Chapter 18
Coastal Dune Hazards

Sara Muñoz Vallés and Jesús Cambrollé

Abstract Coastal dunes constitute plastic systems with a recognized ecological, geomorphological, geological, historical, archaeological, scenic, cultural, and socio-economic value. Furthermore, coastal dunes play a relevant protective barrier role, preventing groundwater salinization due to intrusion of sea water and preserving other natural areas and human settlements from the effects of storm waves, tides and wind. Nevertheless, the current decline of coastal dunes has become in many cases a serious ecologic and economic problem. Dune stabilization, expansion of invasive plant species, anthropogenic impacts mainly associated to urban development and tourism, and effects of climate change are identified as the main current threats to these ecosystems. After examining the main hazards to coastal dunes, the current paradigm of coastal dunes management and conservation focuses on maintaining healthy, equilibrated and dynamic dunes, recovering their natural functioning, what needs for a major scientific-based knowledge of the entire dune systems functioning, the commitment of administrations, managers and urban and landscape planners, and the implementation of integrated coastal zone management programs, as well as a change of mentality toward new and more sustainable designs of development, respecting the coastal dune frame.

18.1 Coastal Dunes: Meaning, Functions and Status

Coastal dunes are aeolian sedimentary landforms originated from the combined action of waves and wind, that mainly develop in association with dissipative coasts dominated by the marine winds, and with an ample supply of loose, sand-sized sediment (Carter 1988; Martínez et al. 2004b; Van der Maarel 1993a). They are distributed worldwide, from polar to tropical latitudes, comprising very diverse

S. Muñoz Vallés (✉) • J. Cambrollé
Departamento de Biología Vegetal y Ecología, Universidad de Sevilla,
Avda. Reina Mercedes, S/N, Seville 41012, Spain
e-mail: saramval@us.es; cambrolle@us.es

C.W. Finkl (ed.), *Coastal Hazards*, Coastal Research Library 6,
DOI 10.1007/978-94-007-5234-4_18,

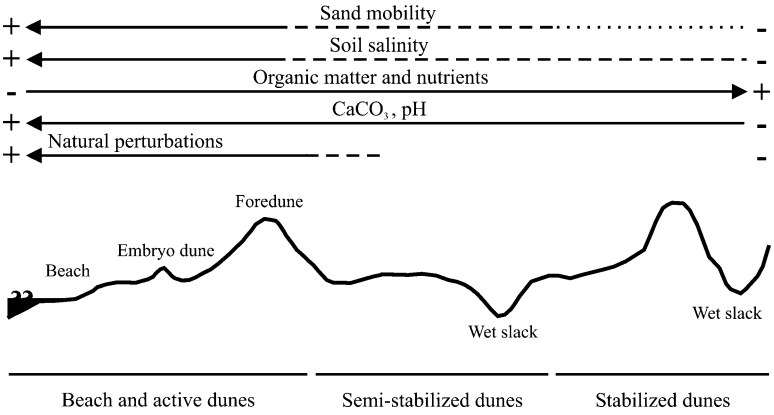

Fig. 18.1 Generalized environmental gradients on coastal dunes (based on Brown and McLachlan 1990; Carter 1988; Ley Vega de Seoane et al. 2011; and Muñoz Vallés, non published data)

climates and biomes, and occurring on ocean, lake and estuary shorelines, leading to a large variety of forms and dimensions related with spatial and temporal variations in sediment supply and wind regime (Hesp 2000, 2004; Nordstrom et al. 1990), but comprising a really limited global area. Located on the transition between two of the great systems of the biosphere, continents and oceans, they constitute very dynamic and plastic systems, linked to the constant sediment exchange between the sea, the beach and the more stable landwards dunes (Carter 1988; Ranwell 1972), and they suffer both natural and anthropogenic perturbations (Carter 1988; Hesp and Martínez 2007; Nordstrom 2008; Panario and Piñeiro 1997; Psuty 2004).

Coastal dunes support particular, complex ecosystems, where species of fauna and flora coexist with a harsh environment, characterized by the scarcity of water and nutrients, substrate mobility and sand burial, incidence of salt spray and sand blasting, high air and soil temperatures and light intensities in low and medium latitudes, and saltwater flooding in the strandline (Carter 1988; Chapman 1976; Heslenfeld et al. 2004; Martínez et al. 1993; Martínez et al. 2004b; Maun 1998, 2009; Ranwell 1972; Van der Maarel 1993b). Most of these factors are ordered in gradients from the shoreline and landwards, associated to the sea and marine winds influence (Fig. 18.1). A characteristic vegetation including unique species with specific adaptations to the environmental conditions establish on them, closely related with sediment dynamics and geomorphological processes of the dune, and continuously interacting with them (Carter 1988; Martínez et al. 1993; Ranwell 1972). All this results in dynamic systems with singular functioning, subjected to delicate equilibriums that originates, in addition, a particular type of landscape (Brown and Mclachlan 1990; Carter 1988; Ranwell 1972).

Apart from the ecological traits, coastal dune systems have a recognized geomorphological, geological, historical, archaeological, scenic, cultural, and socio-economic interest (Heslenfeld et al. 2004; Martínez et al. 2004b; Nordstrom et al. 2000; Van der

Meulen et al. 2004). In addition, coastal dunes play a relevant protective barrier role on the coast, dissipating energy and buffering the effects of storm waves, tides and wind, preventing groundwater salinization due to intrusion of sea water, and acting as sand reservoirs that preserve other natural areas (e.g. coastal wetlands) and human settlements (Carter 1988; Gómez-pina et al. 2002; Kidd 2001), which means an additional significant functional value.

Rates of alteration and degradation of natural ecosystems have notably increased since the last third of the last century (Carter 1988; Martínez et al. 2004a; Nilsson and Grelsson 1995), and this has led to the need to develop techniques and policies aiming the protection, conservation and management of ecosystems. Among the different coastal ecosystems, coastal dunes have suffered the highest degree of human pressure (Carter 1988; Holdgate 1993). Many coastal dune systems worldwide are being seriously degraded at present, some of them irreversibly altered, due to an excessive exploitation of the natural resources and services they offer (e.g. coastal defense, recreation, water and substrate extraction, agriculture, livestock grazing, etc.), as well as to the human demographic expansion and urban and industrial development (Baeyens and Martínez 2004; Carter 1988; Heslenfeld et al. 2004; Martínez et al. 2004a; Van der Meulen and Salman 1996; Williams et al. 1997; Williams et al. 2001). In this regard, most of the existing literature on coastal dune ecology focuses any chapter on the identification of present and potential threats and dune conservation approaches (e.g. Brown and McLachlan 1990; Carter 1988; García Novo et al. 1997; Martínez and Psuty 2004; Maun 2009; Packham and Willis 1997; Ranwell 1972). Different authors identify as the main current threats to these ecosystems both the anthropogenic habitat degradation and destruction (mainly associated to urban development and tourism), dune stabilization and eutrophication, and invasion by alochthonous species (Isermann et al. 2007; Jørgensen and Kollmann 2009; Kutiel et al. 2004). According to Nordstrom (2008), changes associated with the development of coastal areas for human use involves, among others, the loss of natural habitats and biodiversity (Beatly 1991), landscape fragmentation (Berlanga Robles and Ruiz Luna 2002), risks to endangered species (Melvin et al. 1991), reduction of seed sources and decrease on resilience of plant communities after storms in undeveloped areas adjacent to developed ones (Cunniff 1985) or loss of the original aesthetic and recreational value (Da Cruz 1996; Demirayak and Ulas 1996), and loss of natural heritage and image of the coast, among others. The human action is compounded by the effects of global warming and progressive sea level rise (Carter 1988; Panario and Piñeiro 1997; Tsoar 2005).

The following is an attempt to examine the main current hazards to coastal dunes and current approaches for conservation and management.

18.2 Dune Stabilization

Dune fixation and stabilization are terms that have been indistinctly used to refer the process involving the progressive reduction of sand movement. This reduction is closely related to an increase on the vegetation coverage, following a positive

feedback mechanism (Yizhaq et al. 2007), and it entails significant changes in the dune functioning, as well as in the type of communities growing on them (Kutiel et al. 2004; Levin and Ben-Dor 2004; Moreno-Casasola 1986; Muñoz Vallés et al. 2011b). The *stabilization* term has traditionally received a sense of natural process (e.g. Lichter 1998; Martínez et al. 2001; Olson 1958) and, subsequently, it has also been used to designate certain human actions aimed at controlling the excessive advance of sand dunes. On the other hand, *fixation* has been used more frequently in relation with those human actions.

Dune stabilization is a natural process of development in coastal dune succession, from embryo to mature dunes (see Fig. 18.1 in the Introduction section). Nevertheless, the recent increase of sands stability in coastal dunes in different parts of the world is becoming an important environmental problem, resulting in negative consequences to richness and diversity of plant and animal species (Alvarez and Cushman 2002; Avis 1995; Conser and Connor 2009; Isermann 2008b; Isermann et al. 2007; Kutiel et al. 2004; Marchante et al. 2008; Wiedemann and Pickart 1996). The stabilization process encompasses, not only the loss of sands mobility due to an increase on vegetation coverage, but also an increment of organic matter in the incipient soil, which increases the availability of both soil moisture and nitrogen (Connell and Slatyer 1977; Muñoz Vallés et al. 2011a, b; Olson 1958). It promotes changes in the richness and diversity of the plant community species, shifts in dominant species, and species replacement based on burial tolerance (Dech and Maun 2005), resulting in a decrease in the abundance of sand-living flora and fauna species that are specifically adapted to the habitat of shifting sands. At the long term, it may lead to a significant change on the landscape and dune morphology, and the loss of this singular kind of habitat (Kutiel et al. 2004; Levin and Ben-Dor 2004). Furthermore, according to Lubke (1985) and Panario and Piñeiro (1997), the immobilization of a significant portion of dune system can lead to the loss of the protective function of coastal dunes, resulting in coastal recession in the medium and long term by preventing natural sand transfer from dunes to the coast.

Several factors have been identified as causes of the observed increase in sand stabilization rates. On one hand, the reduction or disruption of agricultural and/or livestock land-uses acting as disturbance to sand dune vegetation has, in some cases, allowed this vegetation to spread more efficiently on the dunes where they grow, thus stabilizing them (Isermann et al. 2007; Levin and Ben-Dor 2004). In the Mediterranean coastal dunes of Israel, e.g., Tsoar and Blumberg (2002) found a decreasing average rate of advance of 15 dunes from 3.4 to 1.9 m/year during the period between 1944 and 1995, following the interruption of intense agricultural and pastoral activity, while the vegetation cover increased from 4.3 to 17%. On the other hand, the decrease in herbivory either by domestic livestock or wild grazers such as wild rabbit in some dunes (i.e. due to diseases such as myxomatosis) has led to a rapid evolution of dune vegetation from open grasslands to scrubland and woodland (Levin and Ben-Dor 2004; Ranwell 1960; Thomas 1960). Global or local climatic changes can also lead to an increase on sand stability, mainly induced by changes in wind pattern and power that enables the establishment and densification of dune vegetation (Panario and Piñeiro 1997; Tsoar 2005; Tsoar et al. 2009).

Nevertheless, the main and more immediate cause of dune stabilization in different parts of the world has been essentially anthropogenic. The high mobility of some coastal dunes has seriously threatened human interests such as houses, crops and infrastructure. In attempts to prevent dune erosion, to stabilize blowing transgressive sand sheets, and to preserve the function of dunes as a natural defense of the coast, together with a widespread interest in expanding the beach for recreational needs (Nordstrom and Lotstein 1989), considerable efforts have been invested in stabilizing such systems around the world. Since the end of the eighteenth century, different countries have implemented dune stabilization techniques that included the planting of rapid-grow herbaceous and/or woody species, tolerant to the dune environmental stressful conditions (Avis 1989; Buell et al. 1995; Kithy-Tassara 1946; Kutiel et al. 2004; Li et al. 2009; Pye 1983; Van der Meulen and Salman 1996). In some cases, the plantation of species without any regard to their exotic or native character has led to their excessive spread beyond the plantation areas over time, sometimes displaying invasive behaviors, and causing the further stabilization of surrounding dune systems followed by serious problems for the ecosystem conservation (Avis 1995; Conser and Connor 2009; Isermann 2008a; Kutiel et al. 2004; Marchante et al. 2008; Wiedemann and Pickart 1996).

The loss of functional, natural and ecological value due to coastal dune stabilization is not an easy problem to solve. According to Tsoar et al. (2009), the fact is that, once the dunes were stabilized by vegetation they could not be naturally activated even by increased wind power (Levin and Ben-Dor 2004; Tsoar 2005; Tsoar et al. 2009). Levin and Ben-Dor (2004) observed that military maneuvers, and pedestrians and off-road vehicles traffic increased the dune fragmentation but did not lead to the reactivation of the sands. In this regard, manual thinning of plant cover may seem a suitable management strategy (Kutiel et al. 2000); in any case, the response of fauna and flora to artificial thinning and reactivation of dune mobility must be taken into account.

18.3 Expansion of Invasive Plant Species

Biological invasions are a worldwide problem that affects almost all ecosystems as well as human interests, and has considerable impact on either ecological functioning or human well-being (Perrings et al. 2010). In the last decades, introduction on allochthonous species has increased considerably (Hulme 2009). Coastal ecosystems, and particularly dunes, are among the most threatened and affected by invasion of allochthonous plants. This is mainly due to the significant pressure from human activities to which they are exposed, which favors the introduction and expansion of some of these species (Campos et al. 2004). Furthermore, nearly 50% of the 34 plant species identified by IUCN among the 100 of the world's worst invasive alien species are recognized to occur in coastlands (Lowe et al. 2000).

The expansion of allochthonous species in new habitats depends on the characteristics of both the species themselves (e.g. adaptation to the environmental

conditions, production and dispersal of propagules) and those of the source and the sink habitat, such as ecosystem structure (e.g. diversity, plant covering) and disturbances (Alpert et al. 2000; Davis et al. 2000; Orians 1986; Peters et al. 2006; Perrings et al. 2010). Coastal dunes are susceptible to plant invasions due to a usual low number of species, the existence of micro-sites open to their establishment and to low levels of plant-plant competition (Jørgensen and Kollmann 2009), as well as recurrent natural and anthropogenic perturbation. Some of the invasive species in coastal sand dunes are dune-specific and occupy similar habitats in their native countries; but some others are ruderal species, not exclusive to the littoral strip, also abundant in other types of disturbed habitats (Campos et al. 2004; Isermann 2008a; Muñoz Vallés et al. 2011a, b). In fact, native species can also display invasive behaviors (Alpert et al. 2000), negatively affecting other species and/or significantly altering the ecosystem functioning (e.g. *Retama monosperma* in SW Spain coastal dunes, Muñoz Vallés et al. 2011a, b; *Hippophae rhamnoides* in coastal grey dunes of North Sea island Spiekeroog, Isermann 2008b; *Larrea tridenta* in Chihuahuan Desert of North America; Peters et al. 2006).

Due to a good adaptation to the dune environment and to a rapid and convenient grow form, the introduction of allochthonous species to stabilize sand dunes has been a common practice in the past and still at present (e.g. *Ammophila arenaria, Hippophae rhamnoides, Rosa rugosa*, several species from the genus *Carpobrotus, Acacia, Eucalyptus, Pinus* and *Retama*, among others – Avis 1989; Buell et al. 1995; Isermann 2008b; Kith-y-Tassara 1946; Kutiel et al. 2004; Wiedemann and Pickart 1996; among others). In addition, the widespread recreational use of coastal areas and urban development has been involved with the introduction of such species also in relation with aesthetic, and the associated disturbances from human activities on surrounded dunes have facilitated their arrival and establishment (Gallego-Fernández et al. 2006; Van der Meulen and Salman 1996).

Impacts of allochthonous invasive species in coastal dunes lead to a decrease in the abundance of sand-living flora and fauna species and cause serious problems for the ecosystem conservation (Avis 1995; Conser and Connor 2009; Isermann 2008b; Kutiel et al. 2004; Marchante et al. 2008; Wiedemann and Pickart 1996; among others). Their expansion facilitates, in many cases, the further establishment of other neophytes and alien species (Isermann 2008a; Muñoz Vallés et al. 2011a, b). In addition, the rapid expansion and increase in coverage of some species (particularly shrubs, but also ground cover species such as *Carpobrotus* or *Oenothera*, or with relative dense growth form as *Ammophila*) significantly contributes to the dune stabilization process, promoting a significant change on the dune landscape, causing the lack of sand supply to beaches from the dune, and altering the functioning of the whole ecosystem. (Isermann 2008a; Isermann et al. 2007; Kutiel et al. 2004; Lubke 1985; Wiedemann and Pickart 2004). In the Western coast of North America, for instance, *Ammophila arenaria* has displaced and/or replaced the native dune-forming species in most places, modifying the open and high diversity foredunes, and it has also invaded many back dune ridges and stabilized some formerly active dunes (Wiedemann and Pickart 2004). Nevertheless, it has had a slighter impact on the dunes ecosystem in Southern Cape Coast (Africa; Lubke

2004). Coastal dunes in south Israel have experienced a significant stabilization process and an increase in dune vegetation cover, by 82%, between the years 1965 and 1999, due to the expansion of introduced species (Kutiel et al. 2004). On the other hand, in the case of coastal dunes, degradation subjected to human pressure and/or management for recreation or stabilization leads to a common presence of allochthonous species in these habitats. Aria (1999) found that 52% of total dune vegetation, or 82% of non-forested vegetation, was dominated by introduced species at the Humboldt Bay dunes, California. In six coastal dune systems in the Gulf of Cadiz, SW Spain, Gallego-Fernández, Muñoz Vallés and Dellafiore (2006) recorded an abundance of allochthonous plant species ranging from 4.3 to 25.3% of the total species. Castillo and Moreno-Casasola (1996) found that 89.8% out of 644 species inventoried throughout the coastal dunes located along the Gulf of Mexico were ruderal or secondary species from other nearby communities.

The full extent of the impacts of plant invasions on dune systems is still unknown, and further studies, including measures for control and eradication on invasive species, as well as approaches aiming the restoration of dune species composition, diversity and natural processes, are required.

18.4 Urban Development and Tourism

Humans have used coastal dunes since the ancient times for different purposes, traditionally related to agriculture, livestock grazing and the establishment of settlements (Baeyens and Martínez 2004; Carter 1988; Heslenfeld et al. 2004). Nevertheless, it has not been until recently that dunes have suffered a major degradation and loss rates. At present, it is estimated that 60% of a growing world population of seven billion people live in the coastal region (Holdgate 1993; U.S. Census Bureau International Data Base). Worldwide, coastal dunes are at present seriously threatened by human activities such as urban, engineering and industry development (Fig. 18.2). These activities cause, among others, net loss of habitat, fragmentation of living areas, soil and aquifers alterations, and water and air pollution, what leads to significant changes or complete loss of flora, fauna, landscape quality and functionality of dunes over short periods of time (Carter 1988; Heslenfeld et al. 2004; Martínez et al. 2004a; Williams et al. 1997; Williams et al. 2001). In addition, the establishment of ports and yacht marinas, and hard coastal defense, has altered the natural sedimentary dynamics, causing serious problems of erosion on some coastal stretches. Only in Europe and since 1900, a net loss of coastal dune surface of 25% has been recorded and about 55% of the remaining surface has lost its natural character. It is estimated that approximately 85% of the currently existing dunes in Europe is endangered (Heslenfeld et al. 2004). Coastal dunes are considered, in addition, among the most demanded habitats for recreational use (Kutiel et al. 1999; Martínez et al. 2004a; Williams et al. 1997). In particular, tourism has become the major source of income for the coast but, at present, tourism and its associated impacts cause significant

Fig. 18.2 Dune narrowing and degradation caused by the establishment of infrastructure associated with urban development, and poor management of parking and access to reach the beach (Rota beach, Cádiz, SW Spain)

degradation and direct loss of dunes, and it has led as well to an increase in urban and demographic pressures (Kutiel et al. 2004; Kutiel et al. 1999; Martínez et al. 2004a; Nordstrom 2008; Nordstrom et al. 2000).

Derived impacts from urban development, building of facilities and activities associated to tourism (e.g., gulf courses, recreational use of beaches) range from the obvious direct loss of dune surface (which can easily comprise the total dune surface in some cases) and serious alteration in the coastal sedimentary dynamics and erosion (e.g. due to hard coastal defence works such as groins and breakwaters), to the direct and indirect environmental degradation by pressure of use on the surrounding natural areas (Gallego-Fernández et al. 2003; García Mora et al. 1998; Jackson and Nordstrom 2011; Martínez et al. 2004a; Milne et al. 2012; Nordstrom et al. 2000). Although this second aspect is not so obvious, it can lead alone to the loss of the protected dune plant communities and associated fauna, as well as the natural dynamic of the dune. For instance, intensive and uncontrolled traffic of tourists implies serious environmental modifications such as soil compression, reduction of litter and soil organic matter in the upper layer of the soil, erosion and changes in microclimate, and it also promotes the reduction in plant cover, species richness and diversity, and alterations for fauna species (Andersen 1995a, b; Brown and McLachlan 1990; Heslenfeld et al. 2004; Kutiel et al. 1999; Nordstrom et al. 2000; Williams et al. 1997).

Furthermore, human impact acts as an important destabilizing factor of dune systems, altering the natural stabilization–destabilization balance, and being

Fig. 18.3 Coastal dune disaggregation caused by uncontrolled tourists traffic and inadequate design of access in Zahara de los Atunes beach, Cádiz (SW Spain)

directly related to the coastal dune instability and disorganization and to the loss of coastal dunes' protecting role (Barrère 1992; Brown and McLachlan 1990; Nordstrom et al. 2000; Panario and Piñeiro 1997; Psuty 2004) (Fig. 18.3). Continuous and intensive trampling may induce changes in plant composition, from species specifically adapted to the dune geomorphological processes to other functional groups of species with lower skills to stabilize sands (García Mora et al. 2000; Santoro et al. 2012). This, together with the loss of vegetation cover and wind erosion, causes the formation and growth in wide and depth of bare deflation corridors that contribute to dune fragmentation and negatively affect to the geomorphologic integrity of the dune (Fig. 18.4) (Gallego-Fernández et al. 2003; Muñoz Vallés et al. 2005). Therefore, the system becomes more fragile to natural disturbances. In SW Spain, Muñoz Vallés et al. (2011a, b) compared the status of two dune systems under different tourism pressure and accessibility level. They concluded that ineffectiveness of access structures in avoiding human impact on the dune system makes that coastal segment lacking of adequately designed accesses reach similar levels of dune segmentation and alteration that coastal segment where visitors can come and go uncontrollably.

On the other hand, actions such as mechanical beach cleaning, container establishment or aid positions damage or eliminate beach vegetation and incipient dunes, seed sources for pioneer dune colonizers, food for fauna, and habitat for nesting birds. Besides, the variability in microenvironments necessary for biodiversity gets reduced (Campos et al. 2004; García Mora et al. 1998; Nordstrom et al. 2000). The intensive development of industry and urban settlements and facilities in the coast

Fig. 18.4 The coalescence of antropogenic bare deflation corridors leads to the dune fragmentation and intrusion of sea water in the dune system

flat has also resulted, in many cases, in coastal stretches with high urban development and some isolated dune systems among them (Gallego-Fernández et al. 2011; García Mora et al. 1998; Heslenfeld et al. 2004; Jackson and Nordstrom 2011). This can lead to a disruption to the natural dynamics of dispersion and colonization of plant species, a fact that would also affect the species equilibrium at a regional scale.

18.5 Climate Change Implications

Increases in global average air and ocean temperatures, greater at higher northern latitudes, widespread melting of snow and ice, and related rising global average sea level of 1.8 mm/year over 1961 to 2003 (of about 3.1 mm/year from 1993 to 2003) are among the main changes observed in climate in recent decades (IPCC 2007). Present and predicted climate change effects have the potential to considerably exacerbate hazard risk to coastal dunes, and associated dangerous trends for coastal dunes conservation are mainly related to changes in wind power, rainfall, sea level rise by itself and groundwater salinization (Carter 1991; IPCC 2007; Panario and Piñeiro 1997; Ross et al. 1994; Tsoar 2005; Vestergaard 1997).

Low rainfall and high wind power are driving forces related to climate that negatively affect vegetation growth and cover in coastal dunes, and are in fact closely related with a higher mobility of sand dunes. Changes in rainfall and wind

power can therefore determine the trend of dunes from vegetated, stabilized or semi-stabilized dune systems to bare, mobile dunes of shifting sands or vice versa (Ashkenazy et al. 2011; Panario and Piñeiro 1997; Tsoar 2005). Extremes in both senses would result in loss of ecological value of dunes (Heslenfeld et al. 2004). Trends on this aspect also depend on other factors such as climatic zones, dune dimensions, vegetation cover quality and human impacts (Heslenfeld et al. 2004; García Mora et al. 2000), so generalized predictions for climate change impacts are difficult to reach in this line. For instance, based on empirical data and sand transport model, Panario and Piñeiro (1997) predicted coastal recession in the medium and long term at Cabo Polonio (Uruguay), due to a decrease in coastal dunefield activity induced by changes in wind pattern. But they observed that coastline recession was also related to the antropogenic forestation process that caused the immobilization of a significant portion of the dune system, preventing natural sand transfer to the coast. These changing conditions are added to the projected increase in sea level, heights and incidence of waves, and frequency of flooding by extreme tides, storm surge and wave effects, which causes relevant redistribution of sediments by influencing the coastal erosion/accretion processes. This can cause accumulation of eroded material and rapid foredune creation and development in some areas along the coast, and insufficient sediment supply and erosion in other areas (Carter 1991; Milne et al. 2012; Vestergaard 1997).

Associated reorganization of sands in the dune habitat can also imply ecosystem changes such as sand deposition on wet slacks and semi-stabilized and stabilized dunes, and consequent changes in vegetation composition in accordance with burial tolerance of species (Dech and Maun 2005; Vestergaard 1997). In this regard, generalized sea level rise constitutes a serious problem for conservation of coastal dune communities due to their impossibility of migrating toward inner or upper areas where their habitat is inexistent. Changes in precipitation and wind power can lead to serious threat for rare, drought-sensitive coastal plant species (Fischer et al. 2009). In addition, the progressive sea level rise together with the global redistribution of precipitation caused by climate change leads to an increase of aquifers salinity, and it is predicted that coastal ecosystems will be likely affected by decreased fresh water availability due to saltwater intrusion, negatively affecting specific dune flora (Christensen et al. 2007; Greaver and Sternberg 2006; IPCC 2007; Ross et al. 1994; Sternberg and Swart 1987). One of the most recent research lines on ecology of dunes (and other types of terrestrial habitat) consists of the study of the sources of water (e.g. ocean, ground, and rain) taken up by vegetation, using isotopic analysis of stem water (Andrews et al. 2012; Ehleringer and Dawson 1992; Greaver and Stenberg 2007, 2010). Contrary to the traditionally conceived idea that freshwater from dune aquifer and rain are the only water sources for plants in coastal dunes, recent studies have found that some dune species are able to use ocean water uptake during pronounced drought periods and periodic ocean water influx (Gallego-Fernández et al. 2010; Greaver and Stenberg 2007). Nevertheless, further studies on quantifying species tolerances in this regard are necessary to determine thresholds of community sustainability, in order to assess the coming effects of sea-level rise scenarios and to design suitable management approaches.

18.6 Management and Conservation Paradigm

Diverse risk factors operating at different levels and scales are currently threatening coastal dunes, including other local hazards not described above. Unfortunately, some of these factors were identified at least four decades ago (i.e. coastal impacts of human activities such as urban development or introduction of allocthonous species; Brown and McLachlan 1990; Carter 1991; García Novo et al. 1997; Ranwell 1972), but it appears that associated conservation problems still remain unsolved, somehow. For instance, the introduction of allochthonous plant species for gardening and stabilization of slopes in coastal housings are still common. Administrations and managers invest considerable effort in the eradication of the most problematic species. Nevertheless, the expansion of invasive species is still a problem that leads to the stabilization of the dune, or favors changes in the plant community composition, sometimes towards species with lower skills to stabilize sands (García Mora et al. 2000; Santoro et al. 2012). In these situations, the uncontrolled traffic of tourists through the dune system accentuates these community changes but it does not remobilize the dune (Levin and Ben-Dor 2004) (Fig. 18.5). In both cases, the dune becomes more vulnerable to face wind, sea and waves battering. This vulnerability is significantly higher when the dune barrier has been narrowed or removed due to industrial and urban development, or due to changes on sedimentary dynamics promoted by the establishment of coastal defense structures. Among all, present and future effects of climatic change is likely the most dramatic hazard to coastal dunes, specifically the progressive sea level rise and accentuation of climatic extremes, since they can be predicted but they can hardly be managed in the short term.

In contrast, management approaches have evolved toward preferable "soft" measures and impact removal or minimization, aiming to maintain natural dynamics, functions and values of dunes, and helping natural processes to recover by themselves (Gómez-Pina et al. 2002; Heslenfeld et al. 2004; Ley Vega de Seoane et al. 2011; Pethick and Crooks 2000). Such measures include the morphological dune reconstruction, revegetation with appropriate native species, elimination of allochthonous invasive plant species, beach nourishment, either on the beach or on the shore face, use of passive sand-trapping fences and protection systems, efficient designs of accesses in limiting and routing uncontrolled tourist traffic, allowing the dune mobility and vegetation development, avoidance of buildings and parking areas in the dune system, monitoring of any restoration or conservation work and maintenance. In addition, environmental information appears to be an efficient tool against dune degradation (Carter 1991; Gómez-Pina et al. 2002; Heslenfeld et al. 2004; Ley Vega de Seoane et al. 2011; Muñoz Vallés et al. 2011a, b). These does not necessarily exclude the requirement of implementing some "hard" engineering interventions (such as submerged breakwaters) in certain extreme situations, taking into account the associated consequences on the natural dynamics of dunes and the whole coastal frame in any case (Antunes do Carmo et al. 2010; Heslenfeld et al. 2004).

Fig. 18.5 Foredune totally covered and stabilized by *Carpobrtus edulis* (Cádiz, SW Spain)

Taking into account what has previously been stated, the assessment of coastal dune vulnerability seems an interesting approach that integrates the main factors affecting dune resilience. Dune vulnerability is understood here as "the capacity that a particular ecosystem has to absorb disturbance without undergoing permanent alterations", being an antonym of the concept of "elasticity" (Orians 1975) or "resilience" (Pimm 1991). Different vulnerability indexes have been used in the lasts decades, and methods used to this aim have diversely considered natural and human-induced disturbances (Cooper and McLaughlin 1998; García Mora et al. 2001; Panario and Piñeiro 1997; Pethick and Crooks 2000; Williams et al. 2001). Nevertheless, the use of a holistic evaluation integrating morphosedimentological, ecological and antropogenic features by the application of specific checklists is desirable, and some of these indexes have recently included the vegetation quality as additional variable to monitor for a more complete assessment (García Mora et al. 2001; Martínez et al. 2006; Muñoz Vallés et al. 2011a, b). This is a relevant goal for conservation of dune ecosystems and functions, since vegetation gives structure to ecosystems, it is one of the main supports for wild fauna, and natural diversity of native species provides the characteristic dynamic equilibrium of dunes (Margalef 1977; Van der Putten and Petters 1995). The application of these indices allows the identification of homogeneous units in the coastal frame, determines the main factors affecting them (geomorphological, related with wind or sea impacts, antropogenic or based on vegetation status), and predicts the system response to environmental variations, facilitating the design and implementation of concrete management actions from local to regional scale. Such indexes have been useful in

dune vulnerability assessment in different countries around the world, such as France (Bodére et al. 1991), United Kingdom (Williams et al. 1993), Portugal (Alveirinho Dias et al. 1994; Matias et al. 1998), Spain (García Mora et al. 2001; Muñoz Vallés et al. 2011a, b), Turkey (Marlow and Morris 2003), or Mexico (Martínez et al. 2006).

Coastal dunes are dynamic systems that quickly respond to factors affecting them (García Mora et al. 2001; Heslenfeld et al. 2004; Williams et al. 1993), maintaining a naturally occurring mosaic of dynamics that includes active fronts, semi-stabilized and stabilized dune areas (Martínez et al. 2004b). This equilibrium and plasticity of dunes makes them unique habitats that act as centre of speciation and global biodiversity, and implies one of the major environmental services that dunes offer to human interests as coastal protective barrier in the present natural hazards scenario associated to climate change. Nevertheless, other main environmental benefits that coastal dune offers are likely related nowadays with sustainable tourism, landscape quality or natural carbon sink, in addition to the traditional uses for agriculture or livestock grazing.

We are still relatively far from a wide understanding of the combined effects of hazards on coastal dunes, and from implementing a suitable integrated management of these complex systems. Nevertheless, we are in position to state that, at present, management should be focused to maintain healthy, equilibrated and dynamic dunes that can accomplish their protective role on coastal areas, remaining less vulnerable to erosion, being cheaper to maintain, preserving higher natural values and maintaining the global biodiversity that these habitats support. These goals needs for a major scientific-based knowledge of the entire dune systems functioning, as well as the commitment of administrations, managers and urban and landscape planners, and the implementation of integrated coastal zone management programs, in order to solve this ecologic and economic problem of the current decline of coastal dunes. It is also required a change of mentality toward new and more sustainable designs of development, respecting the coastal dune frame, under the consciousness of the rising sea levels and the protective value of coastal dune barrier.

References

Alpert P, Bone E, Holzapfel C (2000) Invasiveness, invisibility and the role of environmental stress in the spread of non-native plants. Perspect Plant Ecol Evol Syst 3:52–66

Alvarez ME, Cushman JH (2002) Community level consequences of a biological invasion: effects of a non-native vine on three plant communities. Ecol Appl 12:1434–1444

Alveirinho Dias JM, Curr R, Davies P, Pereira A, Williams AT (1994) Dune management vulnerability assessment: Portugal and northwest Europe. In: Association EUROCOAST (ed) Proceedings of Littoral'94 (Lisbon, Portugal), pp 837–848

Andersen UV (1995a) Resistance of Danish coastal vegetation types to human trampling. Biol Conserv 71:223–230

Andersen UV (1995b) The influence of human trampling on the vegetation on artificial coastal grassland in Denmark. In: Salman AHPM, Berends H, Bonazountas M (eds) Coastal management and habitat conservation, vol I, PC96. EUCC, Leiden, pp 427–438

Andrews SF, Flanagan LB, Sharp EJ, Cai T (2012) Variation in water potential, hydraulic characteristics and water source use in montane Douglas-fir and lodgepole pine trees in southwestern Alberta and consequences for seasonal changes in photosynthetic capacity. Tree Physiol 32(2):146–160

Antunes do Carmo J, Schreck Reis C, Freitas H (2010) Working with nature by protecting sand dunes: lessons learned. J Coast Res 26(6):1068–1078

Aria KT (1999) Using aerial photographs rectified with a geographic information system to map coastal dune vegetation and land use in Humboldt County, California. M.S. thesis, Humboldt State University, Arcata, 62 p

Ashkenazy Y, Yizhaq H, Tsoar H (2011) Sand dune mobility under climate change in the Kalahari and Australian deserts. Clim Change. doi:10.1007/s10584-011-0264-9

Avis AM (1989) A review of coastal dune stabilization in the Cape Province of Sotuh Africa. Lands Urban Plann 18:55–68

Avis AM (1995) An evaluation of the vegetation developer alter artificially stabilizing South African coastal dunes with indigenous species. J Coast Conserv 1:41–50

Baeyens G, Martínez ML (2004) Animal life in sand dunes: from exploitation and prosecution to protection and monitoring. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 279–296

Barrère P (1992) Dynamics and management of the coastal dunes of the Landes, Gascony, France. In: Carter RWG, Curtis TGF, Sheehy-Skeffington MJ (eds) Coastal dunes. Balkema, Rotterdam, pp 25–32

Beatly T (1991) Protecting biodiversity in coastal environments: introduction and overview. Coast Manage 19:1–19

Berlanga Robles CA, Ruiz Luna A (2002) Land use mapping and change detection in the coastal zone of northwest Mexico using remote sensing techniques. J Coast Res 18:514–522

Bodére JC, Cribb R, Curr RHF, Davies P, Hallégouet B, Meur C, Pirou N, Williams AT, Yoni C (1991) La gestion des milieux dunaires littoraux. Evaluation der leur vulnérabilité à partir d'une liste de contrôle. Etude de cas dans le sud du Pays de Galles et en Bretagne occidental. Norois 38:279–298

Brown AC, McLachlan A (1990) Ecology of Sandy Shores. Elsevier, Amsterdam, 328 p

Buell AC, Pickart AJ, Stuart JD (1995) Introduction history and invasion patterns of *Ammophila arenaria* on the north coast of California. Conserv Biol 9:1587–1593

Campos JA, Herrera M, Biurrun I, Loidi J (2004) The role of alien plants in the natural coastal vegetation in central-northern Spain. Biodiv Conserv 13:2275–2293

Carter RWG (1988) Coastal environment. An introduction to the physical, ecological and cultural environment. Academic, London, 617 p

Carter RWG (1991) Near-future sea-level impacts on coastal dune landscapes. Lands Ecol 6:29–39

Castillo SA, Moreno-Casasola P (1996) Coastal sand dune vegetation: an extreme case of species invasion. J Coast Conserv 2:13–22

Chapman VJ (1976) Coastal vegetation. Pergamon Press, Oxford, 292 p

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York, pp 849–940

Connell JH, Slatyer RO (1977) Mechanisms of succession in natural communities and their role in community stability and organization. Am Nat 111:1119–1144

Conser C, Connor EF (2009) Assessing the residual effects of *Carpobrotus edulis* invasión, implications for restoration. Biol Invas 11:349–358

Cooper JAG, McLaughlin S (1998) Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis. J Coast Res 14:512–524

Cunniff SE (1985) Impacts of severe storms on beach vegetation. In: Magoon OT, Converse H, Miner D, Clark D, Tobin LT (eds) Coastal Zone'85, Proceedings of the Fourth Symposium on Coastal and Ocean Management. American Society of Civil Engineers, New York, pp 1022–1037

Da Cruz H (1996) Tourism and environment in the Mediterranean. In: Salman L, Salman AHPM, Langeveld MJ, Bonazountas M (eds) Coastal management and habitat conservation, vol II. European Union for Coastal Conservation, Leiden, pp 113–116

Davis MA, Grime JP, Thompson K (2000) Fluctuating resources in plant communities: a general theory of invisibility. J Ecol 88:528–534

Dech JP, Maun MA (2005) Zonation of vegetation along a burial gradient on the leeward slopes of Lake Huron sand dunes. Can J Bot 83:227–236

Demirayak F, Ulas E (1996) Mass tourism in Turkey and its impact on the Mediterranean coast. In: Salman AHPM, Langeveld MJ, Bonazountas M (eds) Coastal management and habitat conservation, vol II. European Union for Coastal Conservation, Leiden, pp 117–123

Ehleringer JR, Dawson TE (1992) Water uptake by plants: perspectives from stable isotope composition. Plant Cell Environ 15:1073–1082

Fischer DT, Still CJ, Williams AP (2009) Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species. J Biogeogr 36 (4):783–799

Gallego-Fernández JB, García Mora MR, Ley Vega de Seoane C (2003) Restauración de ecosistemas dunares costeros. In: Rey Benayas JM, Espigares Pinilla T, Nicolas Ibarra JM (eds) Restauración de Ecosistemas Mediterráneos. Asociación Española de Ecología Terrestre, Alcalá de Henares, pp 157–171

Gallego-Fernández JB, Muñoz Vallés S, Dellafiore CM (2006) Introduction of exotic plants caused by beach and dune management. In: Michallef A, Vasallo A, Cassar M (eds) Proceedings of the second international conference on the management of coastal recreational resources – Beaches, yatchting and coastal ecotourism, Gozo, Malta, pp 355–363, 464 p

Gallego-Fernández JB, Muñoz Vallés S, Dellafiore CM (2010) Expansión de un arbusto nativo-invasivo en dunas costeras: causas y consecuencias ecológicas. Revista Chagual 8:41–48

Gallego-Fernández JB, Sánchez IA, Ley C (2011) Restoration of isolated and small coastal sand dunes on the rocky coast of northern Spain. Ecol Eng 37:1822–1832

García Mora MR, Gallego-Fernández JB, Williams AT (1998) The coastal area of SW Spain: between conservation and tourist development. In: Monsó de Prat JL (ed) Sustainable waterfront and coastal developments in Europe: socioeconomics, technical and environmental aspects, Barcelona, pp 177–185

García Mora MR, Gallego-Fernández JB, García Novo F (2000) Plant diversity as a suitable tool for coastal dune vulnerability assessment. J Coast Res 16(4):990–995

García Mora MR, Gallego-Fernández JB, Williams AT, García Novo F (2001) A coastal dune vulnerability classification: a case study of the SW Iberian Peninsula. J Coast Res 17 (4):802–811

García Novo F, Crawford RM, Díaz Barradas MC (eds) (1997) The ecology and conservation of European dunes. Secretariado de publicaciones de la Universidad de Sevilla, Seville, 375 p

Gómez-pina G, Muñoz-Pérez JJ, Ramírez JL, Ley C (2002) Sand dune management problems and techniques, Spain. J Coast Res 36:325–332

Greaver TL, Sternberg LLS (2006) Linking marine resources to ecotonal shifts of water uptake by terrestrial dune vegetation. Ecology 87:2389–2396

Greaver TL, Sternberg LLS (2007) Fluctuating deposition of ocean water drives plant function on coastal sand dunes. Glob Change Biol 13:216–223

Greaver TL, Sternberg LLS (2010) Decreased precipitation exacerbates the effects of sea level on coastal dune ecosystems in open ocean islands. Glob Change Biol 16:1860–1869
Heslenfeld P, Jungerius PD, Klijn JA (2004) European coastal dunes: ecological values, threats, opportunities and policy development. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 335–351
Hesp PA (2000) Coastal sand dunes: form and function. Massey University/Rotorua Printers, New Zealand, p 24
Hesp PA (2004) Coastal dunes in the Tropics and temperate regions: locations, formation, morphology and vegetation processes. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 29–49
Hesp PA, Martínez ML (2007) Disturbance processes and dynamics in coastal dunes. In: Johnson EA, Miyanishi K (eds) Plant disturbance ecology. Academic Press, Burlington, Massachusetts, pp 215–248
Holdgate MW (1993) The sustainable use of tourism: a key conservation issue. Ambio 22:481–482
Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol 46:10–18
Intergovernmental Panel on Climatic Change (IPCC) (2007) Climate change 2007: the scientific basis. Cambridge University Press, Cambridge
Isermann M (2008a) Classification and habitat characteristics of plant communities invaded by the non-native Rosa rugosa Thunb. in NW Europe. Phytocoenologia 38(1–2):133–150
Isermann M (2008b) Expansion of Rosa rugosa and Hippophaë rhamnoides in coastal grey dunes: effects at different spatial scales. Flora 203:273–280
Isermann M, Diekmann M, Heemann S (2007) Effects of the expansion by *Hippophaë rhamnoides* on plant species richness in coastal dunes. Appl Veg Sci 10:33–42
Jackson NL, Nordstrom LF (2011) Aeolian sediment transport and landforms in managed coastal systems: a review. Aeolian Res 3:181–196
Jørgensen RH, Kollmann J (2009) Invasion of coastal dunes by the alien shrub *Rosa rugosa* is associated with roads, tracks and houses. Flora 209(4):289–297
Kidd R (2001) Coastal dune management: a manual of coastal dune management and rehabilitation techniques. NSW Department of Land and Water Conservation Coastal Unit, DLWC, Newcastle, 96 p
Kith-y-Tassara M (1946) El problema de las dunas del SO de España. Revista de Montes 11:414–419
Kutiel P, Zhevelev H, Harrison R (1999) Te effect of recreational impacts on soil and vegetation of stabilised coastal dunes in the Sharon Park, Israel. Ocean Coast Manage 42:1041–1060
Kutiel P, Peled Y, Geffen E (2000) The effect of removing shrub cover on annual plants and small mammals in a coastal sand dune ecosystem. Biol Conserv 94:235–242
Kutiel P, Cohen O, Shoshany M, Shub M (2004) Vegetation establishment on the southern Israeli coastal sand dunes between the years 1965 and 1999. Lands Urban Plann 67:141–156
Levin N, Ben-Dor E (2004) Monitoring sand dune stabilization along the coastal dunes of Ashdod-Nizanim, Israel, 1945–1999. J Arid Environ 58:335–355
Ley C, Gallego-Fernández JB, Vidal C (2011) Coastal dunes restoration manual. Ministerio de Medio Ambiente, Rural y Marino, 251 p
Li Y, Cui J, Zhang T, Okuro T, Drake S (2009) Effectiveness of sand-fixing measures on desert land restoration in Kerqin Sandy Land, northern China. Ecol Eng 35:118–127
Lichter J (1998) Primary succession and forest development on coastal Lake Michigan sand dunes. Ecol Monogr 68(4):487–510
Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the world's worst invasive alien species A selection from the global invasive species database. Published by the Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), 12 p. Updated and reprinted version: November 2004
Lubke RA (1985) Erosion of the beach at St. Francis Bay, Eastern Cape. Biol Conserv 32:99–127

Lubke RA (2004) Vegetation dynamics and succession on sand dunes of the eastern coasts of Africa. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 67–84

Marchante E, Kjøller A, Struwe S, Freitas H (2008) Short- and long-term impacts of *Acacia longiflora* invasion on the belowground processes of a Mediterranean coastal dune ecosystem. Appl Soil Ecol 40:210–217

Margalef R (1977) Ecología, 2nd edn. Omega, Barcelona, 951 p

Marlow R, Morris A (2003) The vulnerability and management of three sand dune sites in southwestern Turkey. In: Özhan E (ed) Proceedings of the sixth international conference on the Mediterranean coastal environment, MEDCOAST 2003, Ravenna, Italy, vol 2, pp 1381–1391

Martínez ML, Psuty NP (eds) (2004) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, 380 p

Martínez ML, Moreno-Casasola P, Castillo S (1993) Biodiversidad Costera: Playas y Dunas. In: Salazar Vallejo SI, González NE (eds) Biodiversidad Marina y Costera de México. Centro de Investigaciones de Quintana Roo y CONABIO, Chetumal, pp 160–181

Martínez ML, Vázquez G, Sánchez Colón S (2001) Spatial and temporal variability during primary succession on tropical coastal sand dunes. J Veg Sci 12(3):361–372

Martínez ML, Maun MA, Psuty NP (2004a) The fragility and conservation of the world's coastal dunes: geomorphological, ecological, and socioeconomic perspectives. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 355–369

Martínez ML, Psuty NP, Lubke RA (2004b) A perspective on coastal dunes. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 3–10

Martínez ML, Gallego-Fernández JB, García Franco JG, Moctezuma C, Jiménez CD (2006) Coastal dune vulnerability along the Gulf of México. Environ Conserv 33:109–117

Matias A, Dias JA, Ferreira O, Williams AT (1998) Applicability of a dune vulnerability checklist to the Ria Formosa system. In: de Carvalho S, Gomes V, Pinto T (eds) Seminario Dunas da Zona Costeira de Portugal. Instituto de hidráulica e Recursos Hidricos, Leiria, pp 213–224

Maun MA (1998) Adaptations of plants to burial in coastal sand dunes. Can J Bot 76:713–738

Maun MA (2009) The biology of coastal sand dunes. Oxford University Press, Oxford, 265 p

Melvin SM, Griffin CR, MacIvor LH (1991) Recovery strategies for piping plovers in manager coastal landscapes. Coast Manage 19:21–34

Milne FD, Dong P, Davidson M (2012) Natural variability and anthropogenic effects on the morphodynamics of a beach–dune system at Montrose Bay, Scotland. J Coast Res 28 (2):375–388

Moreno-Casasola P (1986) Sand movement as a factor in the distribution of plant communities in coastal dune system. Vegetatio 65:67–76

Muñoz Vallés S, Gallego-Fernández JB, Dellafiore C (2005) Foredune fragmentation and tourist pressure in two natural places in the coast of Huelva, SW Spain. In: Sena A, Ferreira O, Noronha P, Veloso F, Taveira F, Correira F, das Neves L (eds) Book of abstracts of the international conference on coastal conservation and management in the Atlantic and Mediterranean. ICCCM'05, Tavira, Portugal, pp 375–378

Muñoz Vallés S, Gallego-Fernández JB, Dellafiore CM (2011a) Dune vulnerability in relation to tourism pressure in Central Gulf of Cádiz (SW Spain), a case study. J Coast Res 27(2):243–251

Muñoz Vallés S, Gallego-Fernández JB, Dellafiore CM, Cambrollé J (2011b) Effects on soil, microclimate and vegetation of the native-invasive *Retama monosperma* (L.) in coastal dunes. Plant Ecol 212:169–179

Nilsson C, Grelsson G (1995) The fragility of ecosystem: a review. J Appl Ecol 32:677–692

Nordstrom KF (2008) Beach and dune restoration. Cambridge University Press, Cambridge, 185 p

Nordstrom KF, Lotstein EL (1989) Perspectives on resource use of dynamic coastal dunes. Geogr Rev 79(1):37–53

Nordstrom KF, Psuty N, Carter B (1990) Coastal dunes: form and process. Wiley, Chichester, 410 p
Nordstrom KF, Lampe R, Vandemark LM (2000) Reestablishing naturally functioning dunes on developed coasts. Environ Manage 25(1):37–51
Olson JO (1958) Rates of succession and soil changes on southern Lake Michigan sand dunes. Bot Gaz 119(3):125–170
Orians GH (1975) Diversity, stability and maturity in natural ecosystems. In: Van Dobben WH, Lowe-McConnell RH (eds) Unifying concepts in ecology. W. Junk B.V. Publishers, The Hague, pp 139–150
Orians SH (1986) Site characteristics favoring invasions. In: Mooney HA, Drake JA (eds) Ecology of biological invasion in North America and Hawaii. Springer, New York, pp 133–148
Packham JR, Willis AJ (1997) Ecology of dunes, salt marsh and shingle. Chapman and Hall, London, 335 p
Panario D, Piñeiro G (1997) Vulnerability of oceanic dune systems under wind pattern change scenarios in Uruguay. Clim Res 9:67–72
Perrings C, Mooney H, Williamson M (2010) The problem of biological invasions. In: Perrings C, Mooney H, Williamson M (eds) Bioinvasions and globalization. Oxford University Press, Oxford, pp 1–16
Peters DPC, Yao J, Gosz JR (2006) Woody plant invasion at a semi-arid/arid transition zone: importance of ecosystem type to colonization and patch expansion. J Veg Sci 17:389–396
Pethick JS, Crooks S (2000) Development of a coastal vulnerability index: a geomorphological perspective. Environ Conserv 27:359–367
Pimm SL (1991) The Balance of Nature: Ecological Issues in the Conservation of Species and Communities. The University of Chicago Press, Chicago, 434 p
Psuty NP (2004) The coastal foredune: a morphological basis for recreational coastal dune development. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 11–27
Pye K (1983) Coastal dunes. Prog Phys Geogr 7:531–557
Ranwell DS (1960) Newborough Warren, Anglesey: III. Changes in the vegetation on parts of the dune system after the loss of rabbits by mixomatosis. J Ecol 2:385–395
Ranwell DS (1972) Ecology of salt marshes and sand dunes. Chapman and Hall, London, 258 p
Ross MS, O'Brien JJ, Stenberg LSL (1994) Sea-level rise and the reduction in pine forests in the Florida Keys. Ecol Appl 4(1):144–156
Santoro R, Jucker T, Prisco I, Carboni M, Battisti C, Acosta ATR (2012) Effects of Trampling Limitation on Coastal Dune Plant Communities. Environ Manage 49(3):534–542
Sternberg LSL, Swart PK (1987) Utilization of freshwater and ocean water by coastal plants of Southern Florida. Ecology 68:1898–1905
Thomas AS (1960) Changes in vegetation since the advent of mixomatosis. J Ecol 48(2):287–306
Tsoar H (2005) Sand dunes mobility and stability in relation to climate. Phys A: Stat Mech Its Appl 357(1):50–56
Tsoar H, Blumberg DG (2002) Formation of parabolic dunes from barchans and transverse dunes along Israel's Mediterranean coast. Earth Surf Process Landf 27:1147–1161
Tsoar H, Levin N, Porat N, Maia LP, Herrmann HJ, Tatumi SH, Claudino-Sales V (2009) The effect of climate change on the mobility and stability of coastal sand dunes in Ceará State (NE Brazil). Q Res 71(2):217–226
Van der Maarel E (ed) (1993a) Dry coastal ecosystems: ecosystem of the world, vol 2A. Elsevier Scientific Publishing, Amsterdam, 600 p
Van der Maarel E (1993b) Dry coastal ecosystems: scope and historical significance. In: der Maarel V (ed) Dry coastal ecosystems: ecosystem of the world, vol 2A. Elsevier Scientific Publishing, Amsterdam, pp 1–6
Van der Meulen F, Salman AHPM (1996) Management of Mediterranean coastal dunes. Ocean Coast Manage 30(2–3):177–195

Van der Meulen F, Bakker TWM, Houston JA (2004) The costs of our coasts: examples of dynamic dune management from Western Europe. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 259–277

Van der Putten WH, Peters BAM (1995) Possibilities for managenet of coastal foredunes with deteriorated stands of *Ammophila arenaria* (marram grass). J Coast Conserv 1:29–39

Vestergaard P (1997) Possible impact of sea-level rise on some habitat types at the Baltic coast of Denmark. J Coast Conserv 3:103–112

Wiedemann AM, Pickart AJ (1996) The *Ammophila* problem on the Northwest Coast of North America. Lands Urban Plann 34:287–299

Wiedemann AM, Pickart AJ (2004) Temperate zone coastal dunes. In: Martínez ML, Psuty NP (eds) Coastal dunes, ecology and conservation, vol 171, Ecological studies. Springer, Berlin, pp 53–65

Williams AT, Davies P, Curr RHF, Koh A, Bodéré J-C, Hallégouët B, Meur C, Yoni C (1993) A checklist assessment of dune vulnerability and protection in Devon and Cornwall, UK. In: Magoon O (ed) Proceedings of coastal zone '93. American Society of Civil Engineering, New York, pp 3395–3408

Williams AT, Randerson P, Sothern E (1997) Trampling and vegetation response on sand dunes in South Wales, UK. In: García Novo F, Crawford RMM, Díaz Barradas MC (eds) The ecology and conservation of European dunes. Universidad de Sevilla, Sevilla, pp 287–300

Williams AT, Alveirinho Días J, Garcia Novo F, García Mora MR, Curr R, Pereira A (2001) Integrated coastal dune management: checklists. Cont Shelf Res 21:1937–1960

Yizhaq H, Ashkenazy Y, Tsoar H (2007) Why do active and stabilized dunes coexist under the same climatic conditions? Phys Rev Lett 98(18):188001–1–188001–4