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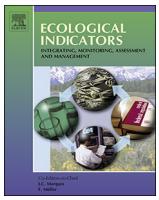

Assessing the current state and restoration needs of the beaches and coastal dunes of Marismas Nacionales, Nayarit, Mexico

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ABSTRACT

Around the world, population growth, land use changes and coastal infrastructure have modified coastlines. In many cases these actions have induced intense degradation and loss of the ecosystems there. Sandy beaches and coastal dunes are amongst the most threatened features. In Mexico, coastal dunes in the state of Nayarit, on the Pacific, have been affected by small scale tourism, the construction of artificial inlets and an increase in agricultural activities, even though they are part of a Biosphere Reserve. While there is a growing need for restoration or rehabilitation programs to protect these coastal dunes, such actions are almost non-existent because of financial limitations, difficulties in deciding which locations most urgently need these strategies, and the uncertainty of the results. Our goal was to evaluate the coastline of the Marismas Nacionales Biosphere Reserve, in the state of Nayarit, Mexico, examining geomorphological, ecological, and socioeconomic variables. Ninety sites were assessed, using the Re-Dune index, 41 beaches were found to be in a good state of conservation, while 43 are degraded but with the potential for success when subjected to restoration measures. Six sites were seen as highly degraded, with rehabilitation being the most viable option. By recovering the coastal dunes of Marismas Nacionales, the hurricane protection provided by them will be enhanced and sustainable social and economic development will be more likely.

1. Introduction

While the wide range of provisioning, regulatory, cultural, and supporting ecosystem services provided by coastal dunes has been recognized for several decades, only recently has their importance been highlighted (Everard et al., 2010). The conservation of healthy dunes, as well as restoration or rehabilitation of specific functions when restoration is not possible, have proven to be cost-effective in protecting infrastructure from storm damage (Elko et al., 2016; Salgado and Martínez, 2017; Sigren et al., 2018). In storms, human settlements with a wide beach and high dunes are spared from storm surge and wave damage (McKenna et al., 2016; Tong and Yi-Ling, 2016). Numerical models and experimental evidence from wave flumes have also demonstrated how vegetation serves as storm protection for coastal dunes (Feagin et al., 2019; Fernández-Montblanc et al., 2020; Maximiliano-Cordova et al., 2019; Silva et al., 2016). There are currently a range of strategies available to deal with the impact of erosion on human assets, depending on the local conditions (Silva et al., 2017). On undeveloped beaches "Retreat" strategies, are suitable; moving the whole system inland. On developed coasts the wide variety of "Protection" strategies are the only viable alternative (Silva et al., 2019).

Over recent years a generalized loss and degradation of coastal dunes has occurred worldwide (Nordstrom, 2008, Nordstrom et al., 2011; McLachlan et al., 2013; Martínez et al., 2013). There is thus a growing need for coastal dune restoration; the recovery of ecosystem health, resistance and resilience, by returning ecosystems to their original undisturbed state, or rehabilitation; actions which seek to return a self-sustaining native community to as close as possible to the original state. The need is increasing if we consider that 24% of the worlds sandy beaches are eroding at rates exceeding 0.5 m/yr (Luijendijk et al., 2018). This situation may be worsened by sea-level rise, which could lead to the near extinction of sandy beaches in the coming decades

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(Vousdoukas et al., 2020).

Mexico has more than 11,000 km of shoreline and 800,000 ha of coastal dunes (Martínez et al., 2014). However, coastal zones have been overexploited, by coastal tourism, over-fishing, urbanization, or changes in land use. It was recently estimated that nearly 50% of Mexican dune systems already have some level of disturbance (Martínez et al., 2014). In this context, restoration or rehabilitation of beaches and coastal dunes is seen as increasingly attractive to help recover the natural dynamics of Mexican coasts, and thereby their biodiversity, and, as a result, effective storm protection (Silva et al., 2014).

In general, restoration of coastal dunes has not been carried out as frequently, or as extensively, as needed in Mexico (Lithgow et al., 2013; Martínez et al., 2014). Instead, urbanization and tourism development of the coasts has become a priority (Lithgow et al., 2019a). With limited budgets, it is essential to, firstly, determine where restoration actions are most needed and, secondly, prioritize sites where these are most likely to be successful. Several indices have been created to identify when a dune system needs to be restored (García-Mora et al., 2001; Pinna et al., 2015). Of these, the ReDune Index (Lithgow et al., 2014) offers variables that characterise the degree of perturbation, the degree of endogenous and exogenous stress, and the presence of elements that may facilitate the restoration process. With this index, the areas where restoration activities were most needed, and most likely to succeed, were determined in the coastal regions of Veracruz state, on the Gulf of Mexico (Lithgow et al., 2014) and the state of Quintana Roo on the Caribbean (Martínez et al., 2016).

Although there are few studies on the Pacific coast of Mexico (Jiménez-Orocio et al., 2014), a nationwide assessment of coastal dunes (Martínez et al., 2014) showed that one of the largest fields of foredunes in Mexico is on the Pacific, in the Marismas Nacionales Biosphere Reserve, in the state of Nayarit (Fig. 1). Extending 15 km inland, this foredune field has more than 200 dune ridges (between 1 and 5 m high) in its widest section. The dune system is estimated to be 3600 to 4750 years old (De la Lanza Espino et al., 1996). Although it is a Biosphere Reserve, land-use changes, fisheries and artificial inlets have modified and altered the beaches and foredunes of this important dune system. As there is no data on the current state of this important system, this study assesses the conservation state of the beaches and foredunes of Marismas Nacionales and determines restoration needs and the feasibility of such actions.

2. Methods

2.1. The ReDune index

The Restoration of Coastal Dunes (ReDune) index is a method for evaluating the need for, and feasibility of, foredune restoration actions (Lithgow et al., 2014). The index is based on a set of variables related to the intensity of perturbation, the presence of endogenous and exogenous stress, the abiotic and biotic elements that may facilitate restoration and interests related to the conservation of the site (Lithgow et al., 2014). The index was created using an Analytic Hierarchy Process where more than 100 variables were extracted from a metanalysis, refined to 36 variables, then weighted by an international expert panel that included geomorphologists, ecologists, and anthropologists. The hierarchically organized, weighted variables were integrated into a checklist. The 36 indicators are grouped into four sections or categories: 1) disturbance level, which determines the intensity of morphology and vegetation perturbation; 2) the presence of endogenous and exogenous stress factors that may compromise the long-term stability of restoration actions; 3) abiotic and biotic elements that may facilitate restoration, and 4) identification of interests related to the conservation of the site and the provision of ecosystem services.

The 36 indicators are further grouped into two general categories: elements with a positive influence on the foredunes and those with a negative influence (Fig. 1). The elements with a positive influence facilitate ecosystem recovery, e.g. biotic and abiotic conditions that facilitate restoration actions, or societal interest in conservation actions may encourage the implementation of restoration projects. Meanwhile, the elements with a negative influence have a detrimental impact on foredunes, e.g. the presence of a high degree of perturbation that cause stress in the system.

The ReDune index focuses on foredunes, which run parallel to the coastline. On prograding coasts, such as Marismas Nacionales, foredune fields may have formed over decades or centuries. When this occurs, they show different degrees of stabilization, with the oldest foredunes being furthest from the shore. In this study, we focused only on the first and most recent foredunes that are located at the back of the beach and remain relatively mobile. These dunes are those most affected by human activities, as well as by storms and hurricanes.

2.2. Study area

The Biosphere reserve of Marismas Nacionales is a large estuarine

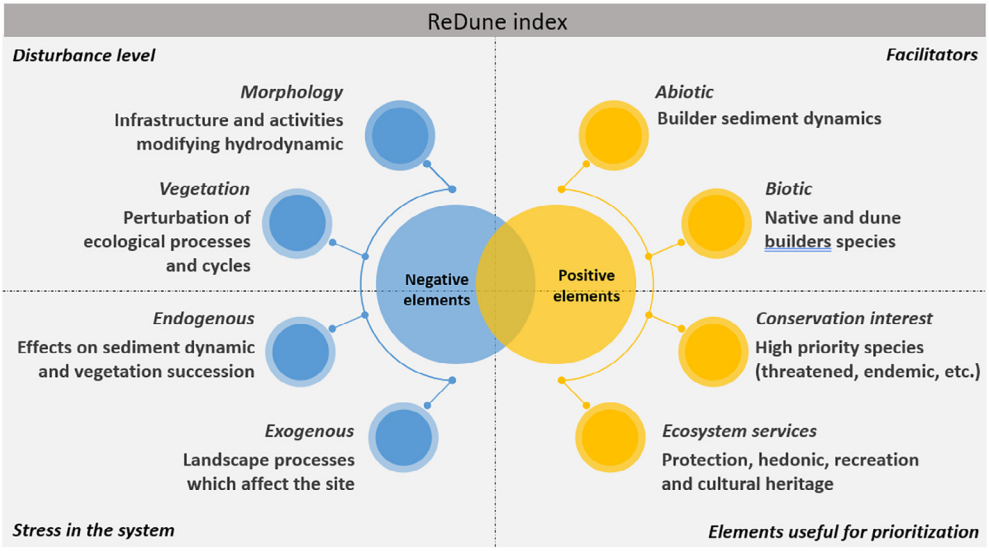

Fig. 1. Elements with positive and negative influences on foredunes, according to the ReDune index (modified from Lithgow et al. 2014).

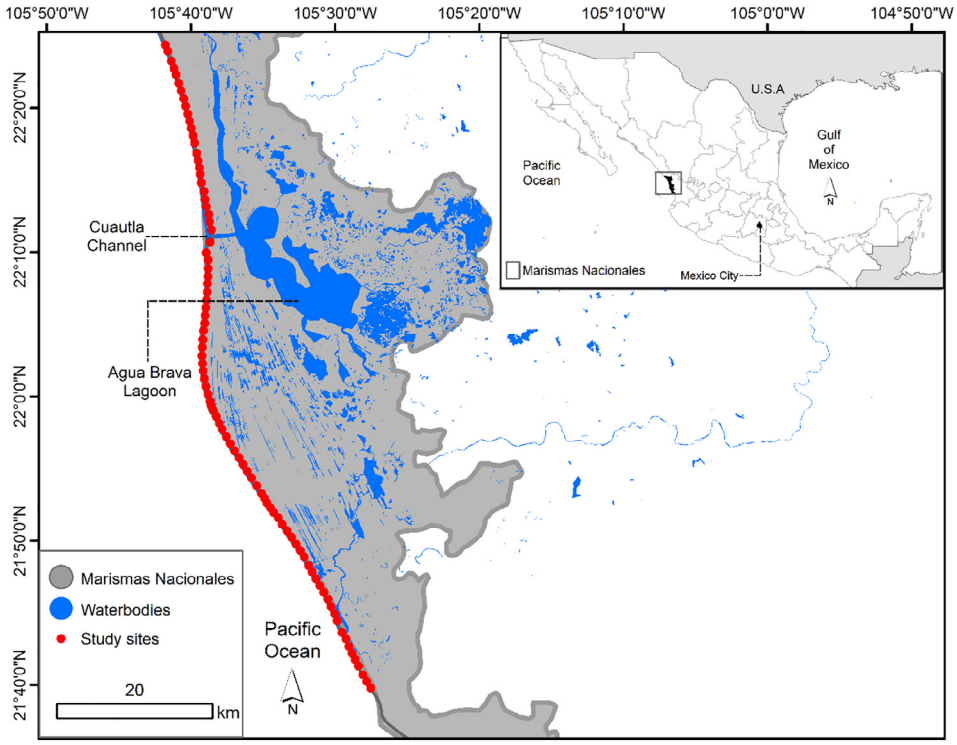

Fig. 2. Study site: Marismas Nacionales, Nayarit, Mexico.

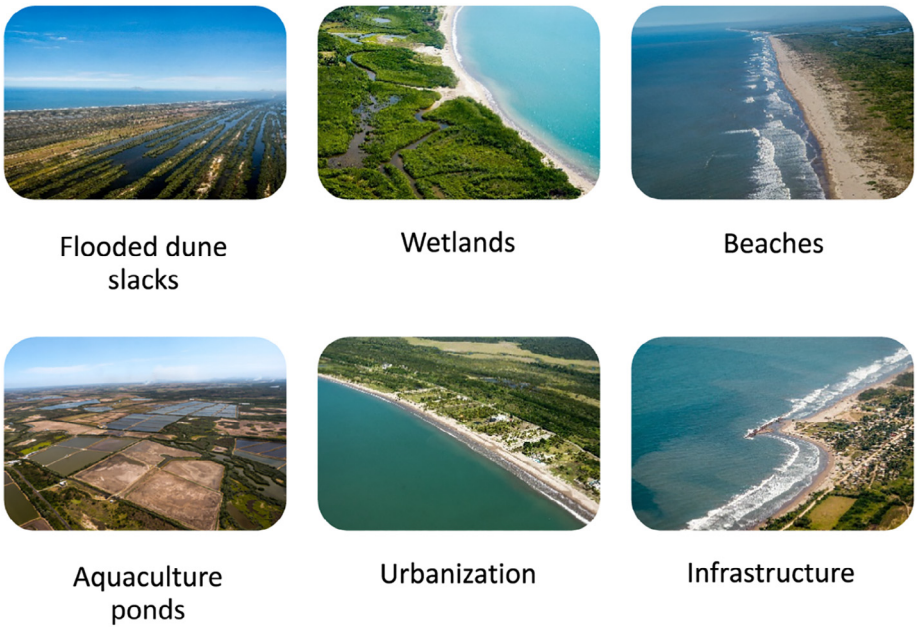

Fig. 3. Marismas Nacionales coastal area has different habitats which are in different state of conservation as well as different types of infrastructures.

complex that covers 220,000 ha. It is located on the north-western Pacific coast of Mexico, on the alluvial plain of the state of Nayarit (22° 15′04″, 22° 17′ 07″ N and 105° 11′ 05″, 105° 13′ 36″ W) (Fig. 2). Marismas Nacionales is the largest area of wetlands on the Mexican Pacific coast and represents 22% of national mangrove extension (CONANP, 2013). The region is very heterogeneous, with complicated topography and high biodiversity. Twelve rivers flow through the area, the dynamics of which produce a complex coastal hydrological system containing a significant extension of wetlands and other ecosystems, which develop along a plain of frontal dunes that extend inland for more than 15 km. The different habitats found in the area include dry (foredunes) and flooded (coastal lagoons, coastal wetlands, mangroves, and swamps) systems. Dune slacks are permanently flooded, providing habitat to wetland species. The combination of dunes and wetlands gives the area a grooved appearance from the air (Fig. 3).

The coastal area is characterized by a mixed semidiurnal tide, with a maximum amplitude of 1.2 m (SMN, 2016). The weather in the region is warm sub-humid, with a mean annual temperature between 26 and 28 °C (average maximum yearly temperature ranges from 30 to 34 °C). Annual rainfall ranges from 800 to 1200 mm, and annual evaporation from 1800 to 2000 mm (Semarnat-Conanp, 2013; Rubio-Cisneros and Aburto-Oropeza, 2013).

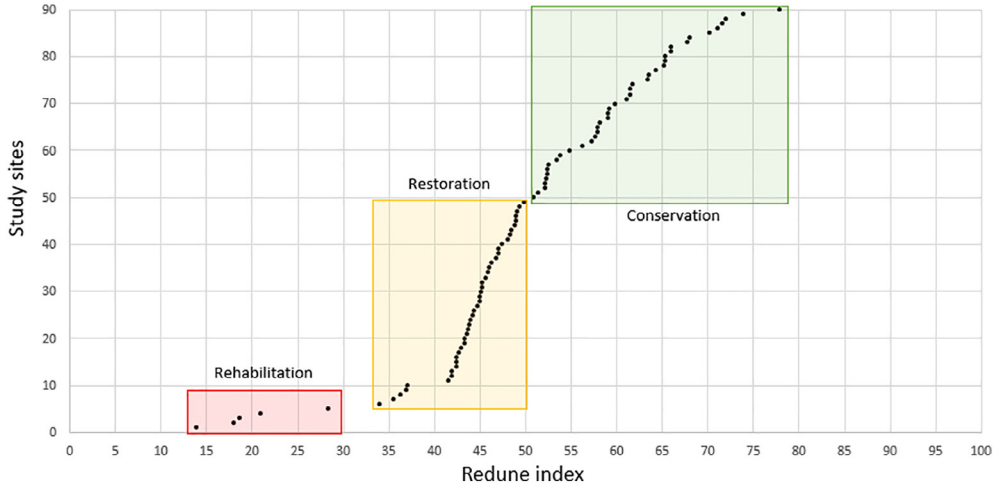

Fig. 4. ReDune Index values calculated for 90 coastal sites at Marismas Nacionales. Conservation (green), restoration (yellow) or rehabilitation (red) values are highlighted.

Marismas Nacionales is an important area for conservation. Besides being a Biosphere Reserve, it has been declared as a Ramsar site, and a Wetland of International Relevance. The combination of marine and freshwater in its coastal lagoons also makes this wetland system one of the most productive shrimp farming areas in northwestern Mexico (Lithgow et al., 2019b). The region also functions as a biological corridor of great importance for the refuge, feeding, and reproduction of resident and migratory birds (Semarnat-Conanp, 2013). In addition, it is an important area of endemism for vertebrates and insects (Rubio-Cisneros et al., 2017). However, in spite of local conservation efforts, the beach and the most recently formed foredunes are not protected.

The main economic activities in the study site include agriculture, cattle ranching, fisheries and shrimp farming (Fig. 3). Many of these activities take place without the key environmental elements of the system, such as the natural dynamics of the water bodies, being considered. Non-integrated management has resulted in haphazard land-use changes, deforestation, salinization of soils, hydrological changes and so on (Blanco et al., 2014). One example of the severe consequences of this type of arbitrary development is the intense and chronic shoreline erosion which has occurred following building of an artificial inlet in 1976. The Cuautla Channel (Fig. 2) was originally 40 m wide, 2 m deep and 4 km long but is now 3 km wide and 20 m deep. More than 500 ha of cropland and mangrove have been lost as a result of this erosion and changes in water salinity (Ochoa et al., 2012). Elsewhere in the reserve other economic activities have been gradually increasing on the coast, including tourism providing only a subsistence economy.

2.3. Fieldwork

The ReDune index was used to assess 90 sites along the coast of Marismas Nacionales, located every 1 km. We sampled each of the 90 km because some variables of the Redune index (such as the exogenous factors that cause stress in the system) are evaluated at that scale. At each site, a 200-m segment, parallel to the shoreline, was used to evaluate the state of beaches and foredunes based on two factors: the homogeneity of the environmental conditions (physical and ecological) of the fragment, including the degree of anthropic pressure, and the representativeness of each site considering the whole area. Then, on site, the ReDune checklist was completed, based on observations and information readily available to the public.

2.4. Data analyses

Once we had gathered all the variables for the 90 sites, using the ReDune checklist, we calculated the ReDune Index for each site (Lithgow et al., 2014), as follows:

$$ReDune\ \ index = \sum_{i-1}^{N} w_i X_i - \sum_{i-1}^{N} w_i Y_i$$
$$= (\sum w_f F + \sum w_p P) - (\sum w_d D + \sum w_s S)$$

The ReDune index is the result of the subtraction of the sections "elements with a positive influence" ($\Sigma w_i X_i$) from "elements with a negative influence" ($\Sigma w_i Y_i$).

In the ReDune index, $\Sigma w_i X_i$ is the sum of the weighted values of all indicators grouped within the criterion "facilitators" ($\Sigma w_f F$) as well as those evaluated by the criterion "elements useful for prioritization" ($\Sigma w_p P$). Finally, $\Sigma w_i Y_i$ is the weighted sum of all the indicators within the criteria "disturbance level" ($\Sigma w_d D$) and "stress in the system" ($\Sigma w_s S$).

Lastly, we standardized the ReDune index so that the index values ranged from 0 to 100, thus making the index easier to understand and to compare locations. The ranges to determine the conservation status with the ReDune index had been previously established, using fifteen reference sites selected by experts, and the following decision rules were developed: non-degraded sites and those that must be conserved (> 50); degraded sites where restoration is possible (35–50), and; degraded sites where restoration is not possible, but potential exists for rehabilitation (< 35).

3. Results

3.1. Sites for conservation

Forty-one sites did not have obvious signs of perturbation and were therefore designated as "conserved" (Fig. 4), with final scores ranging from 50.80 (Site 58) to 77.88 (Site 18), and a mean score of 60.88 (Fig. 5). These sites had beaches with a high rate of sediment transport towards the foredunes, relative high vegetation cover with native and dune-builder species, such as Sea purslane (*Sesuvium portulacastrum*), Beach morning glory (*Ipomoea pes-caprae*), Sensitive partridge pea (*Chamaecrista nictitans*) and Fuzzy flatsage (*Jouvea pilosa*). Dune degradation by human trampling was low.

The excellent conservation state in the southern section, sites 1–29 (Fig. 5), is worth highlighting. Aside from site 12, this zone had the lowest levels of disturbance and stress. The low level of disturbance can be attributed to the absence of temporal or permanent infrastructure on the beaches and mobile dunes (morphology criterion) and the amount of well-conserved vegetation cover. Less than 25% of the vegetation

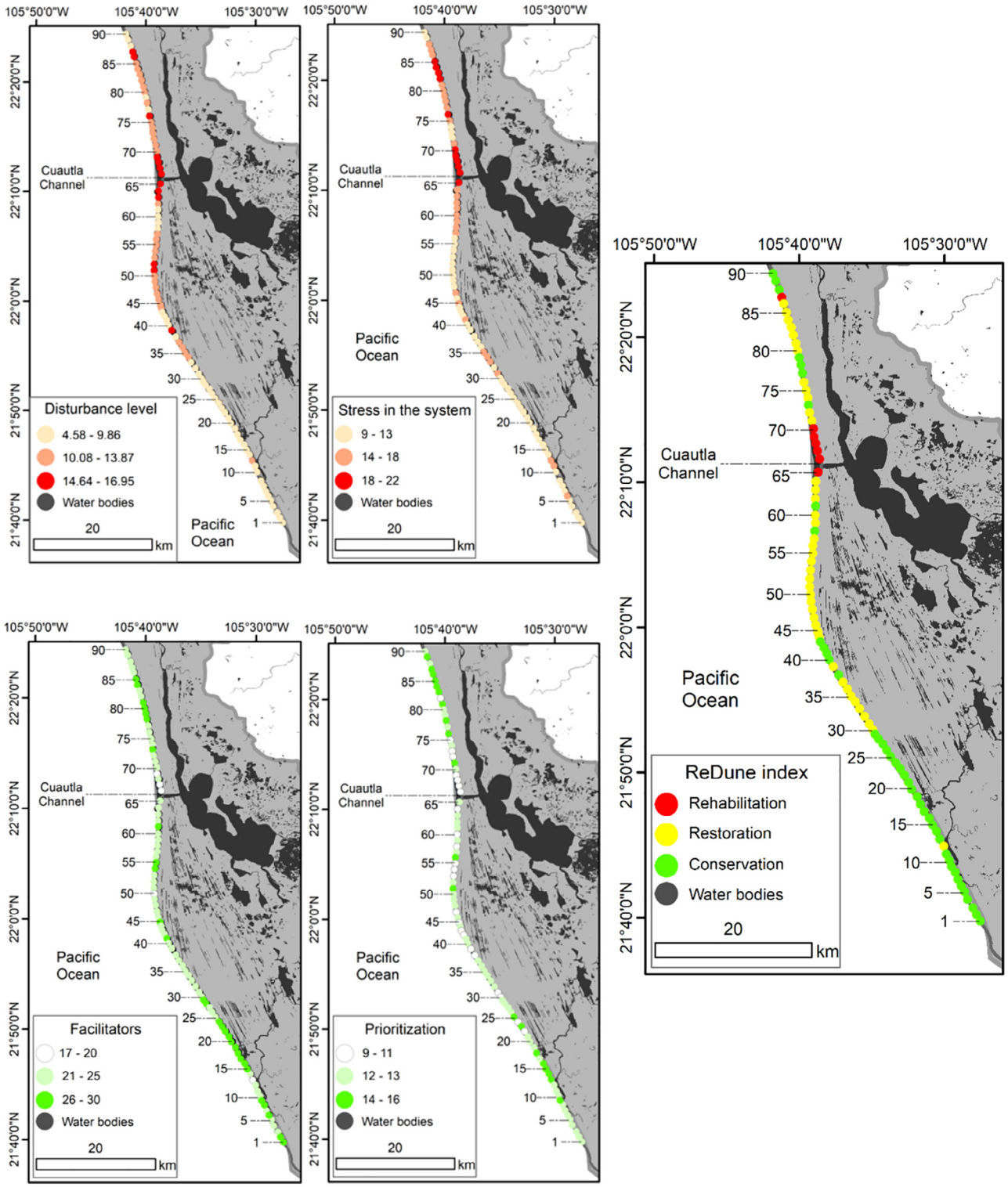

Fig. 5. Elements used to calculate the ReDune index: Negative (disturbance level and stress in the system) and positive (facilitators and prioritization). 90 sites, at 1 km intervals along the coast, were assessed. They were identified with consecutive numbers, from south to north.

presented signs of degradation. Alien species (isolated coconut trees) were only present on the foredunes (vegetation criterion). Coconut plantations were only found in two of the 41 well-conserved sites, (sites 3 and 5) but in both cases, these were small and on the back side of dunes furthest inland.

The only site not given a good conservation status in the southern part of the reserve was site 12. Here, tourism is low throughout the year but the permanent infrastructure of Playa el Sesteo, a rural locality with over 100 inhabitants, was built on the well-established dunes, leading to their degradation. From the level of stress restoration actions are recommended for this site. However, if current trends continue, rehabilitation actions could be necessary.

3.2. Sites in need of restoration actions

Forty-two sites were identified as in need of restoration action

(Fig. 4). Their ReDune Index scores ranged from 35.5 (site 87) to 49.8 (site 57), with a mean score of 44.5 (Fig. 5). The reasons for restoration are manifold. However, the majority of these sites had agricultural fields on the dune ridges, extensive coconut plantations and tourist developments, or were relatively urbanized, all of which affect shoreline dynamics. It is interesting to note that five disturbed sites, in need for restoration, were adjacent to beaches of a better conservation state (sites 30–37, 44–56, and 80–86).

The first zone (sites 30–37) includes tourist beaches, such as Playa Sesteo (Boca de Camichín) and Playa Colorada. These beaches have destabilized foredunes due to the stilt houses and roads built on the dunes and trampling of vegetation. Tourism here is seasonal and fluctuates significantly throughout the year, stimulating development of other economic activities, such as agriculture. Similarly, in the second zone (sites 44–56), the coastal morphology has been modified and the vegetation degraded. However, the establishment of permanent infrastructure on the foredunes is less common here than in the first zone. There is only one small tourist location, El Rodeo Beach (site 44), in the zone. Intensive coconut plantations are present, covering over 50% of the foredunes in some areas (sites 52–55).

In contrast to the previous zones, sites 80–86 are located north of the artificial Cuautla Channel. All the sites in this area have permanent infrastructure on the foredunes, including roads, houses, and small hotels. Five settlements are found here, Mata Palapa, Rancho Minijaja, Rancho Tranquilo, Rancho Julio Morales, and Novillero Beach. The first four have fewer than ten inhabitants, but the latter has over 250. Novillero Beach spans site 86 (south) to 87 (north). The proportion of foredunes degraded by footpath networks is more than 50% here, due to the relatively high number of beach users.

Although the three zones mentioned above all have high levels of degradation, all show elements that would facilitate the implementation of restoration actions (Fig. 5). For example, they have a high rate of sediment supply, as evidenced by the presence of wide and dry beaches, as well as buried vegetation, which indicates continuous inland sand transport. Moreover, patches of the native beach and dune vegetation are present in these sites, or sources of propagules are close by. Furthermore, these potential restoration sites have ecological and socio-economic characteristics (endangered and charismatic species and presence of sites with archaeological relevance) that could successfully attract the national attention and investment needed to recover the dunes.

3.3. Sites without restoration potential, in need of intervention

Six sites close to the Cuautla Channel, sites 64–70, were identified as considerably degraded and in need of rehabilitation actions, but they are unlikely to respond successfully to restoration, and need more drastic interventions (Fig. 5). The construction of poorly planned infrastructure, such as breakwaters, small irrigation, and unplanned urban growth, has significantly modified the hydrodynamics of these sites, eroded the beach, and destroyed the dunes. However, the degradation and stress factors at these sites cannot be controlled in the short term. Continuous erosion in the Cuautla Channel has induced extensive shoreline and beach loss, with substantial property damage in the small town of Palmar de Cuautla.

Finally, Northern Novillero Beach, site 87, faces high anthropogenic pressure on the beach, from visitors and their vehicles. Tourist infrastructure has been built on the frontal dune and there are coconut plantations on the dunes. Thus, only rehabilitation, not restoration, actions are feasible here because of the intense degradation and the low number of elements that would facilitate restoration actions. Rehabilitation actions should focus on controlling and reducing the negative elements affecting the site. Simple actions, such as reducing disorganized trampling, could trigger the establishment of native vegetation and the formation of a new foredune.

4. Discussion

To assess the state of beaches and coastal dunes various different approaches have previously been used: a) to analyse vulnerability (García-Mora et al., 2001); b) to determine the impact of tourism (Leatherman, 1997; Phillips and House, 2009); c) to compare beaches with different types of tourism (Cervantes and Espejel, 2008); d) to assess the quality of the beaches in terms of safety, water quality, facilities, scenic beauty and litter (Micallef et al., 2011), and e) to estimate the value of conservation and the potential for recreation (McLachlan et al., 2013). In addition to the aforementioned indices, the Re-Dune index is a multidisciplinary diagnostic tool that indicates the need for, and feasibility of, restoration or rehabilitation actions, as well as prioritizing areas where these actions are most recommended. This index has been applied previously on stretches of the Mexican coast. In the central region of the Gulf of Mexico (Veracruz), Lithgow et al. (2014) found that, from a total of 35 beaches, nearly half of them showed signs of degradation, indicating the need to restore or rehabilitate. In contrast, on the Mexican Caribbean, in the state of Quintana Roo, Martínez et al. (2016) studied 25 beaches and observed that only six beaches could be considered suitable for conservation; restoration was the recommended in a further two, and the remaining 13 were so degraded that only rehabilitation was seen to be an option.

Our results are in agreement with the findings of Jiménez-Orocio et al. (2014), who concluded that the Mexican Pacific coast is better conserved than other parts of Mexico. We found that 41 sites (45% of the total evaluated) can be considered as in a good conservation state, whereas 43 showed signs of degradation, likely to respond successfully to restoration efforts. The remaining 6 sites were severely degraded and did not have the elements necessary for restoration, and thus, can only be rehabilitated (Fig. 3). These sites are all adjacent to the Canal de Cuautla, which severely affects the dynamics of the shoreline, beach and foredunes. The sites here have elements which indicate that restoration would be feasible and should be implemented to avoid degradation of adjacent beaches, taking advantage of available vegetation and other resources, such as sediment supply in the healthier sites.

We found that large sections of the coastline in the Marismas Nacionales Biosphere Reserve are undergoing degradation processes, mostly as a result of poorly planned infrastructure. For example, the construction of artificial channels for crops and aquaculture ponds, the development of coconut plantations, seasonal tourism, and erosion caused by coastal infrastructure such as breakwaters and the Canal de Cuautla have contributed to the modification of the coastline. The main effect is the loss of the beaches and dunes that protect the biosphere reserve and surrounding areas. At the same time, the degradation of these areas reduces their attractiveness for tourism and, accordingly, hinders future tourism development.

More than half of the sites evaluated in the present study were degraded, despite their low population density and having Ramsar status. The most dramatic levels of degradation were observed close to the Canal de Cuautla, where restoration actions are not feasible. Here, a new dynamic equilibrium should be promoted instead. Actions in this zone are increasingly urgent as the small town of Palmar de Cuautla is experiencing severe erosion and heightened flood risk.

The lack of an integrated approach to coastal development in Marismas Nacionales is evidenced in poor, or non-existent planning. As a result of the approach to development prevalent over recent decades, the natural areas and dunes associated with the few tourist locations in the study area are already in need of restoration. In many cases, permanent infrastructure was built on the beaches, interrupting sediment flux and destroying the dunes.

Finally, our results point to the great potential success of restoration actions. The heterogeneity of the coast of Marismas Nacionales, where sites in good conservation status coexist alongside sites that are severely degraded, needs an integrated approach, as elements that would help restoration actions, such as native species availability, are close to

degraded sites. Successful restoration actions would increase beach and dune resilience and resistance in the region, as the dynamic nature of coastal ecosystems and the coupling of social and ecological systems is well documented. The conservation, restoration, or rehabilitation of the foredunes in the biosphere reserve will help with the protection of inland human assets and natural ecosystems (such as wetlands) from storm impact, as well as from saline intrusion.

5. Conclusion

The conservation and restoration of beach and dune systems in Marismas Nacionales should be a priority because of the importance of the ecosystem services provided by them and also because of the rapid degradation and loss to which they are being exposed. Seingier et al. (2009) recorded the extensive loss of coastal dune vegetation on Mexican coasts over 24 years. The Gulf of Mexico and the Pacific coast were identified as the regions where coastal dune degradation was worst. Therefore, the implementation of conservation, restoration and rehabilitation actions are sorely needed. The adequate selection of measures to preserve, or restore, the ecological functioning of a site, or to rehabilitate certain ecosystem services, requires consideration of several factors. It is crucial to obtain an adequate diagnosis of the state of the ecosystem, or area, to be restored, including the biophysical, ecological, and socioeconomic characteristics that would restrict, or facilitate, restoration actions and to define the solutions available. In this context, the ReDune Index is a cost-effective tool that requires a minimum of information and is easy to implement. It can be applied to determine the most appropriate management strategy and to identify the sites with the greatest need for intervention.

Recovering the beach and coastal dunes of Marismas Nacionales would increase local hurricane protection and encourage sustainable social and economic development. The limitations of economic and human resources can be addressed by prioritizing the sites where restoration actions should be promoted. Actions could include: a) decreasing human disturbance, to allow natural regeneration in the few beaches with tourist activities; b) forbidding infrastructure on top of the dunes; c) limiting artificial inlets such as the Cuautla channel; d) promoting the construction of houses and access to the beach on stilts, and monitoring their impact in comparison with traditional infrastructure; e) analysing the reasons for sediment deficit in the area and addressing this problem urgently and; f) promoting the conservation of coastal dunes, which would enhance the protection of wetlands and human assets.

CRediT authorship contribution statement

Debora Lithgow: Conceptualization, Investigation, Writing - original draft. **M. Luisa Martínez:** Supervision, help writing-review and editing. **Juan B. Gallego-Fernández:** Methodology, Supervision. **Octavio Pérez-Maqueo:** Data curation. **Rodolfo Silva:** Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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