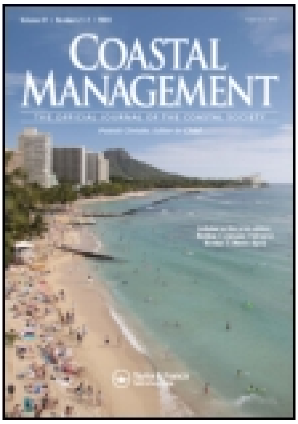

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Assessment of Vulnerability and Integrated Management of Coastal Dunes in Veracruz, Mexico

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Dune systems are essential to the ecological balance and sediment inputs of coastal environments and they provide numerous environmental services; however, their existence is threatened by natural and human stressors that contribute to their degradation. Future impacts are expected to be greater because of global climate change in association with further rises in sea level. Beaches and dune systems occupy large areas along the coastline of the state of Veracruz on the Gulf of Mexico. The aim of this study is to establish the intrinsic vulnerability of nine dune fields in Veracruz to current and future impacts and to assess their integrated management status. These dune–beach systems are more vulnerable to the effects of economic activities and land use change than to those induced by natural forces. Results show that six of these dune systems have medium vulnerability and an ecological conservation policy should be adopted; the other three, with high or very high vulnerability, are candidates for a restoration policy.

Keywords dune systems, dune vulnerability, integrated coastal management, Veracruz dunes–beaches

Introduction

The coastal zone refers to the highly dynamic area of interaction between land and sea, usually characterized by a high density of settlements that contribute to the disruption of the natural cycles of coastal ecosystems. Coasts account for less than 15% of the land surface and accumulate more than 50% of the world population. Two-thirds of the

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world's cities are within 100 km of the sea shore (Viles and Spencer 1995; Small and Nicholls 2003; Martínez, Vázquez, and Sánchez-Colón 2006). Coasts provide economic benefits to society, particularly through the fishing industry, transport, and tourism, resulting in over-harvesting of resources and input of pollutants through sanitary and industrial waste.

Coastal dunes are marine–littoral sedimentary systems, although their lithology can be either terrestrial or marine and consists of a beach area or beach front (bank deposits), a transit zone (wet beach/dry beach and active frontal dune), and a settled area (stable dune). The main sediment sources for dunes are drift currents along the coast, other dune systems, rivers, or the deeper seabed. The main forces in their everlasting construction–destruction cycle are sea waves and tides, and wind is important in reworking sediments after their deposition; sometimes, as in extreme events like hurricanes or tropical storms, the effects of wind can be appreciable.

These extreme events are significant in shaping coastal dune systems, and should be considered as part of their natural cycle; each constitutes a cleansing episode, even if part of the system seems to have been destroyed. Therefore, they are not a hazard to dune persistence, but their effects are difficult to assess when trying to establish a vulnerability level. The most recognized side effects of human activities are the disruption of the natural cycle of sedimentation, and alteration of the balance in favor of erosion or accretion. When the supply of sediment to the front beach is insufficient, the dune becomes eroded; this may be exacerbated by damming and channeling rivers, by dredging of coastal waters at the entrance of the ports, by construction of docks, marinas, and ports, and by leveling, excavation, or construction on adjacent dunes or beaches (Van der Meulen and Salman 1996). Because of the nature of the processes involved in dune systems, infrastructure established on them is at constant risk; this will increase in intensity and frequency as a result of the sea-level rise (SLR) due to global climate change (McFadden 2007), and the common practice of building defenses against flooding or erosion will not be enough to protect them.

The coasts along the Gulf of Mexico have a valuable variety of ecosystems at the marine–terrestrial interface, subjected to the construction of urban and tourist facilities and to industry, mainly hydrocarbon extraction; these represent huge economic benefits but generate strong environmental impacts. This situation is aggravated by the lack of understanding about the dynamics of coastal dunes and beaches that prevails in public policies; consequently, conservation efforts are insufficient (Moreno-Casasola 2004a).

In addressing this type of problem, much emphasis has been placed on the threats acting on coasts; in contrast, the vulnerability of the system has been underestimated. This last term refers to the intrinsic characteristics of the dunes that render them susceptible to external pressures, or that reduce their ability to adapt to change (Williams et al. 2001).

The development of management plans based on scientific foundations will lead to an understanding of the processes and their interaction at both regional and local levels. These plans should also be realistic, integrated, and conceived for the long term, without compromising resources or the quality of life of the inhabitants, as stated in the integrated coastal zone management (ICZM) concept (UNDP-AGENDA 21 1992; Yáñez-Arancibia and Day 2004).

The objective of this study is to adapt and apply a method to assess vulnerability and management of coastal dune systems in Veracruz State, Mexico, using the Analytic Hierarchy Process (AHP) method (Saaty 1980 in Banai-Kashani 1989), widely used as a multi-criteria decision-making tool and recommended by the USEPA (Smith, Tran, and O'Neill 2003). The management framework was assessed by specific checklists based on recent literature reports; these, although focused on the study area, can be tested or adapted in other coastal dune systems.

Background

The active coastal zone should be regarded as a single integral geomorphological system in dynamic equilibrium, where the sand is exchanged between four compartments: (a) beaches; (b) frontal dunes; (c) back beach or surf zone, sand bars, and banks; and (d) river mouths and estuaries. Any change in the balance of sand in one of them may involve changes in others (Tinley 1985; Cooper and Pethick 2005).

Besides being structurally and functionally integrated within the chain of coastal erosion–accretion processes that modulate the effects of large-scale phenomena such as weather and flooding, dune systems have multiple ecological functions and provide a variety of environmental services. Dunes give support to a diverse and specialized vegetation that stabilizes and protects them against meteoric agents; they have a rich variety of relief, soils, and microclimates. They also function as orographic barriers increasing rain frequency on the immediate coast if they reach an elevation of 100 m or more. They constitute valuable genetic resources, geographic landscapes, medicine, food, agriculture, and forest resources; dunes provide corridors for animal migration and plant dispersal; and they sustain rare or endemic species.

Dunes allow a regulated resources use: aquifers as drinking water supply, pastures, and sand mining. They are recognized and requested as part of the coastal environment in which most of the free leisure activities take place (Tinley 1985; Day et al. 2004; Moreno-Casasola 2004a).

Natural processes operating in coastal dunes are linked to climatic factors such as temperature, precipitation, evaporation, and storm regimes; they are also associated with coastal processes such as erosion and accretion, and with geological setting, relief, changes in quantity and quality of groundwater, soil, vegetation, and fauna (Van der Meulen and Salman 1996). Dune systems are considered as fragile or vulnerable ecosystems in any case (Martínez and Psuty 2004), and this condition can be greatly increased by human activities. The perception that dune systems are a threat to human interests gave rise to several management misconceptions, such as that the dunes are better stabilized with trees than with natural vegetation; this led to the use of exotic trees for this purpose (e.g., *Eucalyptus*, *Acacia*, *Pinus* and *Tamarix*), which, in turn, constitute a threat to wild populations, as well as depleting groundwater reserves.

To address the vulnerability of coastal beaches-dunes, procedures that have been tested include the use of environmental checklists; this systematizes the information in order to obtain a preliminary assessment from which to derive vulnerability indices. Variables commonly considered for these purposes cover aspects such as morphology, beach condition, dimensions of the coastal area (200 m wide), ecological processes, land use pressure, and protection measures. Some authors group the variables into geomorphological, ecological, socioeconomic, and threats/risks categories (Williams et al. 2001; Henocque 2003; Ortiz and Méndez 2004; Martínez, Vázquez, and Sánchez-Colón 2006).

Options for calculating a vulnerability index include the use of multicriteria techniques such as the Analytical Hierarchy Process (AHP), widely applied to different environmental problems, especially in resources allocation and planning. It is well accepted by decision makers because it helps organize complex problems into a well-structured hierarchy, and is especially useful in cases where information is incomplete or not available (Smith et al. 2003; Anselin and Meire 1989; Bojórquez-Tapia, Juárez, and Cruz-Bello 2002; Purnendu and Ritwik 2003). Once its vulnerability level has been identified, a dune system can be compared against land use to manage its sustainable use in a balanced way.

The ICZM includes the identification, evaluation, and prioritization of problems. This information is used as a basis for developing and implementing a site-specific plan, which should be further supported by associated normative and educational programs; subsequent continuous monitoring allows adjustments if necessary. However, several factors limit its efficient functioning; among these is the lack of understanding of the natural processes of formation and evolution of the dunes and beaches, which are strongly associated with the geographical conditions that shape the coastal area (Fletcher and Smith 2007; Yañez-Arancibia and Day 2004).

In the European Union, McFadden (2007) believes that administrative failures rather than technical ones are the main problem; for instance, administrative boundaries imposed on coastal areas can dissect an ecological unit into fractions and prevent an integrated management. Other common reported problems are those of land use conflicts, attributed to the ancient social perception that the coasts are a free-access common area where each user can exert his own will (Fletcher and Smith 2007).

The limitations to applying an ICZM in Mexico are similar; although it has >11,000 miles of coastline, it is not considered a coastal country, a perception that has led to neglect of coastal conservation. However, after the Rio Summit in 1992 (UNDEP-AGENDA 21 1992), new initiatives for the productive sectors of the coast were proposed, and a regulatory framework was developed. In spite of this, in the national political agenda, coastal issues are not approached in terms of integrated sustainable development. Information on coasts is heterogeneous and fragmented because it has been generated to meet partial and scattered objectives.

Management plans and programs are scattered in several public institutions without clear articulation, and have been developed on a sectorial basis. There are conceptual inaccuracies regarding the definition, for example, of the Federal Maritime Terrestrial Zone (ZOFEMAT). Approximately 20,000 nationally registered activities in the ZOFEMAT have been reported, of which fewer than 3% have official authorization (SEMARNAT 2006).

As for the management of dunes-beaches, Day et al. (2004) point out that Mexican environmental legislation lacks regulations. Measurement of beach erosion is in its infancy, as is assessment of its implications for dune stability and its relationship to coastal tourism development and global climate change. Moreno-Casasola (2004a) and Martínez, Vázquez, and Sánchez-Colón (2006) present an overview of the problems of coastal dunes and beaches of the Gulf of Mexico highlighting the dangerous phenomena of natural origin as well as human-induced threats.

Planning tools developed by academic and government institutions include the National Development Plan, Municipal Development Plans, Urban Development Plans, and Management Plans for Natural Protected Areas (Zárate 2004; SEMARNAT 2006). These are supported by legislation at federal, state, and local levels, but with serious limitations in their application. Also, planning workshops for the conservation of representative sites of the coastal zone have been conducted (Peresbarbosa-Rojas 2005).

Veracruz still does not have a decreed strategic management plan to guide environmental policies and the use of the coastal territory based on criteria of greater economic, social, and environmental sustainability. At a regional scale, ecological management plans for the lower basin of the Coatzacoalcos and Bobos rivers were officially enacted in 2008, and are being implemented. At a local scale there is only the community management plan for La Mancha-El Llano.

Table 1
Protection categories in the coastal region of Veracruz

Federal NPA	State NPA	Private NPA	RAMSAR sites
National Park Reef System of Veracruz	Médano del Perro*	Barra de Galindo*	Reef System of Veracruz National Park
Biosphere Reserve of Los Tuxtlas*	Isla del Amor*	El Dorado	Mangroves and wetlands of Sontecomapan
Protected Area of Flora and Fauna Reef System Lobos-Tuxpan (proposed)	Arroyo Moreno*	Dos Esteros	Alvarado Lagoon System*
	Ciénega del Fuerte	La Joya	La Mancha-El Llano*
	La Alameda (in decree process)	La Mancha*	Inter-dune lagoons of Veracruz city*
			La Popotera*
			Tamiahua Lagoon*
			Mangroves of Tumilco and Tampamachoco
			Mangroves and Wetlands of Tuxpan

Source: Peresbarbosa-Rojas (2005).
NPA = Natural protected area.
*Includes all or part of dune-beach systems.

A strategy for protecting and managing natural areas is the Official Categories of Natural Protected Areas (NPA), which is the main instrument for conservation *in situ* of global biological diversity (Ortiz-Lozano, Gutiérrez-Velázquez, and Granados-Barba 2009). In Veracruz, two areas are officially recognized and one proposed at the federal level, five at state level, five private areas, and nine RAMSAR sites (Table 1).

All areas and designated sites, to a greater or lesser degree, have been subject to processes of conservation planning. Further, many of these instruments overlap, that is, one area may belong wholly or partially to two or more categories of conservation or management, as is the case of dune systems.

In this study we considered the criteria and specific recommendations suggested for ICZM planning by several authors (Tinley 1985; Henocque 2003; Moreno-Casasola 2004b; Peresbarbosa-Rojas 2005), and also those referred to in national laws, rules, and regulations on environmental protection. We built a series of checklists and used them to rank the nine dune fields according to their management status. These are briefly explained in the methods and developed in the Results sections.

Study Area

The study area on the coast of Veracruz state is a strip of variable width and a length of 785.2 km, of which 91.6% (719.05 km) is sandy, 6.7% (52.8 km) is rocky coastline, and 1.7% (13.33 km) forms the mouths of rivers. The coastal environmental systems include wetlands, beaches, coastal dunes, deltas, barrier islands, sand bars, barrier reefs, estuaries, and inner islands.

A set of dune fields was selected from this area with reference to their surface and their structural and functional characteristics. For management and mapping issues they were divided into nine sectors: Cabo Rojo, Barra San Agustín, Farallón-La Mancha, Chachalacas,

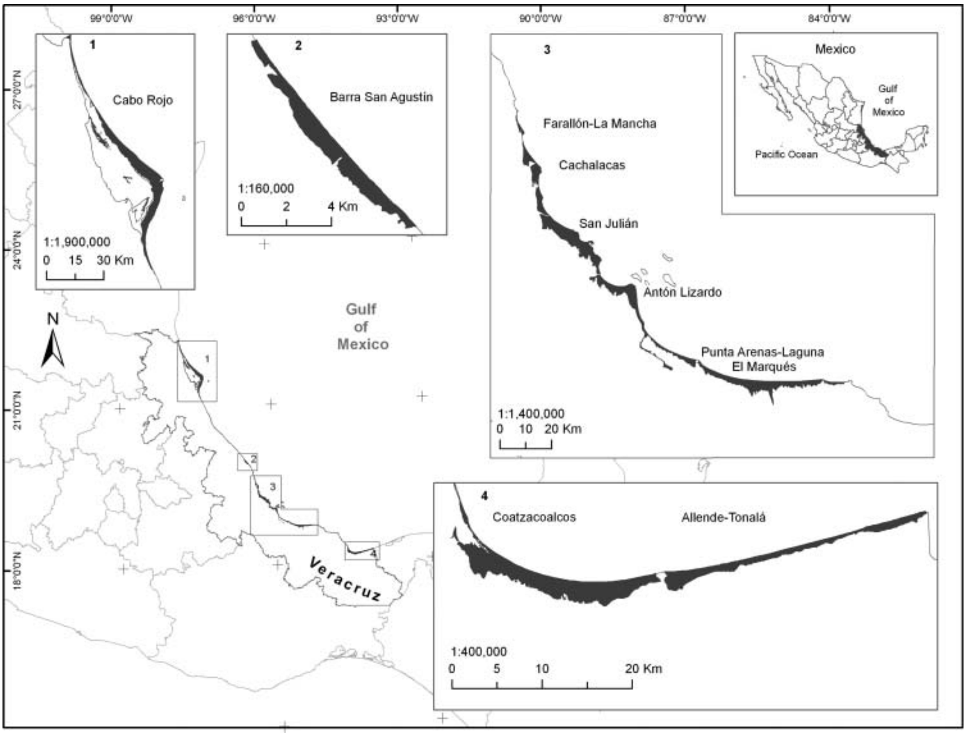

Figure 1. Location of major dune fields in Veracruz.

San Julián, Antón Lizardo, Punta Arenas-Laguna El Marqués, Coatzacoalcos, and Allende-Tonalá (Figure 1, Table 2).

The dune fields are spatially stable owing to the physiographic boundaries. The landward boundaries often coincide with lagoon water bodies that have served as barriers to movement inland.

From a geomorphological perspective, the relief of these systems corresponds to coastal plains formed by ascending (and to a lesser extent by descending) weak or very weak neotectonic forces. Two main types of floodplain consisting of sandy coastline deposits are recognized: the marine-eolic and the marine-cumulative. The former are flat and undulating, with chains of parabolic and transverse dunes and coastal bars; the orientation of their major axis is north–south and northeast–southwest, with heights reaching up to 200 m. The latter are low and very low plains formed by systems of coastal cords, with heights less than 10–15 m. Adjacent to both types of plains are sandy beaches (Hernández-Santana, Méndez Linares, and Figueroa Mah-Eng 2006). It is in the marine-eolic plains that major dune fields have developed, and the marine-cumulative plain and the beaches are the sources of material that winds rework to form the dunes. Most of the Veracruz coast consists of weakly consolidated or unconsolidated sandy deposits from the Quaternary.

Trade winds and “Nortes” are responsible for the orientation and movement of sand dunes. In the Gulf of Mexico, trade winds cause low-energy marine-derived currents that persist throughout the year, except in winter when the “Nortes” with wind speeds that

Table 2
Physical characteristics and land use of the dune fields

Dune field	Area (km^2)	Maximum length (km)	Maximum width (km)	Landforms	Dune area (%)	Reaching height (m)	Main forms of the dunes	Land use (%)
Cabo Rojo	391	145	10	Barrier island complex system of littoral cords and coastal dunes with inter-dune lagoons	10	>30	Longitudinal	1) 10.1 5) 6.1 2) 2.8 6) 0.7 3) 48.1 8) 0.1 4) 32.1
San Agustín	6.4	10	0.8	Barrier	47.9	<20	Longitudinal	1) 48.0 8) 0.5 4) 51.5
Farallón-La Mancha	7.3	13	1.3	Series of bars and cords parallel to each other, separated by inter-dune depressions	35.7	100	Parabolic in closed U or half-moon shapes	1) 35.7 4) 2.1 3) 61.9 8) 0.3
Chachalacas	67.3	32	4	Littoral sediment with cords and inter-dune lagoons	37.5	>50	Longitudinal	1) 38.2 6) 1.0 3) 32.5 7) 0.1 4) 5.0 8) 0.5 5) 22.7
San Julián	128.5	33	5	Undulating eolian-marine plain	6.7	120	Parabolic and transverse	1) 8.3 5) 3.1 3) 33.2 6) 42.5 4) 10.9 8) 2.1

Antón Lizardo	120	56	4	Littoral sediment plain with cords	10.3	50	Parallel and transverse	1)10.4 3) 20.7 4) 36.1 5) 25.6	6) 6.7 7) 0.2 8) 0.3
Punta Arenas-Laguna El Marqués	138.8	60	10	Undulating eolian-marine plain	6.8	100	Longitudinal	1) 6.9 3) 32.9 4) 53.7	5) 5.8 6) 0.6 8) 0.2
Coatzacoalcos	47.8	28	3	Undulating eolian-marine plain	10.6	30	Parabolic	1) 10.7 3) 6.5 4) 49.3	6) 32.9 8) 0.6
Allende-Tonalá	24	30	0.3–2.3	Barrier and littoral cords	6.2	20	Longitudinal	1) 6.3 2) 2.6 3) 5.9 4) 7.2	6) 22.3 7) 1.2

Land use: 1) Vegetation of coastal dunes and areas without apparent vegetation, 2) Wetlands, 3) Perturbed vegetation, 4) Natural grassland, induced or cultivated, 5) Irrigated and rainfed agriculture, 6) Human settlements, 7) Industrial areas, 8) Water bodies.

exceed 118 km h^{-1} (63 knots) become very important in modeling the dune field. Trade winds are the input path of sediments and the "Nortes" have a remodeling action.

The main winds on the coast of Veracruz are from the north, northwest, northeast, east, and southeast. The following relief forms are common: coastal cords and parabolic, transverse, forked, longitudinal, and complex-parabolic dunes. Natural hazards that affect these areas are significant in shaping the dunes. Even if these phenomena could be considered hazardous to these systems, they are also part of their natural cycles, so the dune physical characteristics can be interpreted as the resulting balance between constructive and destructive forces.

Some of these dune fields have supported settlements since pre-Hispanic times (San Julián-port of Veracruz) but most of them became populated around the 1980s as a consequence of the hydrocarbon industry development. Nowadays, population distribution is somewhat peculiar; 388 localities, of which 382 (98.5%) are rural, have fewer than 5,000 inhabitants. They are practically on the banks of these fields, particularly in the areas of Cabo Rojo, Antón Lizardo, and Punta Arenas. There are only four urban localities with a population over 15,000: Veracruz and Coatzacoalcos cover a wide area of the dune fields, and Allende and Alvarado do so but to a lesser extent. Boca del Río (10,000–15,000 inhabitants) is mixed urban–rural, and Antón Lizardo is rural–urban (Figure 2). In a way, this distribution is related to the degree of vulnerability of the dune fields, as demographic pressure has a greater impact on these more fragile ecosystems.

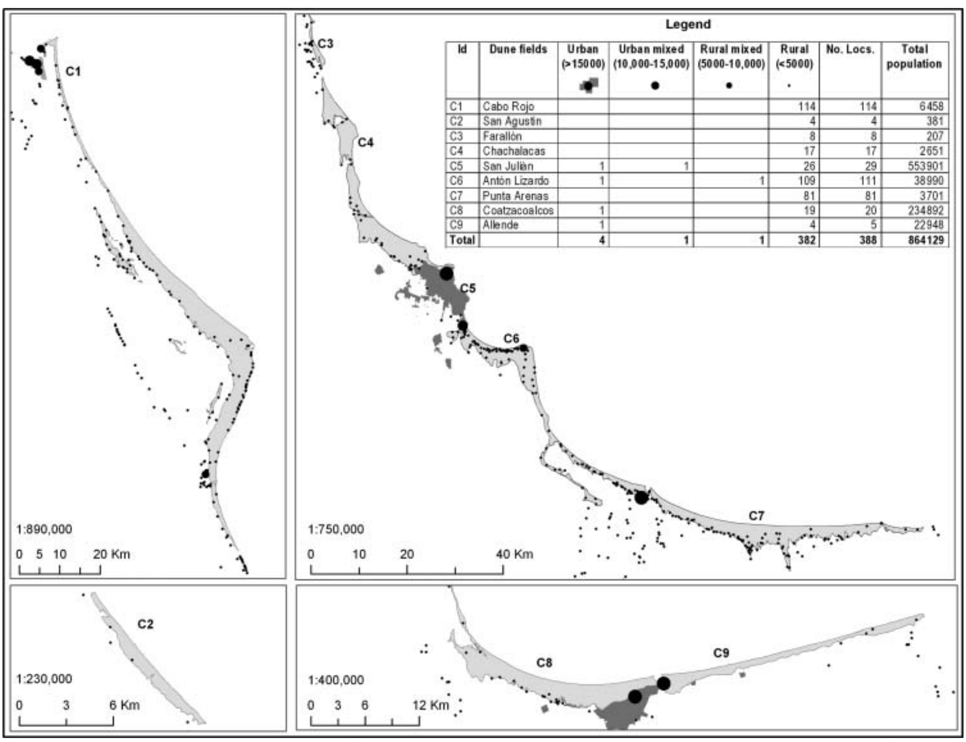

Figure 2. Distribution of population centers in the dune fields. *Source:* INEGI (2001).

Materials and Methods

The nine dune fields and beaches were delineated and analyzed by remote sensing tools (Figure 3) managed in a geographic information system (GIS) ArcGIS Desktop V.9 ESRI. Vegetation and land use were examined in each dune field. All this was supplemented by fieldwork.

Vulnerability of these dune fields was assessed by the AHP, a method that has been intensively applied since its creation, alone or in combination with other methods; its versatility allows a wide range of applications (Cram et al. 2006; Mardle, Pascoe, and Herrero 2004; Bojórquez-Tapia, Juárez, and Cruz-Bello 2002; Li and Hui 2001; Smith-Korfmacher 2001). To apply the AHP, threats were grouped into three variable categories: (i) natural (heavy rains, erosion/sedimentation, drought, and pests-diseases), (ii) anthropogenic (land use changes by agricultural activities, urban, industrial and tourism developments, oil exploitation and extraction of sand, and pollution), and (iii) mixed (forest fires, coastal erosion by human action, sea-level rise related with climate change, and slope instability such as landslides).

A hierarchical model was constructed, the first level stating the three main types of hazards—natural, anthropogenic, or mixed. At the second level these were subdivided: for example, natural hazards into heavy rains and erosion/sedimentation. The third level further divided heavy rains into "Nortes," hurricanes, and "others" (Table 3).

Later, a set of matrices was constructed with the hazards corresponding to each hierarchical level, and scores were assigned by pairwise comparison of possible threats:

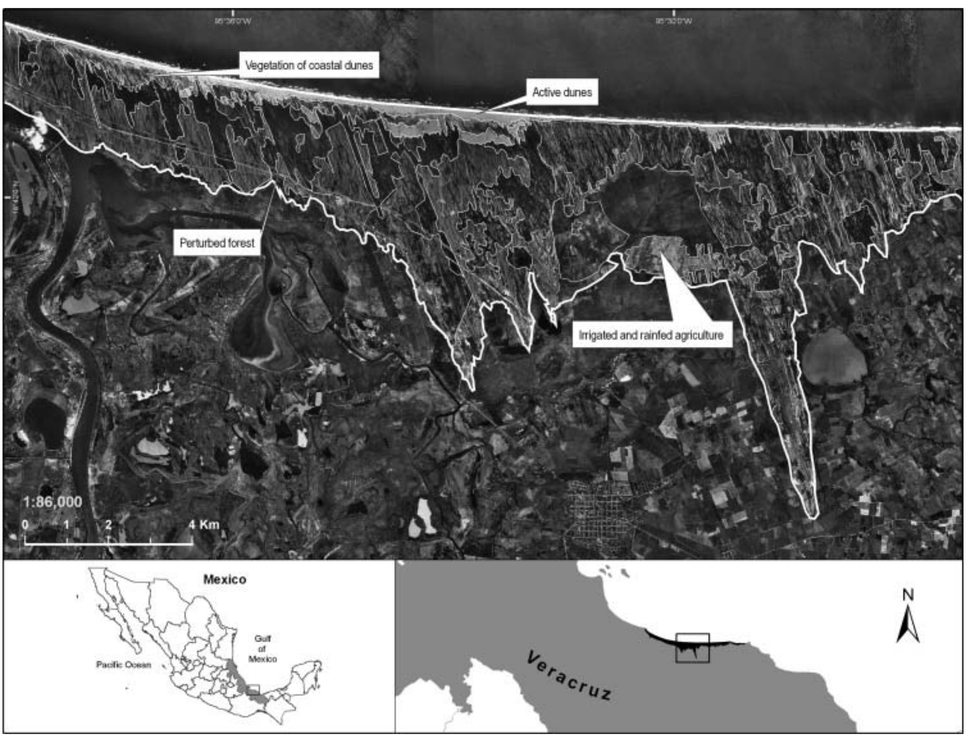

Figure 3. RGB Composite (254) of the dune field Punta Arenas-Laguna El Marqués.

Table 3
Hierarchical work scheme

1st level	2nd level	3rd level	4th level
Natural	Heavy rains	“Nortes”	
		Hurricanes	
		Other	
	Erosion/sedimentation	Wind	
		Water	Waves
			River
	Droughts		
	Pests and diseases		
Anthropogen	Land use change	Urban/Industrial	
		Livestock	
		Agricultural	
		Secondary vegetation	
	Pollution	Soil	
		Water	
		Air	
Mixed	Forest fires		
	Coastal erosion by human action		
	Sea level rise		
	Landslides		

1 = equal, 3 = slight difference, 5 = moderate difference, 7 = large difference, and 9 = completely different. These matrices were numerically solved according to Banai-Kashani (1989) calculations, to obtain factor weights.

A similar procedure compared each possible pair of dune fields for each hazard in turn. The matrices (9 × 9) obtained were also numerically solved, and a score for each field per hazard was obtained. These values were then multiplied by the weight obtained by the first procedure. By adding the values for the different threats for a specific dune field, a final score was derived. These final scores were ranked according to magnitude; the greater the score the more vulnerable a dune field. For each of the matrices an internal inconsistency index was calculated; this should have a value lower than 0.1 to be acceptable according to Banai-Kashani (1989).

Current management plans were reviewed to compare them against recognized scientific and technical management criteria. The main features to be considered for establishing good management practices are summarized in three tables used as check lists; a count of the favorable conditions indicates the management status.

The first table includes general administrative/legal criteria that regulate access or ownership of coastal areas, emphasizing the need to develop management plans and the most important points they should contain. The other two tables consider technical and scientific criteria to ensure the smooth functioning of dune and beach formation. When the necessary activities are defined, qualified personnel should be available to carry them out, comply with established schedules, and keep records for further tracking. These criteria include planning and design of coastal routes, specifically in terms of their position and orientation, since these trigger the proliferation of human interferences. Other criteria deal with coastal building designs and land use planning.

The last table focuses on the main criteria during the rehabilitation and monitoring of dune fields. It addresses points that will ensure understanding of the natural processes of dune formation and stabilization prior to any intervention measures. The recommendations stipulate the preferred materials and necessary precautions during the dune stabilization process.

Results and Discussion

The AHP method gathers useful characteristics for this application and is simple to perform and easy to understand; this is desirable since it will eventually be applied by unspecialized or technical personnel after suitable training. This method is practical when basic information is incomplete or lacking, which is a common situation in developing countries. It allows the transcription of field observations recorded by experienced personnel into categorical values, thereby reducing the time and costs required for their execution. Quantitative and qualitative data can be mixed, avoiding the rejection of important factors due to information gaps. Even if no precise or exact results are obtained, it is useful for a general and rapid comparison of alternative sites by means of numerous factors, so that a general idea of the vulnerability can be rapidly obtained.

Another advantage of the AHP method is that the scores are assigned through paired comparisons of alternative dune fields, and so results express an internal or relative scale. This is a highly desirable feature for IZCM at the regional scale, because it is feasible to separate dune fields into different categories: those that require most attention and resources for their recuperation or conservation; those that must be monitored or observed in order to avoid eventual degradation; and those that can support extra stressors and could be devoted, for example, to a tourist use. However, this could be also considered a disadvantage because the lack of an objective scale precludes comparison with other regions or conditions.

Based on the indices derived from the application of the AHP method, four levels of vulnerability were identified (Table 4). No dune field had low vulnerability. Cabo Rojo, San Agustín, Farallón-La Mancha, Chachalacas, Antón Lizardo, and Punta Arenas-Laguna El

Table 4
Vulnerability levels for dune fields of Veracruz state by the AHP method

Dune field	Final score	Score based 10	Vulnerability
			Low (0–2.5)
Chachalacas	0.06	2.7	Medium (>2.5–5)
Barra San Agustín	0.07	3.2	
Farallón-La Mancha	0.07	3.2	
Cabo Rojo	0.08	3.6	
Punta Arenas-Laguna El Marqués	0.09	4.1	
Antón Lizardo	0.10	4.5	
Allende	0.13	5.9	High (>5–7.5)
Coatzacoalcos	0.18	8.2	Very High (>7.5–10)
San Julián	0.22	10	

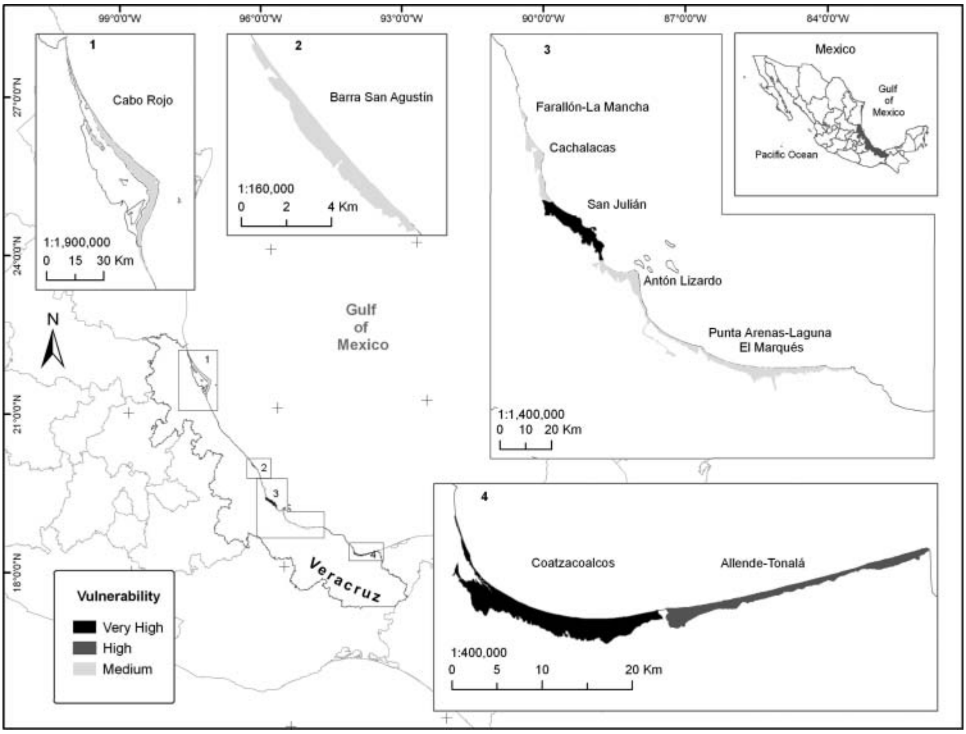

Figure 4. Vulnerability level of dune fields of Veracruz.

Marqués showed medium vulnerability; Allende-Tonalá high vulnerability; and San Julián and Coatzacoalcos very high (Figure 4).

The analysis reveals that human activities are triggering the destructive processes of these ecosystems, mainly by changes in land use due to agricultural, urban, industrial, tourism, oil exploitation, and sand extraction activities, as in San Julián-Veracruz port and Coatzacoalcos. With regard to general criteria (Table 5), ZOFEMAT is officially stated (1), but its limits are restricted to 20 m, and the active coastal zone is not well defined. It remains an urgent task. Admission to turtle nesting sites (2) is prohibited to the general public, but in practice is not observed. Admission is restricted to academic groups, civil organizations, and Navy personnel who support the protection work.

Environmental authorities issue development licenses without on-site assessment. The Federal Attorney for Environmental Protection (PROFEPA) imposes fines that are often already included in the project budget. Environmental authorities do not perform systematic field checks (3, 4, 5).

There is only one local community management plan, at La Mancha-El Llano (C3), that specifically involves a dune-beach-wetland system. Other plans such as the one for the lower basin of the Coatzacoalcos river (C8, C9), the RAMSAR sites, and those for the natural protected areas (C1, C3, C5, C7) are biased toward one component of this system (6).

The participation of local people in the formulation of management plans is considered, but, in practice, they are usually excluded (7). The other criteria (environmental education programs, formation of an advisory coastal body, involvement of experts in coastal ecology,

Table 5
General criteria (administrative/legal)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Comments
1) Legal statement of the federal maritime-terrestrial zone (≥100 m)	Y	Y	Y	Y	Y	Y	Y	Y	Y	But is insufficient (20 m approx.)
2) Banned access to sites or at some seasons (e.g., turtle nesting)	N	P	P	N	N	N	N	N	N	Ban is not observed
3) Control by environmental authorities of tourism or other developments	N	N	P	N	N	N	N	N	N	
4) Ratification *in situ* by environmental authorities for the issue of licenses for developments	N	N	N	N	P	P	N	P	N	Occasionally
5) Continuous assessment of the limits of the active littoral zone	P	P	Y	P	P	P	P	P	P	Changes by SLR. Urgent task
6) With Management Plan (MP) or other planning instrument	P	N	Y	N/I	P	N/I	P	Y	P	Only one local management plan
7) Local people are taken into account in formulating the MP	N/I	N	Y	N/I	N/I	N/I	P	P	P	Not in real terms
8) The MP includes environmental education programs in coastal areas	Y	N	Y	N/I	Y	N/I	Y	Y	Y	Not in real terms
9) The MP includes the formation of a coastal advisory body	N/I	N	Y	N/I	N/I	N/I	N/I	Y	Y	Only in the proposals
10) MP includes a technician on coastal ecology on-site	N/I	N	Y	N/I	N/I	N/I	N/I	Y	Y	Only in the proposals
11) MP considers the recording of data to monitor coasts, including the limits of the active coastal zone	Y	N	Y	N/I	N/I	N/I	N/I	Y	Y	Only in the proposals
12) MP states that, whenever possible, developments that destroy the dunes should be avoided (e.g. golf courses)	Y	N	Y	N/I	Y	N/I	Y	Y	Y	Only in the proposals
13) MP is based on local, municipal, state, national, or international laws	Y	N	Y	N/I	N/I	N/I	Y	Y	Y	There is no control on law enforcement

Y, Yes; N, No; N/I, No information; P, Partially.

C1, Cabo Rojo; C2, San Agustín; C3, Farallón-La Mancha; C4, Chachalacas; C5, San Julián; C6, Antón Lizardo; C7, Punta Arenas-Laguna El Marqués; C8, Coatzacoalcos; C9, Allende-Tonalá.

systematic registration of data, avoidance of dune destruction, legal support) are included in coastal management plans; but in practice, environmental education workshops are seldom conducted, advisory committees do not represent all the sectors involved, not enough trained technicians in ecology are available on site, and there is no systematic monitoring, sampling, and data logging. Overlapping of organizational competence is common, leading to unarticulated strategies, contradictions, and legal gaps, and developers take advantage of these circumstances to achieve their goals (8, 9, 10, 11, 12, 13).

As for the main technical-scientific measures (planning and use) to be considered in coastal management plans, and their comparison with the few existing schemes (Table 6), dune-beaches are important but neglected by government institutions (1). Little is known about natural variation of the beachfront line and erosion processes. Erosion processes have been reported for some beaches such as Chachalacas, Antón Lizardo, Allende-Tonalá (C4, C6, C9); the few cases measured suggest a rate of 1 to 2 m year^{-1} (SM-AM 2002) but continuous records are needed especially in relation to SLR (2, 3, 4). Some sites are known as particularly vulnerable to sea level changes, but the observed general tendency in these dunes is their growth toward the sea (5) as a result of the significant sediment input through large rivers (Pánuco and Papaloapan).

Most coastal roads in the area are less than 5 km from the beach; they have no or sparse tangential accesses to the beach, and these are poorly branched and badly paved (6, 7, 8, 9). With the exception of Antón Lizardo (C6), roads in the dune fields are more or less protected against the prevailing wind directions. In most of the fields wind direction is not taken into account for building projects (10).

In the fields with urban, industrial and tourism use (C4, C5, C6, C8, and C9) developments are sited in any type of relief, not just behind the dunes (11,12) (Figure 5). There are land use restrictions, but these are poorly observed (13, 14). There is degradation in all field dunes as they have been used extensively for livestock purposes and, to a lesser extent, for tourism.

Also, no attention is paid to harmonizing architectural design with the landscape, or according to sustainable tourism (15, 16). Settlements are not self-sufficient in services, and on almost all beaches there is visual and soil pollution by solid wastes, and dune water is polluted (17, 18).

Maps of current land use at regional scale (1:250,000) are available for the entire coast of the state. More detailed cartography of the dune fields is scarce. Land use maps

Figure 5. Removal of large volumes of sand from coastal dunes for the development of a housing complex.

Table 6
Technical–scientific criteria (stages: planning and use)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Comments
1) The scenic, cultural, educational, and/or scientific values of the site are established	Y	Y	Y	Y	Y	Y	Y	Y	Y	State and national importance
2) Erosion is measured at the site	P	P	P	P	P	P	P	P	P	In some sectors
3) In erosion areas, the rate of shoreline retreat is monitored	N	N	P	P	P	P	N	P	P	Should be monitored according to sea-level rise
4) The boundaries of the active coastal zone are set	N	N	N	N	N	N	N	N	N	Should take into account the sea-level rise
5) Sections most vulnerable to change are identified	P	P	P	P	P	P	P	P	P	Partially but must take into account the sea-level rise
6) Coastal Routes (CR) are more than 5 km from the beach	N	N	N	P	P	P	N	N	N	
7) CR have only tangential and spaced accesses to the beach	N	N	P	P	P	P	P	P	N	
8) The accesses to the beach from the CR are not branched or paved	N	N	P	P	P	P	P	P	P	
9) The CR and its accesses are directed away from prevailing wind directions	P	P	P	P	P	N	P	P	P	
10) The area beyond which building permits are granted meets the above CR criteria	N/I	N/I	N	N	N	N	Y	N	N	
11) In case of no apparent erosion, developments are behind the dunes	Y	X	Y	N	N	N	Y	N	N	
12) It is noted if there are buildings on the following landforms: frontal dunes, beaches, inlets, estuaries, river banks, floodplains, margins of lagoons and seasonally flooded areas	Y	Y	Y	Y	Y	Y	Y	Y	Y	
13) The buildings referred to in criterion 12, have regulations that specify restrictions and obligations for such use										
14) Measures to protect the frontal dune from trampling (livestock or destructive tourism) are specified										

(Continued on next page)

Table 6
Technical–scientific criteria (stages: planning and use) *(Continued)*

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Comments
15) The architecture of the buildings is in harmony with natural processes (low, with air circulation, on stilts)	N	N	N	N	N	N	N	N	N	
16) Tourism developments are of rustic cabins or of an ecotourism type										
17) The settlements are self-sufficient in services (lighting, cooling, water supply, waste disposal)										
18) Waste disposal (water and trash) must not affect the quality of the fresh water under the dunes	Y	Y	Y	Y	Y	Y	Y	Y	Y	
19) There are maps of land use at local and regional scale of both current and potential land use										
20) In land use maps, the coastal buffer is marked	N	N	N	N	N	N	N	N	N	Must be defined in terms of sea- level rise
21) The maps show the actual and potential protected-conserved areas	Y	N	Y	Y	Y	Y	Y	Y	N	Only in specific maps
22) The maps show the potential uses and intensity of sustainable use for each field	N/I	N/I	Y	N/I	N/I	N/I	N/I	Y	N/I	To be defined according to the sea-level rise
23) The intensity of use of survival resources (gathering, hunting, fishing, firewood, timber) is established	N	N	N/I	N/I	N/I	N/I	N/I	N/I	N/I	
24) There are measures and infrastructure for fire fighting	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	
25) Extractive activities are regulated in the dune systems, specifying intensity of use and major impacts	N	N	P	N	N	N	N	N	N	
26) The access of motorized vehicles to dunes and beaches is explicitly forbidden	N	N	N/I	N	N	N	N	N	N	

Abbreviations as in Table 5.

at 1:50,000 were produced for this work (19) but the coastal buffer strip is not shown in these maps (20). Areas under conservation/protection are marked on specific maps (21). Except for La Mancha and Coatzacoalcos (C3 and C8) no information about the potential uses or intensity of sustainable use was available. Information about the measures and infrastructure for fire control is lacking; however, many dunes are occupied by cultivated and induced grasslands where fires are common (22, 23, 24).

Even if there were regulations regarding mining activities in the dune systems, these would hardly operate until a legal management status for protected areas is adopted (25). Access of motorized vehicles to the dune fields is not forbidden (26), and this is a major threat particularly in Chachalacas and San Julián (C4 and C5).

Table 7 lists scientific and technical criteria aimed at recovering, intervention, and monitoring of dune fields, and compares them with the current situation in the study area. Little information was obtained on this issue, clearly showing the need to intervene in these dune-beaches to counter the degradation imposed by natural and human phenomena.

In Cabo Rojo and San Agustín (C1 and C2) there is no significant deterioration (1). The landscape is a good indicator of sand mobilization (2, 5) and of inherent vulnerability (3); studies must be specific to each landscape if the dynamics of erosion/sedimentation processes are to be understood. Our vulnerability analysis revealed that in most of these dune systems transgressive marine processes dominate; even if accretion is not uniform, the trend is that the bars and littoral cords grow towards the sea, as in the north central part of Cabo Rojo and Punta Arenas-Laguna El Marqués (C1, C7) (4). The actions necessary to protect dunes and beaches may be known, identified and prioritized, but the sources of supply, the dimensions of the coastal strip, and the role played by natural forces are seldom taken into account (6, 7, 8). In the case of dune stabilization, there is scant information on the measures that are being implemented, but some native pioneer plants are being used in La Mancha (C3) and *Opuntia* sp. in Antón Lizardo (C7). All dune fields are invaded by exotic plants; *Casuarina* sp. is used as a windbreak (10, 11, 12, 13). The functioning of the aquifers underlying the dunes is in most fields unknown. The possible supply of sand from the dunes to the adjacent beaches is not taken into account (14, 15, 16).

A better understanding of the issue and involvement of local people in management programs (17) is found only in La Mancha (C3). A monitoring program has been established, but further information is unavailable (18, 19, 20, 21).

The coastline of Veracruz state is vulnerable to SLR (Ortiz and Méndez 2004; Zavala et al. 2010), but dune-beaches act as barriers, buffering the effects of this phenomenon and protecting human settlements and several wetland systems that still cover a considerable area. The coastline of the Gulf of Mexico is subjected not only to SLR but also to subsidence in the littoral zone along almost all its length, rendering it particularly sensitive. The SLR will exacerbate the migration inland of dune fields, and this may threaten their associated wetlands. In other cases, the growth inland will be limited by the landward physiography: by a steep rise in ground level as in Allende-Tonalá; or by orthogonal relief systems formed by wind corridors with a prevailing north-south direction, and by estuaries with an east–west orientation, as in the dune fields of central Veracruz from San Agustín to Antón Lizardo. SLR and subsidence will lead to erosion of front beaches and sand dunes, and important sand inputs to wetlands causing wetland loss, but the spatial structure of the coast is preserved as bars grow.

The potential of dune fields and beaches as protective barriers for the inner land is best exemplified at Cabo Rojo and Punta Arenas-Laguna El Marqués. San Julián, Antón

Table 7
Technical–scientific criteria (stages: recovery/intervention and monitoring)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Comments
1) Intervention is imperative where dunes are experiencing problems or threats	N	N	Y	Y	Y	Y	Y	Y	Y	This applies in most fields owing to their current decline and to the sea level rise
2) Active processes are identified	P	P	Y	P	P	P	P	P	P	
3) Types of dunes and their inherent vulnerability are identified	Y	Y	Y	Y	Y	Y	Y	Y	Y	
4) The trend and direction of change are identified										
5) Movement of sands is explained in terms of the specific landscape	P	P	P	P	P	P	P	P	P	Established by some academic groups
6) Needed actions are identified and prioritized	N	N	Y	Y	Y	Y	N	Y	P	
7) The actions focus on these two points: a) Sources of sand supply b) Coastline zone (beach-dune)	N/I	N/I	Y	N/I	N/I	N/I	N/I	N/I	N/I	Few studies
8) On these measures natural forces are allowed to act by themselves	N	N	Y	N	N	N	N	N	N	
9) In case of dune stabilization (DS) degradable and open-pore materials are used	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	
10) In case of DS natural materials are available in abundance in the area	N/I	N/I	N/I	N/I	Y	N/I	N/I	N/I	N/I	
11) Quantity and placement of these structures is established	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	
12) Invasion of exotic plants in the dunes is monitored	Y	Y	Y	Y	Y	Y	Y	Y	Y	

13) Preference is given to native pioneer plants to repopulate/stabilize the dunes	N/I	N/I	Y	N/I	N/I	Y	N/I	N/I	N/I
14) The functioning of the aquifer, (fluctuations, water quality, level of development, etc.) is characterized and regulated	N/I	N/I	P	N/I	N/I	N/I	N/I	N/I	N/I
15) Water table levels are controlled to keep the dunes in place	N	N	N	N	N	N	N	N	N
16) In the DS a possible sand supply from the dunes to the beach is considered (control headers)	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I	N/I
17) For the local population a plan to promote planting of pioneer species at the front of the dunes exists									
18) Natural vegetation zoning is considered when reseeding									
18) The DS specifies the target degree of stability without affecting natural functions	N	N	N	N	N	N	N	N	N
19) A monitoring plan is conceived to check the development of recovery achievements	N	N	N/I	N	N	N	N	N	N
20) This plan specifies who, what, how, where and how often the measurements and records are taken and who shall interpret and perform corrective actions									

Abbreviations as in Table 5.

Lizardo and Coatzacoalcos have a very limited potential, since human settlements on the windward section of dunes affect the primary succession processes. The potential of the Allende-Tonalá field to provide a barrier has been restricted by dune destruction in order to build Allende city.

From a scientific and educational point of view, San Agustín, Farallón-La Mancha and Chachalacas have great potential because they have a succession of morphological types, as well as a rich mosaic of plant communities ranging from pioneers, grassland, and herbaceous vegetation, to shrubs and trees. This also imparts greater stability to the dune-beaches system.

This analysis of dune-beaches vulnerability and the present poor coastal management suggests the following environmental policies. (1) *Conservation.* This applies to those areas that meet an important ecological role. Few and limited activities should be permitted; scientific-technological research, sightseeing, bird watching, trekking, or educative visits following established routes, would preserve natural conditions and promote the recovery of environmental equilibrium. This status is recommended for Cabo Rojo, San Agustín, Farallón-La Mancha, Chachalacas, and Punta Arenas-Laguna El Marqués. These areas have heterogeneous environments of high-productivity; they are important refuges for migratory and local birds, and are also nesting areas for sea turtles; in addition, some of their associated inter-dune lagoons have a high endemism of freshwater species. The regional context and relationships with neighboring ecosystems should be included in their management plans. (2) *Restoration*. This is advised for damaged areas whose original features should be rehabilitated to restore important habitats or ecological processes. It should be considered as a priority in the areas of San Julián, Antón Lizardo, Coatzacoalcos, and Allende-Tonalá to be applied on the few areas which still can be recovered. The methods and environmental policies used in this work are based on the integrated scope and sustainable development suggested by the IZCM (UNDP-AGENDA 21 1992), so the present results for the nine dune fields of Veracruz can be considered as a comparative standard for other countries with the same environmental issues such as Argentina, Chile, Brazil, Costa Rica, and the Mediterranean countries (Barragán 2010).

Conclusions

The AHP method is easy to use and renders rapid results; these, even on a relative scale, allow the comparison of diverse regional and local situations to make reasonable management suggestions. Reinforcement with the proposed checklists enhances the method by incorporating recognized strategies of coastal management and assessing their status on each site. The analysis, results and suggestions obtained thereby are a valuable platform for decision makers.

The results of this investigation show that the coastal dune systems and beaches of Veracruz are more vulnerable to the impacts generated by economic activities than to natural phenomena. The conservation of these systems will enhance the environmental services they provide, particularly against the effects of global climate change and SLR.

IZCM in Mexico is still in its infancy even though there are sufficient planning tools with well-founded criteria and indicators that show an adequate scientific and technical capacity focused on conservation and sustainable use of coastal resources. For the IZCM of Veracruz, it is essential to develop and enact a management plan that seriously considers all coastal dune-beaches systems, or at least to consider them in all types of plans (state, regional, and local levels). Some mechanisms to implement these plans should be sought, even if the lack of economic resources is always argued. The main limitations of a plan in the initial stages of its application are the opposition of local users motivated by their own interests and profit, and the lack of understanding of coastal processes. Farallón-La Mancha is the only dune field with a local management plan, and this should be taken as a prototype for environmental education and for technical training in urgent action to promote community plans for the other dune fields. This diagnosis for the dune fields of Veracruz can be used as a comparative standard by other countries to analyze their situation and adopt measures to cope with the effects of the present SLR on their overexploited coastal resources.

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