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Regional variability of coastal dunes observed along the Emilia-Romagna littoral, Italy

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ABSTRACT

The knowledge of the evolution and conservation of the coastal dunes inside a beach–dune system is fundamental for their protection and for appropriate coastal management. We analyze and classify the coastal frontal dunes present along the Emilia-Romagna according to beach and dune characteristics as well as human activities by using aerial photographs and field measurements. Aeolian sand transport was calculated using a simple predictive equation. The results show that 62 coastal dune systems extending for 31 km are still bordering the 130 km coastline of the Emilia-Romagna region and we observe an alongshore variability of the dune's characteristics. This variability is controlled by the sedimentary budget, beach orientation to the wind-wave direction and human impacts. Four groups of frontal dunes are identified through factorial analysis: two groups are natural dunes, while the other two display characteristics that demonstrate the consequences of human activities. However, the dunes that present the worst conditions are natural dunes corresponding to regressive forms. It also appears that human intervention, when the human impacts have cancelled the original characteristics of the dunes or have obstructed the formation and growth of incipient dunes, have allowed their conservation and protection. We therefore suggest that the dunes presenting the worst conditions, which are often bordered by a narrow beach, need to be protected, considering that the most efficient protection of the dune is provided by a wide, stable beach. This highlights how successful beach nourishment has a positive impact on the foredune's systems favoring their development and conservation.

1. Introduction

Coastal dunes represent fundamental geomorphological features for the beach equilibrium. They provide several functions such as providing a protective buffer against erosion and are in addition, ecological niches (Psuty, 2004). However, coastal dune systems are today particularly fragile environments and several potential dangers threaten them. Dune formation, evolution and conservation is under threat due to both natural factors and human activities. The present work deals with the development and evolution of the coastal dunes still present in the upper part of the beach along the Emilia-Romagna littoral. The foredune's origin was first explained by the dynamic binomial sand-vegetation method of Burollet (1923) and successively by the sand–wind-vegetation trinomial, and more recently, the effect of human activities has been included. Today, the morphology, dimension and development of foredunes are determined by various factors such as sand supply (Psuty, 1988; 2004; Sherman and Bauer, 1993; Aagaard et al., 2004), sediment transport rate (Nickling and Davidson-Arnott, 1990; Bauer and Davidson-Arnott, 2002; Bauer et al., 2009 Namikas et al., 2010; Delgado-Fernandez, 2011), wave and wind forces (Short and Hesp, 1982; Hesp, 1988; Carter and Wilson, 1990; Ruz and Allard, 1994), wind flow over dunes (Rasmussen, 1989; Arens et al., 1995; Hesp et al., 2005; Walker et al., 2006), long-term beach state (Carter, 1988; Psuty, 1992; Davidson-Arnott et al., 2005), occurrence and magnitude of storm events (Orford et al., 1991; Davidson-Arnott and Law, 1996; Giles and McCann, 1997; Morton, 2002) and vegetation cover (Hesp, 1988; Ruz and Allard, 1994; Arens, 1996; Martinez et al., 2001; Miot da Silva et al., 2008).

Many other factors play a pivotal role in sediment delivery and in the dune's morphological variability. For instance, the sediment availability is directly related to the beach width and the fetch but other factors limit the wind-driven sediment transport (sediment properties, moisture, species presence and beach geometry) (Short and Hesp, 1982; Hesp, 1988; 2002; Bauer and Davidson-Arnott, 2002; Anthony et al., 2006; de Vries et al.,

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2012). The variability of all these factors makes it difficult to define the changes of the actual sediment budget to the beaches and foredunes.

For most of the Mediterranean coastal areas, population growth and accelerated development of productive activities (tourism in particular) has led to tensions and conflicts regarding different uses of the coasts. In fact, coastal dune systems are under huge pressure due to sand loss by the construction industry, military usage, golf courses and seaside infrastructures. As reported by Van der Meulen and Salman (1996), during the previous 30 years almost 75% of Mediterranean coastal dunes had been damaged or destroyed mainly as a result of tourism. The remainder must therefore be managed with nature conservation as the main objective.

The interest of the scientific community and administrative institutions toward the management, protection and planning of coastal areas gained new visibility and political legitimacy with the establishment (World Coast Conference, 1993) of the Integrated Coastal Zone Management (ICZM) setting rules and procedures for proper management coastal zone resources, including dunes. In Emilia-Romagna, dunes are so rare and are at risk in many places such that implementing design procedures and methods of recovery, which can act as a supporting tool to intervention strategies, is the subject of much debate.

Beach–dune interaction models can be invaluable tools for land managers and policymakers. For instance, Cleary and Hosier (1979) identified a cycle of spatial–temporal dune stages based on storms and washover topographies. Short and Hesp (1982) studied beach–dune interaction with an emphasis on the morphodynamic response to wind and wave energy of the foredunes adjacent to modal beach states as described by Short (1979). Furthermore, the authors provided a global model that included additional wave-wind environments as described by Davies (1964). Indeed, the Psuty models (1988, 2004) provide a starting point for identifying the most important variables (beach and dune sediment supplies) for predicting foredune morphology and behavior. Sherman and Bauer's (1993) conceptual model relating beach and dune sediment budgets, assumes that vegetative factors within the dune system are secondary and that internal heterogeneities within individual beach and dune systems are unimportant.

Hesp (1999, 2002) synthesized the models of Hesp (1988), Carter (1988), Arens and Wiersma (1994) into a classification system based upon the morpho-ecological foredune states. Foster and Cheng (2001) provided a substitute for beach sediment supply used by Psuty (1988, 2004) and the erosion/accretion rate was used to identify a pattern, or groupings, of foredunes in different stages of a cycle of development from incipient and low dune forms, to larger foredunes. Recently, Houser (2009) and Houser and Hamilton (2009) found that the nature and timing of storm occurrences are critical to beach–dune development.

However, current knowledge as outlined by Hesp (2002) is far from satisfactory for decision managers and, even the most accredited beach–dune interaction models (Short and Hesp, 1982; Psuty, 1988; Sherman and Bauer, 1993) are not applicable for all coastal systems. Human factors are often not considered. As a consequence, land use policies may be designed based on false pretenses or assumptions. This could lead to poor land management, resulting in long-term erosion and sustainability issues, and increased difficulties in maintaining the dynamic coastal systems that the policies were designed to protect.

The aim of this study is to map and characterize the coastal frontal dunes of the Emilia-Romagna still present and to describe their morphological evolution in relation to beach evolution and the use of the surrounding coastal area. Our study discusses the variability of the dune's characteristics related to sedimentary budget, beach orientation to wind direction and human impacts. Furthermore, by applying principal component analysis we identify different groups of frontal dunes, which represents a simplified, and therefore useful, tool for practical management purposes; and we present an evolutionary model that trends according to the importance and interference of variables, both natural and anthropogenic, acting on the beach–dune system.

2. Study area

The study area, about 110 km long, is located on the northern Adriatic coast between Cesenatico (South) and the Po Goro mouth (North) (Fig. 1). The coastal area consists of a low sandy coast, interrupted by vast lagoon areas (11.000 ha for the Comacchio valleys), harbor jetties and numerous hard coastal defense structures (Simeoni et al., 2006; 2010), which were built during the first half of the 20th century to protect the Emilia-Romagna littoral against erosion. These interventions, though mitigating erosion somewhat, have not been able to reverse the trend (ARPA, 2007).

The prevailing winds blow from between NNE and E (locally called Bora), from between ESE to SSE (Sirocco) and from NW (Maestrale) (Idroser, 1982). Most of the intense storm events come from N, NE and SSE with similar intensities. Due to the extension, orientation and morphology of the coast, the wind conditions are variable. Wind velocity is stronger from the shorter fetch sector of Bora reaching 18 m/s, whereas, from the longer fetch sector of Scirocco it seldom exceeds 16 m/s (ARPA Emilia-Romagna, 2002). Furthermore, the main wind directions vary along the Emilia-Romagna littoral (Brunelli, 2010).

At Lido di Volano winds blow principally from three main sectors: NW, NE and SE with a seasonal differentiation: during the spring and summer seasons the winds are essentially from between E and S while during autumn and winter the most intense winds blow from NE, E and SE. At Marina di Ravenna (Fig. 1), the main directions are from E and W. During the autumn and winter seasons the westerly winds increase while the most intense winds (velocity greater than 20 m/s) still blow from E. Finally, at Cesenatico, in autumn the most frequent winds are from W (40% of the wind) and the most intense are from N, E and SE, while during the winter period the dominant directions are from SE and NW.

The coast of Emilia-Romagna is semidiurnal microtidal with a mean average spring tidal range of about +0.4 m and extreme yearly values around +0.85 m. The coastline is characterized by medium-to-high wave energy conditions with an average significant wave height of about 1.5 m and a mean wave period from 7 to 9 s. Storm waves with a one-year return period, with directions NE–E–SE, have wave heights around 3 m and periods of 7.5 s (Idroser, 1996). The prevailing waves are principally from ENE and secondarily from ESE. The analysis of extreme waves that are divided into the three directions producing more severe effects on the coast (Bora 060°N, Levante 090°N and Scirocco 120°N) indicates that the exceeding frequency for high waves ($H_s > 5.8$ m) only occurs for Bora and Levante being nevertheless very limited (around 2% for both sectors, Martinelli et al., 2010)

According to the classification proposed by Wright et al. (1979), the beaches of Emilia-Romagna can be described as dissipative with a low nearshore slope and a wide surf zone. However this assertion seems to not represent the local situation since most of the active dunes that present evident "features" of erosion are bordered by a narrow beach and by a moderately steep nearshore (sometimes higher than 5°).

In the 19th century almost the entire Emilia-Romagna coast was bordered by a series of dunes (Cencini, 1980; Simeoni and Bondesan, 1997; Simeoni et al., 2006). These dune systems reached a length of a few kilometers and a width from 100 m to more than 700 m in the Rimini and the Ravenna provinces, respectively. At the end of that century, the first human interventions began to