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Land use changes and sea level rise may induce a "coastal squeeze" on the coasts of Veracruz, Mexico

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ABSTRACT

"Coastal squeeze" refers to the process in which coastal ecosystems are threatened by the combination of sea level rise (SLR) and the presence of a physical barrier, such as human infrastructure. This situation prevents the landward migration of ecosystems and species, as the coastline moves inland, and they are thus exposed to local extinction. Our objective was to explore coastal squeeze in the state of Veracruz, Mexico, through the study of urban expansion on the coast, an analysis of coastline geodynamics, and a projection of the potential effect of SLR on the distribution of two focal plant species which are endemic to the coastal dunes of Mexico. Urbanization of the coast, parallel to the shoreline, has been taking place increasingly rapidly, displacing ecosystems, both natural (mangroves, beaches and coastal dunes) and transformed (cultivated fields and pastures). Taking into consideration the geodynamic trends of the coastline and an analysis of its historical evolution, it can be seen that the coastal strip is eroding at rates that vary from slow to very rapid. Finally, the results of ecological niche modeling indicate that, under scenarios of SLR, the potential distribution of the two focal species would diminish: *Chamaecrista chamaecristoides* by 6–28%, and *Palafoxia lindenii* by 2–15%. These results indicate that "coastal squeeze" is likely in the study area, and that measures to limit or mitigate this process are required. Such measures could include urbanization programs which limit development to appropriate zones, the restoration and rehabilitation of deteriorated ecosystems and the conservation of those ecosystems which are still healthy.

1. Introduction

It has been estimated that around 41% of the world's population live within 100 km of the coast and that 10% are concentrated in a very narrow strip, which is only 10 m.a.s.l. (McGranahan et al., 2007). Human encroachment on coastlines throughout the world has become increasingly intense and extensive (Nordstrom, 2008; Martínez et al., 2013). In many cases, the degradation and loss of coastal ecosystems is a consequence of both local and distant factors. Local activities, such as land use change, waste disposal, agriculture, mining and even military activities have an immediate effect on the coast. Modifications to fluvial regimes, by the construction of inland dams or irrigation schemes and forest clearance, can alter sediment budgets, which eventually has consequences on the coast. Similarly, pollutants released in the water basin can cause serious environmental degradation on the coast, over time. These actions, which may take place far from the coast, can modify soil properties, alter natural processes, reduce topographical variability, cause fragmentation, degrade or eliminate habitats, reduce biodiversity and threaten endemic species in the littoral zone (Nordstrom, 2008; Martínez et al., 2014).

In addition to increasing human encroachment, the coasts are also vulnerable to another element of pressure: mean sea level rise (SLR), associated with climatic variability and climate change (Li et al., 2009; Mendoza-González et al., 2013), to which the effect of subsidence can be added in some cases. For almost 25 years, various authors have been predicting that SLR will increase coastal erosion (Carter, 1991; Feagin et al., 2005, 2010; Nicholls and Cazenave, 2010; Ranasinghe et al., 2012) and that, in combination with changing temperature and precipitation, the spatial distribution of the biota may be altered (Metzing and Gerlach, 2001;

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Greaver and Sternberg, 2007; Peterson et al., 2010; Ciccarelli et al., 2012; Mendoza-González et al., 2013). The expected response to coastal erosion is the landward migration of certain species in line with the new coastline, due to the shifting of wet and dry zones and the increase in saline intrusion (Greaver and Sternberg, 2007; Provoost et al., 2011). However, local extinction of the species that are less tolerant of flooding and salinity may occur, and be followed by the occupation of newly flooded zones by species that are characteristic of these environments (Greaver and Sternberg, 2007).

One factor that limits the possible landward migration of species and coastal ecosystems is the existence of rigid barriers in the continental coastal zone, which block migration. This produces "coastal squeeze", which is defined as "the loss of coastal habitats, where the high water mark is fixed by a hard structure (sea wall, or a city) while the low water mark migrates landwards in response to SLR" (Doody, 2004; Schleupner, 2008; Comin et al., 2010; Pontee, 2013). The term "coastal squeeze" was originally employed to describe conditions in salt marshes and estuaries (Nicholls, 2004; Schleupner, 2008; Doody, 2013; Torio and Chmura, 2013), but it also occurs on rocky coastlines (Jackson and Mcvenny, 2011) and on beaches and coastal dunes (Schleupner, 2008; Mendoza-González et al., 2013). The problem can be further exacerbated when poorly designed coastal protection structures create a static or erosive coastline (Comin et al., 2010).

Mexico is no exception to these worldwide trends: nearly 30% of the population lives within 100 km of the coast (Martínez et al., 2007). Here, coastal squeeze is a growing reality on large parts of the coastline, where the impact of human activities has increased, causing a transformation of the landscape and possible scenarios of SLR. Coastal squeeze has important ecological, economic and social impacts. Furthermore, damage to coastal ecosystems reduces their ability to protect the coast against extraordinary events such as storms and hurricanes (Costanza et al., 2008).

One of the states of Mexico with an increasing risk of coastal squeeze is Veracruz, located in the central region of the Gulf of Mexico. The coast of Veracruz (745 km long) is of great ecological, social and economic importance at local, regional and national level. Veracruz state has one of the largest areas of sand dunes in Mexico (106,600 ha), with a wide variety of different types of dune (with parabolic dunes being the most abundant types in the country) (Martínez et al., 2014). The dune systems in Veracruz are unique worldwide, since they also feature rare forms such as the "star dunes" and gegenwall dunes found in the central part of the coast of Veracruz (Hesp et al., 2011). Furthermore, the vegetation that grows on the dunes of Veracruz is one of the most diverse in the country, because of the occurrence of tropical forests on dunes (Moreno-Casasola et al., 1998; Martínez et al., 2014).

One fifth of the cities of Veracruz are coastal and 27% of the population, (about 2 million people), live less than 20 km from the coast (Mendoza-González et al., 2012). The Veracruz coastline has commercial ports of great importance at national level: Tuxpan, Veracruz and Coatzacoalcos process 24% of all the cargo that passes through Mexican ports (SCT, 2012). Moreover, 11% of national electricity generation takes place on the coasts of Veracruz, in the thermo electrical center at Tuxpan and the nuclear power station at Laguna Verde (SENER, 2014). Finally, the coast of Veracruz is a popular tourist destination, both nationally and internationally (Propin-Frejomil and Sánchez Crispín, 2007; Martínez et al., 2014). Over the last 30 years, these human activities have brought about rapid changes in land use, with a 36% reduction in the original forest cover and intense soil erosion (SEFIPLAN, 2005). Added to this, the National Institute of Ecology and Climate Change has predicted that most of the coastal zone of Veracruz is at risk from sea level rise. http://www2.inecc.gob.mx/cclimatico/edo_sector/estados/veracruz.html.

Considering the importance of the Veracruz coast, the growing human pressure and the predictions of SLR, it is important to determine the risks and probability of coastal squeeze to which this coastline is exposed. This will enable the proposal of preventative and remedial measures. The objective of this study is, therefore, to explore coastal squeeze on the coastline of Veracruz. Based on pre-existing information, patterns of land use change and urban expansion on the coast were studied, coastline geodynamics were analyzed and the potential effect of SLR on the distribution of two focal plant species that are endemic to the coastal dunes of Mexico was projected. From the results obtained, we identified areas with a high risk of erosion and species extinction as well as zones that could function as refuges for biodiversity and where conservation should be a priority. From these exercises, various proposals are outlined for the protection and restoration of the beach and dune ecosystems at risk, which protect human settlements and infrastructure.

2. Methods

2.1. Land use change

Land use changes were examined in three areas with contrasting tourist activities and different patterns of urban growth; Boca del Río, Chachalacas and Costa Esmeralda. The area studied in the three sites is similar and the three share a warm humid climate, with annual precipitation that ranges from 1018 mm in Chachalacas to 1694 mm in Boca del Río. The urban, demographic and economic characteristics of the three sites are different however (Table 1): Boca del Río is the most urbanized site, while Chachalacas has the least area covered by urban infrastructure.

High-resolution aerial images from 1995 and 2006 were used to elaborate land use polygons in order to analyze changes that have taken place. ArcView 3.2 was used to digitalize the land use and this was then verified in the field. The area analyzed in each case extended from the coastline to 2.5 km inland. Finally, transition matrices of the land use changes were calculated.

2.2. Sea level rise

It has been predicted that SLR will potentially take place 2–4 times more rapidly than the increment observed in the past

Table 1
Social and economic characteristics of Boca del Rio, Chachalacas and Costa Esmeralda in Veracruz, Mexico.

Site of study	Municipality	Surface (ha)	Urbanization	Predominant economic activities	Population (inhabitants)
Boca del Río	Boca del Río	2290	Intense: mostly urban infrastructure	Tourism and commerce	141,906
Chachalacas	Úrsulo Galván	2630	Low: Suburban infrastructure	Agriculture, Livestock production, fishery, tourism, commerce	26,909
Costa Esmeralda	Tecolutla, San Rafael, Nautla	3060	Medium: Sparse urbanization	Agriculture, Livestock production, fishery, commerce, tourism	25,680

Data from INEGI (2007).