Coastal Dune Restoration : Trends and Perspectives

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Abstract

Sandy coasts are distributed worldwide and they are all heterogeneous ecosystems in terms of morphology, vegetation, and dynamics. Psammophytes are common in these environments. Besides these widespread attributes, sandy beaches and coastal dunes also share the intense impact of humans. Because of their privileged location at the coast, they are preferred sites for urban and maritime development, destinations for tourists, and locations for many other human activities. Thus, over the years (but especially during the last few decades) many of the previously natural dunescapes have been lost to urban, tourist, and industrial developments. Furthermore, a recurring problem of many coastal dune systems is over-stabilization, which is mostly the result of human actions. The urgent need to preserve the natural and valuable coastal dune remnants and, as much as possible, restore those that have been degraded, is evident. There are many different and contrasting actions that have been followed during restoration activities. Restoration actions have involved “soft” methods, such as sand fences, and “hard” methods, such as geotubes and herbicides. Also, restoration may lead not only to the stabilization of dunes, but also to the re-mobilization of sand. On

an overcrowded planet where the coasts are ecosystems to which humans gravitate, conservation and restoration actions become exponentially important.

Chapter 20
Coastal Dune Restoration: Trends and Perspectives

M. Luisa Martínez, Patrick A. Hesp and Juan B. Gallego-Fernández

20.1 Introduction

Sandy beaches and coastal dunes suffer the intense impacts of human activities. Because of their foremost locations on the coast, they are preferred sites for urban and maritime development, destinations for tourists, and the location of many other human activities that take place on the beach or on coastal dunes. Thus, over the years (but especially during the last few decades) many of the previously natural dunescapes have been lost to urban, tourism, and industrial developments. Furthermore, a recurring problem of many coastal dune systems is over-stabilization, which is mostly the result of human actions (Hesp 1991; Nordstrom et al. 2000; Hanson et al. 2002; Arens et al. 2004; Everard et al. 2010). AQ1

In brief, coastal dunes throughout the world are being rapidly lost and degraded; thus, it is evident that there is an urgent need to preserve the natural and valuable coastal dune remnants and, as much as possible, restore those that have been degraded.

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20.2 How can a Coastal Dune be Restored?

The society for ecological restoration (SER) defines restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed. It is an intentional activity that initiates or accelerates ecosystem recovery with respect to its health (functional processes), integrity (species composition and community structure), and sustainability (resistance to disturbance and resilience)” (http//www.ser.org/content/guidelines_ecological_restoration.asp). Certainly, this is a broad concept that applies to many situations and ecosystems, but it is not easy to use it when it comes to coastal dune restoration, because recovery or restoration of coastal dune ecosystems may include a wide array of situations.

What can be considered to be the “recovery” of a coastal dune ecosystem? Does it mean recovering former landform types or geomorphological units? Does it mean recovering mobile stages or to stabilizing mobile dunes and recovering dune vegetation? Does it refer to restoring the environmental heterogeneity? Or recovering the many successional stages that can be found in a single system, adjacent to one another? Does it refer to the dynamic geomorphology, the vegetation, or both? Certainly, it seems that obtaining a clear definition of coastal dune restoration is not a simple task.

Because coastal dunes consist of very dynamic landforms and dynamic communities, heterogeneous and diverse (Martínez et al., Chap. 1, this volume), their restoration is anything but a simple and straightforward activity. There is no single way to restore a coastal dune. The commonly used definition of ecological restoration does not seem to apply to these environments, because there are many scenarios of recovery that can be looked for in a coastal dune restoration project. That is, the health, integrity, and sustainability of coastal dunes can refer to many situations.

The compendium of restoration projects gathered in this book is an example of the complexity and variety of coastal dune restoration activities that are taking place in a variety of countries from different continents. These activities include many contrasting actions, such as the creation of artificial dunes, the destruction of artificial dunes and berms, and the creation of more natural ones, the recovery after mine extraction activities, the reactivation of stabilized dunes, or the stabilization of active dunes, and the elimination of invasive species. All of them are attempts to recover functional processes and ecosystem integrity.

A summary of the different restoration activities that have taken place at coastal dunes in various countries and that are described in this book follows (Table 20.1). From this set of examples it is obvious that the restoration of coastal dunes has many goals, facets, and mechanisms.

Table 20.1 Summary of the restoration actions shown in this book. Order of authors follows chapter order

Chapter	Authors	Country	Disturbance	Goals for restoration	Morphology	Restoration actions	Costs	Funding agency
2	Nordstrom and Jackson	USA	Erosion by storm surges, human activities	Protection and recreation, habitat, refuge	Foredunes	This is a review of different methods used for coastal dune restoration	No data	Government
3	Psuty and Silveira	USA	Human and natural	Restore, recover sediment dynamics, maintenance of the processes	Foredunes	Passive restoration with no human intervention; allow dune inland migration; some human intervention with bulldozer, beach scraping and sand transportation	No data	Government; public parks
4	Vestergaard	Denmark	Human activities	Protection and recreation	Foredunes	Creating artificial dune; planting native vegetation	US$ 2,229/ha	Government; public parks
5	Hesp and Hilton	New Zealand	Grazing, planting exotics, reshaping, land use change, urbanization	Restore morpho-ecological states in a metropolitan context; restore natural dynamics of transgressive dunes stabilized with marram grass	Foredunes and transgressive dunes	Foredunes re-shaped with bulldozer; exotics sprayed with herbicide; native plants were planted; destabilization after eliminating marram; natural dynamics recovered	US$ 1,123/m	Government; public parks
6	Feagin	USA	Hurricanes	Protection of human infrastructure, aesthetic value; restoration after hurricane Ike	Foredunes	Three restoration projects: geotubes; reintroduction of *Uniola paniculata*; backhoes and tractors.	US$ 275/m	Stake-holders, government

(continued)

Table 20.1 (continued)

Chapter	Authors	Country	Disturbance	Goals for restoration	Morphology	Restoration actions	Costs	Funding agency
7	Arens et al.	Netherlands	Stabilization leads to loss of biodiversity	Restoring dune mobility and increasing biodiversity	Foredunes; dunefield; parabolic dunes	Sod-cutting; restoration of aeolian processes; engineering; archeological research (to prevent damage to archeological heritage)	US$ 9/m^3	Government
8	Rhind et al.	Wales, UK	Overstabilization, loss of herbivores	Restoring dune mobility and increasing biodiversity	Foredunes and dunefields	Deep ploughing; this is a review of different methods	No data	–
9	Muñoz-Reinoso et al.	Spain	Overstabilization, biodiversity loss, urbanization, tourist pressure	Recovery of Juniperus woodland	Dunefield	320 ha, 70,000 saplings were planted; pine tree clearings; hand removal of *Carpobrotus edulis*	No data	Government
10	Pickart	USA	Invasive exotic	Restoring biotic and abiotic processes	Foredune–blowout–parabolic dune complex	Hand removal of invasive species *Ammophila arenaria* and *Carpobrotus chilensis*	US$ 65, 293/ha	Government; public parks
11	Kutiel	Israel	Stabilization leads to biodiversity loss	Restoring dune mobility and increasing biodiversity	Dunefield	Uprooting woody vegetation with bulldozer	No data	Nature reserve
12	Acosta et al.	Italy	Human trampling	Vegetation recovery	Foredunes	Fencing to avoid human trampling; natural recovery of vegetation	US$ 962/ha	Government

(continued)

Table 20.1 (continued)

Chapter	Authors	Country	Disturbance	Goals for restoration	Morphology	Restoration actions	Costs	Funding agency
13	Lubke	South Africa	Mining for minerals: total destruction	Recreate previously existing natural ecosystems	Dunefield	Building dunes, planting plants and then spontaneous restoration	No data	Private (mining company)
14	Moreno-Casasola et al.	Mexico	Urbanization	Stabilization; preventing sand from affecting the city	Dunefield; parabolic dunes	Planting with *Casuarina trees*	No data	Government; port authorities
15	Grootjans et al.	Netherlands	Overstabilization leads to biodiversity loss; planting of pine forests	Recover hydrological regime and aeolian dynamics; dune vegetation	Foredunes; slacks and dunefields	Mowing and grazing; sod-cutting, re-wetting	US$ 12,053/ha	Water Company
16	Lopez Rosas et al.	Mexico	Invasion of exotic species	Restoring flooding regime and recovering biodiversity	Slacks	Ploughing; digging	No data	Government; nature reserve
17	Lehrer et al.	Israel	Expansion of exotic invasive species	Eliminating invasive species and recovering diversity	Dunefield	Cutting, clearing, burning, spraying, uprooting, solar sterilization	US$ 640,917	Government; LTER
18	Pérez-Maqueo et al.	No specific country	Any kind	Any goal	Foredunes and coastal dunes	This is a review of the costs of restoration and evaluation of ecosystem services	Wide range of costs	Different sources
19	Lithgow et al.	Mexico	Any kind	Any goal	Foredunes and coastal dunes	Multicriteria analysis to improve planning, implementation and monitoring of coastal dune restoration	No data	Different sources

20.2.1 Restoring Foredunes

Foredunes are exposed to many different disturbing events, such as the invasion of exotic species, artificial stabilization, nitrogen deposition, urbanization, storm surges, storms and hurricanes, human trampling, and 2WD and 4WD vehicle activity (Nordstrom and Jackson, Chap. 2, this volume; Psuty and Silveira, Chap. 3, this volume; Hesp and Hilton, Chap. 5, this volume; Acosta et al., Chap. 12, this volume; Wilcock and Carter 1977; Nordstrom et al. 2000; Miller et al. 2003). As a consequence, the goals of foredune restoration are equally diverse and include beach nourishment; the recovery of morpho-ecological states; the recovery of sediment dynamics; the restoration of natural vegetation and endemic species; and the creation of habitat refugia. Frequently, however, foredunes are restored for the protection of human infrastructure, recreation, and aesthetic values (Nordstrom and Jackson, Chap. 2, this volume; Vestergaard, Chap. 4, this volume; Feagin, Chap. 6, this volume; Peterson et al. 2000; López and Marcomini 2006; Nordstrom et al. 2000; Muñoz-Pérez et al. 2001). In general, the actions required to guarantee an adequate sediment supply to reach the location of pioneer vegetation, accumulate, and create the heterogeneous natural topographic features is the essence of restoration in foredune systems (Psuty and Silveira, Chap. 3, this volume; Webb et al. 2000; Miller et al. 2003).

The activities required to achieve these goals are very different, and range from "soft" measures, such as the modification of aeolian processes and sediment dynamics by using sand fences and/or vegetation planting (Nordstrom and Jackson, Chap. 2, this volume; Psuty and Silveira, Chap. 3, this volume; Nordstrom et al. 2002) as well as eliminating exotics by hand (Pickart, Chap. 10, this volume), through more intense methods, such as the eradication of exotics by means of herbicides (Hesp and Hilton, Chap. 5, this volume; Feagin, Chap. 6, this volume; Hilton et al. 2009), to "hard" methods, such as the use of geotubes to strengthen the foredune foundation and utilizing earth-moving equipment to restore/rebuild/build the foredunes (Nordstrom and Jackson, Chap. 2, this volume; Vestergaard, Chap. 4, this volume; Hesp and Hilton, Chap. 5, this volume; Feagin, Chap. 6, this volume; Jones et al. 2010). In addition, the negative impact of human actions also needs to be controlled by means of controlling access to beaches to avoid human trampling (Acosta et al. Chap. 12; Kutiel, Chap. 11; Hesp et al. 2010; Pye and Neal 1994), restricting beach raking that eliminates plants and propagules, and limiting driving on beaches and dunes (Kutiel, Chap. 11, this volume).

It is important to bear in mind that commonly, the restoration of the morphology and vegetation on foredunes may take 10 years or more and that, because of the dynamic nature of these systems, restoration may in fact need to be a recurrent action (Psuty and Silveira, Chap. 3, this volume; Hesp and Hilton, Chap. 5, this volume; Feagin, Chap. 6, this volume). Repeated beach nourishment is perhaps inevitable in the case of a sand-deficient environment, such as eroding shorelines (Nordstrom and Jackson, Chap. 2, this volume; Psuty and Silveira, Chap. 3, this volume; Muñoz-Pérez et al. 2001; Bezzi et al. 2009; González et al. 2009).

20.2.2 Restoring Dunefields: Vegetation vs Sand

Dunefields are very diverse and range from foredune plains, foredune–blowout complexes, parabolic dunefields to transgressive dune sheets and dunefields.

Restoration of dunefields can be very generally grouped into two contrasting sets of actions: the reactivation of stabilized dunes and the stabilization of mobile dunes. Usually, the goal is to restore the heterogeneity of features in the geotemporal context (Psuty and Silveira, Chap. 3, this volume; Hesp and Hilton, Chap. 5, this volume; Arens et al. 2004), and improve/change the environment for psammophyte species including plants and animals (Pickart, Chap. 10, this volume; van der Hagen et al. 2008). Needless to say, human needs are also a common reason for restoration.

Drivers influencing dune stabilization can be direct and human-induced (e.g., removal and/or flattening of dunes; stabilization by urban, industrial and farming infrastructure; plantations of grasses, herbs, shrubs or trees; introduction or removal of grazing, off-road vehicle activity, nutrient enrichment due to pollution); indirect and external (e.g., changes in sediment supply, salt spray, and water availability and water table heights, nutrient enrichment, and climate change); and internal (such as soil development, and grazing) (Rhind et al., Chap. 8, this volume; Arens and Geelen 2006).

From perhaps the earliest historic times humans destroyed, modified or changed dune systems, both continental and coastal, often because of farming activities and forest felling. The creation of drifting sands was enhanced in some cases by climatic events (e.g., the Little Ice Age in Europe). Humans then tended to view *all* drifting sands as bad and attempted to stabilize them, often with considerable success, but commonly by introducing exotic species and creating mono-specific stands (Muñoz-Reinoso et al., Chap. 9, this volume; Arens et al., Chap. 7, this volume; Moreno-Casasola et al., Chap. 14, this volume; Pickart, Chap. 10, this volume; Grootjans et al. 2001; van der Meulen and Salman 1996; Bossuyt et al. 2007). This trend continued into the late 1900 s in some countries, and, led by agriculturalists and soil conservationists in particular, many exotic species were introduced into coastal dunes, and then spread from those sites, becoming invasive species.

Stabilization (both natural and artificially induced) of the natural dunes results in the loss of space or habitat for the native species (Hesp and Hilton, Chap. 5, this volume; Pickart, Chap. 10, this volume); the rare and uncommon obligate or semi-obligate psammophytes (Rhind et al., Chap. 8, this volume); the dune slack hygrophytes (Grootjans et al., Chap. 15, this volume); as well as many other impacts. When dunes become stabilized, diversity decreases because the early successional stages disappear, and certain landform units may not be formed (e.g., deflation basins and plains, wet slacks, gegenwalle ridges, precipitation, and trailing ridges, etc.) resulting in habitat and diversity losses or changes (Arens and Geelen 2006; Arens et al., Chap. 7, this volume; Rhind and Jones 2010; Rhind et al., Chap. 8, this volume; Grootjans et al. 2001). It must be recognized that this is a perfectly natural evolutionary trend for coastal dunes in the absence of human impact or interference. For example, foredunes can eventually evolve from incipient foredunes dominated by a few pioneer species to stabilized relict foredunes covered in a few tree and shrub species. Transgressive dunefields evolve from highly mobile systems with minimal plants present, through various evolutionary steps or phases. At some point the dunefields may have active interdunes, precipitation, and trailing ridges, deflation plains and slacks, nebkha, etc., with many rare and endemic species present. At a later stage these may all disappear as large-scale natural stabilization takes place (e.g., Martinho et al. 2010). We must be careful not to view this as ecologically or geomorphologically "bad" just because the natural diversity has decreased or changed. The negative impact of the human-driven stabilization of dunescapes has been demonstrated in many dune systems of the world, such as Israel (Kutiel, Chap. 11, this volume), Wales (Rhind et al., Chap. 8, this volume), the Netherlands (Grootjans et al., Chap. 15, this volume; Arens et al., Chap. 7, this volume); New Zealand (Hesp and Hilton, Chap. 5, this volume), the USA (Pickart, Chap. 10, this volume), Spain (Muñoz-Vallés et al. 2011), South Africa, and many other countries.

Note that stabilization may also occur as a result of a *reduction* in human activities, such as occurred in Israel. Here, when the State of Israel was established in 1944, grazing was banned and exploitation of coastal vegetation was stopped. Bedouin nomads, who intensively used the coastal dune vegetation for grazing and fuel, moved elsewhere. The result was rapid dune stabilization (in a few decades) and the loss of many endemic psammophytic species (Kutiel, Chap. 11, this volume). Coastal dunes have also become artificially stabilized as a result of atmospheric nitrogen deposition from atmospheric pollution, which enhances the growth of a few species (Kooijman and de Haan 1995).

Different plant species have been used in stabilization actions, such as grasses (*Ammophila arenaria*, or marram grass), shrubs (*Acacia karroo*, *Acacia saligna*, *Retama monosperma*), and trees (*Pinus* spp., *Eucalyptus* spp., *Casuarina* spp.).

20.2.3 Reactivating Stabilized Dunes

Because of the perceived negative impact of artificial stabilization of dunes on diversity and the formation/evolution of geomorphological units, the most frequent restoration action currently taking place on parabolic and transgressive dunefields is re-mobilization. In a way, restoration actions through the application of a "desertification process" aimed at reducing vegetation cover sound quite paradoxical. Nevertheless, it should be emphasized that in this case, a truly healthy dune system according to some (but not all) requires all successional stages, including mobile dunes. When all successional seres occur in a coastal dune system, biodiversity increases and functionality is strengthened.

A range of options to counter stabilization have been used and again, similar to restoration actions on foredunes, they range from low-impact and small-scale, to high-impact and large-scale. In terms of low-impact and small-scale actions, local disturbance can be promoted by increasing the levels of grazing pressure through encouraging rabbits, or by the use of domestic stock such as cattle, sheep or horses. Heavy grazing can, however, result in severe destabilization (Rhind et al., Chap. 8, this volume) and changes in plant communities (Zunzunegui et al., 2012), but when used at perceived "proper" intensities, may reactivate the system, as was found by Grootjans et al. (Chap. 15, this volume, and 2001) and López Rosas et al. (Chap. 16, this volume)

Elimination of exotic species is also a difficult task. Sometimes they have been sprayed with herbicides (Hesp and Hilton, Chap. 5, this volume; Hilton et al. 2009), although some invasives, such as marram grass (*Ammophila arenaria*) are difficult to eradicate, even with continued application of herbicides and mechanical removal. In contrast to the above, softer techniques have also proven to be effective. For instance, in Northwestern USA, marram grass was removed by hand. This involved painstaking labor, with many volunteer-hours involved. But in the end, biodiversity increased naturally once the dominant exotic grass was eliminated (Pickart, Chap. 10, this volume). In the Netherlands remobilization has been achieved by sod cutting, as well as hand removal of re-sprouting roots for a number of years (Grootjans et al. 2001). Intensive volunteer work has also been necessary. Inhibitory woody vegetation has been removed by pruning and felling (Muñoz-Reinoso et al., Chap. 9, this volume), but also with bulldozers (Kutiel, Chap. 11, this volume).

Larger scale, more invasive options to reactivate coastal dunes and restore original vegetation include mechanical disturbances, such as the removal of alien soils and materials and the creation of new dunes (Hesp and Hilton, Chap. 5, this volume; van Aarde et al. 1998), and topsoil stripping and deep ploughing (Rhind et al., Chap. 8, this volume; Graham and Haynes 2004). The latter inverts the soil profile by burying any surface nutrients and unwanted seeds, while exposing low fertility subsoil, and inhibits the germination of undesired species (Jones et al. 2010). Another high impact large-scale mobilization action includes beach and shoreface nourishment in order to counteract shoreline erosion. This strategy has proven to be very successful in The Netherlands (Arens et al., Chap. 7, this volume), where the coastline retreat has been reduced and the transfer of sand into the dunes has increased considerably. A potential drawback of these activities is the quality of the sand used for nourishment. If the nourished sand differs from the original sand, e.g., in grain size, carbonate content or mineralogical compounds, there may be ecological consequences affecting species colonization and growth. The bottom of the ocean floor, where sediment is removed for beach nourishment, may also be severely affected after these dredging activities, and some would argue that this is not a medium- to long-term sustainable action, as coastline retreat is likely to eventually occur.

Once blowouts are reactivated the dune systems may become destabilized (Rhind et al., Chap. 8, this volume; Arens et al. 2004). However, maintenance of coastal dune mobility can be a long-term project, requiring periodic human intervention. In this sense, Arens and Geelen (2006) found that even extensively destabilized areas (tens of hectares) are likely to re-stabilize within a few decades and that new measures to reduce stabilization may be required every 10 or 20 years (see Arens et al, Chap. 7, this volume). Lastly, it is very important to bear in mind that any attempt to create dunes where they do not exist, or to increase the dynamism of stabilized dunes, must have a strong public information component to demonstrate their feasibility and increase their acceptability. When people are informed, they may even be willing to pay for the remobilization of dunes, as well as the containment and elimination of exotic species (Lehrer et al., Chap. 17, this volume).

20.2.4 Stabilizing Active Dunes

Having shown the negative effects of overstabilization, it is necessary to also consider that stabilization and re-vegetation can sometimes be a required action. This is the case when coastal dunes are created de novo, artificially, and they need to be planted with preferably native plants in order to enhance further sand accumulation and dune growth (Vestergaard, Chap. 4, this volume; Gallego-Fernández et al. 2011). Sometimes, cities may develop on coastal dunes or are surrounded by them, as occurs with the Port of Veracruz, on the Gulf of Mexico, Mexico. For centuries, the Port of Veracruz has suffered the consequences of its unfortunate location, with sand blowing into the city from neighboring mobile transgressive dunes when the strong winds blow and the weather is relatively dry during the winter months. In this case, the stabilization of mobile dunes was seen as a societal need (Moreno-Casasola et al. 2008). The relevant fact is, in these cases, how restoration–revegetation was performed.

In Denmark, an artificial dune was built with earth-moving machinery and was then planted with native species and natural regeneration was allowed to occur (Vestergaard, Chap. 4, this volume). In contrast, the dunes surrounding the city of Veracruz were stabilized with the exotic tree *Casuarina equisetifolia*. Usually, this is a very aggressive invasive species that does not promote natural regeneration (Mailly and Margolis 1992; Moreno-Casasola et al., Chap. 14, this volume). Nevertheless, Moreno-Casasola et al. (Chap. 14, this volume) found that, under high moisture conditions and if tropical rainforest remnants occur in the vicinity, the original tropical forest can, in fact, regenerate beneath the shade of the exotic trees. This is a very peculiar situation and should not be interpreted as a sign that *Casuarina* is a good option for dune re-vegetation outside its native distribution range (Australia). Native species should always be the preferred plants in any restoration project. Interestingly, in spite of the overwhelming evidence of the negative impacts of artificial stabilization, coastal dune forestation programs are still commonplace in many countries.

Building artificial dunes and enhancing the arrival and growth of vegetation has also been promoted after heavy mineral dune mining (Lubke, Chap. 13, this volume; Zeppelini et al. 2009; Grainger et al. 2011). For example, in Namibia, nets were used as wind traps for rehabilitation following diamond mining acting to trap sand. In addition, top soil was spread onto the site and native plants were transplanted and allowed to follow their natural successional sequence (Lubke, Chap. 13, this volume).

20.2.5 *Restoring Wet Slacks*

Wet slacks (also termed deflation plains and basins, ponds and wetlands) are located in the lower parts of the coastal dune system. Here, the water table is close to the surface of the sand and thus, slacks may become flooded during the rainy season, creating interdune ponds and lagoons (ephemeral or permanent).

Wet slacks can be severely affected by artificial fluctuations in water tables because of the production of drinking water for human populations (e.g., in the Netherlands), for watering crops, and also because of high atmospheric nitrogen deposition from agricultural lands and industrial areas. The result is a decline in species diversity, and the local extinction of endemic species. In this case, restoration activities involved rewetting wet slacks, and re-establishing the hydrological regime; mowing, grazing, and sod-cutting (Grootjans et al., Chap. 15, this volume; López Rosas et al., Chap. 16, this volume; Grootjans et al. 2001, 2002). Once the hydrological conditions are restored, restoration projects in slacks are generally successful, especially when the top soil is removed. Nevertheless, repeated maintenance is also necessary (López Rosas et al., Chap. 16, this volume).

20.3 Who Pays for Coastal Dune Restoration?

Coastal dunes and beaches are amongst the most intensely used natural ecosystems, because of the associated economic benefits. They offer a wide array of ecosystem services to society and are exploited by human society throughout the world. No doubt, there are many interests that acknowledge the need to restore those dune systems that are degraded as efficiently as possible and in the best way: beaches are nourished every year; coastal dunes are re-mobilized; coastal dunes are stabilized. Because humans gravitate to the coast, with 40 % of the world population living at or near the coast, and because coastal tourism is significant, human intervention in and on coastal ecosystems is constantly high.

Thus, it is obvious that there is a societal need at times and in certain places to restore and rehabilitate coastal ecosystems, such as beaches and coastal dunes. Stakeholders (hotel and private property owners) as well as the general public tend to benefit from these restoration practices. Who pays for them? The restoration examples presented in this book show that restoration and rehabilitation are mostly financed by Government authorities (Table 20.1). Restoration of dunes and the re-mobilization of stabilized dunes is frequently performed in public parks/

conservation regions and financed by government agencies. Private funds for restoration and rehabilitation are less frequent, for example, the case of the mining company (Lubke, Chap. 13, this volume), and Galveston in Texas, where stakeholders and local government agencies pay for rehabilitation after every hurricane that affects this island (Feagin, Chap. 6, this volume). As human impacts increase, so will the need for more funds for restoration and rehabilitation.

20.4 Discussion

Independently of how effective the restoration actions were, what we have learned from numerous restoration projects at dune sites is that we cannot fully compensate for the ecological functioning of natural processes, such as, for example, intensive aeolian transport, local blowout development and maintenance, a regular supply of nonpolluted groundwater, or shoreline protection. As much as possible, dunes should be allowed to evolve and move freely, or at least to the extent possible within the constraints of human infrastructure (on developed coasts). The heterogeneity of these systems needs to be maintained in order to protect their integrity and conservation values.

Coastal dune restoration must take into account the spatial and temporal scale of their evolution, landforms, structures, and functions, and therefore dune restoration plans should have a regional approach, incorporating landscape-scale processes (Gallego-Fernández et al. 2011). In general, coastal dune restoration practices require the following actions. First, and independently of the goals for restoration (rehabilitation, remobilization, stabilization), the factors and conditions that are driving coastal beach and dune dynamics, development, and evolution need to be determined so that these factors can be addressed. Second, once these factors are determined, one can decide on the best actions that need to be taken. Natural sediment and vegetation dynamics should be allowed to occur wherever possible. In order to allow this we need to protect dune systems far better, and one priority should be to work toward the creation of many more dune conservation areas around the world. In addition, there are many actions we can take to better protect beach–dune system dynamics: beach raking and driving on beaches and dunes should be eliminated; reducing and preferably eliminating pollution should be of paramount importance; protecting endangered species, restricting or eliminating invasive species should be a primary objective; construction on foredunes should be declared illegal; and the creation of set-back zones where construction is forbidden should become a common planning requirement. Chiefly, natural aeolian processes and natural vegetation dynamics should be allowed to function wherever and whenever possible. By accepting more natural system dynamics and natural mobility, coastal dunes can be more functional, better preserved, and protect more efficiently.

Restoration of coastal dunes and recovery of characteristic dune species are difficult tasks. Long-term monitoring of remobilization actions, for example, has shown that a single restoration intervention is not sufficient to restore the large-scale landscape forming process or to eliminate invasive species (Kutiel, Chap. 11, this volume; Hesp and Hilton, Chap. 5, this volume). In this sense, Arens et al. Chap. 7, this volume argue that for a number of years, a certain form of maintenance, such as the removal of re-growing roots, is necessary to get the dune moving. In addition, recent evidence (Arens et al. 2004) shows that mobilization of coastal dunes is more effective when dunes are connected to the coastline (Psuty and Silveira, Chap. 3, this volume; Arens et al., Chap. 7, this volume). Thus, it seems that foredune erosion, with sediment being transferred to inland coastal dunes, might "restart the engine" of coastal dune mobility (Arens et al., Chap. 7, this volume).

An important question here is whether there is equilibrium between the protection of human assets and the dynamic nature of coastal dunes. How much should they be allowed to move? Is it possible to nourish our coasts, prevent shoreline erosion, allow sand movement, and protect human infrastructure and lives? Can we have it all? This is certainly an important challenge for the coming years. While working on this challenge, it is essential to bear in mind that there is no equilibrium form or dimension in a functional dune system: each one is unique and has its own dynamic equilibrium that changes in time and space.

AQ2

Restoration is not always a real possibility. When coastal dunes and beaches are very degraded, as occurs on urban and developed coasts, rehabilitation may be the only viable option. In this case, the system is not self-sustainable and requires periodic human intervention that repairs and maintains the integrity of the system. When sediment is insufficient, as occurs on eroding coasts, rebuilding a dune is not really restoration, but an artificial creation of a sand ridge that is unsustainable over time (Psuty and Silveira, Chap. 3, this volume). Adaptive management, with continued human input, is critical where space is restricted and long-term erosion continues. Sustainability of natural features in developed areas requires humans to act as intrinsic agents of landform change.

20.5 Conclusions

Coastal dune restoration efforts require the combination and integration of different criteria, including ecological, geomorphological, and social, so that we can maximize the goods and services that coastal dunes can provide (Nordstrom and Jackson, Chap. 2, this volume; Lithgow et al., Chap. 17, this volume; Pérez-Maqueo et al., Chap. 19, this volume). A theoretical and empirical catalog of the actions needed to perform adequate coastal dune restoration should consider:

1. Assessing the factors that are affecting the dune systems, and in particular, understanding the evolutionary state of each dune system.
2. Eliminating or reducing factors of tension.
3. Creating the landforms or the conditions necessary for natural landform creation where they have been eliminated or truncated.

4. Allowing these new or modified landforms to function as natural dunes by allowing them (or some portions) to be dynamic, but also to evolve and change over time.
5. Eliminating exotics or invasive species.
6. Favoring dune and vegetation evolution through time by following adaptive management strategies.
7. Last but not least important, convincing society to accept coastal dunes, with their natural dynamism, as a natural feature of the coast.

Finally, the ever-increasing human population (especially at the coast) (Martínez et al. 2007), and human-related environmental changes, such as climate change and potential sea level rise, coupled with possible increased storminess, will add more stress to the world's coastal beaches and dunes. Humans and natural ecosystems will be increasingly affected by these changes. More than ever, humans will benefit from the protection gained from the natural functioning of coastal dunes. Restoration of these ecosystems will thus become increasingly important as human impact (direct and indirect) destroys or disrupts them. Further research on the dynamics and functionality of coastal dunes and how ecosystem services such as protection are related will become increasingly relevant, and restoration and conservation will likely become more necessary on an increasingly crowded planet.

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