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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).

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

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.

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.

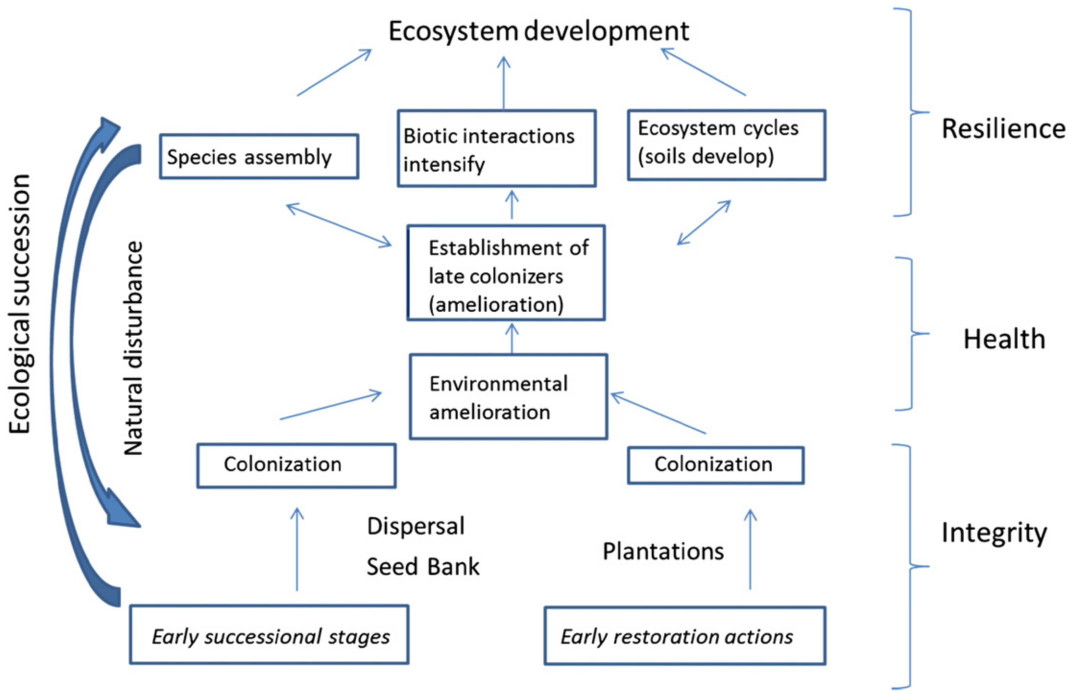

Fig. 1. Simplified mechanisms of ecosystem change during restoration actions and during natural succession, showing the three attributes (integrity, health and resilience) set by the Society of Ecological Restoration (SER) to assess progress of ecological restoration. Notice how, unlike ecological restoration, ecological succession can "go back" to early successional stages, after the impact of natural disturbances.

3. Results

3.1. General trends

Since 1988, we found a total of 150 articles. From these, only 67 evaluated restoration efforts or monitored restoration cases in non-urbanized landscapes (wilderness approach) and assessed the progress of restoration. The rest only mentioned "restoration" but these studies did not exactly focus on restoration but considered that the studies "might be useful" for restoration activities. Thus, these studies were omitted from our analyses. In general, the number of published articles on coastal dune restoration was reduced in comparison with the vast literature that has been produced on other restoration efforts (more than 500 studies). This certainly does not relate to the intensive and urgent need of restoration actions that are necessary for the increasingly degraded coasts. The last twelve years, however, witnessed a larger number of studies (53) than in the previous twenty-two (14).

We found studies on coastal dune restoration from every continent, except for Antarctica (Fig. 2). Most of them have taken place in Europe, followed by the North America (we found no studies from South America), Africa, Asia and Oceania. The oldest studies on coastal dune restoration that we found were performed in the Americas (USA) and Europe (The Netherlands), but in the Netherlands, the USA and South Africa nearly the same amount of studies (17, 13 and 12, respectively) has been published since 1988. We found a reduced number of published studies on coastal dune restoration for UK (3), France (3) and Spain (4) (Fig. 2).

Fixed dunes have been the habitat most frequently restored (54%), followed by semi-mobile dunes (30%), mobile dunes (27%) and dune slacks (16%) (Fig. 3a).The major driver of perturbation was plant invasion (33%) (Fig. 3b), followed by mining (24%) and fragmentation (15%). The most frequently used restoration mechanism was revegetation (42%), followed by controlling invasive species (30%) and landscaping (28%) (Fig. 3c), but several studies used more than one technique (Table 2). Twenty-nine studies (43%) did not provide information on the reference sites, twenty four (36%) had one and thirteen (19%) had more than one. In all cases, percentages add up to more than 100% because many articles evaluated more than one type of habitat, more than one disturbance driver and more than one restoration technique.

3.2. Restoration success

Some restoration success has been assessed directly and indirectly by measuring one or a few ecosystem variables. Five studies (7%) measured only one ecosystem attribute, forty two studies (62%) measured two, and twenty two studies (32%) measured three.

It became obvious from our exploratory analysis that some ecosystem attributes have been monitored more frequently than others (Fig. 4). For instance, ecosystem integrity (composition and structure)

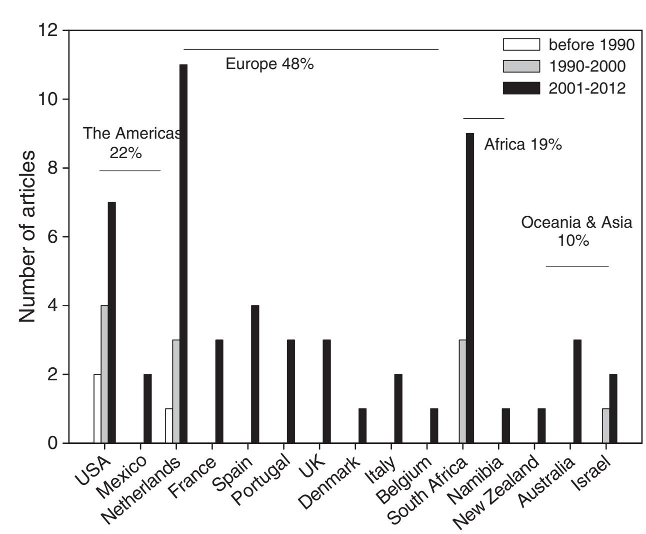

Fig. 2. Number of articles on coastal dune restoration per country during different time periods.

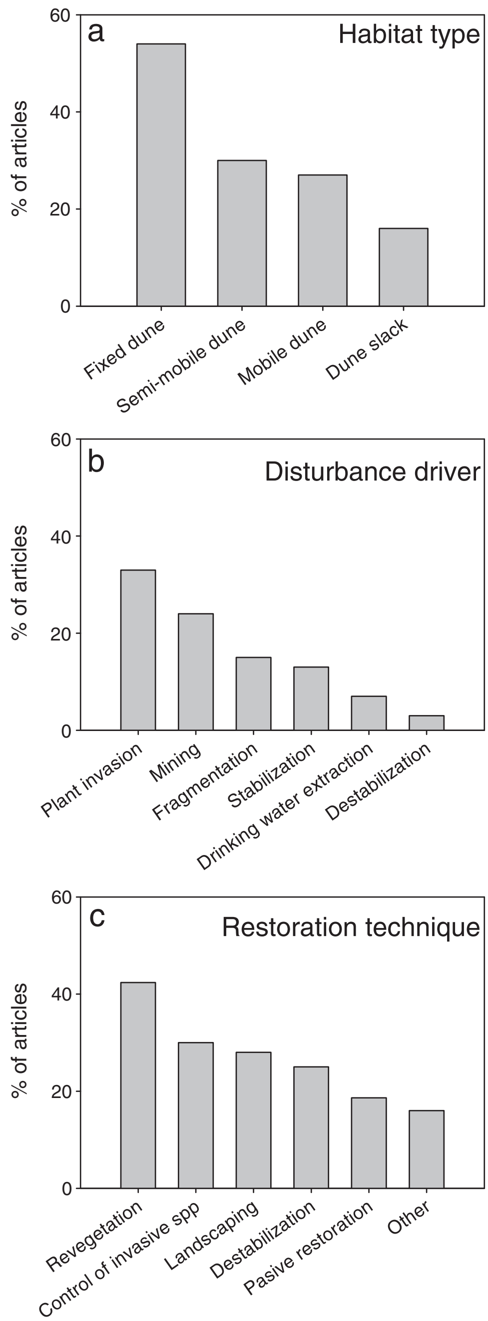

Fig. 3. a) Type of habitats where restoration actions in coastal dunes have been performed. b) Disturbance drivers. c) Restoration techniques. All the variables can add up to more than 100% because many articles evaluated more than one habitat type, more than one disturbance driver and more than one restoration technique.

was monitored in the majority of the studies. Ecosystem health (nutrient cycle and biotic interactions) was explored occasionally and ecosystem sustainability (resistance to disturbance and resilience) was largely missing from assessments of restoration success. Biotic interactions mostly referred to plant succession. These results show the unbalance of ecosystem attributes that are analyzed when restoration success is monitored and highlights the need to consider ecosystem sustainability.

3.3. Integrity (species composition and ecosystem structure)

The integrity of ecosystems can be assessed through species composition and ecosystem structure. Diversity and richness were the variables most commonly used to measure ecosystem recovery, adding a total of 59 studies (88%). From the total number of studies that we reviewed, 59 (88%) focused on plants, two (3%) focused on animals and 12 on plants and animals (18%) (Table 2). After plants, the taxa most commonly evaluated were arthropods (37%) (van Aarde et al., 1996; Davis et al., 2003; Wassenaar et al., 2005; Emery and Rudgers, 2010; Kutiel, 2013;) followed by birds (16%) (van Aarde et al., 1996; Wassenaar et al., 2005; Russell et al., 2009; Grainger et al., 2011) and mammals (16%) (Kutiel et al., 2000; Wassenaar et al., 2005; Russell et al., 2009). A handful of studies (21%) evaluated several taxa (Jungerius et al., 1995; van Aarde et al., 1996; Wassenaar et al., 2005; Russell et al., 2009) but most of them (78%) measured diversity in only one group. The interaction between different taxonomic groups in restoration progress is obvious, but has not been observed frequently. Russell et al. (2009) measured the effects of ongoing restoration efforts on wildlife abundance and diversity of plants, birds and ground-dwelling vertebrates in a dune system in San Francisco, California. They found that the diversity and abundance of wildlife species, as well as the richness and cover of native plants species were greater in the restored areas in comparison with sites where the only restoration action was a restricted visitor access. In contrast, Davis et al. (2003) assessed the pattern of vegetative and microclimatic changes and the impact on dung beetle assemblages. These authors used a 23-year vegetational chronosequence on rehabilitated mined dunes and observed that lasting convergence in the abundance of dung beetles between a restored site and a reference natural forest can only be attained when the regenerating forest resembles a secondary natural forest.

Ecosystem structure can be evaluated through several methods but vegetation cover and biomass were the most commonly used. Ecosystem structure (cover and biomass) was evaluated in 58 studies. From the total number of studies that we found, 78% measured vegetation cover (Table 3) whereas 9% measured biomass and only 5% assessed both variables (see for example Ernst et al., 1996; Emery and Rudgers, 2010). Usually, it is expected that diversity and plant cover change in the same direction. This is, however, not always the case. Andreu et al. (2010) evaluated the ecological success of the manual removal of the invasive *Carpobrotus* by comparing plots that had been treated by hand pulling, non-invaded, and invaded. They observed that treated plots had a significant increase in species richness, but all had the same native plant cover and diversity.

3.4. Health (ecological processes)

The health of an ecosystem can be assessed through ecological processes, such as nutrient cycles and species interactions. Nutrient cycles were analyzed in 17 studies. These studies showed that the recovery of ecosystem health may take a long time. Marchante et al. (2008) studied the changes in soil C and N pools induced by *Acacia longifolia*, a N2-fixing invasive tree, and found that it takes several years (more than five) before soil nutrients and processes return to pre-invasion levels, after removal of the invasive shrub *A. longifolia.*

Plant succession was basically the only ecological process explored in terms of biotic interactions. Plant succession is the result of the combination of many biotic interactions (facilitation and competition) (Miller and terHorst, 2012), so, in the absence of better defined studies on biotic interactions, it can be considered as a good proxy that summarizes biotic interactions as a whole. Natural plant and animal succession has been explored through chronosequences that analyzed soil properties (Ernst et al., 1996; Graham and Haynes, 2004); vegetation recovery (Lubke et al., 1996; Grainger et al., 2011; Zaloumis and Bond, 2011); ecosystem functioning (Emery and Rudgers, 2010); invasive species control (Marchante et al., 2008); soil seed banks (Plassmann et al., 2009) and invertebrates (Weiermans and van Aarde, 2003; Redi et al., 2005; Wassenaar et al., 2005). Long-term monitoring has also been followed for invertebrates (van Aarde et al., 1998; Davis et al., 2003; Grainger and van Aarde, 2012); vertebrates (Denton et al., 1997);

Table 2
General information.

Author	Country1	Habitat type2	Source of perturbation3	Driver of perturbation4	Aims of Restoration5	Rest Technique6
Acosta et al., 2013	IT	FxD	H	Fr	RB	Rv
Andreu et al., 2010	ES	SMD	H	PI	Cv	CIS
Arens and Geelen, 2006	NL	DS	H	DWE	RB	Dstb, Lcp
Arens et al., 2004	NL	MD	H	Stb	RB	Dstb
Arens et al., 2005	NL	SMD, DS	H	Stb	RB	Dstb, Oth
Arens et al., 2013	NL	MD	H	Stb	RB	Dstb
Bakker et al., 2005	NL	DS	H	DWE	RB	Dstb, Oth
Bossuyt et al., 2007	FR	DS	H	PI, Oth	RB	CIS
Cater et al., 2007	USA	FxD	H	Oth	RB, ES	Rv
Christensen and Johnsen, 2001	NL	FxD	H	Fr, Dstb, Oth	RB	Rv
Conser and Connor, 2009	USA	FxD	H	PI	RB	CIS
Davis et al., 2003	ZA	FxD	H	Mn	RB	Lcp, Stb, Rv
De Lillis et al., 2004	IT	MD, SMD	H	Oth	RB	Lcp, Rv
Deblinger and Jenkins, 1991	USA	FxD	N	PI	Cv, RB	CIS, Rv
Denton et al., 1997	UK	FxD	H	Oth	Cv	CIS, Oth
DeSimone, 2011	USA	FxD	N	PI	RB	PR, CIS, Rv
Emery and Rudgers, 2010	USA	FxD	H, N	PI, Mn, Oth	RB, ES	Rv
Ernst et al., 1996	NL	DS	N	DWE, Oth	RB	CIS
French et al., 2011	AU	FxD	N	PI	RB	CIS
Gallego-Fernández et al., 2011	ES	MD, FxD	H	Fr	RB	Rv, Lcp
Gómez-Piña et al., 2002	ES	MD, SMD	H	Mn, Oth	Cv, RB	Lcp, Rv
Graham and Haynes, 2004	BE	FxD	H	Mn	RB	Rv, Lcp
Grainger and van Aarde, 2012	ZA	FxD	H	Mn	RB	PR, Rv, Lcp
Grainger et al., 2011	ZA	FxD	H	Mn	RB	Lcp, Rv, PR
Grootjans et al., 2013	NL	MD, DS	H	Pl, Oth	RB	Dstb
Hesp and Hilton, 2013	NZ	MD	H	Pl, Stb	RB,	CIS
Jansen et al., 2004	NL	FxD	H	DWE, Oth	RB	CIS
Jones et al., 2010	UK	SMD	N	Oth	RB	Oth
Jungerius et al., 1995	NL	DS	H	Oth	RB	PR
Ketner-Oostra and Sýkora, 2000	NL	FxD	H, N	Oth	RB	CIS
Ketner-Oostra et al., 2006	NL	SMD	N	PI	Cv	PR
Kollmann et al., 2011	DK	SMD	H	PI	Cv	CIS
Kutiel, 2013	IL	MD	H, N	Stb	RB	Dstb
Kutiel et al., 2000	IL	SMD, FxD, DS	N	PI, Oth	Cv	CIS
Lemauviel et al., 2003	FR	SMD, FxD, DS	H	Oth	Cv	Oth
Lubke, 2013	MA, NA	FxD	H	Mn	RB	Lcp & Rv
Lubke et al., 1996	ZA	FxD	H	Mn	RB	Lcp & Rv
Marchante et al., 2008	PT	FxD	N	PI, Oth	RB	CIS
Marchante et al., 2011	PT	FxD	N	PI, Oth	RB	CIS
Mason et al., 2007	AU	SMD, FxD	N	PI, Oth	RB, ES	CIS
Moreno-Casasola et al., 2008	MX	SMD	H	Oth	ES	Rv & Stb
Moreno-Casasola et al., 2013	MX	FxD	H	Pl	RB	PR
Mpanza et al., 2009	ZA	FxD	H	Mn, Oth	Cv, RB	Rv
Muñoz-Reinoso et al., 2013	ES	MD	H	Pl	RB	Dstb
Pickart, 2013	USA	MD	H	Pl	RB	Dstb
Pickart et al., 1998a	USA	MD, SMD	H	PI	RB	CIS, Rv
Pickart et al., 1998b	USA	FxD	H	PI	RB	CIS
Plassmann et al., 2009	UK	DS	H	Stb, Oth	RB	Dstb
Redi et al., 2005	ZA	MD, SMD, FxD	H	Mn	Cv, RB	PR
Rhind et al., 2013	UK	MD	H	Stb	RB	Dstb
Rosati and Stone, 2009	USA	SMD, FxD	N	Fr, Oth	Cv	Rv, Stb, Lcp
Rozé and Lemauviel, 2004	FR	MD, SMD	H	Oth	Cv, RB	Lcp, Rv
Russell et al., 2009	USA	MD, SMD, FxD	H	PI, Oth	Cv, RB	PR, CIS, Rv, Stb, Lcp
Schreck Reis et al., 2008	PT	MD	H	Fr, Oth	Cv, RB	Rv, Lcp
Schwendiman, 1977	USA	FxD	H	Fr	ES	Rv, Oth
Seliskar, 1995	USA	MD	N	Oth	Cv	Oth
Sharp and Hawk, 1977	USA	SMD	H, N	Oth	RB	Oth
Soulsby et al., 1997	UK	MD, SMD, FxD, DS	H, N	Fr, Oth	RB, ES	Stb, Lcp
Sturgess and Atkinson, 1993	UK	MD	H	Stb, Oth	Cv, RB	Oth
Thomas et al., 2006	AU	MD, SMD	H, N	Mn, Oth	RB	CIS, Oth
van Aarde et al., 1996	ZA	FxD	H	Mn	Cv, RB	Lcp, Rv, PR
van Aarde et al., 1998	ZA	FxD	H	Mn	RB	Lcp, Rv, PR
van Boxel et al., 1997	NL	SMD	H	Oth	RB	Dstb
van der Hagen et al., 2008	NL	DS	H	DWE	RB	Dstb
Vandenbohede et al., 2010	BE	DS	H	PI, Oth	RB	CIS, Dstb
WallisDeVries and Raemakers, 2001	NL	MD, SMD	N	Oth	RB	Dstb
Wassenaar et al., 2005	ZA	FxD	H	Mn	RB	Lcp, Rv, PR
Weiermans and van Aarde, 2003	ZA	FxD	H	Fr, Mn	RB	Lcp, Rv, PR
Zaloumis and Bond, 2011	ZA	FxD	H	Stb, Oth	RB	Dstb, Oth

1 Australia (AU), Belgium (BE), Denmark (DK), France (Fr), Israel (IL), Italy (IT), Madagascar (MA), Mexico (MX), Namibia (NA), New Zealand (NZ), Spain (ES), Portugal (PT), South Africa (ZA), The Netherlands (NL), United Kingdom (UK), United States of America (USA).
2 Mobile dune (MD), semi-mobile dune (SMD), fixed dune (FxD), dune slack (DS).
3 Natural (N), human (H).
4 Mining (Mn), fragmentation(Fr), plant invasion (PI), stabilization (Stb), destabilization (Dstb), drinking water extraction (DWE), other (Oth).
5 Ecosystem services (ES), conservation (Cv), restore biodiversity (RB).
6 Destabilization (Dstb), landscaping (Lcp), revegetation (Rv), control of invasive species (CIS), passive restoration (PR), other (Oth).

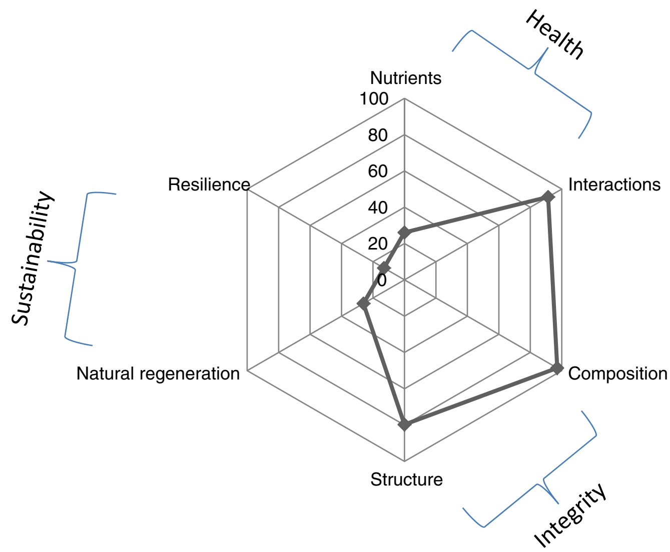

Fig. 4. Spider diagram of the percent of studies that have assessed the progress of coastal dune restoration according to three ecosystem attributes: Health, Integrity and Sustainability, each with two elements, according to SER. (Axis scale is in percent).

vegetation (Jungerius et al., 1995; Rozé and Lemauviel, 2004; Ketner-Oostra et al., 2006) and hydrogeology (Soulsby et al., 1997). Oftentimes, succession was the natural mechanism for passive restoration, once the disturbance drivers were removed from the system (Russell et al., 2009; Acosta et al., 2013). Most of the studies that we found (94%) followed plant succession during different periods of time (Table 3) and only a few monitored animal succession. Redi et al. (2005) surveyed and compared millipede assemblages in two chronosequences. One of them had been actively restored through the reshaping of the dunes and the addition of topsoil containing seeds of pioneer species, and the second chronosequence was regenerating spontaneously. They found that the similarity of millipede assemblages between reference sites and restored plots increased with regeneration age, but this recovery of community composition occurred faster on the rehabilitated chronosequences than on the chronosequence that regenerated spontaneously (Redi et al., 2005).

3.5. Sustainability (self-sustainable and resilience)

A basic principle of restoration is that restored ecosystems should be self-sustainable and resilient to disturbances. Assessing resilience needs long-term monitoring in a time scale that is adequate for the focal ecosystem, as well as a clear definition of the variables that will reveal whether the ecosystem is self-sustainable or not. This is certainly difficult and expensive to assess as is demonstrated by the lack of studies in this area. Only a reduced number of studies explored whether restored ecosystems were self-sustainable and resilient to disturbances. Self-sustainability, although not explicitly approached, was assessed in terms of the ability of the ecosystem to regenerate naturally, as occurred in projects of passive restoration (18 studies; 27%). In turn, resilience to disturbance was mentioned explicitly in a few studies only (9; 13%). Usually, it was mentioned whether the restored ecosystem was able to thrive after it had been hit by additional natural disturbances, such as hurricanes or winter storms (Miller et al., 2001; Khalil and Lee, 2004; Gallego-Fernández et al., 2011). In northern Spain, Gallego-Fernández et al. (2011) monitored natural colonization of plant species in a restored dune over a period of seven years. They found that the vegetation dynamics followed a process of primary succession, with a progressive increasing species richness, plant cover and heterogeneity. These dunes and the vegetation were lost because of the winter storms of 2008, seven years after the restoration actions. The system did not recover spontaneously after these major disturbances, although in a landscape scale, species pool was sustained. In this sense, these authors suggest that, because of the regional dynamics of coastal dunes, resilience should encompass the landscape of coastal dunes instead of a single coastal dune system.

4. Discussion

4.1. Coastal dune restoration: different aims and different methods

Coastal dune ecosystems are dynamic and diverse, and the geomorphic and ecological characteristics vary around the world. The flora and fauna that inhabit the many habitats found here is equally diverse and dynamic, as well as the disturbance drivers affecting these ecosystems. In consequence, the restoration of coastal dunes is neither simple nor straightforward: it involves a wide array of activities, because no single "best" way exists to restore a dune. Many scenarios of recovery and many different restoration actions exist, because restoring, maintaining, and/or changing the integrity, health and/or sustainability of coastal dunes can refer to many situations. It is indeed difficult to predict the endpoints of ecological coastal dune restoration (Temperton and Hobbs, 2004). An extreme case occurs when restoration is directed towards ecosystems that coexist with the new conditions set by human activities (Clewell and Aronson, 2008).

It is imperative to acknowledge that an important difference between most restoration actions and natural succession is that restoration is often driven by the paramount need to increase vegetation cover in a reduced period of time, and the resulting community needs to be as resilient as possible (meaning un-changeable). Instead, natural communities are always exposed to natural disturbances, resulting in a shifting mosaic of different types of vegetation that display an array of communities with different conditions of fertility, disturbance, composition and structure (Del Moral et al., 2007). That is, disturbance is a natural attribute of communities that "re-sets" the succession sequence and leads to heterogeneity and diversity, which is not accomplished by single trajectories towards a single goal, as is the case of many restoration projects (Fig. 1). According to this, Choi (2004) recommends that, instead of setting a single goal of restoration, it is necessary to have alternative, multiple goals, as well as multiple trajectories for unpredictable endpoints.

It is also relevant to consider that human activities and interests are incorporated in restoration actions because priorities and project implementations are ultimately dependent on human systems. Ecological restoration is ultimately linked to human interests (Choi, 2007) and humans use their own judgment to set the goals of restoration. Hence, the goals of restoration lie within an inevitable economic and social framework (Hobbs and Norton, 1996; Choi, 2004; Davis and Slobodkin, 2004; Choi, 2007) from which coastal dune restoration cannot depart (Lithgow et al., 2013; Pérez-Maqueo et al., 2013). The more ecosystem services of coastal dunes become considered as relevant to society, the more efforts will take place to protect and restore these ecosystems. Already it has been demonstrated that the public and private owners are willing to pay to protect and restore coastal dunes (Feagin, 2013; Lehrer et al., 2013).

4.2. Measuring the success of coastal dune restoration

According to SER, "a degraded ecosystem can be considered to have been restored when it regains sufficient biotic and abiotic resources to sustain its structure, ecological processes and functions with minimal external assistance or subsidy. It will then demonstrate resilience to normal ranges of environmental stress and disturbance". Certainly, it is very difficult to achieve this state. The progress of restoration actions is assessed through several ecosystem attributes: some of them are measured relatively easily (such as ecosystem

Table 3
Ecosystem attributes and variables that have been measured to assess a successful coastal dune restoration (after SER).

	Integrity					Health		Sustainability			
	Composition			Structure		Nutrients	Biologial interactions[1]				
Author	Diversity or richness	Plants	Animals[2]	Cover	Biomass			Natural regeneration	Resilience	Monitoring time[3]	Refernce site[4]
Acosta et al., 2013	X	X		X			Sc	X	X	4 years	HR
Andreu et al., 2010	X	X		X			Sc			1 years	1
Arens and Geelen, 2006	X	X		X			Sc			8 years	HR
Arens et al., 2004	X	X								5 years	HR
Arens et al., 2005	X	X					Sc			5 years	HR
Arens et al., 2013	X	X							X	1-12 years	HR
Bakker et al., 2005	X	X		X			Sc			3 years	HR
Bossuyt et al., 2007	X	X					Sc			NA	HR
Cater et al., 2007	X	X					Sc			3 years	1
Christensen and Johnsen, 2001	X	X					Sc			NA	NA
Conser and Connor, 2009	X	X		X			Sc			NA	1
Davis et al., 2003	X	X	Arth	X			Sc			21 years (Csq)	1
De Lillis et al., 2004	X	X		X			Sc			5 years	HR
Deblinger and Jenkins, 1991	X	X		X			Sc			NA	NA
Denton et al., 1997	X	X	Am	X		X	Sc			25 years	NA
DeSimone, 2011	X	X		X			Sc	X		2 years	NA
Emery and Rudgers, 2010	X	X	Arth	X	X	X	Sc			25 years (Csq)	1
Ernst et al., 1996	X	X			X	X	Sc			30 years (Csq)	1
French et al., 2011	X	X		X			Sc			1 yr	NA
Gallego-Fernández et al., 2011	X	X		X			Sc		X	7 years	1
Gómez-Piña et al., 2002							Sc			NA	NA
Graham and Haynes, 2004	X	X	Mic			X	Sc			25 years (Csq)	1
Grainger and van Aarde, 2012	X	X		X			Sc	X		10 years	HR
Grainger et al., 2011	X	X	Bd	X			Sc	X		50 years (Csq)	NA
Grootjans et al., 2013	X	X		X		X	Sc			15 years	1
Hesp and Hilton, 2013	X	X						X		5-10 years	HR
Jansen et al., 2004	X	X		X		X	Sc			5 years	1
Jones et al., 2010	X	X				X	Sc			1.5 years	HR
Jungerius et al., 1995		X	Arth, Nm	X			Sc	X		13 years	1
Ketner-Oostra and Sýkora, 2000	X	X		X			Sc			4 years	HR
Ketner-Oostra et al., 2006	X	X					Sc	X		11 years	HR
Kollmann et al., 2011	X	X		X		X	Sc			2 years	NA
Kutiel, 2013	X	X	Arth	X			Sc	X		3 years	HR
Kutiel et al., 2000	X	X	Mm	X			Sc			3 years	1
Lemauviel et al., 2003		X		X			Sc			4 years	1
Lubke, 2013	X	X		X			Sc			1 yr	1
Lubke et al., 1996	X	X		X		X	Sc			1 year, (8 Years Csq)	NA
Marchante et al., 2008	X	X		X		X	Sc			5 years, (20 years Csq)	1
Marchante et al., 2011	X	X		X			Sc		X	6 years	1
Mason et al., 2007	X	X			X		Sc			NA	
Moreno-Casasola et al., 2008	X	X		X			Sc			5 years	NA
Moreno-Casasola et al., 2013	X	X		X		X	Sc	X	X	40 years	Cq
Mpanza et al., 2009	X	X		X	X	X	Sc			5 months	NA
Muñoz-Reinoso et al., 2013	X	X		X			Sc	X	X	3 years	HR
Pickart, 2013	X	X		X			Sc	X	X	20 years	HR
Pickart et al., 1998a				X			Sc			4 years	NA
Pickart et al., 1998b	X	X		X			Sc			1.5 years	1
Plassmann et al., 2009	X	X		X			Sc			16 years (Csq)	1
Redi et al., 2005	X		Arth				Sc	X		2 years	1
Rhind et al., 2013	X	X				X				2 years	HR
Rosati and Stone, 2009		X		X			Sc		X	NA	NA
Rozé and Lemauviel, 2004	X	X		X			Sc			10 years	HR
Russell et al., 2009	X	X	Mm Bd, Am, Rp	X			Sc	X		2 years	1
Schreck Reis et al., 2008	X	X		X			Sc			2 years	NA
Schwendiman, 1977		X		X			Sc			NA	NA
Seliskar, 1995			Nm	X		X	Sc			2 years	1
Sharp and Hawk, 1977	X	X		X		X	Sc			5 years	NA
Soulsby et al., 1997	X	X		X					X	12 years	1
Sturgess and Atkinson, 1993	X	X		X	X	X	Sc			2 years	1
Thomas et al., 2006	X	X		X			Sc	X		4 years	1
van Aarde et al., 1996	X	X	Arth, Bd	X			Sc	X		NA	1
van Aarde et al., 1998	X	X			X		Sc	X		16 years	1
van Boxel et al., 1997	X	X		X			Sc			3 years	NA

Table 3 (*continued*)

Author	Integrity					Health		Sustainability			
	Composition			Structure		Nutrients	Biologial interactions$_1$				
	Diversity or richness	Plants	Animals$_2$	Cover	Biomass			Natural regeneration	Resilience	Monitoring time$_3$	Refernce site$_4$
van der Hagen et al., 2008				X			Sc			5 years	1
Vandenbohede et al., 2010						X				3 years	NA
WallisDeVries and Raemakers, 2001	X	X	Arth	X			Sc	X		4 years	1
Wassenaar et al., 2005	X	X	Mm, Bd, Arth	X			Sc	X		25 years (Csq)	1
Weiermans and van Aarde, 2003				X			Sc			18 years (Csq)	1
Zaloumis and Bond, 2011	X	X		X			Sc			17 years (Csq)	1
Total	59	62	14	52	6	17	63	18	9		
% from total number of articles	0.88	0.93	0.21	0.78	0.09	0.25	0.94	0.27	0.13		

1 Succession (Sc).
2 Arthropods (Ath), nematodes (Nm), mammals (Mm), birds (Bd), amphibian (Am), reptiles (Rp); microbial (Mic).
3 Chronosequence (Csq).
4 Historical reference (HR), chronosequence (Cq); None, none available or not clear (NA).

integrity and health) whereas others (sustainability and resilience to disturbance) surpass time frames and budgets of restoration projects and are either not assessed or assessed indirectly. Because of these difficulties, oftentimes, to determine a successful restoration action it is considered sufficient to observe an "appropriate trajectory towards the intended reference condition" (SER, 2004). This sounds like a logical and good idea, but it should be stressed that long-term monitoring is needed to fully evaluate the progress and success of any restoration action (Jungerius et al., 1995; Rozé and Lemauviel, 2004; Ketner-Oostra et al., 2006).

Our review indicates that ecosystem integrity (species composition) and health (nutrients and biotic interactions) are frequently assessed to monitor the progress of restoration and that long-term monitoring is a field that needs to be studied. How is the progress of ecological restoration of coastal dunes being assessed? We will next discuss this issue in the light of the three ecosystem attributes: integrity, health and sustainability.

4.3. Integrity

One of the primary goals of restoration is to enhance the ecological integrity (DellaSala et al., 2003) of an ecosystem. In most of the studies, at least two of the variables suggested by the SER were monitored to assess the progress of restoration (Table 1). Plant diversity and richness were the most commonly used variables and only a few studies included data on fauna. Ecosystem structure was almost exclusively evaluated through vegetation cover and just a few studies included biomass measures.

Plants are always included because of practical and maybe conceptual issues. Plants are much more practical to survey and monitor than animals: the richness and diversity do not fluctuate according to day to day weather-mediated effects as in the case of animals like insects (Majer, 1989; Davis et al., 2003). That implies less time and effort invested. Also, a faster survey process reduces costs and money is always a major concern in restoration efforts. Some conceptual issues are also related with the dominance of plants surveys. Restoration is still perceived as botanically biased (Morrison, 1998; Young, 2000; Davis et al., 2003) and it is assumed that mobility allows animals to colonize the restoration sites (Clewell and Rieger, 1997). This assumption has some problems in case of lack of connectivity between undisturbed patches and restoration sites, because the colonization could be difficult and metapopulation persistence could be very improbable (Swart and Lawes, 1996; Metzger, 1997; Dewenter and Tscharnke, 1999; Davis et al., 2003). Furthermore, when animals are set aside, important services which are helpful for the recovery process (pollination, seed dispersal) can be diminished (Clewell and Rieger, 1997). In brief, ecosystem integrity needs to be assessed through monitoring of flora and fauna.

4.4. Health

Health-related processes have been measured less than integrity. Only a few studies evaluated biotic interactions, such as competition or mycorrhizae. Most of them evaluated plant succession which, in the absence of direct studies on biotic interactions, can be considered as a proxy, because many interactions take place during the successional replacement, especially after the initial harsh environmental conditions have been ameliorated by the early colonizers. Succession measures are preferred over interaction measures because monitoring species composition and community structure is easier either through chronosequences or long-term monitoring.

Specific studies focused on species interactions during restoration would be most enlightening for restoration practices. Studies on facilitation would shed light on which species may act as nurse-plants and they could then be used to promote the establishment of target species that do not thrive well during early successional stages or that are affected by herbivory (Connell and Slatyer, 1977; Valladares and Gianoli, 2007). On the other hand, most efforts at coastal dune restoration should at least include nutrient availability in monitoring because coastal dunes are oligotrophic and the structure and composition of plant communities are determined by low levels of N, P and K. Eutrophic soils lead to community changes, thus, maintaining low nutrient availability is a condition necessary to recover native biota and avoid invasions. It is important to bear in mind that the naturally occurring community processes, such as nutrient cycle and succession, can be modified by restoration actions when colonization, establishment and species accumulation are manipulated, and they can, eventually, modify community development (del Moral et al., 2007).

4.5. Sustainability

Resilience and resistance to disturbance are rarely measured because long-term evaluation is required and most restoration projects have a short time frame. Also, most of the studies have just one or a few reference sites (end-point) against which it is possible to compare the restoration sites. Endpoints are often unpredictable (Temperton and Hobbs, 2004) and the sustainability of reconstructed 'historic' ecosystems appears to be an unlikely goal in the ever-changing and unpredictable future environment (Vitousek et al., 1997; Choi, 2004).

Assessing resilience is very important because a low resilience implies a reduced ability of the system to survive and stand changes. Therefore, an enhanced resilience may be the most pragmatic and effective way to assess the progress of restoration actions (Nicholls and Branson, 1998).

4.6. Methodological caveats

In this review we analyzed the 67 studies that we were able to find in the refereed literature (principally journal articles) spanning 24 years, from 1988 to 2012 and that referred to coastal dune restoration in natural settings, with no direct urban impact. The total number of published articles might be considered as relatively small, considering the large number of restoration and rehabilitation efforts that are taking place in urban coasts. Certainly, the occurrence of infrastructure and dense human populations is a very important driver that directs restoration efforts to developed rather than natural coasts. In addition, the scarcity of refereed literature on restoration actions of undeveloped dunes may be explained as follows: a) most restoration actions are taking place in urban settings because of the direct impact on human society and, hence, the relevance of restoring these coasts. We did not address urbanized coasts and foredunes, because these have been already thoroughly reviewed in detail (Nordstrom, 2008; Nordstrom and Jackson, 2013; Psuty and Silveira, 2013; Vestergaard, 2013); b) many government agencies and private consultants are responsible for restoration actions of coastal dunes in non-urbanized settings and they usually do not publish their methods or results in the refereed literature, but in the gray literature that is difficult to find and is not always refereed. This is the case of The Netherlands and Spain, where nearly 100 coastal dune restoration projects have been implemented, and yet, we only found 15 and 4 published studies, respectively; thus, very few of their restoration projects actually get published (A.P. Grootjans; J.B. Gallego-Fernández, pers. comm). Evidence of this is that, in most of the studies that we found, the address of at least one of the authors was an academic institution, where it is common or mandatory to publish the findings of scientific research. We did not find a single study where every author belonged to non-scientific or non-academic institutions; c) certainly restoration actions occur that are not successful, and therefore, they are perhaps not considered as publishable (by the authors, by the editors and referees in peer-reviewed journals). This is a problem, because lessons can be learned from successful restoration actions, and also from failures (Ormerod, 2003). Thus, the increase in knowledge of restoration theory and practice is reduced because of these omissions (Bradshaw, 2002).

4.7. Challenges and opportunities

Coastal dune restoration projects have been performed in a variety of ways: in small or large scale; via government programs, community groups, or individuals; and with soft and with hard methods. In most cases, the ultimate goal, in general, was to improve ecosystem integrity, health and sustainability. Assessing whether these goals were achieved or not has been difficult and still requires a great deal of effort, especially in terms of assessing ecosystem health and sustainability. The establishment of long-term monitoring assessments is important, and many challenges still exist ahead for us to adequately assess and measure efforts of coastal dune restoration.

Finally, it is important to acknowledge that there is no perfect restoration job or assessment, but we can improve them. The theory of ecological succession provides a theoretical background for restoration and emphasizes on the role of natural disturbance as a key element of community dynamics (Grainger and van Aarde, 2012). Thus, restoration activities, based on the theory of ecological succession, are a desirable approach, and natural disturbances and dynamics need to be considered as part of the restored system to really improve ecosystem integrity, health and sustainability. Impediments that affect restoration activities and the assessment of their success include the difficulty of monitoring sustainability (both theoretically and logistically), lack of funding for long-term monitoring and an emphasis on developed coasts in general. To overcome these obstacles we need to acknowledge the relevance of restoring natural systems as a strategy for our future survival (Hobbs and Harris, 2001).

Several actions that could improve coastal dune restoration should include: a) setting clear and achievable goals, based on the dynamic properties of ecosystems (Sterk et al., 2013); b) defining the desired ecosystem attributes in the future (Hobbs and Harris, 2001), which should consider integrity, health and sustainability; c) improving the definition of sustainable and resilient ecosystems, that could, for example, consider plant functional traits (Demars et al., 2012; Sterk et al., 2013); d) considering that successful restoration actions can be increased when decisions are taken based on scientific knowledge and social needs (Hopfensperger et al., 2007); d) integration of interdisciplinary criteria (Carpenter et al., 2001; Hobbs and Harris, 2001); and e) weighting the different interdisciplinary components (Lithgow et al., 2013). In brief, it is likely that restoration ecology will be one of the most important fields of this century (Hobbs and Harris, 2001) and restoration actions will have to meet the challenges of meshing ecological science, practice and policy.

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