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Review

Linking restoration ecology with coastal dune restoration

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ABSTRACT

Restoration and preservation of coastal dunes is urgently needed because of the increasingly rapid loss and degradation of these ecosystems because of many human activities. These activities alter natural processes and coastal dynamics, eliminate topographic variability, fragment, degrade or eliminate habitats, reduce diversity and threaten endemic species. The actions of coastal dune restoration that are already taking place span contrasting activities that range from revegetating and stabilizing the mobile substrate, to removing plant cover and increasing substrate mobility. Our goal was to review how the relative progress of the actions of coastal dune restoration has been assessed, according to the ecosystem attributes outlined by the Society of Ecological Restoration: namely, integrity, health and sustainability and that are derived from the ecological theory of succession. We reviewed the peer reviewed literature published since 1988 that is listed in the ISI Web of Science journals as well as additional references, such as key books. We exclusively focused on large coastal dune systems (such as transgressive and parabolic dunefields) located on natural or seminatural coasts. We found 150 articles that included "coastal dune", "restoration" and "revegetation" in areas such as title, keywords and abstract. From these, 67 dealt specifically with coastal dune restoration. Most of the studies were performed in the USA, The Netherlands and South Africa, during the last two decades. Restoration success has been assessed directly and indirectly by measuring one or a few ecosystem variables. Some ecosystem attributes have been monitored more frequently (ecosystem integrity) than others (ecosystem health and sustainability). Finally, it is important to consider that ecological succession is a desirable approach in restoration actions. Natural dynamics and disturbances should be considered as part of the restored system, to improve ecosystem integrity, health and sustainability.

1. Introduction

1.1. The need to restore

For millennia, the coastal environment has been one of the preferred settings for urban, industrial and maritime development, and more recently, for mining, tourism and recreation (Nordstrom, 2008). Nearly 40% of the world human population lives within 60 km from the coast (Martínez et al., 2007), and it is expected that human encroachment on the coast will increase to 60% by 2020 (UNCED, 1992). Such a continuously growing population will result in an increasing human impact with the degradation or loss of coastal ecosystems. Of these, sandy beaches and coastal dunes are among the most damaged by human activities. Indeed, these unique ecosystems are increasingly becoming trapped between the expanding human populations and the effects of global climate change, such as sea level rise (Defeo and De Alava, 1995; Cencini, 1998; Nordstrom, 2000; Schlacher et al., 2007). These pressures act across multiple dimensions in time and space, and result in ecological impacts that occur at many temporal and spatial scales so that today the vast majority of beaches and coastal dunes are threatened by human activities (Nordstrom, 2008; Defeo et al., 2009).

Coastal dunes are degraded and lost because of a wide array of human actions and activities (Ketchum, 1972; Nordstrom, 2008), which can be aggregated into six groups: 1) housing and recreation; 2) industrial and commercial use; 3) waste disposal; 4) agriculture; 5) mining and 6) military activities. Typically, they alter coastal dynamics and natural processes, eliminate topographic variability, fragment, degrade or eliminate habitats, reduce biodiversity and threaten endemic species (Nordstrom, 2000, 2008; Ayyad, 2003; Martínez et al., 2006, 2013a,b; De Luca et al., 2011; Faggi and Dadon, 2011).

1.2. Conceptual scheme

The increasingly rapid loss and degradation of coastal dunes clearly shows the urgent need to preserve these ecosystems, and, as much as

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possible, restore those that have been degraded. Different actions are already taking place to restore coastal dunes, and they span contrasting activities that range from revegetating and stabilizing the mobile substrate, in one extreme, to removing plant cover and increasing substrate mobility in the other (Martínez et al., 2013a,b). With such a wide array of restoration possibilities, it is necessary to evaluate the progress and success of restoration with clearly established criteria. To address this problem for coastal dunes (and any other ecosystem that is being restored), the Society for Ecological Restoration (SER, 2004) produced a list of attributes that are associated with ecosystem integrity, health and sustainability and that can be used to measure restoration success (Table 1).

The elements on this list (Table 1) cover different stages of ecosystem development and can be associated with the ecological theory of natural succession: "the natural recovery of ecosystems after the impact of disturbances" (Connell and Slatyer, 1977; del Moral et al., 2007). According to the ecological theory, restoration and ecological succession are similar in the sense that they share several elements: site colonization (natural or after human intervention); vegetation establishment (natural or assisted); structuring of ecosystem cycles, species assembly and biotic interactions. Finally, in the last successional stages (or after long-term restoration), the ecosystem is structurally complex and relatively resilient (Fig. 1).

The ecosystem (naturally recovering or restored) develops through similar processes that affect the ecosystem integrity, health (functionality) and resilience. In early successional stages (or early restoration actions), colonization occurs after natural dispersal, from seed banks or because of human intervention (plantations). These early colonizers ameliorate the environment and facilitate the colonization of late colonizers, which become established and modify the physical environment even further. After establishment, different species assemblages are integrated, biotic interactions intensify and soils develop (Fig. 1). The ecosystem develops gradually through these events.

Some of the more measurable attributes that are frequently used to monitor the progress of restoration and hence, ecosystem development and recovery, include (SER, 2004): a) community structure and composition (integrity); b) a handful set of ecological processes, such as nutrient cycling and species turnover during plant succession (health); and c) the ability to recover after the impact of additional disturbances by means of natural regeneration of the restored ecosystem (sustainability). The success of restoration based on these attributes has been monitored before, but not in the context of coastal dunes. For example, Ruiz-Jaen and Aide (2005) analyzed how restoration success was being measured in restoration projects that had been published in the peer-reviewed journal: "Restoration Ecology" from 1993 to 2003. In general, they found that different elements were used to measure restoration success, but they were not always related to the three ecosystem attributes. They only registered two studies on coastal dune restoration that referred to restoration actions after mining in South Africa (van Aarde et al., 1996, 1998).

Because of the relevance of restoring coastal dunes and assessing the success of these restoration actions, our goal was to review how the relative progress of ecological restoration actions has been assessed for coastal dunes, according to the ecosystem attributes outlined by SER: namely, integrity, health and sustainability and that are derived from the ecological theory of natural succession (Gann and Lamb, 2006). Recommendations on new paths that are needed to improve the activities for coastal dune restoration were derived from this analysis.

Table 1
Ecosystem attributes and variables that can be measured to assess a successful restoration, according to SER (http://www.ser.org/resources/resources-detail-view/ecological-restoration-a-means-of-conserving-biodiversity-and-sustaining-livelihoods) (Gann and Lamb, 2006).

Ecosystem attributes	Ecosystem variables
Integrity (species composition and community structure)	• Diversity • Richness • Presence of indigenous species • Functional groups
Health (functional processes)	• Physical environment that sustains viable populations • Interactions • Nutrient cycle
Sustainability (resistance to disturbance and resilience)	• Integration with the landscape • Elimination of potential threats • Resilience to natural disturbances • Self-sustainability

2. Methods

Peer reviewed articles published between 1988 and 2012 were included in the assessment. Articles were extracted from four digital databases (ISI Web of Science, EBSCO, SCOPUS, and JSTOR). Articles from two journals that publish papers in restoration ecology (Ecological Restoration and Journal of Coastal Conservation) but are not abstracted in the databases were included in the assessment. Articles were extracted by searching the terms 'coastal dune', 'restoration' and 'revegetation' within the title, abstract, and keywords of papers. Key monographs and edited volumes on coastal dune restoration also were included in the assessment, including those authored by Ley Vega de Seoane et al. (2007), Nordstrom (2008), Perrow and Davy (2008) and Martínez et al., 2013a.

We only considered articles (and a few book chapters) whose main objective was to restore a site, monitor restoration efforts or evaluate restoration success of coastal dunes (like transgressive dune fields and parabolics) located in non-urbanized areas and with a Wilderness or Arcadian approach. The Wilderness Approach considers biological and physical processes as key features that direct the flows of energy and matter. In this case, natural systems are considered as self-regulating with little or no human influence. The Arcadian Approach refers to semi-natural systems with some human influence that enhances biodiversity, instead of self-regulation (Swart et al., 2001). We omitted studies that referred to restoration actions on urban coasts (mostly beaches and foredunes) because these have already been analyzed by Nordstrom (2008), Nordstrom and Jackson (2013), Psuty and Silveira (2013) and Vestergaard (2013).

A general description of the state of the art of coastal dune restoration began by describing the geographic region (country), habitat type (fixed dune, semi-mobile dune, mobile dune or dune slack), source of perturbation (natural or human), driver of perturbation (invasion by exotic species, extreme expansion of native species with an impact similar to that of invasion by exotic species, mining, trampling, fragmentation, stabilization, drinking water extraction and other), restoration technique (revegetation, control of invasive species, landscaping, destabilization, stabilization and other), number of reference sites, monitoring time and self-sustainability.

We then categorized the measures used to assess restoration success according to the following ecosystem attributes and variables: integrity (species composition and ecosystem structure), health (ecological processes such as nutrient cycling and biotic interactions) and sustainability (occurrence of natural regeneration and resilience after the impact of additional disturbances). Specifically, measures of species composition included diversity of fungi, plants, invertebrates, and vertebrates, whereas ecosystem structure was assessed through data on vegetation cover and species biomass. Ecological processes included nutrient cycling, nutrient availability, soil organic matter, and biological interactions (e.g., species turnover during successional sequence, herbivory, mycorrhizae, pollination, predation, and parasitism). Sustainability was assessed by evidence of the occurrence of natural regeneration and the ability to recover from new disturbances.