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

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ABSTRACT

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

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