significant network typology proposed in the ZigBee standard is based on a multi-hop mesh network: it is a decentralized architecture where each node can act either as a receiver, a transmitter or a repeater (Fig. 1). Every node is able to transmit only to its neighbours: when a data packet has to be sent to a node that is too far to be reached in a single hop, the intermediate nodes act as repeaters. Such a kind

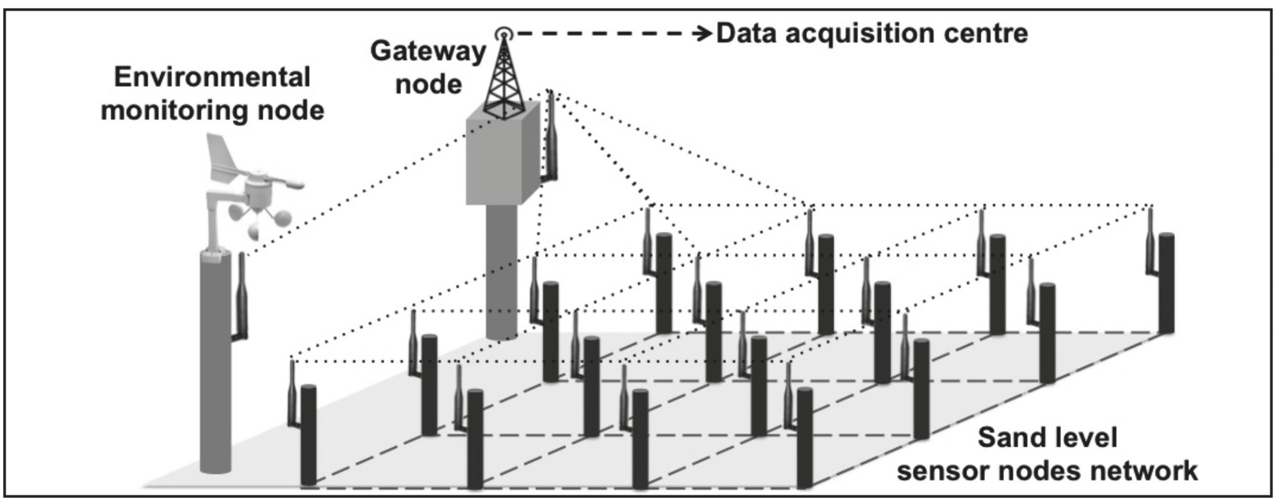

Fig. 1 - Architectural overview of the wireless sensor network.

of network is then able to cover long distances and it is extremely reliable in that the malfunctioning of a single node does not compromise the efficiency of the whole network.

The dynamics of sand dunes can be analysed in real-time by deploying an ad-hoc WSN based on a mesh topology and implementing the ZigBee protocol: this monitoring solution will be able to measure the variations of the sand dune height in several points and to collect data about wind speed, air and soil temperature and humidity. The proposed architecture integrates the following components: *i*) a set (15-20) of sensor nodes for the measurement of ground elevation; *ii*) a sensor node for the measurement of the other environmental parameters (wind speed and direction, soil moisture); *iii*) a gateway node for the remote data transmission.

The sand level sensor nodes are very simple devices, including only a sensor, a radio transmitter and a powering circuit. Two different solutions have been studied for the sensor designed for the measurement of the dune height. The first solution is based on the use of a Sharp GP2Y0A21YK0F analog distance sensor: this sensor is able to measure the distance of an object or a surface in the range of 10-80 cm. The return time of the infrared light is converted into a voltage and then interpreted as a distance measure. For the measurement of the dune height the sensor node will be tied to a wooden structure, with the surface where the sensor is positioned facing the dune surface: the sensor will then be able to measure its distance from the ground. The second solution is based on the use of a set of photoresistors. In these devices the resistance decreases with increasing incident light intensity: the value of this parameter allows to measure the light radiation. In the proposed solution a set of photoresistors (20) is positioned on a 1 cm wide and 1.5 m long plastic rod: the photoresistors are spaced 5 cm. This plastic rod is put inside a transparent rubber tube, and tied to a wooden pole that is stuck into the ground. The rubber tube is partially under and partially outside the dune surface. The buried photoresistors will not detect the presence of any source of light: instead, the number of photoresistors detecting the presence of light will give a measure of the length of the portion of the rod that is not buried, providing in turn a measure of the dune height. Both these solutions are able to provide an efficient measure of the variations in the dune height: while the first solution is easier to be developed in terms of sensor realization, the second one is notably easier to be deployed, with a lower impact in terms of equipment to be installed on site. The second solution will be chosen for the experimentation due to low environmental impact requirements (Fig. 1): however, the first solution has also been described in that it can be useful in other scenarios where wooden structures for the sensor node installation already exist on site.

The dune height sensor will be then integrated in hardware platform including an XBee radio transmitter based on the ZigBee protocol and a power management circuit, required to control the power consumption, allowing thus to extend as much as possible the lifetime of the battery used to power the node. The node intended for the environmental parameters monitoring is a more complex platform based on an Arduino Uno board: this platform integrates an ATmega328 microcontroller, it provides 6 analog input pins and 14 digital input/output pins and it can be equipped with an XBee radio transmitter. Three sensors will be connected to the node: *i*) a soil moisture/temperature sensor; *ii*) an anemometer for the wind speed measurement; *iii*) an air humidity/temperature sensor. The Arduino board will allow not only the data collection, but also their analysis and encapsulation in a single data packet to be transmitted to the gateway. The data collected by the sensor network will be acquired and transmitted to a remote data acquisition centre by a Gateway node, also based on an Arduino Uno board: this device will be equipped both with an XBee transmitter acting as the Coordinator for the ZigBee network, and a GPRS transmitter that will be in charge of transmitting the received data to a remote data collection centre.

The array of sensor nodes will be positioned according to a grid subdivision of the chosen site, which will depend on the characteristics of the dunes. This will allow the acquisition of the real-time data concerning the elevation of the single points of the dune, in order to depict the dynamic variation of the elevation of the whole surface along a span of time up to three months, in agreement with the battery lifetime.

3. Pilot site

This multidisciplinary approach has been implemented on a pilot site within the Migliarino – San Rossore – Massaciuccoli Regional Park (herein referred to as San Rossore Park). This site was chosen because of a variety of physical features that made it an appropriate place to test the system. The San Rossore Park is located along the Ligurian Sea, in the northern part of Tuscany, Italy (Fig. 2), in an area characterized by sectors subjected to erosion and accretion processes (Pranzini, 2001; Bini *et al.*, 2008). This aspect is crucial because the system can monitor the evolution of both sectors, gathering information about the behavior of eroding and accreting beaches. Dunes are well established where erosion processes do not affect the coast, reaching a maximum height of about 7 m on the crest (Bertoni *et al.*, 2014). Elsewhere they are generally lower, at times almost completely eroded. On the back of the frontal dunes there is an area of variable width (about 30 to 100 m) characterized by semi-mobile dunes, backed by several ancient dune ridges referred to as steady dunes (Bertoni and Sarti, 2011).

Fig. 2 - Map of the site where the Wireless Sensor Networks have been set up: the red dots point out the area where the sensors have been deployed (the background satellite image has been taken from the Google Earth database, 2014).

The Wireless Sensor Network has been installed north of the mouth of River Arno (Fig. 2), the most important source of sediment of the area (Cipriani *et al*., 2001), where the littoral drift is univocally northward-trending (Gandolfi & Paganelli, 1975). The beach is prevalently composed of medium sand, the mean diameter of the sediments that constitute the backshore is about 0.3 mm (Bertoni & Sarti, 2011). Wave climate on this sector of the Ligurian Sea is characterized by dominant southwesterly wave direction, with wave heights usually about 1 m (Fig. 3); most powerful storms come from the southwest as well (Bertoni *et al*., 2013). Being a natural reserve, the whole area is not subjected to any anthropogenic activity, which is essential to get undisturbed data.

The study site is characterized by the prevalence of shifting dunes with *Ammophila arenaria* and plant communities of fixed beach dunes; while annual vegetation of sand beach and plant communities of embryonic shifting dunes are less present, because coastal erosion has cancelled in several sites the first vegetation towards the sea (Ciccarelli *et al*., 2012).

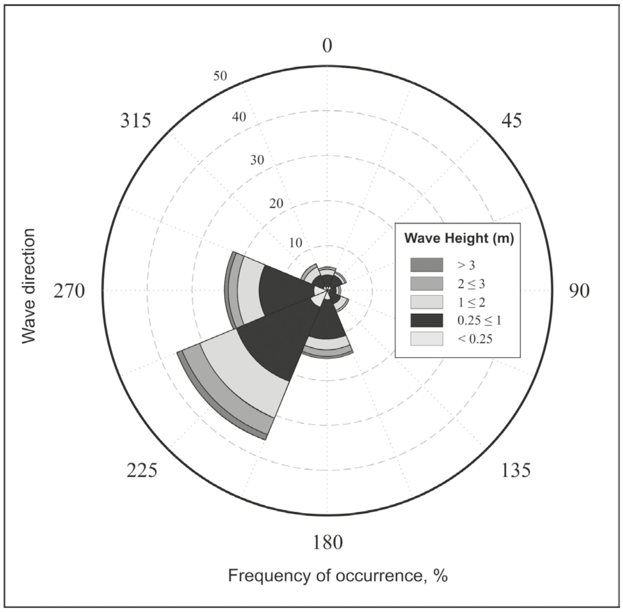

Fig. 3 - Historical wave climate (height and direction) of northern Tuscany coast collected during the years 1989-2007 by the ISPRA buoy located offshore La Spezia.

4. Future perspectives

The solution here presented represents a significant change in the way costal dune systems are studied. This all-around approach provides datasets as full as any, embracing different disciplines that are all instrumental to improve the understanding of this environment. Geologic and biologic data are linked together (Bertoni *et al*., 2014; Ruocco *et al*., 2014) and as such they cannot be analyzed separately: the Wireless Sensor Network enables to measure considerable amount of parameters with minimal in situ human effort, thus allowing the chance to collect data about sediment grain-size, topography, and subsurface stratigraphy simultaneously. Besides, UAV flights provide for a high-definition photographic coverage of the site, which makes possible to identify the vegetation up to the species remotely: this level of accuracy could not be reached with techniques such as traditional aerial coverage or even LiDAR surveys. Any measurement and analysis result will be stored: such a database is unique and it will be useful to set up a fitter management of the dune system. In particular, the outcomes this approach yields will be valuable to improve the efficiency of protection schemes involving artificial dune reconstruction, which is frequently used *i*) where erosion processes already struck the coast, in order to prevent further retreat, and *ii*) to prevent the onset of the erosion processes where they have not hit the coast yet.

A significant advantage of this solution is constituted by the fact it is not tied to a specific site with peculiar characteristics: it can be implemented elsewhere and properly customized to fit in the place where it is installed to maximize the results. Since the sensors are relatively inexpensive, the wireless network system can be set up also on large dune fields, not only on narrow beaches characterized by a small dune ridge. Hence, the approach here proposed will be soon realized on a second site, totally different relative to the MSM Park: the Acarai State Park (southern Brazil). Acarai State Park beaches are characterized by frontal dunes about 5-10 m high, backed by parabolic dunes, which can reach a crest height of about 20 m, or by irregularly shaped dunes, followed by ridge alignments classified as fixed dunes (Possamai *et al*., 2010). Blowouts punctuate non-vegetated areas, whereas they are almost completely vegetated. This will be paramount to test the efficiency of the system on a different setting, and to check the consistency of the collected data. In addition, the results from both sites regarding geologic, biologic and physical parameters will be compared and integrated in order to conceive an index of coastal dune vulnerability that can be applied to any dune field and not only on a given setting. On that regard, the integration of such different datasets will require severe attention in order to avoid inconsistency of the results the system might produce. Therefore, the collected data will be processed through Canonical Correspondence Analysis (CCA) to find correlations between every physical parameter that will be measured and plant community coverage (Ter Braak, 1986; Ter Braak, 1987).

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PAPER IV

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Heterogeneous Wireless Sensor Network for Real Time Remote Monitoring of Sand Dynamics on Coastal Dunes

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Abstract. In this paper, the architecture of a heterogeneous Wireless Sensor Network (WSN) to be deployed on coastal sand dunes is described, the aim of which is to provide real time measurements of physical parameters to better define the sediment transport in connection with Aeolian processes. The WSN integrates different typologies of sensors and is provided with both local and remote connection. In particular, three different typologies of sensors are integrated in the network: a multilayer anemometric station, a sensor developed ad-hoc to measure the sand dune level and a sand collector capable of measuring the weight of trapped sand and its quantity. Each sensor node is made up at least of a ZigBee radio module that is able to transmit the data collected by the sensor at a distance of about 100 meters. While the sand level sensor and the sand collector are provided only with this transmission module, the anemometric station also integrates a microprocessor board in charge of data processing. A Gateway node provided with a GSM connection for remote data transmission and a Zigbee radio module for Local Area communication has also been developed. This node is in charge of collecting all the data packets sent by the Sensor Nodes and transmit them to a remote server through GPRS connection. A Web server has been set up to collect these packets and store them in a database. The proposed WSN can provide both a static and a dynamic framework of sand transport processes acting on coastal dunes.

1. Introduction

The term "Wireless Sensor Networks" (WSN) includes all the monitoring infrastructures made up of a set of sensing platforms, called Sensor Nodes, communicating both among them and with the outside world through radio connection [1]. Each Sensor Node is roughly made up of one or more sensors, a micro-controller, and one or more communication modules. Sensor Nodes can also be equipped with memories for data storage or with energy harvesting solutions to allow their autonomous functioning for long spans of time. Due to all these features, WSNs are a key technology to be employed for environmental monitoring, especially when real-time, remote data collection is required [2, 3, 4].

WSNs can also be a key technology to estimate the temporal evolution of sand dunes in conjunction with aeolian processes [5, 6, 7]: The solution proposed in this paper focuses on the arrangement of different typologies of sensors, interconnected among them and with the outside world through GPRS connection, to collect heterogeneous data sets that allow the definition of the dynamic processes of a sand dune.

2. Architecture of the Wireless Sensor Network

The overall architecture of the WSN is shown in Figure 1 and can be roughly subdivided in the following subsystems:

- The *Sand Level Sensor Network*, that is made up of a number of sensor nodes, arranged in a grid layout, in charge of the measurement of sand level and sand transport;
- The *Environmental Monitoring Node*, in charge of the measurement of wind direction and speed at different heights;
- The *Gateway Node*, communicating with all the other nodes of the network and in charge of data routing from the network to the remote data collection centre.

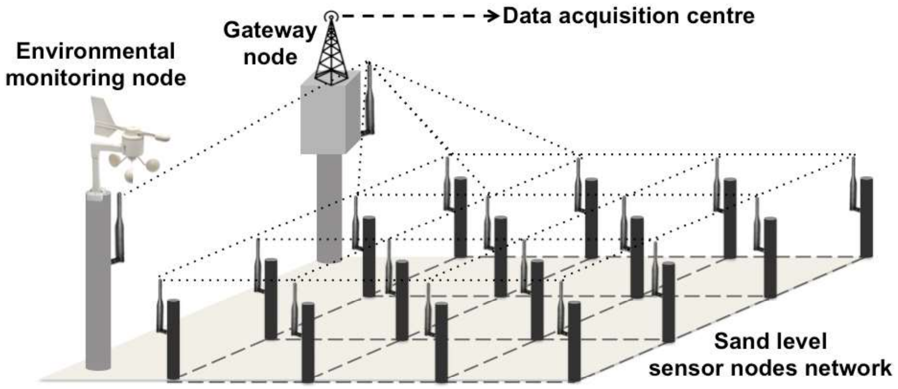

Figure 1. Architecture of the WSN

The *Sand Level Sensor Network* includes two typologies of sensor nodes: The *Sand Level Node* and the *Sand Collector Node* (see Figure 2).

The *Sand Level Node* includes an XBee Series 2 radio module in charge of local data transmission, a control logic system to optimize power consumption, a 9V battery and the sensing structure. This is made up of an array of 24 photoresistors (LDRs) mounted on a plastic tube 5 cm apart from each other (reaching a total length of 120 cm). Sunk LDRs do not sense sunlight and transmit a 0 value. Surfacing LDRs detect sunlight and transmit a higher value. By counting sunk LDRs, it is possible to measure the current level of the dune. During the data acquisition, all the values of the LDRs are sent to the Gateway node that calculates the sand level value before transmitting it to the remote data collection centre.

The *Sand Collector Node* is mainly a plastic cylinder about one-meter-high, which is able to orientate according to the wind direction. The wind-blown sand flows inside the cylinder through an opening in its side and is collected on its bottom. The plastic cylinder integrates in its upper section an XBee Series 2 radio transmission module in charge of data transmission, together with 4 1.5V batteries. A load cell is positioned on the bottom of the cylinder, connected with the battery and the transmission module by 4 wires running inside the cylinder body. The load cell measures the weight of the collected sand. This value can then be used to calculate the sand dune level.

The Environmental Monitoring Node is mainly an anemometric station integrating three anemometer/anemoscope couples positioned 40 cm, 120 cm and 200 cm from the ground. The node integrates an Arduino UNO microprocessor board that is required to calculate in real time the values of the speeds and of the directions, and an XBee Series 2 module for data transmission. While during the first tests the node was powered with a 9V battery, an energy harvesting solution based on the use of a solar panel has been set up, in order to allow the operation of the node for long spans of time.

The *Gateway Node* integrates an XBee Series 2 radio module, a GSM data transmission module and Arduino UNO board, required to manage the data reception from the various nodes and its routing to the remote data acquisition centre through GPRS connection. The Gateway Node is also provided with an energy harvesting system based on the use of a solar cell: this solution is required due to a high power consumption of the GSM module.

The Remote Data Collection centre is based on a Glassfish server provided with a Web Application that receives all the data packets transmitted by the GPRS module. These packets are then stored in a MySQL database according to the transmitting node. The Web Application also allows the visualization through Internet of the stored data.

3. Results and Discussions

The proposed architecture was tested in March, 2016 on the sand dunes located in the San Rossore regional park, Pisa, Italy. For the tests, 5 nodes WSN was set up: this included three *Sand Level Nodes*, one *Sand Collector Node* and one *Environmental Monitoring Node*. The three Sand Level Nodes were arranged in line, perpendicularly to the beach, 10 meters apart from each other. The Sand Collector Node was positioned close to the top Sand Level Node. The Environmental Monitoring Node was positioned on the top of the sand dune 5 meters apart from the top Sand Level Node. The Gateway Node was positioned close to the Environmental Monitoring Node.

Figure 2. The Sand Collector Node (on the left) and the Sand Level Node (on the right)

Figure 3. The Environmental Monitoring Node

The system was tested for a period of 24 hours. The sampling rate of the Environmental Monitoring Node was set at one sample each 20 minutes. As previously stated, wind speed and direction was calculated directly on the Arduino Uno Board and then a packet made up of the six data (three speeds and three directions) was sent to the Gateway.

Regarding the Sand Level Node, the sensor was sampled once per hour, three data packets were sent every time, each packet with the reading of 8 LDRs. The level value was calculated on the Gateway before being transmitted to the remote server.

Moreover, the Sand Collector Node was sampled once per hour. The value of the load cell was transmitted to the Gateway that calculated the sand weight before transmitting this value to the remote server.

All the data were received by the Glassfish server that stored them in the MySQL database. Each table was visible in real time directly on the beach using a Tablet PC connected to the server by the Internet.

A portion of the WSN can be seen in Figure 4. The central Sand Level Node can be seen in the foreground while the top Sand Level Node together with the Sand Collector Node can be seen in the background. The Environmental Monitoring node and the Gateway node are visible.

Figure 4. A section of the deployed WSN

4. Conclusions

The proposed WSN architecture for sand dynamics monitoring on coastal dunes was tested with success in a real time scenario, proving its effectiveness in collecting data useful to define the sand transport in conjunction with Aeolian processes. While the aim of the first tests was the proof of the technological infrastructure, further data collection experiments are expected to be performed in the next months for prolonged periods. The 24 hours span of time proved to be too short to allow the collection of a significant data set.

Moreover, as described, the first tests were performed with a small scale WSN, integrating only 5 sensor nodes. Additional nodes are being developed in order to deploy a larger network, integrating least 9 Sand Level and Sand Collector nodes. This number will allow the arrangement of the network on a grid layout for a better definition of the dynamics of a whole portion of the dune surface.

Finally, the network architecture has been designed to be easily expanded with the introduction of new typologies of Sensor Nodes. A new sensor node, able to measure the near-shore dynamics of sea currents and waves is being designed and developed. The introduction of this kind of structure in the WSN will allow the extension of the study area also to the portion of sea close to the coast for an overall definition of the sediment transport processes.

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PAPER V

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

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A B S T R A C T

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

1. Introduction

Coastal dune ecosystems are highly dynamics because of shifting substrates, burial by sand, bare areas among plants, the porous nature of sands, and little or no organic matter, particularly during the early stages of dune development (Maun, 2009). In addition,

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these ecosystems have been severely degraded as a result of excessive natural resource exploitation, urbanisation, industrial growth, and worldwide tourism (Brown and McLachlan, 2002; Defeo et al., 2009); consequently, coastal management often requires the use of vulnerability indices to facilitate the decision-making process.

In literature, the fact that the vulnerability of any system at any scale reflects (or is a function of) the exposure and sensitivity of that system to hazardous conditions and the ability, capacity, or resilience of the system to cope, adapt, or recover from the effects of those conditions is accepted (Smit and Wandel, 2006). Adaptations are therefore manifestations of the adaptive capacity that represents ways of reducing vulnerability. In addition, a system can be vulnerable to certain perturbations and not to others. Two other widely accepted arguments include (i) the multi-scale nature of disturbances and (ii) the fact that most ecosystems are typically exposed to multiple, interacting perturbations (Gallopin, 2006). In particular, the concept of vulnerability is associated with the tendency or the predisposition to be negatively affected by natural or human factors (IPCC, 2014). Although different perspectives on the meaning of coastal vulnerability exist (Green and McFadden, 2007; Vafeidis et al., 2004), the main objective of vulnerability assessment is to provide information to guide the process of adaptation and enhance society's adaptive capacity (Kelly and Adger, 2000; Smit and Wandel, 2006). Therefore, the function of the vulnerability index is to simplify a number of complex and interacting parameters, represented by diverse data types, to a form that is more readily understood and therefore has greater utility as a management tool (McLaughlin and Cooper, 2010). In fact, vulnerability is affected by a diverse range of parameters such as interactions among airflow, sediment transfers, and vegetation that drive landform and habitat dynamics within coastal dunes; hence, these parameters should be considered simultaneously to estimate the vulnerability of a dune system. Recently, Newton and Weichselgartner (2014) reviewed the coastal vulnerability terminology focusing on key terms such as natural hazard, disaster risk, sensitivity, and resilience. They proposed that human drivers and pressures act in synergy with environmental drivers and contribute to the coastal vulnerability. This interaction is very important to develop and use a novel conceptualisation of risk that includes broader societal causes.

One of the first pioneer works on coastal vulnerability was conducted by Dal Cin and Simeoni (1994) who analysed the morpho-dynamic risk of the Adriatic littoral (Italy). Subsequently, many authors attempted to assess the beach/dune/coastal vulnerability of sandy coasts worldwide. Most of them analysed (i) physico-geographical characteristics such as beach and coastal morphology, sedimentology, climatic parameters, and marine hydrodynamic factors (Alexandrakis and Poulos, 2014; Anfuso and Martínez Del Pozo, 2009; Domínguez et al., 2005; Satta et al., 2016); however, the other authors integrated abiotic variables with (ii) human influence and/or biotic factors such as vegetation conditions and animal biodiversity (e.g. Bernatchez et al., 2011; Corbau et al., 2015; García-Mora et al., 2000, 2001; Idier et al., 2013; Martínez et al., 2006). Agreement on how many variables must be pooled into any vulnerability index and whether each variable should be weighted or not has not been achieved. Given that coastal dune environments are complex systems whose equilibrium depends on several abiotic and biotic factors, the need to assess vulnerability by adopting a holistic and multidisciplinary approach becomes evident (e.g. Alexandrakis and Poulos, 2014; Bagdanavičiūte et al., 2015; Botero et al., 2015; Ruocco et al., 2014; Fenu et al., 2013a).

The objective of this study was to develop a Mediterranean dune vulnerability index (MDVI) for sandy coasts, starting from the existing dune vulnerability index (DVI) developed for oceanic coastal environments (García-Mora et al., 2000, 2001). In fact, the Mediterranean Sea exhibits unique characteristics because it is a semi-enclosed basin surrounded by a complex orography, which strongly affects the local climate (Ruti et al., 2008). Further, it is characterised by high water temperature and salinity, more limited tides, and waves and meteorological phenomena with respect to the oceanic storms and hurricanes. These characteristics are attributed to the scarce exchange with the low-salinity water from the Atlantic Ocean and mainly to the high levels of evaporation (Weyl, 1970; King, 1975). Moreover, confined air circulation and strong seasonal variability also make the Mediterranean climatology peculiar (D'Ortenzio et al., 2005). Given that the Mediterranean sandy coasts are quite different from the oceanic coasts, we elaborated an MDVI introducing several adjustments and integrations. The first step of the present work was to assess the vulnerability of the coastal dune systems along the Mediterranean Basin by adopting a multidisciplinary methodology. Second, we developed an easy-to-use instrument as the MDVI, which likely to be a valuable support to improve the management of the Mediterranean coastal areas. In particular, our research addressed the following questions: (1) Which variables among the geomorphological conditions of the dune system (GCD), marine influence (MI), aeolian effect (AE), vegetation condition (VC), and human effect (HE) are the most critical for the Mediterranean coastal systems? (2) How can the MDVI be used to develop appropriate strategies of conservation and management for these ecosystems?

2. Materials and methods

2.1. Study area

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

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

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

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

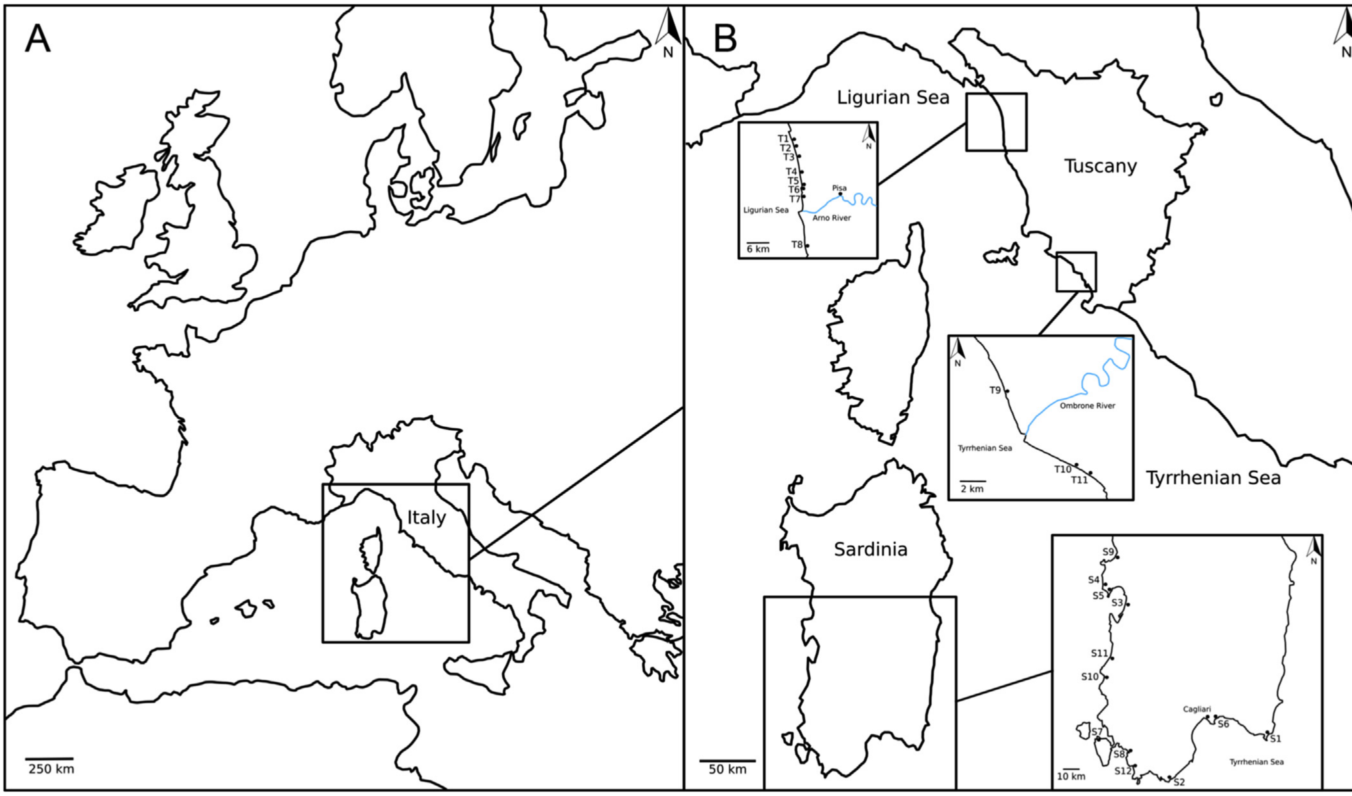

Fig. 1. **A**. Map of Europe. **B**. Map of Italian coastal dune systems analysed in the study. Abbreviations: T, Tuscan sites and S, Sardinian sites. Coastal areas considered in this study: T1: Viareggio; T2: Torre del Lago; T3: Marina di Vecchiano; T4: San Rossore; T5: San Rossore; T6: San Rossore;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

(see Appendix 1 for details).

2.2. Methodology

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

2.2.1. Geomorphological condition of the dune system (GCD, 7 variables)

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

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

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

2.2.2. Marine influence (MI, 13 variables)

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

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

Table 1
Variables considered in the coastal dune vulnerability classification procedure (adapted from García-Mora et al., 2001 and integrated with Idier et al., 2013). Class of vulnerability of each variable ranged from 0 (absence of vulnerability) to 4 (very high vulnerability).

	Variables	Vulnerability class				
	1. Geomorphological Condition of the Dune System (GCD)	**0**	**1**	**2**	**3**	**4**
1	Length of homogeneous active dune system (m)***	>20	>10	>5	>1	>0.1
2	Average height of secondary dunes (m)***	>25	>10	>5	>1	<1
3	Average height of frontal dunes (m)*	>25	>15	>10	>5	<5
4	Foredune, slope steepness***	Moderate		Gentle		Steep
5	Relative area of wet slacks measured from map (%)*	Moderate		Small		None
6	Degree of dunes system fragmentation*	Low		Medium		High
7	Particle size of the frontal dune-Phi sizes*	< −1	0	1	2	3
	2. Marine Influence (MI)	**0**	**1**	**2**	**3**	**4**
1	Orthogonal fetch (km)*	<25	<100	<250	>500	>1000
2	Berm slope (degrees)*	Moderate		Gentle		Steep
3	Width of intertidal zone (m)***	>0.5	>0.2	>0.1	>0.05	<0.05
4	Tidal range (cm)***	<2		2–4		>4
5	Coastal orientation to wave direction (degrees)*	10-45°		0-10°		0°
6	Width of the zone between HWSM and dune face (m)*	>75	<75	<25	<10	0
7	Breaches in the frontal dune due to wash over, relative total area*	0	<5%	<25%	<50%	>50%
8	Particle size of the beach-Phi sizes*	0		0–2		>2
9	Shoreline changes since 1980***	No retreating				Retreating
10	Mean wave height - MWH (m)**	≤0.5	0.5–1	1–1.25	1.25–1.4	>1.4
11	Mean wave incident angle - MWA (°)**	≤10	10–15	15–25	24–40	>40
12	Storm frequency - SF (event yr^{-1})**	≤5	5–15	15–25	25–35	>35
13	Storm duration - SD (d)**	≤1	1–2	2–3	3–4	>4
	3. Aeolian Effect (AE)	**0**	**1**	**2**	**3**	**4**
1	Sand supply input*	High		Moderate		Low
2	Blowouts: % of the system*	<5%	<10%	<25%	<50%	>50%
3	If breaches-depth as % of dune height*	<5%	<10%	<25%	<50%	>50%
4	Natural litter drift cover as % surface*	0	<5%	>5%	>25%	>50%
5	Pebble cover as % surface*	0	<5%	>5%	>25%	>50%
6	% seaward dune vegetated*	>90	>60	>30	>10	<10
	4. Vegetation Condition (VC)	**0**	**1**	**2**	**3**	**4**
1	% cover of Type III plants in the beach*	>50	>25	>15	>5	<5
2	% cover of Type III plants in the seaside of the frontal dune*	>90	>60	>30	>15	<15
3	Relative proportion of Type II plants in the seaside of the frontal dune (% cover)*	<5	<15	<30	<60	>60
4	Relative proportion of Type I plants in the seaside of the frontal dune (% cover)*	<1	>1	>5	>10	>30
5	Relative proportion of alien species in the seaside of the frontal dune (% cover)*	0	<1	<5	<15	>15
6	Relative proportion of alien species along the transect (% cover)***	0	<1	<5	<15	>15
7	Relative proportion of endemics in the seaside of the frontal dune (% cover)***	>1		<1		0
8	Relative proportion of endemics along the transect (% cover)***	>1		<1		0
9	Number of associations along the transect***	≥5	4	3	2	1
	5. Human effect (HE)	**0**	**1**	**2**	**3**	**4**
1	Visitor pressure*	Low		Moderate		High
2	Visitor frequency*	Low	Moderate	High		
3	Access difficulty*	High		Moderate		Low
4	On dune driving*	None		Some		Much
5	On beach driving *	None		Some		Much
6	Trampling by animals***	None		Some		Much
7	Path network as percent of the frontal dune	0%	<5%	>5%	>25%	>50%
8	Anthropogenic litter: cover as % surface cover*	0%	<5%	>5%	>25%	>50%
9	Amount of sand (%) extracted for building etc. *	0%	<5%	>5%	>25%	>50%
10	Summer beach cleaning frequency (High is twice a day; medium, daily)*	Low		Moderate		High
11	% upper beach cleaned*	0	<25	<50	<75	>75
12	% permanent infrastructure replacing active dunes (roads, houses, etc.)*	0	<25	<50	<75	>75
13	% ephemeral infrastructure replacing active dunes (outdoor facilities, camping, etc.)*	0	<25	<50	<75	>75
14	Relative surface (%) forested in the system (200 m inland from the foredune)*	0	<25	<50	<75	>75
15	Relative surface (%) of agriculture in the system (200 m inland from the foredune)*	0	<25	<50	<75	>75
16	Grazing on the active system***	None	Low	Moderate	High	Intensive

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

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2.2.3. Aeolian effect (AE, 6 variables)

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

2.2.4. Vegetation condition (VC, 9 variables)

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

2.2.5. Human effect (HE, 16 variables)

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

Table 2
Partial and total Mediterranean dune vulnerability index (MDVI) values for Tuscan (T) and Sardinian (S) sites.

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

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

2.3. Data analysis

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

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

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

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

3. Results

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

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

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

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

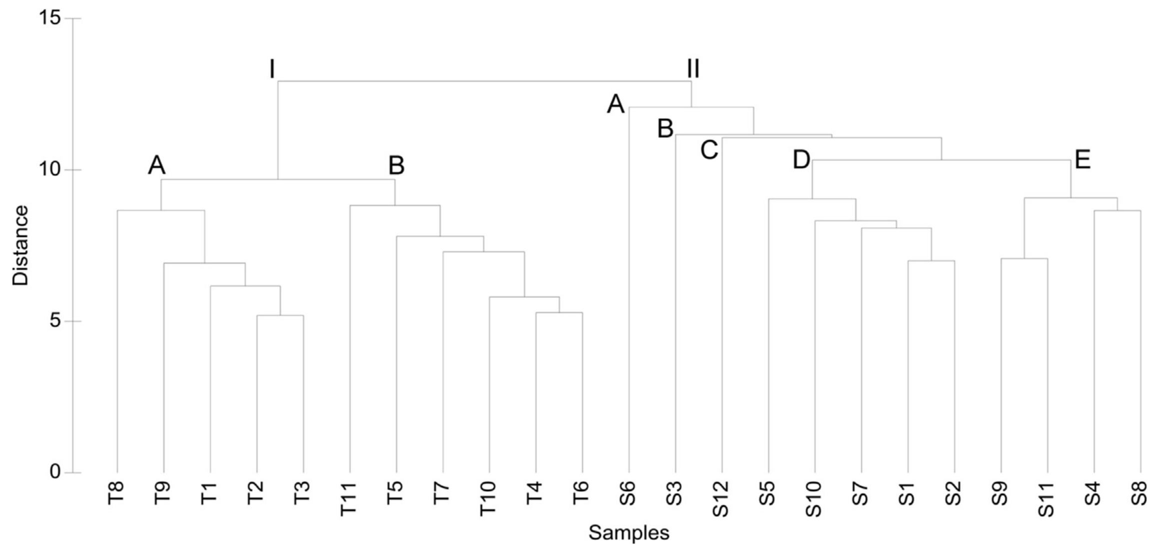

Fig. 2. Dendrogram obtained by average-linkage cluster analysis (CA) based on the Euclidean distance of 23 Italian sites. The CA separated Tuscan coastal sites (Group I) from Sardinian ones (Group II) with a distance of ~13%. Sample abbreviations: S = Sardinia, T = Tuscany.

from IB and IID from IIE.

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

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

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

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

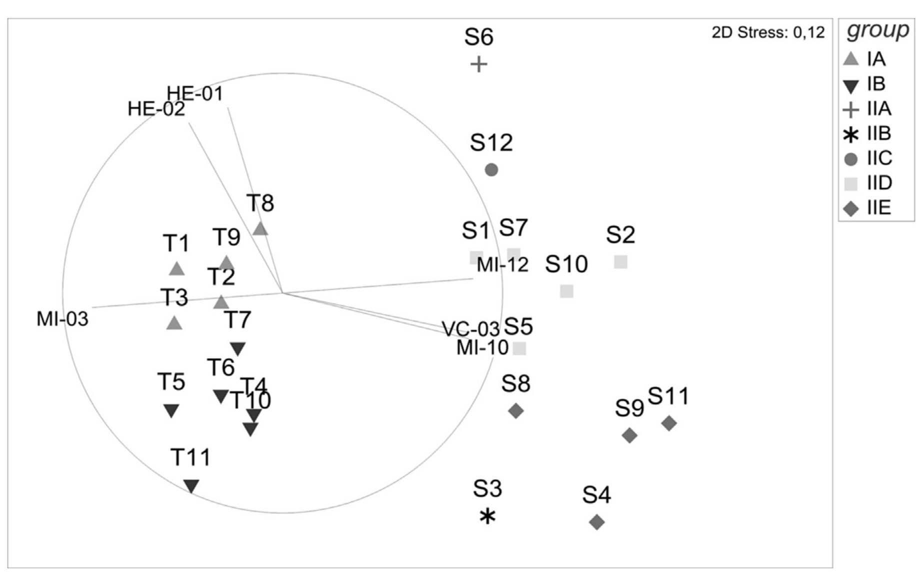

Fig. 3. NMDS diagram based on the dissimilarity (measured by the Euclidean distance) occurring in 23 Italian sites. All shown variables have a Spearman correlation coefficient >0.8 with the two axes. Sample abbreviations: S = Sardinia, T = Tuscany. Variable abbreviations: HE-01 = visitor pressure, HE-02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

Table 3
Mean values (±SD) of partial and total Mediterranean dune vulnerability index (MDVI) values calculated for each group defined by cluster analysis (indicated by roman letters – see Fig. 4). Means followed by the same letters are not significantly different at 5% according to the non-parametric Kruskal-Wallis test after the Bonferroni correction for multiple comparisons.

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

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

4. Discussion

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

The obtained results highlighted that all the analysed Italian coastal sites showed a medium vulnerability value (ranging from 0.32 to 0.49). In particular, the GCD, MI, and VC parameters showed intermediate values of vulnerability along the Italian coasts. The most well-preserved coastal segment was located in northern Tuscany (Viareggio – T1) where the littoral is prograding and large; however, Poetto (S6) in south Sardinia, a beach that is approximately 8-km long and highly frequented by the inhabitants of Cagliari throughout the year and additionally by tourists in the summer, exhibited the highest MDVI value. This result is also consistent with the result of a previous study, carried out at the Italian level and considering five types of pressures (land-use, river, industry, ports, and artificial structure), showing significant human-induced pressures in this coastal site (Lopez y Royo et al., 2009).

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

Conversely, the vulnerability of Sardinian sites was mostly related to the MI and the AE. Among them, the variables with the highest vulnerability values were the orthogonal fetch, the width of the zone between the HWSM and the dune face, and the shoreline changes (MI-01/06/09), in addition to the supply input and the percentage of

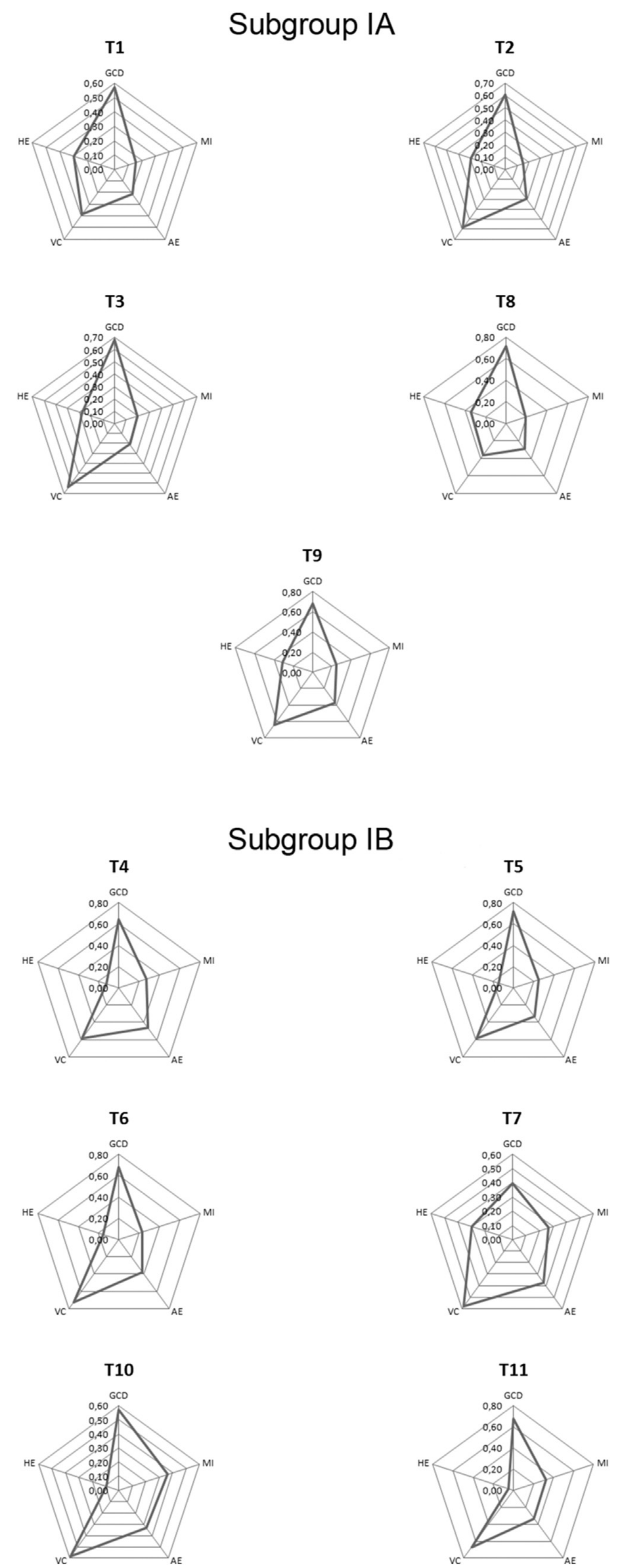

Fig. 4. Graphic representation of partial coastal dune vulnerability index of subgroup IA and IB sites.

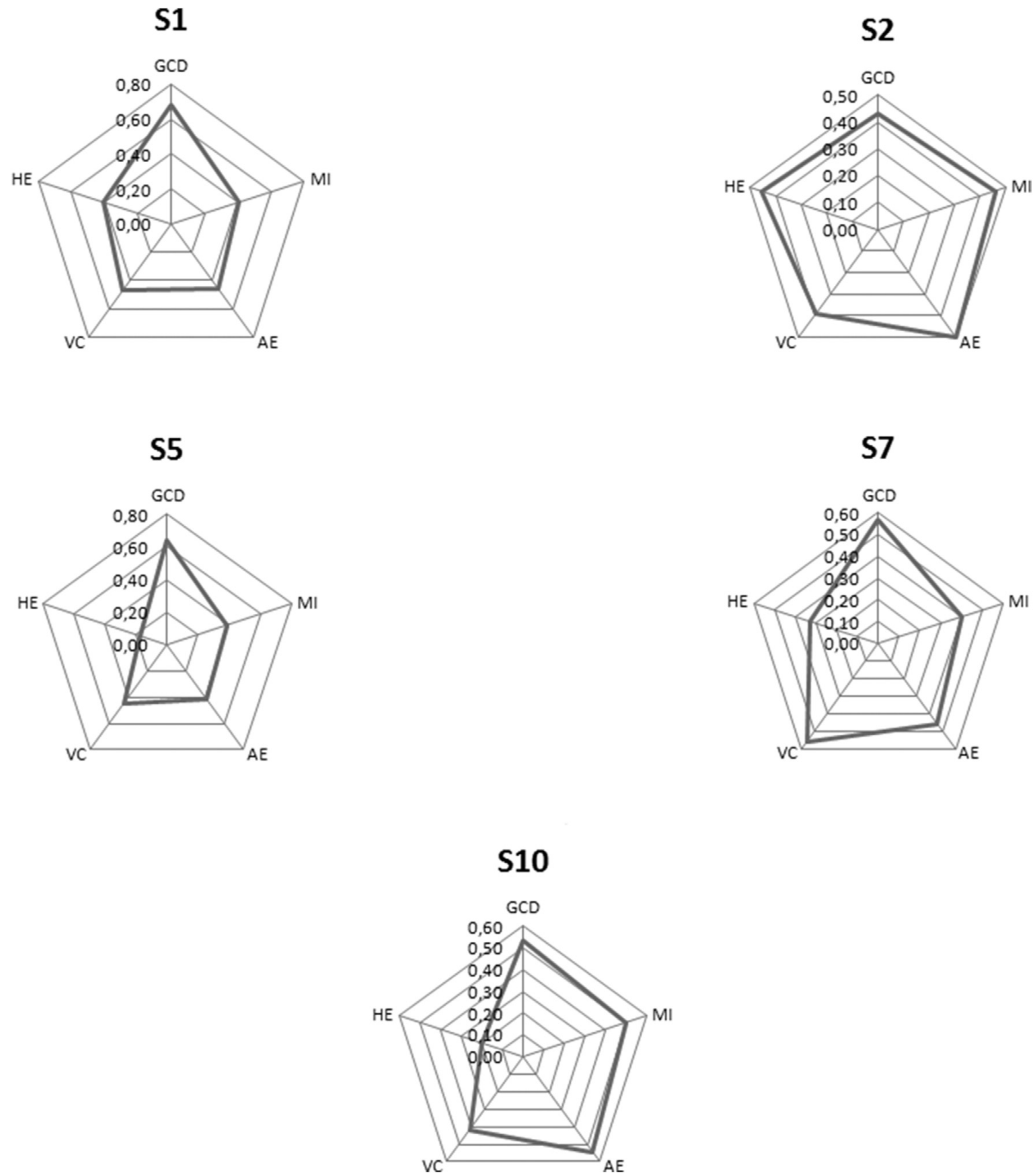

Fig. 5. Graphic representation of partial coastal dune vulnerability index of subgroup IID sites.

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

The NMDS ordination of the Italian samples in the bidimensional

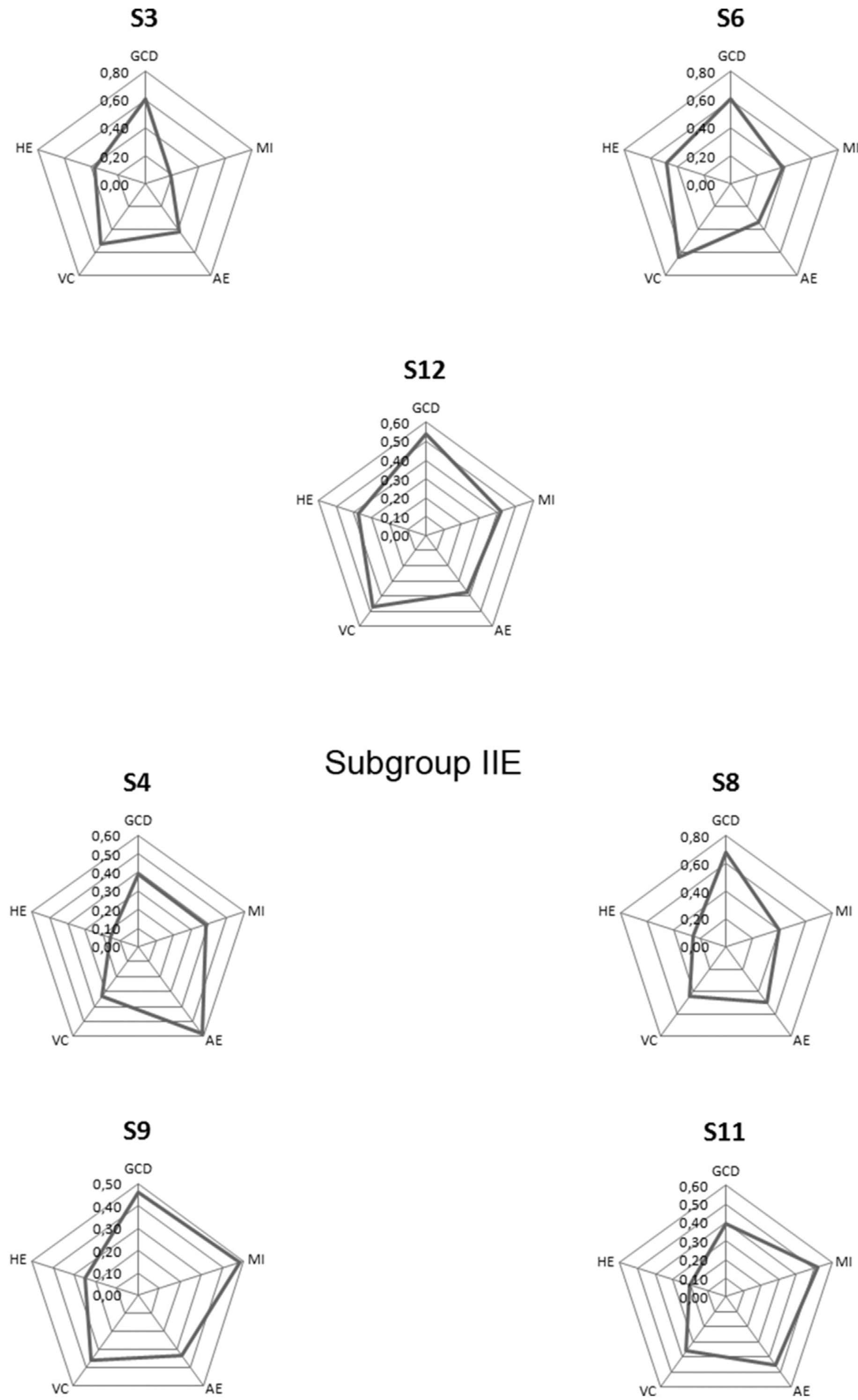

Fig. 6. Graphic representation of partial coastal dune vulnerability index of subgroup IIA-C and IIE sites.

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

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

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

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

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

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2016.12.008.

Appendix 1

Main characteristics of coastal dune sites examined in the present study. The levels of urbanization for each site were estimated considering the following parameters: number and frequency of visitors, presence of ephemeral and permanent infrastructures and presence of agricultural activities.

No.	Site/Location (code)	Shoreline dynamic	Prevailing wind	Storm predominant direction	Urbanization
1	Viareggio (T1)	Accretional	SW	240°–270°	Low
2	Torre del Lago (T2)	Accretional	SW	240°–270°	Low
3	Marina di Vecchiano (T3)	Accretional	SW	240°–270°	Low
4	San Rossore (T4)	Erosional	SW	240°–270°	Low
5	San Rossore (T5)	Erosional	SW	240°–270°	Low
6	San Rossore (T6)	Erosional	SW	240°–270°	Low
7	San Rossore (T7)	Erosional	SW	240°–270°	Low
8	Calambrone (T8)	Stable	SW	240°–270°	High
9	Principina (T9)	Stable	NE, SE	170°	High
10	Maremma (T10)	Erosional	NE, SE	170°	Low
11	Maremma (T11)	Accretional	NE, SE	170°	Low
12	Villasimius (S1)	Accretional	NE, SE	100°	High
13	Chia (S2)	Erosional	SE	120°–180°	High
14	S'Ena Arrubia-Abbarossa (S3)	Stable	NW	270°–330°	Low
15	Maimoni (S4)	Erosional	NW	270°–330°	Low
16	San Giovanni (S5)	Erosional	NW	270°–330°	Medium
17	Poetto (S6)	Accretional- Erosional	NW, SE	280°–320°; 90°–140°	High
18	Le Saline (S7)	Stable	NW	270°–330°	High
19	Porto Botte-Is Solinas (S8)	Erosional	NW	270°–330°	Low
20	Is Arenas Oristano (S9)	Erosional	NW	270°–330°	Low
21	Buggerru (S10)	Erosional	NW	270°–330°	Low
22	Piscinas (S11)	Erosional	NW	270°–330°	Low
23	Porto Pino (S12)	Accretional- Erosional	NW	240°	High

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PAPER VI

Study of coastal vulnerability Acaraí State Park (Santa Catarina, Brazil)

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1. INTRODUCTION

Coastal areas have always exerted a great attraction to humans, either by economic, social or recreational opportunities (De Jong *et al*., 2014). At the same time, they are highly valued social environments, they are accompanied by a high risk to extreme weather conditions (Satta *et al*., 2016, Harley *et al*., 2015). According to the United Nations Environment Programme (UNEP/GRID Arendal 2007), 40% of the world's population lives less than 100 km from the coast, an area that represents only about 20% of the global land mass (Idier *et al*., 2013). Only in Europe, between the years 1980-2009, approximately 9 million people were affected by disasters in coastal areas (Newton & Weichselgartner, 2014).

Brazil follows the global trend, according to the IBGE (2011) about 50,7 million brazilians occupy coastal areas or areas near the coast, representing 26,6% of the inhabitants of the country. The high concentration of people in brazilian coastal regions has historical and cultural origin, and it is not expected an opposite movement. Learning to cope and adapt to this trend of human occupation is necessary (IPCC, 2014).

Moreover, as evidenced by Germani *et al*. (2015), the intensity of tropical and extratropical storms will increase in the next decades summing to climate change and a rising sea level (Nicholls *et al*., 2010, Alsahli & AlHasem, 2016), making the coastal areas extremely vulnerable.

The northern coast of Santa Catarina, is not a region known historically for recurrent natural disasters such, cyclones or frequent and intense storms, but as the whole coastal area is already experiencing serious environmental problems such as coastal erosion, degradation of the dunes, urbanization, pollution and loss of biodiversity.

However, assessing the environmental vulnerability in disturbed areas can provide important information on short and medium term. The knowledge of the impact magnitude, for example of climate changes and related hazards, affects land use planning and other coastal development policies (Satta *et al*., 2016).

Currently, there are many models and tools to assess coastal vulnerability that differ in complexity (Satta *et al*., 2016), scales and in their outputs. The most commonly used are index-based or indicator-based approaches including related GIS applications, decision support systems and computer models (ETC-CCA, 2011). In literature, the concept of vulnerability is associated with the tendency or the predisposition to be negatively affected by natural or anthropogenic factors (IPCC, 2014), while system resilience adapts to these conditions (Smit & Wandel, 2006).

The aim of this work was to apply a Dune Coastal Vulnerability Index (CDVI) following the index proposed by Ciccarelli *et al*. (submitted) in Acaraí State Park and analyze which the most sensitive areas of environmental changes.

2. STUDY AREA

São Francisco do Sul Island is located in the northern portion of the state of Santa Catarina (Brazil) under the geographic coordinates 26°09'48" and 26°27'12" south latitude and 48°29'34" and 48°42'49" west longitude. It has a triangular shape with 35 km maximum length and 16 km maximum width (Figure 1), with 12 sandy beaches (Zular, 2011), located he eastward with Atlantic Ocean to the west and northwestward by Babitonga Bay and southwestward Linguado Channel (Horn & Simo, 2008).

According to the classification of Köppen (1948), the climate is mesothermic (Cfa – humid temperature climate with hot summers), characterized by annual precipitation that ranges from 1000 to 1500 mm and an annual average temperature between 16° C and 20° C (Horn Filho, 1997). The average relative air humidity is between 84 and 86% (Vieira, 2015). Prevailing wind direction is from SW, followed by NE and S quadrants (Truccolo, 2011). The most significant wave directions are from SE and E (Alves, 1996, Truccolo, 1998, Alves & Melo, 2001). The strongest storms in terms of significant wave height most frequently occur from SSE, with typical values ranging from 1 m to 3.5 m; the littoral drift is northwards trending (Zular, 2011).

São Francisco do Sul Island is the domain of mesotidal regimen (Davies, 1964), semidiurnal, tide cycles, with average amplitude ranging from 1.3 m and 1.9 m (Bogo *et al*., 2015).

Evaluation of the index occurred in two stretches of the Grande Beach (Figure 1), with characterized by a different confirmation in order to enable comparison between plant association on the parabolic dunes to the north (Zone A) and on the transverse dunes to the south (Zone B). Still, the area A of this next urbanized areas in comparison with the B Zone, less anthropic. Both A and B are within the limits of Acaraí State Park, Conservation Unit created by State Decree 2005/3517.

This area was selected because of its environmental relevance regarding *restinga* vegetation, being considered by PROBIO (2003) as the largest remaining area remains in the State of Santa Catarina and its extremely high priority for biodiversity conservation (Melo Jr & Boeger, 2015).

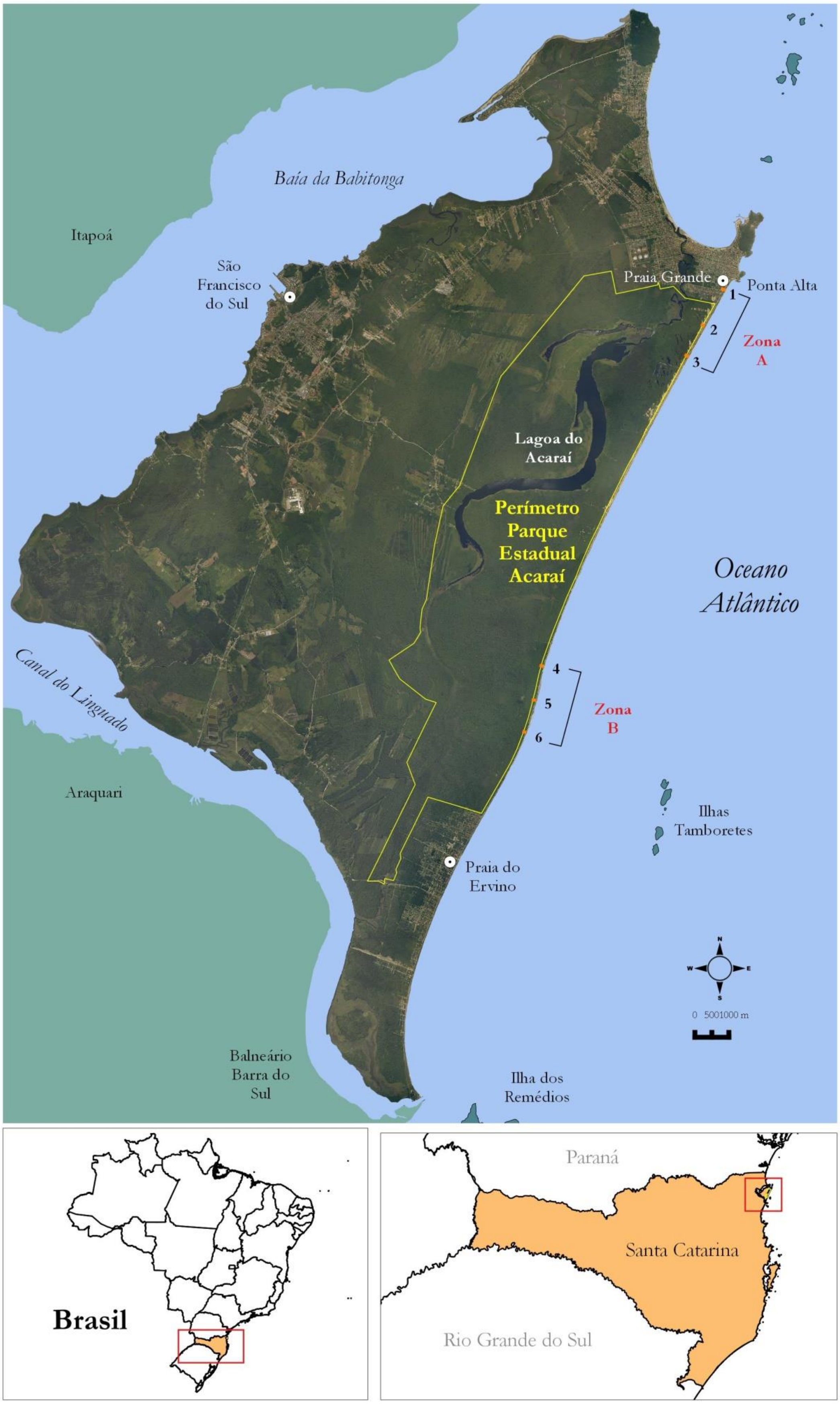


Figure 1. Geographical location of the study area (Zone A and B) and 6 transects posed into the Acaraí State Park (Santa Catarina, Brazil).

3. MATERIALS AND METHODS

The index was developed based on the parameters described by Ciccarelli *et al*. (submitted) to the Mediterranean coast. As the Brazilian coast has some influence oceanic variables were modified to meet the specific local features. A CDVI was determined for six transect (3 in Zone A and 3 in Zone B), that were posed perpendicular to the coastline (Figure 1), 1km spaced, started from the shoreline and ended to the woody vegetation.

Dunes Coastal Vulnerability Index (CDVI)

The CDVI index was calculated taking into account 51 variables distributed in five groups of parameters (Table 1): Geomorphological dune system condition - GCD, Marine influence - MI, Aeolian effect - AE, Vegetation condition - VC and Human effect - HE. To calculate the index, each variable was associated with a five point scale, ranging from 0 (no vulnerability) to 4 (very high vulnerability).

In each group, the sum of the variables was divided by the sum of the maximum achievable rating within each group, in this way generating a partial index expressed as a percentage, classified in category (García-Mora et al., 2001):

- Group I: $CDVI < 0.25$ = low risk
- Group II: $0.25 < CDVI \leq 0.5$ = medium risk
- Group III: $0.5 < CDVI \leq 0.6$ = high risk
- Group IV: $CDVI \geq 0.6$ = very high risk

The final CDVI was calculated on the unweighted average of the five partial indexes through the algorithm:

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

Finally, ANOVA was used to test if there were any significant differences between transects.

Table 1: Variables used to classify the vulnerability of coastal dunes. 0 = absence of vulnerability and 4 = very high vulnerability (from Ciccarelli et al., submitted).

Variable		Class of Vulnerability				
1. Geomorphological dunes system condition - 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 sizes	< -1	0	1	2	3
2. Marine influence (MI)		**0**	**1**	**2**	**3**	**4**
1	Orthogonal fetch (km)	< 25	< 100	< 250	> 500	> 1000
2	Berm slope (degrees)	Moderate		Gentle		Steep
3	Width of intertidal zone (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 sizes	0		0-2		> 2
9	Shoreline changes since 1980	No retreating				Retreating
10	Mean wave height - MWH (m)	≤ 0.5	0.5-1	1-1.25	1.25-1.4	> 1.4
11	Mean wave incident angle - MWA (°)	≤ 10	10-15	15-25	24-40	> 40
12	Storm frequency - SF (event yr^{-1})	≤ 5	5-15	15-25	25-35	> 35
13	Storm duration - SD (d)	≤ 1	1-2	2-3	3-4	> 4
3. Aeolian effect (AE)		**0**	**1**	**2**	**3**	**4**
1	Sand supply input	High		Moderate		Low
2	Blowouts: % of the system	< 5%	< 10%	< 25%	< 50%	> 50%
3	If breaches-depth as % of dune height	< 5%	< 10%	< 25%	< 50%	> 50%
4	Natural litter drift cover as % surface	0	< 5%	> 5%	> 25%	> 50%
5	Pebble cover as % surface	0	< 5%	> 5%	> 25%	> 50%
6	% seaward dune vegetated	> 90	> 60	> 30	> 10	< 10
4. Vegetation condition (VC)		**0**	**1**	**2**	**3**	**4**
1	% cover of Type III plants in the beach	> 50	> 25	> 15	> 5	< 5
2	% cover of Type III plants in the seaside of the	> 90	> 60	> 30	> 15	< 15

	frontal dune					
3	Relative proportion of Type II plants in the seaside of the frontal dune (% cover)	< 5	< 15	< 30	< 60	> 60
4	Relative proportion of Type I plants in the seaside of the frontal dune (% cover)	< 1	> 1	> 5	> 10	> 30
5	Relative proportion of alien species in the seaside of the frontal dune (% cover)	0	< 1	< 5	< 15	> 15
6	Relative proportion of alien species along the transect (% cover)	0	< 1	< 5	< 15	> 15
7	Relative proportion of endemics in the seaside of the frontal dune (% cover)	> 1		< 1		0
8	Relative proportion of endemics along the transect (% cover)	> 1		< 1		0
9	Number of associations along the transect	≥ 5	4	3	2	1
5. Human effect (HE)		**0**	**1**	**2**	**3**	**4**
1	Visitor pressure	Low		Moderate		High
2	Visitor frequency	Low	Moderate	High		
3	Access difficulty	High		Moderate		Low
4	On dune driving	None		Some		Much
5	On beach driving	None		Some		Much
6	Trampling by animals	None		Some		Much
7	Path network as percent of the frontal dune	0%	< 5%	> 5%	> 25%	> 50%
8	Anthropogenic litter: cover as % surface cover	0%	< 5%	> 5%	> 25%	> 50%
9	Amount of sand (%) extracted for building etc.	0%	< 5%	> 5%	> 25%	> 50%
10	Summer beach cleaning frequency (High is twice a day; medium, daily)	Low		Moderate		High
11	% upper beach cleaned	0	< 25	< 50	< 75	> 75
12	% permanent infrastructure replacing active dunes (roads, houses, etc.)	0	< 25	< 50	< 75	> 75
13	% ephemeral infrastructure replacing active dunes (outdoor facilities, camping, etc.)	0	< 25	< 50	< 75	> 75
14	Relative surface (%) forested in the system (200 m inland from the foredune)	0	< 25	< 50	< 75	> 75
15	Relative surface (%) of agriculture in the system (200 m inland from the foredune)	0	< 25	< 50	< 75	> 75
16	Grazing on the active system	None	Low	Moderate	High	Intensive

Geomorphological dunes system condition - GCD

Geomorphological data were acquired with survey with the use of a Leica RTK-GPS (Universal Transverse Mercator projection, Zone 22 S, Datum SAD69); points were recorded at any break-in slope along the cross-shore profile. The instrument accuracy of about 1 cm was obtained post-processing the raw data using as reference the available technical data from the IBGE - Brazilian Institute of Geography Geodetic Station Araquari SAT 96171 (Latitude: 26°23'37.52" e Longitude: 48°44'14.78"). Sea-weather information during the survey were provided by DHN (http://www.mar.mil.br): mean wave height was 1.65 m, with a peak of 1.84 m; the average tide condition was 0.7 m, while the tidal range was about 1.7 m.

Sediment sampling was carried out together with the topographic survey along the same 6 transects (Figure 1). Samples of about 1 kg each were collected from the surface by means of a small shovel. The sediment was sampled in specific spots, that is the beachface, the dune crest, the dune back-toe, and the steady dune. Grain-size analysis was then performed on all the 31 samples collected on the beach. Prior to the sieving procedures, all samples were accurately treated according to Bertoni *et al*. (2014). Once dried and reduced to a quantity still representative of the whole sample (about 100 g), the samples were sieved for ten minutes using a mechanic sieve shaker. Sieves from 0.75 mm to 0.063 mm were used, with mesh interval of 0.5 phi. The sediment retained on each sieve was weighed by means of a digital scale (instrument error of 0.01 g). The data were processed by SYSGRAN 3.0 software (Camargo, 2006), which provided the most important Folk & Ward (1957) textural parameters such as the Mean (Mz).

Marine influence - MI

Wave patterns of data were obtained from the literature (Alves, 1996). To identify the conditions of the sea for the day of collection we used the information from Centro de Hidrografia da Marinha - CHM (http://www.mar.mil.br/dhn/chm/box-previsao-mare/tabuas/) and the database on waves for the duration and frequency of storms. It considered only storm wave height of 1.0 m above data from 12 consecutive hours (Trucollo, 1998, 2011; Alves & Melo, 2001; APAT, 2004; Abreu de Castilhos *et al*., 2006; Vieira *et al*., 2008; Abreu, 2011; Zular, 2011).

The importance of wave action along the coast (km) followed Nemes & Marone (2013), corresponding to an estimated variable indirectly for the southern region of Brazil. The systematic tracing of the coastline was carried out analyzing aerial photographs and ortho-photographs, spanning from 1938 to 2010 (72 years). The images were properly georeferenced and used to build photo-mosaics of the entire coast for each year of aerial coverage (1938, 1957, 1978 and 2010) (Table 2). For each mosaic the shoreline was traced out using QGIS vectorization tools at 1:2000 scale. The shoreline is defined by the mean high water line, which is represented by the wet/dry line (Crowell, *et al*., 1991; Leatherman, 2003; Mazzer & Dillenburg, 2009).

Table 2: List of aerial photographs and ortho-photographs used to set up the shoreline evolution in a 72 year timespan.

Product	Year	Scale	Source
Aerial photos	1938	1:20000	North American Marine
Aerial photos	1957	1:12000	Aerophotogrammetric services Cruzeiro do Sul S/A
Aerial photos	1978	1:25000	Aerophotogrammetric services Cruzeiro do Sul S/A
Ortho-photos	2010	1:10000	Municipality of São Francisco do Sul

Aeolian effect - EE

Wind data followed those described by Zular (2011). The percentage of waste of natural origin, gravel cover and other variables were analyzed visually in the field and/or where necessary, through photo interpretation.

Vegetation condition - CV

The percentage of vegetation coverage was estimated in 2 x 2 m plots along 6 cross-shore transects (Figure 1). The plots were placed on specific spots on the frontal dune, on the backdune area and on the fixed dune. The vegetation coverage was visually estimated according to the Causton (1988) scale. Species classification followed Christenhusz et al. (2011) and APG III (2009). Species names and authors were in accordance with the Species List of the Botanical Garden of Brazil Flora of Rio de Janeiro (http://jbrj.gov.br/nosso-jardim/plantas).

Human effect - EH

All information was collected visually in October 2015. Regarding the variable "visitor pressure", all types of physical infrastructure were considered (such as home, parking, lots, restaurants, lifesavers, street, etc.).

Statistical analysis

The plant functional types (PFT) value was calculated using cluster analysis and Euclidean distance as the dissimilarity index following García-Mora *et al*. (1999). A matrix was elaborated with seven traits of plants (Table 3) with respect to the degree of exposure in coastal environments for the 53 species vascular plant (traits 7 x 53 species) All analyses were done with the software Primer 6.0.

Table 3: Selected seven traits on the degree of exposure to the coastal environment to the functional group classification (from García-Mora *et al*., 1999).

Characteristics	Classification	Constraint factor
Persistence	annual	Exposure to the shore
	perenial	
Canopy height	> 15 cm	Wind exposure
	≤ 15 cm	
Below-ground storage organs	present	Water and nutrient unavailability
	absent	
Below-ground structures	shallow fibrous or thin tap	Below-ground resource capture. Soil mobility
	thick spreading	
Leaf characteristics	thin and soft	Climatic stress
	tought/suculent/pubescent	
Capability of withstanding deep sand burial	present	Sand input
	absent	
Dispersal by sea-water	present	Linear habitat
	absent	

4. RESULTS

The result of partial CDVI values do not show significant differences between transects (*p-value* 0.70), ranging from 0.42 to 0.48 (Table 4). The parameter that showed the highest difference between transects was the HE followed by AE.

Through this percentage, the total vulnerability to the study area was considered medium. The dominant parameters in each transect are demonstrated through of radial graphs. Each axis of the graph corresponds to a class of vulnerability. The vulnerability of the site is directly proportional to the surface of the radial graphic: the larger the surface most vulnerable is the area. (Idier *et al*., 2013).

Regarding Zone A, the parameters showing higher partial CDVI were GCD (maximum value 0.78 – T2 and T3) and MI (maximum value 0.59 – T1). Then, VC values showed little difference between the transects, 0.38 (T3) to 0.48 (T1). The HE was the same for all transects (0.35). Finally, the AE was the lowest for all transects ranging from 0.16 (T1) to 0.33 (T2 and T3) (Figure 2).

Regarding Zone B, the GCD also showed highest partial CDVI, ranging 0.78 (T4) to 0.71 (T5 and T6). The MI values were different for the three transects, 0.55 (T4), 0.57 (T5) and 0.59 (T6).

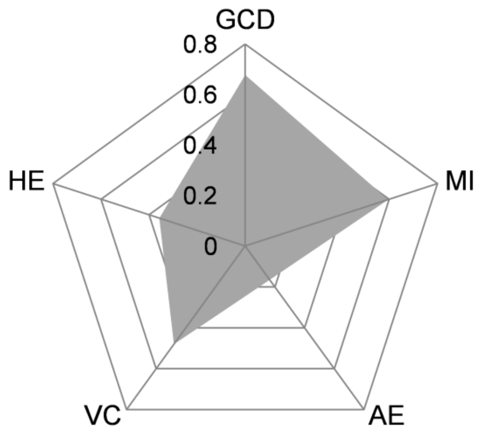
The AE ranges from 0.33 (T4) to 0.50 (T5 and T6). The VC showed little difference between the transects, 0.30 (T4) to 0.44 (T5 and T6). The HE was the same for the all transects (0.14) (Figure 3).

The result of the PTF divided of the species in three functional groups being classified as A (Type II), B1 (Type III) and BII (Type I) (Figure 4). Dendrogram obtained by cluster analysis showed a separation between zone A and B (Figure 5).

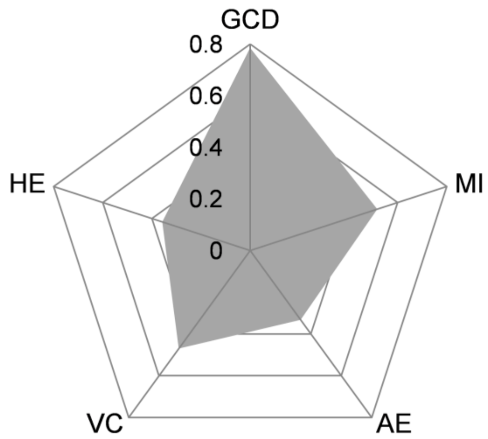
The floristic list showed the presence of 53 vascular plant species (Table 5) belonging to 33 families. The most representative families in species number were: Fabaceae (5), Poaceae (5), Asteraceae (4) and Cyperaceae (4). Of this total, 21 occurred exclusively in Zone A and 23 exclusively in zone B.

Tabela 4. CDVI parcial e total para todos os transectos analisados.

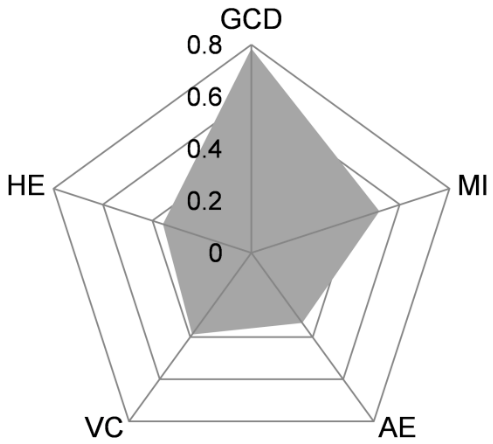
Zone	Transects	Partial vulnerability					Total vulnerability
		GCD	MI	AE	VC	HE	CDVI
A	1	0.67	0.59	0.16	0.48	0.35	0.45
	2	0.78	0.51	0.33	0.47	0.35	0.49
	3	0.78	0.51	0.33	0.38	0.35	0.47
B	4	0.78	0.55	0.33	0.30	0.14	0.42
	5	0.71	0.57	0.50	0.44	0.14	0.47
	6	0.71	0.59	0.50	0.44	0.14	0.48



T1

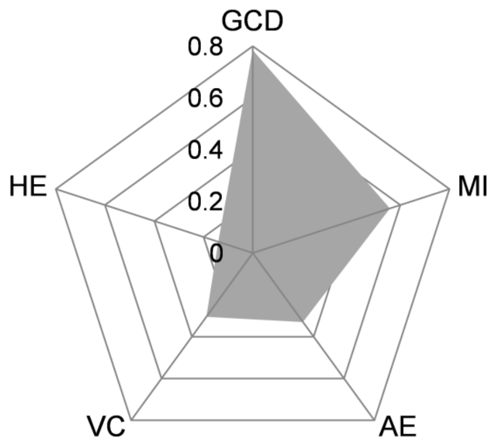


T2

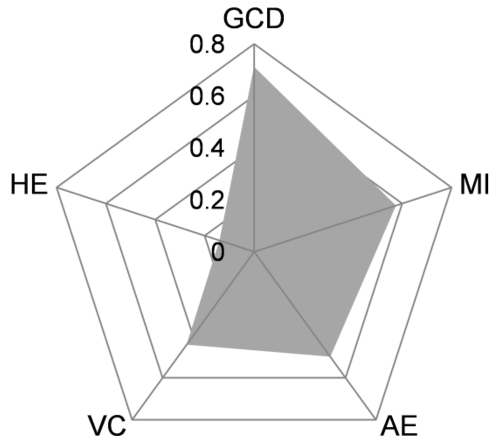


T3

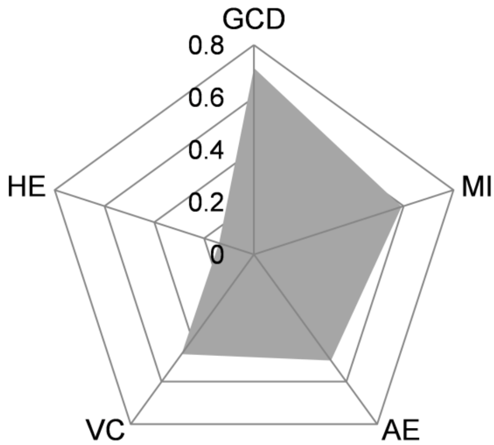
Figura 2. CDVI diagrams for zone A.



T4



T5



T6

Figura 3. CDVI diagrams for zone B.

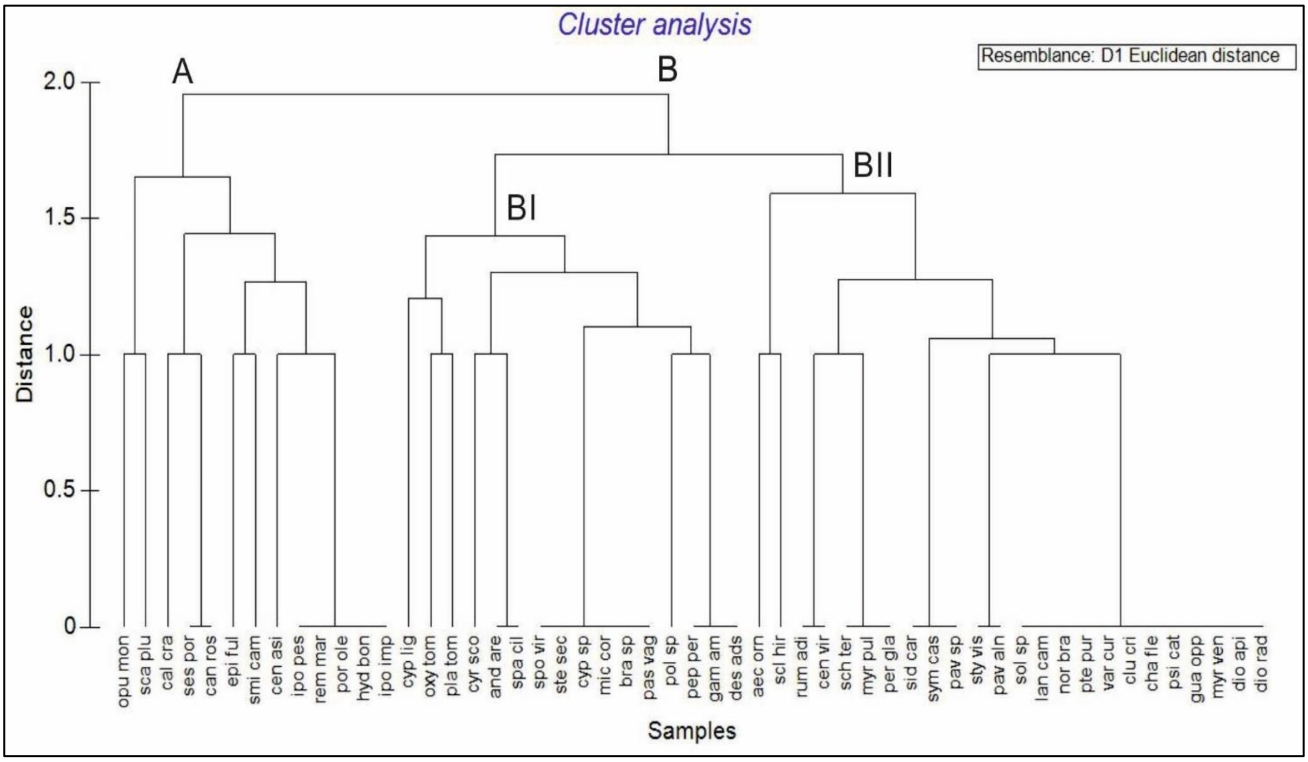


Figura 4. Dendrogram of plant species showing the following main clusters: A = Type II), B1 = Type III, and BII = Type I.

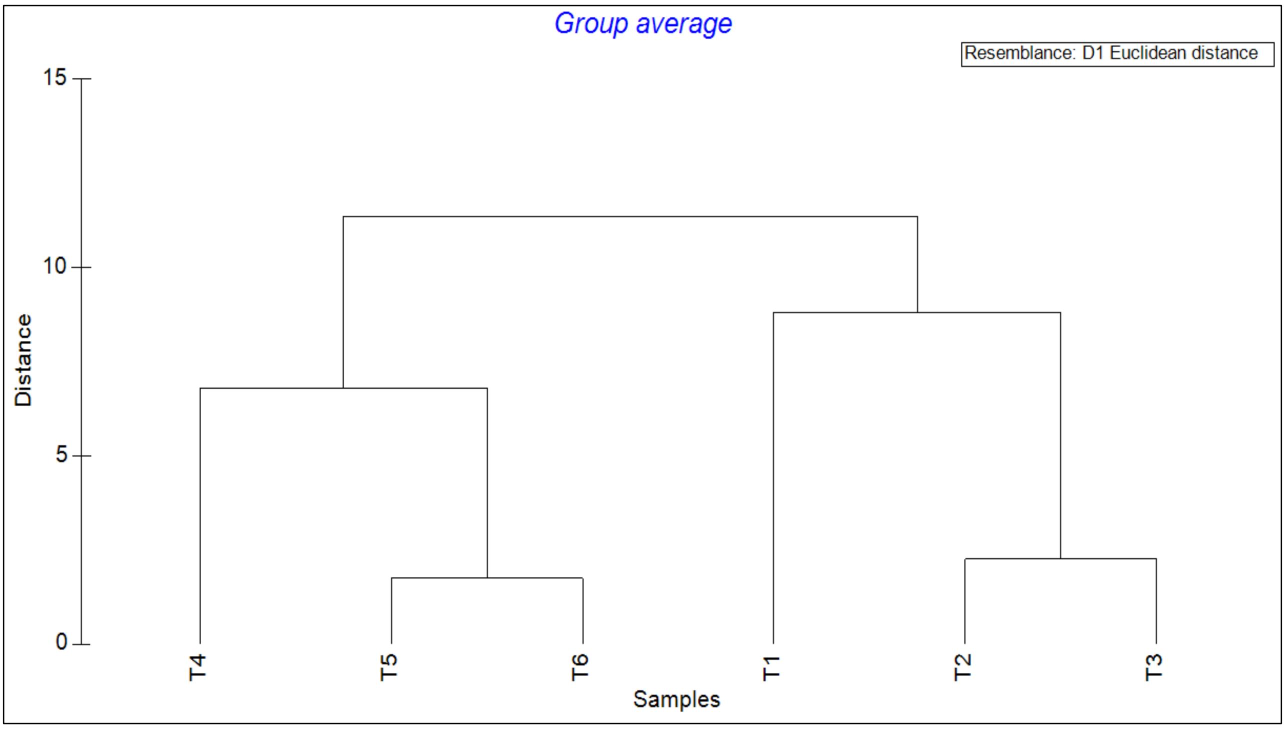


Figura 5. Dendrogram of cluster analysis partial CDVI for São Francisco do Sul Island.

Table 5. Species found along transects on the Acaraí State Park. Legend: Life forms (Fv): herb (e), subshrub (sa), shrub (ab) and tree (av). Zone: A (north) and B (south). Plant functional types (PFT): I, II and III.

Familie	Species	Popular name	FV	Zone	PFT
Aizoaceae	*Sesuvium portulacastrum* (L.) L.	Bredo-da-praia	e	B	II
Anacardiaceae	*Schinus terebinthifolius* Raddi	aroeira-vermelha	av	B	I
Apiaceae	*Centella asiatica* (L.) Urb.	Centelha	e	A	II
Araliaceae	*Hydrocotyle bonariensis*	erva-capitao	e	A, B	II
Apocynaceae	*Oxypetalum tomentosum* Wight ex Hook. & Arn.	Cipó-de-leite	e	A, B	III
Asteraceae	*Pterocaulon purpurascens* Malme	-	sa	A	I
Asteraceae	*Cyrtocymura scorpioides* (Lam.) H.Rob.	erva-preá	sa	A, B	III
Asteraceae	*Gamochaeta americana* (Mill.) Wedd.	Macelinha	e	A, B	III
Asteraceae	*Symphyopappus casarettoi* B.L. Rob.	Vassoura-do-campo	ab	A	I
Boraginaceae	*Varronia curassavica* (Jacq.) Roem & Schult.	Erva-baleeira	ab	B	I
Bromeliaceae	*Aechmea ornata* Baker	bromélia	e	B	I
Cactaceae	*Opuntia monacantha* Haw.	Palma	ab	B	II
Calyceraceae	*Calycera crassifolia* (Miers.) Hicken	-	e	A	II
Clusiaceae	*Clusia criuva* Cambess.	Mangue-de-formiga	ab	B	I
Convolvulaceae	*Ipomoea imperati* (Vahl) Griseb.	Cipó-da-praia	e	A, B	II
Convolvulaceae	*Ipomoea pes-caprae* (L.) R. Br.	Pé-de-cabra	e	A	II
Cyperaceae	*Cyperus ligularis* L.	tiririca	e	A	III
Cyperaceae	*Cyperus sp*	-	e	A	II
Cyperaceae	*Remiera maritima* Aubl.	Capim-pinheirinho-da-praia	e	A, B	II
Cyperaceae	*Scleria hirtella* Sw.	Junco-de-cobra	e	B	I
Dryopteridaceae	*Rumohra adiantiformis*	-	e	B	I
Euphorbiaceae	*Microstachys corniculata* (Vahl) Griseb.	Granxuma-de-chifre	e	B	III
Fabaceae	*Canavalia rosea* (Sw.) DC.	Feijão-da-praia	e	A	II
Fabaceae	*Chamaecrista flexuosa* (L.) Greene	peninha	e	A	I
Fabaceae	*Centrosema virginianum* (L.) Benth	feijão-bravo	e	A	I
Fabaceae	*Desmodium adscendens* (Sw.) DC.	Pega-pega	e	A	III
Fabaceae	*Stylosanthes viscosa* (L.) Sw.	Vissitudo	sa	A	I

Goodeniaceae	*Scaevola plumieri* (L.) Vahl	mangue-da-praia	sa	A	II
Malvaceae	*Pavonia sp*	-	sa	A	I
Malvaceae	*Pavonia alnifolia*	-	sa	A	I
Malvaceae	*Sida carpinifolia* L.	mata-pasto	sa	A	I
Marcgraviaceae	*Norantea brasiliensis* Choisy	cachimbeira	ab	B	I
Myrtaceae	*Myrcia pulchra* (O.Berg) Kiaersk.	-	ab	B	I
Myrtaceae	*Psidium cattleianum* Sabine	araçá	ab	A	I
Nyctaginaceae	*Guapira opposita* (Vell.) Reitz	maria-mole	ab	B	I
Orchidaceae	*Epidendrum fulgens* Brongn.	Orquídea-da-praia	e	B	II
Peraceae	*Pera glabrata* Poepp. Ex Baill.	Coração-de-bugre	ab	B	I
Piperaceae	*Peperomia pereskiaefolia* (Jacq.) Kunth	-	e	B	III
Plantaginaceae	*Plantago tomentosa* Lam.	Tansagem	e	A	III
Poaceae	*Andropogon arenarius Hack.*	Capim-da-praia	e	A	III
Poaceae	*Brachiaria sp*	-	e	A	III
Poaceae	*Paspalum vaginatum* Sw.	Arame-da-praia	e	B	III
Poaceae	*Spartina ciliata* Brongn.	Capim-da-praia	e	A, B	III
Poaceae	*Sporobolus virginicus* (L.) Kunth	capim	e	B	III
Poaceae	*Stenotaphrum secundatum* (Walter) Kuntze	grama-santo-agostinho	e	A, B	III
Polypodiaceae	*Polypodium sp*	-	e	B	III
Portulacaceae	*Portulaca oleracea* L.	capanga	e	A	II
Primulaceae	*Myrsine venosa* A.DC.	capororoca	av	B	I
Rubiaceae	*Diodella apiculata*	engana-bobo	e	B	I
Rubiaceae	*Diodella radula* (Willd. Ex Roem. & Schult.) Delprete	erva-de-lagarto	e	B	I
Smilacaceae	*Smilax campestris* Griseb.	Salsaparrilha	e	A, B	II
Solanaceae	*Solanum* sp	-	e	B	I
Verbenaceae	*Lantana camara* L.	camará	sa	B	I

5. DISCUSSION

The CDVI showed average vulnerability values for the entire coast of Acaraí State Park, ranging from 0.42 to 0.48, considered as medium vulnerability to the two areas analyzed (A and B).

Among the five parameters used in this study the GCD was the one which presented high to very high vulnerability values for all transects. (0.67 to 0.78). MI was also important with values between moderate to high in all transects (0.51 to 0.59). The other parameters (AE, VC and HE) showed values of vulnerability among low and medium (0.14 to 0.50).

In zone A, all the transects (T1, T2 and T3) showed medium vulnerability (0.25 < CDVI ≤ 0.5 = medium risk), ranging from 0.45 to 0.49. This zone is characterized by parabolic dunes up to 15 m high, well developed, but wide blowouts interrupt their regularity. The beach is subjected to erosion processes (GCD partial vulnerability as very high risk) that at times produced the demolition of the frontal dune and the generation of a steep scarp at the transition between the backshore and the dunes. These results are consistent with other studies described for beaches of the north of the State of Santa Catarina (Abreu, 2011). The loss of frontal dune and embryo dune causes not only in the loss of physical territory but also biodiversity loss (Maun, 2009), resulting in a breakdown of the biological successional process (Ciccarelli, 2014). The partial MI was classified as high risk for transects (ranging from 0.51 to 0.59), almost in limit the very high risk category. The partial AE were considered medium risk, although the T1 (0.16) have presented partial indexes of low risk. May be the presence of the Ponta Alta promontory generates modifications in the local hydrodynamics as described in Abreu (2011). The partial VC was ranging from 0.38 to 0.48 (0.25 < CDVI ≤ 0.5 = medium risk). This environment presents greater biodiversity of species compared to Zone B, but the presence of exotic species: Centella asiatica, Cyperus sp, Brachiaria sp and Portulaca oleracea. The most common species found were: Scaevola plumieri, Ipomoea imperati and Ipomoea pes-caprae. Human pressure (HE was the same for all transects, 0.35 – medium risk) is significant in this portion of the beach. In fact, the height of the dunes draws the interest of those who want to test their vehicles off the regular roads, causing relevant damage to the natural configuration of the dunes, intensified in the summer period.

In Zone B, the transects showed medium vulnerability (0.25 < CDVI ≤ 0.5 = medium risk), ranging from 0.42 to 0.48. The lowest total vulnerability in T4 (0.37) may be influenced by the presence of the Tamboretes Islands about 5 km offshore, which likely induce wave diffraction processes, generates modifications in the local hydrodynamics. The influence of this physical barrier near offshore was also discussed in the work Abreu (2011). This zone is characterized by transverse dunes of the lower height (hardly over 7 m) almost entirely covered by vegetation fixed. It was not observed the presence of mobile dunes, only front and fixed dune. The partial GCD showed very high risk for all transects (ranging from 0.78 to 0.71). The MI was high risk (0.5 < CDVI ≤ 0.6), ranging from 0.55 to 0.59. The AE ranging from 0.33 to 0.50. A partial VC was medium risk (ranging from 0.30 to 0.44), having the vegetation coverage more dense that the zone A and with rapid transition from herbaceous to vegetation shrub. The T4 was presented the lowest vulnerability, may be justified by the greater distance from the urbanized area of the beach Ervino.

It has been observed, especially in this zone, to remove irregular of species Rumohra adiantiformis for use, possibly, in floriculture of the region. The partial HE was practically absent in all transects (0.14). probably justified by the greater distance from the area to urban centers, being respectively the T6 Ervino Beach (south), 2 km long and T4 Praia Grande (north), 11 km.

6. CONCLUSION

The result of this work, based on multidisciplinary parameters, can be classified as medium vulnerability. In particular, the geomorphological factor must be strictly monitored at Grande beach, because the wide blowouts in Zona A and the frontal dune retreat raise some concerns. The high partial values of GCD and MI parameters possibly depend on the tight correlation between geomorphological aspects and coastal morphodynamics with the characteristics of the oceanic environment, where the exposure to wave energy is higher. Although limited to the areas where it was applied, the CDVI provided useful insights about the state of the dunes at Grande beach and proved to be a valuable tool as a guiding management policy to the coast of Sao Francisco do Sul. As a matter of fact, it is suggested to coastal management to monitoring the accretion/retreat ratio of the beach system, especially after strong storms, in order to understand whether this is a cyclic or erosive affect.

In addition, the CDVI can be easily implemented with new variables and applied frequently to check the evolution of the site on a regular basis.

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PAPER VII

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Vulnerability Assessment of a Coastal Dune System at São Francisco do Sul Island, Santa Catarina, Brazil

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Abstract. In this paper a Coastal Dune Vulnerability Index (CDVI) has been applied on a beach located in the eastern side of São Francisco do Sul Island (Brazil). The aim of this study is to assess the vulnerability of a coastal dune system and to identify the areas that result most sensitive to environmental changes. The CDVI has been applied along six transects traced out on two sectors that have been selected based on dune characteristics: Zone A is characterized by well developed parabolic dunes, whereas Zone B is characterized by transverse dunes. The analysis involved 51 quantitative and qualitative variables, divided into five groups: geomorphological dune system condition, marine influence, Aeolian effect, vegetation condition and human effect. The total CDVI was computed as the unweighted average of the partial vulnerability indices. In summary, the total vulnerability can be classified as medium: the geomorphological factor must be monitored at Grande beach, in particular the blowouts in Zone A and the frontal dune retreat in Zone B. The results of the study confirm that the management of coastal areas might be improved using a tool such as the CDVI, which can be easily applied on a regular basis to take under control the factors that mostly affect the evolution of the site.

1. Introduction

Coastal areas have always exerted a great attraction to humans due to economic, social or recreational reasons. Being highly valued social environments that are accompanied by a high risk to extreme weather conditions, they are in need of an aware management and conservation [1, 2]. According to the IBGE, in 2011 about 50.7 million Brazilians occupy coastal areas or areas near the coast, which corresponds to 26.6% of the inhabitants of the entire country. Moreover, the intensity of tropical and extratropical storms will increase in the next decades adding up to climate change and rising sea level, making the coastal areas extremely vulnerable [3, 4]). The northern coast of Santa Catarina is not known historically for recurrent natural disasters such as cyclones or frequent and intense storms. Regardless, it is already experiencing serious environmental problems such as coastal erosion, degradation of the dunes, urbanization, pollution and loss of biodiversity. However, assessing the environmental vulnerability in disturbed areas can provide important short-to-medium term information. Currently, there are many models and tools to assess coastal vulnerability that differ in complexity, scales and in their outputs [5]. The most commonly used are index-based or indicator-based approaches including related GIS applications, decision support systems and computer models (ETC-CCA [6]). In literature, the concept of vulnerability is associated with the tendency or the predisposition to be negatively affected by natural or anthropogenic factors (IPCC [4]), while system resilience adapts to these conditions [7]. The aim of this work was to apply a Coastal Dune Vulnerability Index (CDVI) on a dune field formed in oceanic environment following the index proposed by Ciccarelli et al. [8] for the Mediterranean coasts. The results of the study further suggest that assessing the vulnerability of coastal dune systems with an easy to use instrument as the CDVI might be a valuable support to improve the management of coastal areas, in particular those subjected to erosion issues.

2. Study areas

São Francisco do Sul Island is located in the northern portion of the state of Santa Catarina, southern Brazil (Figure 1). The climate is mesothermic (Cfa) in accordance with the classification of Köppen [9]; the annual rain precipitation is comprised between 1000 and 1500 mm, while the annual average temperature ranges between 16 and 20°C, [10]. The most frequent wind direction is from SW, subordinately from NE and S. The predominant wave directions are from SE and E. The tidal regimen is mesotidal, ranging on average between 1.3 m and 1.9 m [11].

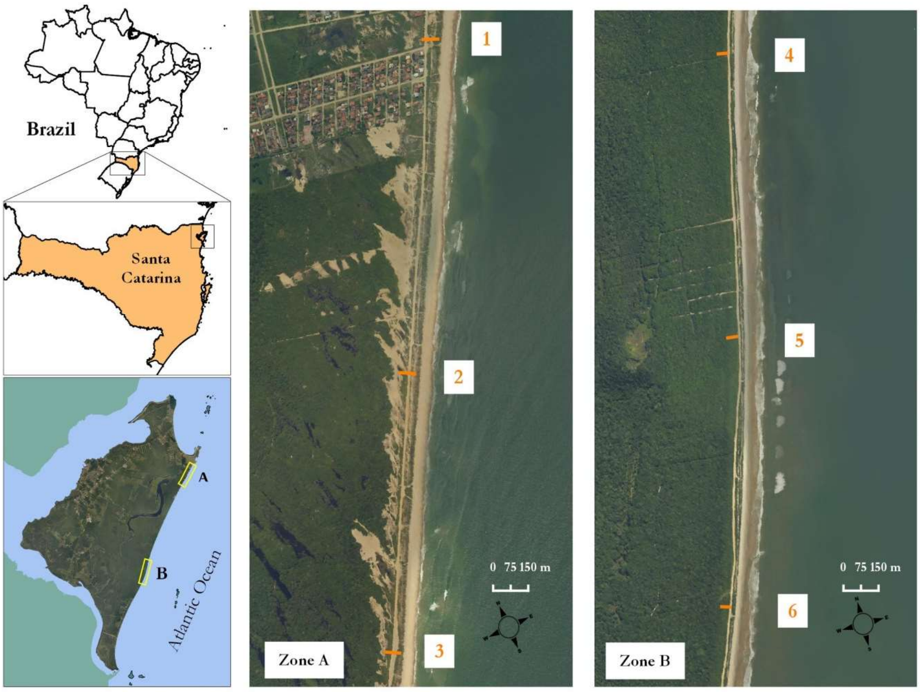

Figure 1. Geographical localization of São Francisco do Sul Island. Middle and right maps represent the detail of Zone A and Zone B; the progressive numbers associated to the orange lines point out the transects where the CDVI have been calculated

The evaluation of the vulnerability index has been done on two sectors (Zone A and Zone B) of the largest beach on the island, Grande beach (Figure 1). These sites are located toward the northernmost (Zone A) and the central (Zone B) portion of the beach, which are characterized by two different dune types: parabolic dunes prevail in Zone A, whereas transverse dunes are predominant in Zone B.

Another relevant difference between the two areas is the human impact: Zone A is strongly affected by urbanization, while Zone B is more preserved. Both sites are encompassed within the limits of the Acaraí State Park (Figure 1). As a matter of fact, this specific area has been selected because of its naturalistic relevance, being considered as the largest remaining sector of Santa Catarina characterized by the *restinga* vegetation, which is in extreme need of biodiversity conservation [12].

3. Methods

The CDVI was calculated according to the protocol for the Mediterranean coasts proposed by Ciccarelli et al. [8], which was modified after García-Mora et al. [13] to meet the needs of local features. To adapt the CDVI to the oceanic setting, length and distance measures have been expressed in kilometers rather than meters. A total of six transects perpendicular to the coastline were traced out on two separate sectors (Zone A and Zone B) along Grande beach (Figure 1). The transects were spaced 1 km and started from the shoreline to the woody vegetation. The CDVI was calculated taking into account 51 quantitative and qualitative variables distributed in five greater groups: geomorphological dune system condition (GCD), marine influence (MI), aeolian effect (AE), vegetation condition (VC) and human effect (HE). To calculate the index, each variable was associated with a five-point scale, ranging from 0 (no vulnerability) to 4 (very high vulnerability). In each group, the sum of the variables was divided by the sum of the maximum achievable rating within each group, thus generating a partial index expressed as a percentage, classified in four categories: i) CDVI < 0.25 = low risk; ii) 0.25 < CDVI ≤ 0.5 = medium risk; iii) 0.5 < CDVI ≤ 0.6 = high risk; iv) CDVI ≥ 0.6 = very high risk (following García-Mora et al. [13]). The final CDVI was calculated on the unweighted average of the five partial indices through the algorithm: CDVI = (GCD + MI + AE + VC + HE)/5.

4. Results and discussions

The resulting total CDVI values calculated along each transect do not show any significant difference between Zone A and Zone B and within both zones separately, ranging from 0.42 to 0.49 (Table 1). Based on this outcome, the total vulnerability of the sites can be classified as medium risk. Considering each parameter separately, no major differences can be observed as well. Only HE shows a clear separation comparing Zone A (0.35) with Zone B (0.14), thus implying that human activity is affecting less the southern sector rather than the northern one, which is actually closer to the village Praia Grande. Another exception is represented by the AE value along transect 1, which is lower relative to the other transects of Zone A (0.16 to 0.33): being the transect closest to the promontory located on the northern edge of the island, it might be affected by a partial screening of the wind (Abreu [14]).

Table 1. Partial and total CDVI values for each transect

Zone	Transect	Partial vulnerability					Total vulnerability
		GCD	MI	AE	VC	HE	
A	1	0.67	0.59	0.16	0.48	0.35	0.45
	2	0.78	0.51	0.33	0.47	0.35	0.49
	3	0.78	0.51	0.33	0.38	0.35	0.47
Average		0.74	0.53	0.27	0.44	0.35	0.47
B	4	0.78	0.55	0.33	0.30	0.14	0.42
	5	0.71	0.57	0.50	0.44	0.14	0.47
	6	0.71	0.59	0.50	0.44	0.14	0.48
Average		0.73	0.57	0.44	0.39	0.14	0.45

The radial plots show the impact of each parameter along the transects (Figure 2). Each axis of the plot corresponds to a vulnerability class. The vulnerability of the site is directly proportional to the surface of the radial plot: the larger the surface, the most vulnerable is the site. The parameter showing the highest CDVI values is GCD: along each transect the GCD is over 0.6, which means that the vulnerability is classified as very high risk. Zone A and Zone B present almost identical values on average (0.74 and 0.73 respectively); the lowest value (0.67 along the northernmost transect, that is transect 1) is likely a consequence of the modification on wave dynamics produced by the northern promontory as for the wind (Abreu [14]).

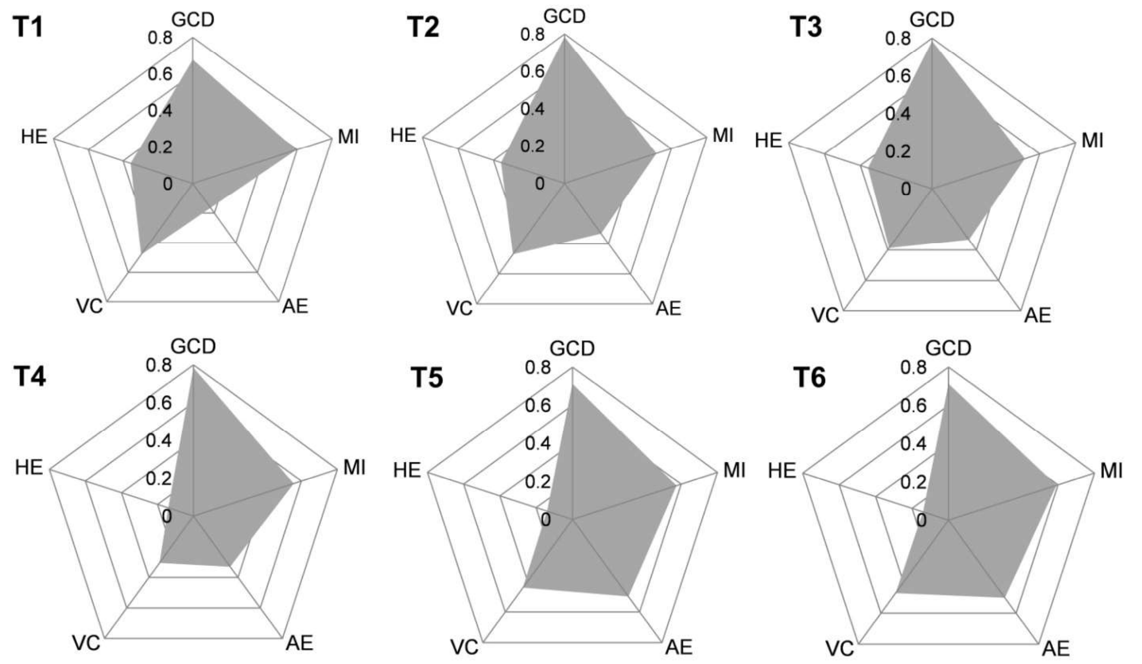

Figure 2. Radial plots showing partial CDVI values for each transect

The importance of the geomorphological factor on the area is obviously related to the ongoing erosion processes the beach is subjected to. As a matter of fact, the parabolic dunes characterizing Zone A show several large blowouts and the erosion of the frontal dune, which at times generates a steep scarp at the transition between the backshore and the dunes. The transverse dunes in Zone B are widely covered with fixed vegetation and do not show any blowout, but they are subjected to a strong erosion of the frontal dunes alike the dunes in the northern sector. The only other parameter whose CDVI values cross the threshold of 0.5 is MI (Table 1), but still is subordinate to the influence of GCD. GCD and MI parameters are both connected to wave and sea processes, which are relevant especially on an oceanic setting like Grande beach at São Francisco do Sul Island. Therefore, the higher energy of the oceanic environment might be responsible of the GCD parameter dominance on this site.

5. Conclusions

The application of the CDVI along Grande beach enabled to assess the vulnerability of two sectors of a coastal dune system at São Francisco do Sul Island. As a result, the total vulnerability for this site can be classified as medium: in particular, the geomorphological factor must be strictly monitored at Grande beach, because the wide blowouts in Zone A and the frontal dune retreat in Zone B rise some concerns. The high partial values of GCD and MI parameters possibly depend on the tight correlation between geomorphological aspects and coastal morphodynamics with the characteristics of the oceanic environment, where the exposure to wave energy is higher.

Although limited to the areas where it was applied, the CDVI provided useful insights about the state of the dunes at Grande beach and proved to be a valuable tool as a guiding management policy to the coast of São Francisco do Sul. As a matter of fact, it is suggested to coastal managers and stakeholders to monitor the accretion/retreat ratio of the beach system, especially after strong storms, in order to understand whether this is a cyclic effect or erosive effect. In addition, the CDVI can be easily implemented with new variables and applied frequently to check the evolution of the site on a regular basis.

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PAPER VIII

Coastal Dune Vulnerability Index (CDVI): An Integrated Tool to Support Coastal Management In Different Settings (Brazil and Italy)

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ABSTRACT

In this paper, the vulnerability of two dune fields from completely different settings (Atlantic Ocean and Mediterranean Sea) was defined through the assessment of a Coastal Dune Vulnerability Index (CDVI) adapted for the two sites. Five main groups of factors were taken into account in the design of the index: geomorphological conditions (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): therefore 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 and vegetation condition also resulted relevant on the Oceanic site and on the Mediterranean site respectively. The results emphasize the reliability of tools such as a CDVI to address the management of such environment, which are crucial to the economy and the ecosystem of most regions. Besides, its easy applicability on much different settings makes the index a ready-to-use instrument for anybody who runs the decisions on coastal areas.

Keywords: coastal dunes, vulnerability index, coastal management, Brazilian coast, Italian coast.

RESUMO

Nesse artigo, a vulnerabilidade de dois campos de dunas, de áreas completamente diferentes (Oceano Atlântico e Mar Mediterrâneo), foi definida através de um Índice de Vulnerabilidade de Duna Costeira (CDVI) adaptado para os dois locais. Cinco grupos principais de fatores foram considerados: condições geomorfológicas (GCD), influência marinha (MI), efeito eólico (EI), condição de vegetação (VC) e efeito humano (HE) para um total de 51 variáveis. O índice de vulnerabilidade total foi calculado para cada local. A análise cluster e o escalonamento multidimensional não métrico identificaram dois grupos principais, ambos caracterizados por valores médios de vulnerabilidade (0,32 a 0,49): portanto, a vulnerabilidade de ambos os sites pode ser definida como "média". O GCD foi o fator mais influente em ambas as configurações; Ainda, a influência marinha e a condição da vegetação também resultaram relevantes para as praias Oceânicas e nas praias do Mediterrâneo respectivamente. Os resultados fornecidos pelo presente trabalho enfatizam a confiabilidade da ferramenta como um CDVI para a gestão desse ambiente, que são cruciais para a economia e o ecossistema da maioria das regiões. Além disso, sua fácil aplicação em configurações muito diferentes torna o índice um instrumento pronto para uso para quem executa as decisões em áreas costeiras.

Palavras-chave: duna costeira, índice de vulnerabilidade, gestão costeira, costa brasileira, costa italiana.

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 dune 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 & Psuty, 2004; Maun, 2009; McLachlan *et al.*, 2013; Botero *et al.*, 2015). Additionally, the natural processes concur 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 of 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 & Ergin, 2010; IPCC, 2014; Germani *et al.,* 2015; Alsahli & AlHasem, 2016). Brazil is already suffering from the change in tidal regime and has been struggling to manage the effects of erosion all along its coasts (Mazzer, 2007; Mazzer & Dillenburg, 2009; Figueiredo, 2013; Ribeiro *et al.*, 2013; Lima & Amaral, 2015; Alquini *et al.,* submitted). In Brazil, 50,7 million people occupy coastal areas or areas near the coast (IBGE, 2011). Developed countries such as United States, Holland, England, Japan, Australia and Italy 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) (Sathler, 2014).

1.1. State of the art

The technological improvement in image acquisition, in developing more efficient index based tools and dynamic computational models contributed to the rapid scientific growth of coastal monitoring methods. 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 & Coelho, 2013; Ribeiro et al., 2013; Alexandrakis & Poulos, 2014). In addition, the index is easily upgradeable and the outcome is promptly understandable by coastal managers and practitioners (Satta et al., 2016).

In the last 15 years a significant increase in the production of scientific papers involving the use of coastal vulnerability to classify the quality and the state of coastal areas has been reported. In more detail, the vulnerability was correlated to three main factors: i) rising sea level and flooding (Vafeidis et al., 2008; Rao et al., 2008; Özyurt & 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 & AlHasem, 2016; Hereher, 2016); ii) erosion in the coastal zone (Menezes & Klein, 2006; Hegde & Reju, 2007; Boori, 2010; McLaughlin & Cooper, 2010; Palmer et al., 2011; Kane et al., 2012; Pereira & Coelho, 2013; Ribeiro et al., 2013; Alexandrakis & Poulos, 2014); iii) vulnerability to natural and anthropogenic disturbances (Martínez & Psuty, 2004; Martínez et al., 2006; Williams et al., 2011; Tabajara et al., 2013; Portz et al., 2014; Ribeiro & Melo Jr., 2016; Ciccarelli et al., submitted). The vulnerability can be understood as the result of an arrangement of different variables that are exposed to high-energy events and as the capacity of the system to recover from the effects of those conditions (Smit & Wandel, 2006; Ciccarelli et al., submitted).

The aim of this work is to apply a Coastal Dune Vulnerability Index (CDVI) on two sandy beaches located in the Atlantic Ocean (São Francisco do Sul, Brazil) and in the Mediterranean Sea (Pisa, Italy) in accordance with the index proposed by Ciccarelli et al. (submitted). In particular, the present study contributed to improve the knowledge about the factors that drive the evolution of beach–dune systems in both the Oceanic and the Mediterranean climates. In addition, the index is a multidisciplinary tool that can operate in different physio-geographical settings and can be easily integrated into strategic and coastal management plans.

1.2. Characterization of the working sites

This work 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 test 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/retreat state), vegetation cover and anthropization. On each sector 3 cross-shore transects were traced out from the shoreline to the woody vegetation, 12 transects as a whole.

São Francisco do Sul Island is located in the northern part of the Santa Catarina State (southern Brazil). The two sectors A and B are on the eastern coast along Grande beach, which is the island's longest beach (about 18 km long), facing the Atlantic Ocean. 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); the annual rain precipitation is comprised between 1000 and 1500 mm and the annual average temperature range between 16 and 20°C (Horn Filho, 1997). 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 m to 3.5 m; the littoral drift is northwards trending (Alquini *et al.*, 2016). Tidal range is mesotidal, on average between 1.3 m and 1.9 m (Bogo *et al.*, 2015). The beaches are generally composed of medium sands (Abreu, 2011).

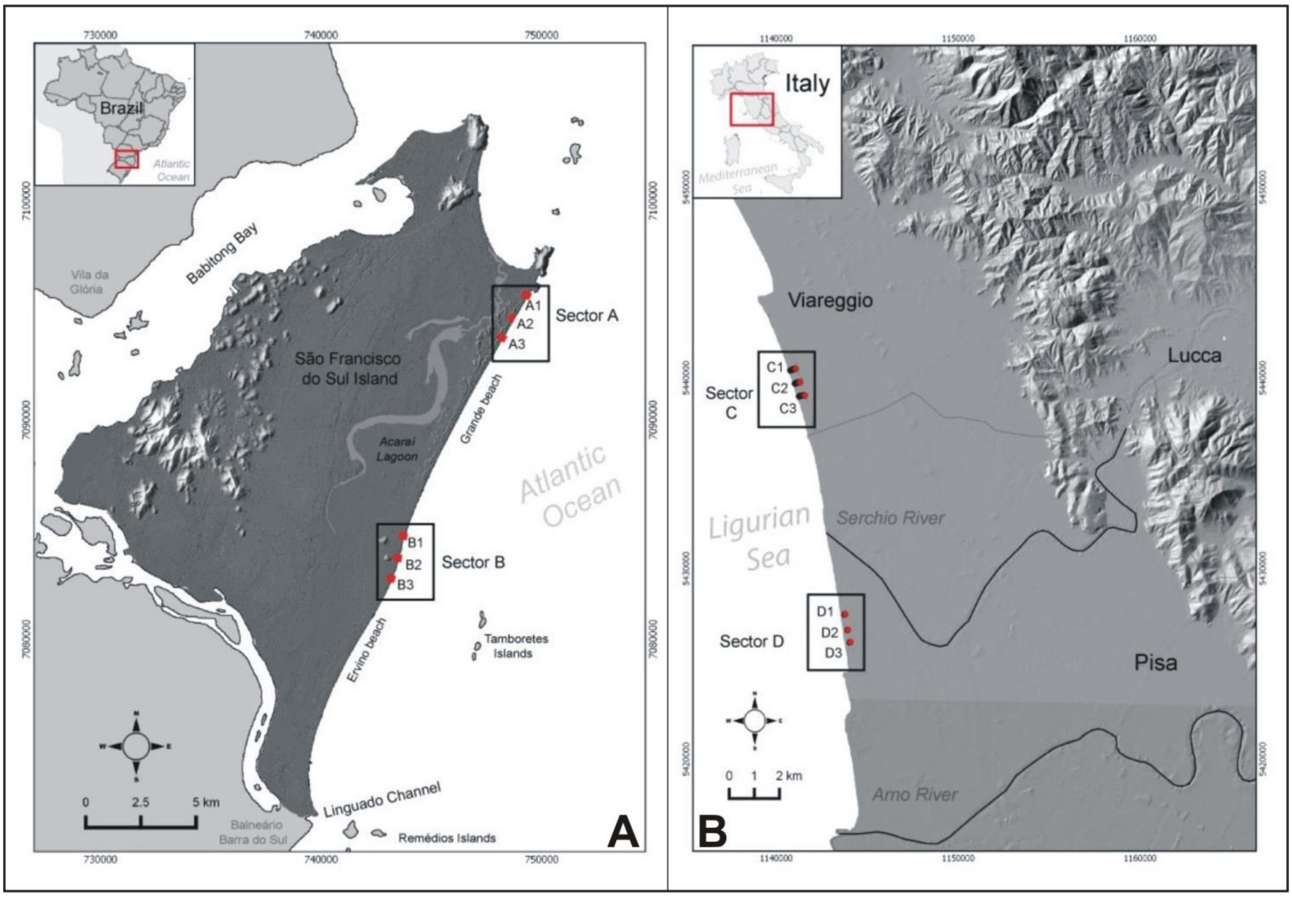

Figure 1. Localization of the study sites. A: Brazil; B: Italy. The four squares with three red dots each point out the exact location of the transects.

The Pisan coast is located in the central portion of Tuscany (western Italy). The two sectors C and D are along a stretch of coast extending for the entire length of the physiographic unit (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; Bertoni *et al.,* 2013). 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).

2. MATERIALS AND METHODS

2.1. 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. (submitted). The index takes into account 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 was calculated associating each variable to a five point scale, ranging from 0 (no vulnerability) to 4 (very high vulnerability). 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 final CDVI was calculated on the unweighted average of the five partial indices through the algorithm:

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

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.

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

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

2.2. Data collection for the beach system

The geomorphological variables (beach width and length, dune length and height, etc.) were defined through a series of topographic surveys using an RTK-DGPS instrument. The collected data were then processed in QGIS 2.8.2 in order to obtain indications about the topographic parameters of the beaches. 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 & Sarti, 2011; Ruocco et al., 2014). Sample collection and analysis followed the procedure used in the

Mediterranean site, which is comprehensively described in Ruocco et al. (2014). 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., submitted) 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 percentage of vegetation coverage was visually estimated (plots of 2 x 2 m) along the transects of each sector according to the procedure described in Causton (1988). 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 & 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 aerial images were shot in 2010 for the Brazilian site and in 2013 for the Italian site. 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 on regards to the variable “visitor pressure”.

2.3. Statistical analysis

The PFT classification was obtained using cluster analysis and Euclidean distance as the dissimilarity index following García-Mora et al. (1999). Two separate matrices, one for the Brazilian site and one for the Italian site, with seven plant traits were arranged including all the species occurring on each site. About the vulnerability index, in order to investigate the relationship between the variables and the two sites, a matrix of 51 variables for 12 sites was compiled and processed by cluster analysis using Euclidean distance as the dissimilarity index. The outcome was subjected to a non-metric multidimensional scaling (NMDS) with a Spearman correlation coefficient > 0.8. Finally, an analysis of variance (ANOVA) including the partial values of vulnerable groups (I and II) and subgroups (IA, IB, IIA and IIB) was carried out in order to check for significant differences between the values. Each statistical analysis was calculated with the software Primer 6.0 and Excel.

3. 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 site, while 0.35 for the Italian site. The partial GCD presented 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 (IA, IB, IIA and IIB), with a Euclidean distance of ~14% (Figure 2).

Two separate groups can be pointed out: Group I, characterized by the Brazilian sites (A1 – B3) and further divided into two subgroups IA (B1, B2 and B3) and IB (A1, A2 and A3); Group II, characterized by the Italian sites (C1 – D3) and further divided into two subgroups IIA (C1, C2 and C3) and IIB (D1, D2 and D3).

Table 2. Partial and total CDVI for each sampling site. Abbreviations: GCD: Geomorphological condition of 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*

The NMDS computation (Figure 3) resulted in a distinct separation (horizontal axis) between Mediterranean and Oceanic sites (stress value of 0.04) and between Zone A and Zone B (vertical axis). The Brazilian sites were dominated along the horizontal axis by human effect (HE7), marine influence (MI4, MI7) and geomorphological factors (GCD1), while the vertical axis was particularly influenced by marine influence (MI6, MI3, MI8, MI2). The Italian sites resulted to be mainly affected by human effect (HE1, HE2) and vegetation conditions (VC6) along the horizontal axis, and by aeolian effect (AE6), geomorphological factors (GCD2) and human effect (HE16) along the vertical axis.

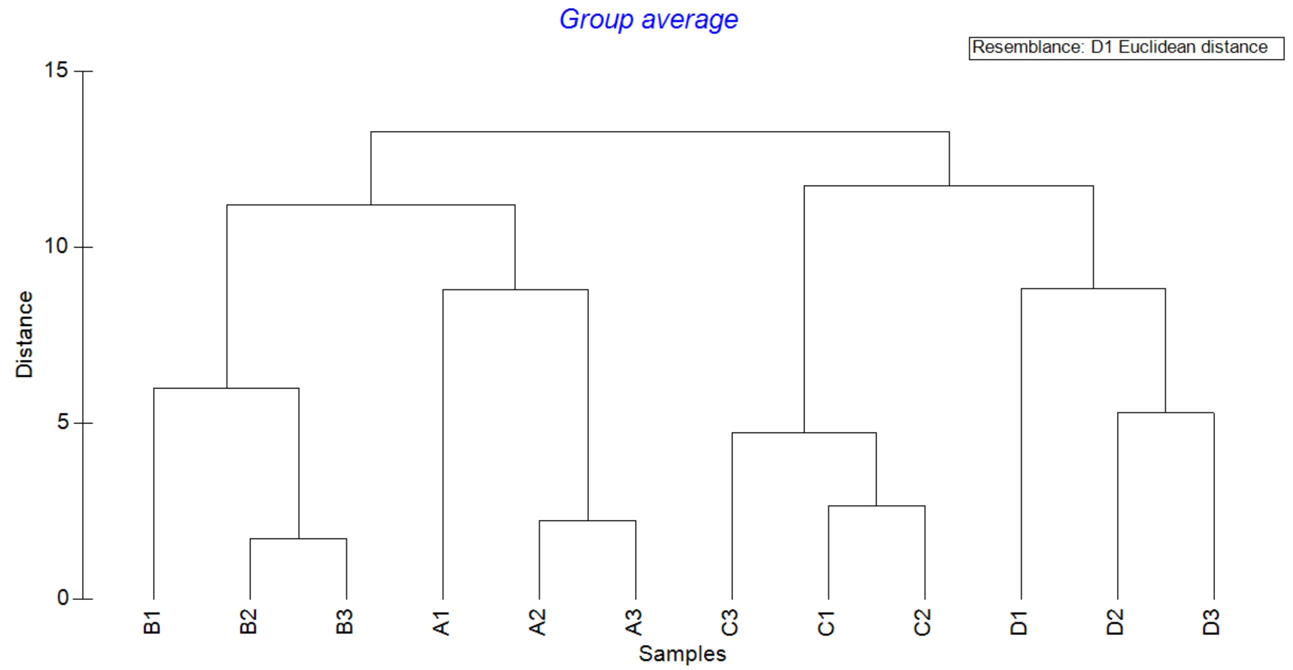

Figure 2. Dendrogram of 12 costal dune sites according to partial CDVI.

In the Brazilian sites (Table 3 and Figure 4), the analysis of the average CDVI of subgroup IA (B1, B2 and B3) showed high values of GCD (0.73) and low values of HE (0.14). On the contrary, subgroup IB (A1, A2 and A3) showed high values of GCD (0.74), medium values of MI (0.53) and moderate value of AE (0.27). In the Italian sites (Table 3 and Figure 5), the analysis of the average CDVI revealed that subgroup IIA (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 subgroup IIB (D1, D2 and D3) by high values of GCD (0.75) and low values of MI and HE (0.19).

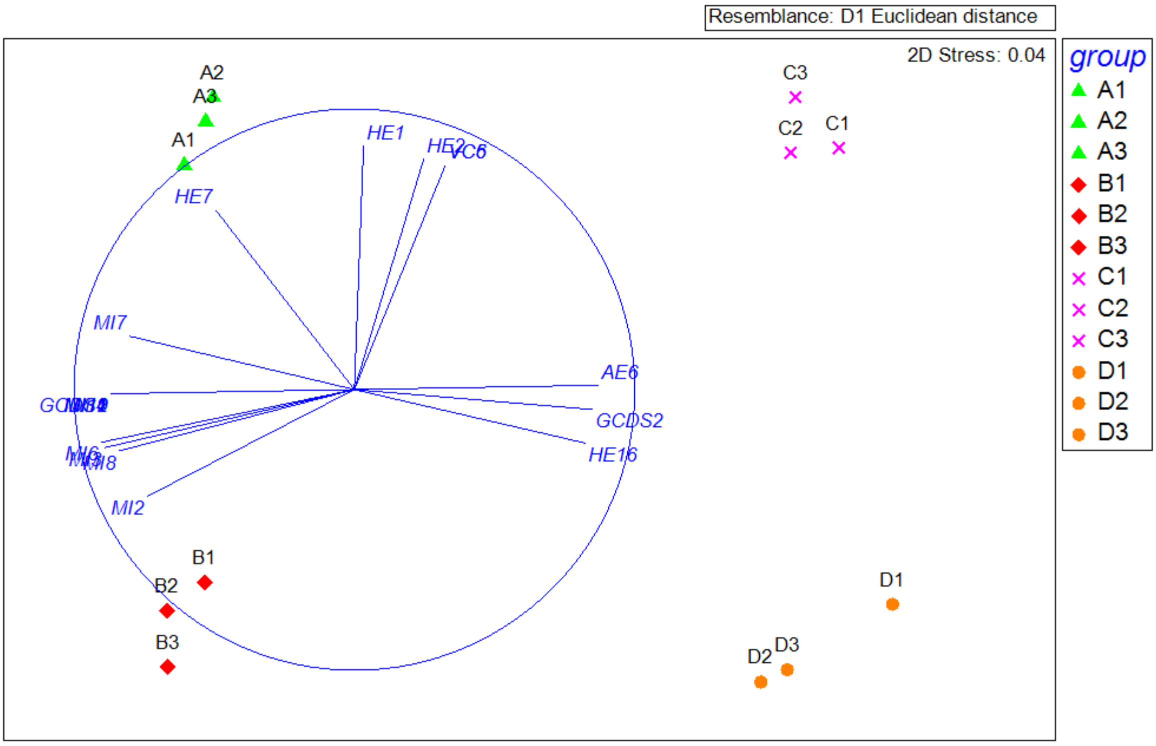

Figure 3. NMDS diagram based on dissimilarity (measured by Euclidean distance) for 12 dune sites. Abbreviations: visitor pressure (HE1), visitor frequency (HE2), relative proportion of alien species in the seaside of the frontal dune (VC6), percentage of vegetated seaward dune (AE6), average height of second dunes (GCD2), grazing on the active dunes (HE16), berm slope (MI2), 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).

The ANOVA results (Table 3) are significant if all CDVI values are taken into account as a whole (p-value 0.011); however, the results are not as much significant if the values are considered one at a time for each group (IA, IB, IIA and IIB).

Table 3. Mean values of partial CDVI calculated for each group defined by cluster analysis.

Group	IA	IB	IIA	IIB
GCD	0.73 ± 0.04	0.74 ± 0.06	0.59 ± 0.06	0.75 ± 0.04
MI	0.57 ± 0.02	0.53 ± 0.05	0.13 ± 0.00	0.19 ± 0.02
AE	0.44 ± 0.09	0.27 ± 0.10	0.21 ± 0.00	0.42 ± 0.08
VC	0.39 ± 0.08	0.44 ± 0.06	0.45 ± 0.07	0.43 ± 0.14
HE	0.14 ± 0.00	0.35 ± 0.00	0.26 ± 0.01	0.19 ± 0.05
CDVI	0.45 ± 0.03	0.47 ± 0.02	0.33 ± 0.01	0.40 ± 0.03

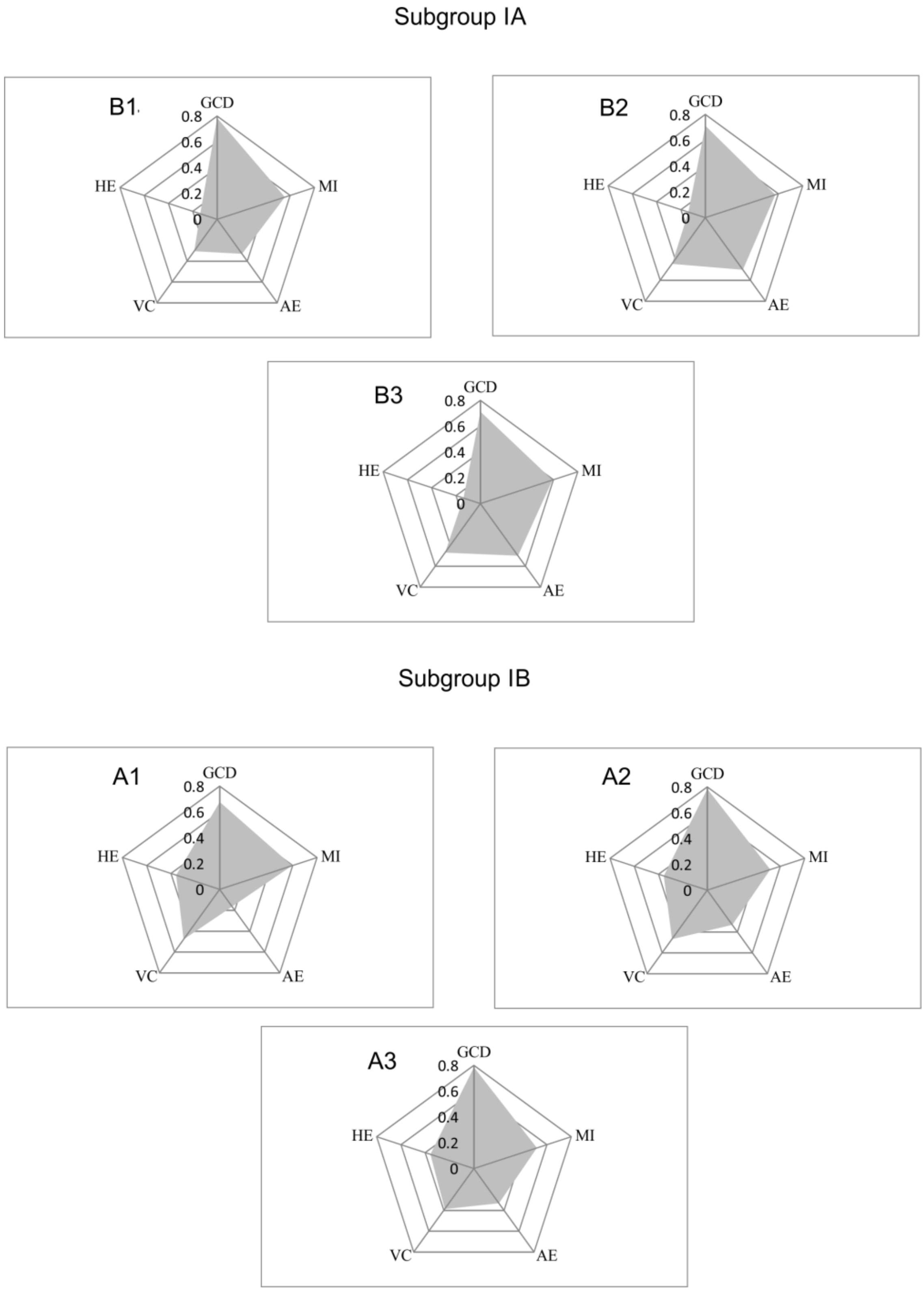

Figure 4. Graphical representation of CDVI partial values for subgroups IA and IB.

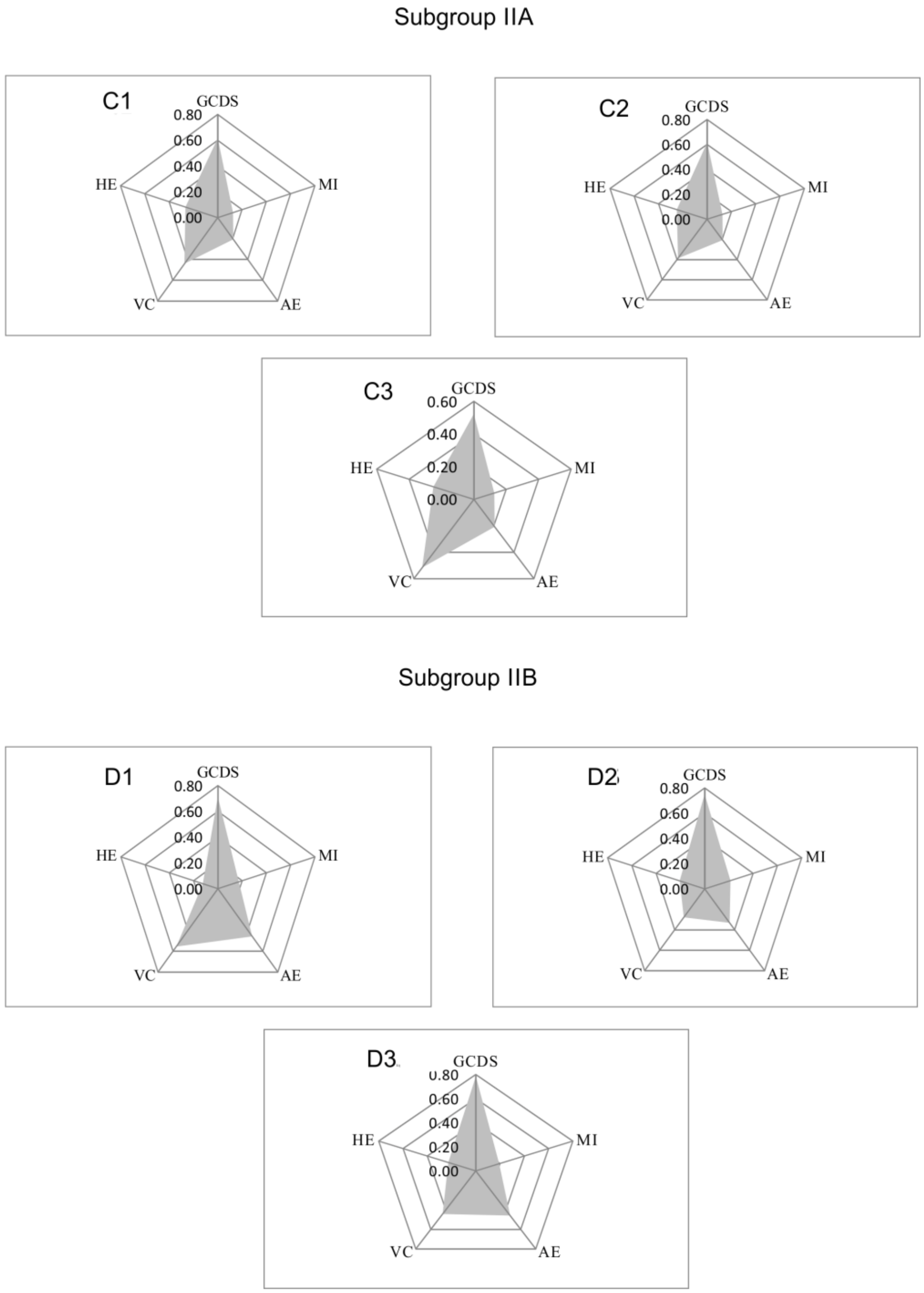

Figure 5. Graphical representation of CDVI partial values for subgroups IIA and IIB.

4. DISCUSSION

Based on all the analyses performed within the present work, the overall vulnerability for the two investigated sites can be classified as medium, ranging from 0.32 (C2 and C3) to 0.49 (A2). In particular, GCD resulted to be the factor that exerts more influence on both settings (ranging from 0.52 to 0.79); subordinately, MI affects the Oceanic sites (medium, 0.55), while VC the Mediterranean sites (medium, 0.43). The NMDS, used to describe the environmental characteristics that most closely correlate to each of the analyzed dune fields, showed that for the Oceanic sites the dune system can be divided in two different environments, mainly influenced by GCD, MI and HE variables. The variables characterized by higher values are: berm slope, particle size of beach, width of intertidal zone, length of homogeneous active dune systems, tidal range, breaches in the frontal dune and path percentage of the frontal dune.

The resulting vulnerability at the São Francisco do Sul Island falls in the medium interval (0.46). The group IB (A1, A2 and A3) includes the sites localized in the northern sector of the São Francisco do Sul Island, which are characterized by parabolic dunes of NNE orientation, maximum backshore width of 25 m and maximum frontal dune height of 6 m. 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. Erosion is a global problem at present times (Brunelli, 2008), 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 & Muehe, 2008; Abreu, 2011). 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). The cluster analysis showed that VC is defined by medium vulnerability (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 & Pammenter, 2004); in addition, they usually reduce the reproduction rate in stable environmental conditions (Maun, 1985). Besides, the proximity of this area to the beach resorts built on Grande beach produces high rates of human pressure, which 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 & Boeger, 2015).

On regards to group IA (B1, B2 and B3), the NMDS pointed out that visitor pressure and frequency, percentage of alien species, percentage of vegetated seaward dune, height of secondary dunes and grazing were the most critical variables for this site. The cluster analysis considered GCD, MI, AE and VC as the most vulnerable parameters, 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 without blowout occurrence. Likewise the base of the foredunes is subjected to scouring processes: despite the erosion, 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.

For the Mediterranean sites, the vulnerability was classified as medium (0.35). The results remarked that the variables that mostly affected the vulnerability for group IIA (C1, C2 and C3) were visitor pressure, visitor frequency and percentage of alien species along the transect, while for group IIB the percentage of vegetated seaward dune, height of secondary dunes and grazing on the active system (Figure 3). As evidenced by the cluster analysis, the group IIA 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 favors 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. NMDS highlighted the percentage of alien species along transects (VC6) as a factor of separation between environments, which is represented by Oenothera biennis and Xanthium orientale in this habitat. 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 and beach resorts. 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, exotic species invasion, trampling, expansion of agricultural areas and fire are all aspects that influence the vulnerability assessment in this site.

The group IIB (composed of sites D1, D2 and D3) is characterized by significantly shorter profiles in comparison to group IIA; it is also highly variable in terms of morphological features (Bertoni & Sarti, 2011). The dune system can reach an 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 eventually its collapse. 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 confirm the stress caused by rapid morphological changes in the dunefield, which are not tolerated by all the species (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 cluster analysis showed that the significance of MI and HE can be defined as low in terms of vulnerability.

5. CONCLUSIONS

The results provided by the present work showed that the most significant controlling factors for either the Brazilian and the Italian settings belong to the geomorphological group (GCD). The morphology of the sand 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 that colonize the dunes vary geographically, but often share the same adaptive responses to the environment (Maun, 2009). In this contest, the CDVI might be perceived as a good tool to help decision-makers evaluate the options and take conscious decisions. The present study used a multidisciplinary approach, developed at a local scale, establishing tight correlations between the existing knowledge about the investigated sites and all the data gathered by ongoing surveys. The index can be used for different purposes, such as the prioritization of the factors that mostly affect shoreline evolution (Hegde & Reju, 2007; Alexandrakis & Poulos, 2014), human pressure (Coelho et al., 2006) and spatial/temporal evolution of the vulnerability (Idier et al., 2013). The promising results remarked 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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APPENDIX I

APPENDIX II