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Exploring the co-occurrence between coastal squeeze and coastal tourism in a changing climate and its consequences

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ABSTRACT

"Coastal squeeze" occurs when there is a chronic loss of coastal habitats landward associated with long-term processes such as sea level rise, land subsidence, sediment deficit and the occupation of space by infrastructure. This phenomenon may also affect socioeconomic activities such as tourism. The goal of this study was to explore the co-occurrence of tourism with coastal squeeze and flooding along the coasts of the Mexican Gulf of Mexico and Mexican Caribbean. Our results reveal that thirty percent of the tourist destinations are exposed to flooding; 62% of the total study area had a moderate to severe degree of coastal squeeze and 66% of the hotels are in squeezed beaches. Finally, we found that most tourist destinations undergoing coastal squeeze are in flood-prone sites, placing communities in high-risk conditions. Different alternatives (such as ecosystem-based protection) to overcome this problem are discussed.

1. Introduction

Coastal areas are particularly vulnerable to relative sea level rises and changes in wind and wave climates, associated with multiple unpredictable factors, such as changes in hydrodynamics (i.e., storm surge and littoral currents), land subsidence and sand transport patterns. The vulnerability of coasts is exacerbated by the accumulation of multiple stressors, such as increasing human population, urbanization, sea level rise and storminess as well as the "rigidization" of the coast (Nicholls, 2007, p. 33; Williams, Rangel-Buitrago, Pranzini, & Anfuso, 2017). These stressors contribute to a phenomenon recognized as coastal squeeze (Doody, 2013), which is defined as "*one form of coastal habitat loss, where intertidal habitat is lost due to the high water mark being fixed by a defence or structure (i.e. the high water mark residing against a hard structure such as a sea wall) and the low water mark migrating landwards in response to SLR*" (Pontee, 2013). This process is exacerbated "in areas where land claim or coastal defense has created a static, artificial margin between land and sea, or where the land rises relative to the coastal plain, and habitats become squeezed into a narrowing zone" between the ocean (with an increasing level) and inland obstruction (Doody, 2013). The presence of artificial barriers can also alter the hydro-sedimentary dynamics (Williams, Rangel-Buitrago, Pranzini, & Anfuso, 2017) and the high-water mark of a coastal ecosystem and thus lessen the capacity of coastal ecosystems to respond to disturbances by preventing them from migrating inland (Pontee, 2013). Under this scenario, it is expected that coastal squeeze will increasingly affect natural ecosystems and relevant socioeconomic activities such as tourism.

In 2016, the global tourism industry employed 10% of the world's workforce, providing jobs for 292 million people (WWTC, 2017a). The direct contribution of travel and tourism to global GDP was 10.2% (US $7.6 trillion) in 2016, and it is projected to reach 11.4% of global GDP by 2027 (WWTC, 2017a). Coastal tourism is one of the largest segments of the tourism industry and the fastest growing in terms of job opportunities and economic importance (Papageorgiou, 2016). Coastal tourism is a source of revenue in many megadiverse tropical and mild weather countries. Here, an enormous variety of habitats are found within a relatively small area, and warm weather provides desirable conditions for tourists seeking leisure or outdoor recreational activities, such as sunbathing, diving, kayaking and surfing (Moreno & Becken, 2009).

Since the 1950's the Mexican tourism industry has grown to become a significant economic force, especially in the last 20 years. In 2016, this sector contributed 8.5% to Mexico's GDP, which is double the

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OECD average (OECD, 2017) and it is expected to be 17.2% of the GDP by 2027. The contribution of tourism to the GDP grew by 80% from 1995 to 2014 while the overall economy has grown by 72% (WTTC, 2017b). Comparatively, the contribution of tourism to the GDP is twice that of the automotive manufacturing sector and agricultural activities (WWTC, 2017b).

More than 35 million international tourists arrived in Mexico in 2016 (OECD, 2017). Foreign tourists mainly visit sun-sea-sand destinations where coastal resorts and other facilities are highly concentrated (e.g., Cancun, the Riviera Maya and Los Cabos). While cruise passengers are not counted in international tourist arrival data, they are another important source of visitors. For example, four Caribbean destinations received over two million passengers from 2014 to 2015. The Bahamas, in first place with 3.5 million visitors, followed by Cozumel (2.97 million), St. Maarten (2.05 million) and the U.S. Virgin Islands (2.04 million) (FCCA, 2015, p. 95).

Indeed, sun and beach tourism activities have an enormous economic potential. The expansion of this sector is a very relevant economic strategy for many coastal areas. It has triggered a substantial migration toward the coast, with a concomitant increase in the development of littoral regions, through urban and industrial growth and accompanying recreational and transportation facilities (Onofri & Nunes, 2013). However, negative consequences may also be associated with the economic expansion and development of coastal areas. The operation of cruise-ships and hotels, as well as the construction of roads and other supporting infrastructure, frequently generates pollution, destroys and degrades habitats, alters biodiversity and introduces invasive species (Blackman, Naranjo, Robalino, Alpízar, & Rivera, 2014). In turn, as coastal environments are degraded, the recreational experience of tourists is adversely affected. Coastal development and changes to the environment can be counterproductive for tourism (Chen & Bau, 2016; Semeoshenkova, Newton, Contin, & Greggio, 2017), as tourists often seek pristine environments where the aesthetic aspects are undamaged by excessive touristic development.

Given current and future scenarios of climate change and the ongoing modification of coastal ecosystems (urbanization), coastal squeeze is of growing concern, especially considering the predictions of sea-level rise and increased storminess which will exacerbate flooding in coastal areas owing to both SLR and increased storminess (Gopalakrishnan et al., 2013; Webster, Forbes, MacKinnon, & Roberts, 2006). The future of coastal tourism is therefore at risk from increasing coastal squeeze, environmental degradation, erosion and marine inundation related to extreme weather events (Rulleau & Rey-Valette, 2017), and Mexico is no exception of this (Fig. 1). In the present study, we explored the co-occurrence between coastal squeeze and tourism on the Mexican Gulf of Mexico and Mexican Caribbean. Our goal was to identify the places where tourism activities are highest and that are also highly exposed to flooding and coastal squeeze. This is necessary to look for alternatives that can help reverse this trend. To achieve this, we first analyzed the spatial patterns of urban development in areas with coastal tourism along the Gulf of Mexico and the Caribbean coasts. Then, we assessed the risks of coastal squeeze and coastal flooding. Finally, with this set of observations, recommendations for coastal tourism management were made, in which we considered coastal squeeze and flooding combined.

2. Methods

2.1. Study site

The present study focused on the coasts of the Gulf of Mexico, in the Mexican states of Tamaulipas, Veracruz, Tabasco, Campeche, and Yucatan and the Mexican Caribbean Sea in the state of Quintana Roo (Fig. 2). The Mexican Gulf and Caribbean coasts are micro tidal; with ranges of less than 0.62 m, and wave processes are the primary agents of morphodynamic changes and sediment transport (Silva et al., 2008). The climate is semiarid in the northern state of Tamaulipas and humid subtropical in the other five states.

Historically, the coastal and marine ecosystems on the Gulf of Mexico and the Caribbean have had high ecological and socioeconomic value. The biological diversity along these coasts is high, and a rich array of ecosystems are present, including mangroves, wetlands, seagrass beds, coral reefs, coastal lagoons, coastal dunes, sandy and rocky beaches (Martínez et al., 2017; Silva et al., 2014). Human activities such as commercial trade and fishing have taken place along these coasts for centuries (Martínez et al., 2017; Propín-Frejomil & Sánchez-Crispín, 2007). In many cases, tourism activities have led to the loss or degradation of natural ecosystems, negatively affecting the provision of ecosystem services, such as scenic beauty, recreation and shoreline protection (Everard, Jones, & Watts, 2010).

2.2. Procedure

We assessed the co-occurrence of coastal tourism and coastal squeeze as follows (Fig. 3). First, we located all the tourist destinations in the study area and assessed the intensity of tourism activities in terms of infrastructure (hotels). This was a proxy of urbanization. Second, coastal squeeze was assessed by using intersections among the cartographic representations of three parameters: the need for ecosystems to migrate inland, the actual possibility of inland migration and the long-term coastal sustainability of urban development in terms of flood risk (Table 1). The calculations for all the variables are described below.

2.2.1. Tourism intensity

Tourist sites on a 10-km-wide coastal belt were geo-localized for each state. Five categories were selected for each littoral cell (Table 1), from no tourism to high intensity tourism. A low number of hotels does not necessarily reflect a low capacity of tourist accommodation or low tourism pressure because a single hotel may have many rooms. So, the number of hotel rooms was also considered, as massive all-inclusive resorts have proliferated along the Mexican Caribbean coast. Thus, a new data layer from the National Institute of Statistics and Geography (INEGI) showing the number of rooms per location was overlaid on the tourism destinations studied. Those sites labeled as low tourism (with a reduced number of hotels) but with more than one thousand rooms were re-labeled as medium intensity category.

2.2.2. Coastal squeeze

Coastal squeeze was determined with a GIS-based model. Three parameters reflecting the probability of coastal squeeze were selected: the need for ecosystems to migrate inland, the actual possibility of inland migration, and the long-term coastal sustainability (flood risk) (Table 1).

a) Need to migrate

The need of ecosystems to migrate inland depends on different local attributes of the coast: a decreased resistance to disturbance owing to fragmentation; a decreased resilience, which is indirectly determined by an erosion threshold, and the capacity of protection provided by natural ecosystems. It was calculated based on the estimated impact of disturbance variables (flood risk, erosion, and storms) that could force ecosystems to migrate inland. When assessing the need to migrate we considered coastal resistance and resilience as follows.

Decreased resistance- Resistance was considered as the capacity of an ecosystem to deal with perturbations (remain unchanged) and was determined according to the geological and ecological attributes of coastal ecosystems (Liquete et al., 2013). Coastal resistance was considered as a measure of the state of conservation of an ecosystem, assuming that a decline in vegetation cover can affect the capacity to trap sediments and increase sand erosion (Pontee, 2013). Fragmentation was therefore considered to reflect a decrease in ecosystem resistance.

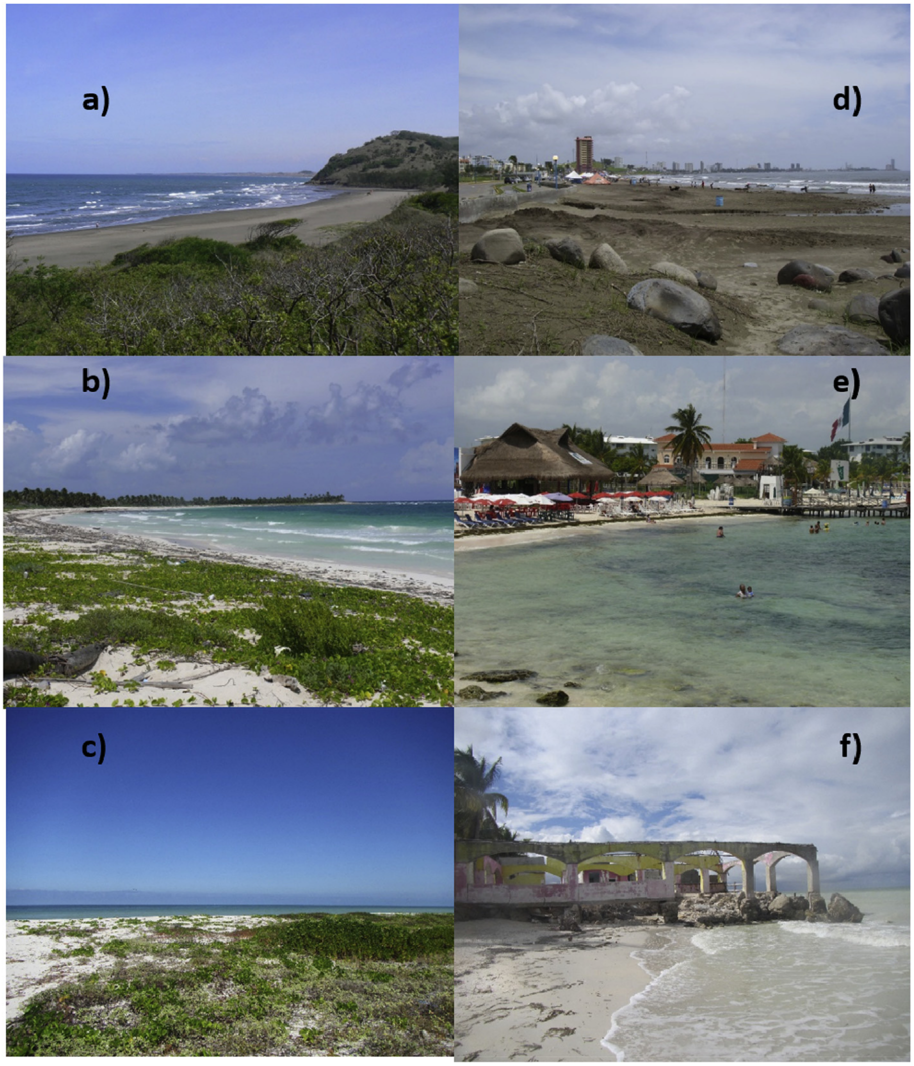

Fig. 1. Examples of coasts on the Mexican Gulf of Mexico and the Mexican Caribbean, showing natural dynamics (left hand column) and coastal squeeze (right hand column). a) Central Veracruz state; b) Quintana Roo; c) Campeche; d) Port of Veracruz (Veracruz); e) Cancún (Quintana Roo); f) Payucan (Campeche). (Pictures credits: Veracruz and Quintana Roo, M.L. Martínez; Campeche, D. Ramírez).

Maps of the occurrence and degree of perturbation of mangrove and coastal dune ecosystems from previous works were considered (CONABIO 2016; Martínez et al., 2014b, p. 350). Both diagnostics were national maps produced using high-resolution remote sensing data, field work and aerial photographs. We focused on coastal ecosystems (mangroves and coastal dunes) and created maps with their conservation status, based on information previously generated, as explained below.

2.2.3. *Mangrove perturbation*

In the Mexican Atlas of mangroves (CONABIO, 2016) it is estimated that this ecosystem covers a total area of 770,057 ha, in a 1:50,000 scale. The perturbation map of the Atlas was produced mainly from multispectral images of the SPOT-5 satellite (10 m spatial resolution) from 2015. Then, digital elevation models (2015), vegetation indexes and field data were used to classify the images. Finally, the map was validated through an extensive field campaign and helicopter overflights by the Secretary of Mexican Marine Defense, always accompanied by experts on mangrove vegetation. The country was divided in five regions (Gulf of Mexico, Yucatan Peninsula, Northern Pacific, Central Pacific and South Pacific) and nine classes (anthropic development, crop and animal husbandry, other vegetation types, unvegetated, mangrove, disturbed mangrove, other wetlands, water bodies, other). To achieve the goals of this study, two regions were selected (Gulf of Mexico and Yucatan Peninsula) and two land use classes (mangrove and perturbed mangrove). The layer of perturbed mangrove was overlapped with a map of infrastructure. The final three classes ranged from conserved mangroves to highly perturbed areas (Table 1).

2.2.4. *Coastal dunes perturbation*

Martínez et al. (2014b) performed a national diagnostic of Mexican coastal dunes. Google Earth images were used to digitalize and classify coastal dunes. First, the authors regionalized Mexican coasts into five areas (North Pacific, Gulf of California, South Pacific, Gulf of Mexico and Yucatan Peninsula). Then, coastal dune systems were digitized, and the conservation status of each system was determined according to land use, inhabited areas (from villages to cities), density of roads and highways, as well as all the elements that may cause dune fragmentation (a description of the five levels of conservation status is shown in Table 1).

Decreased resilience**.** In this study, resilience was defined as the capacity of ecosystems to respond to disturbances and retain the essential structures, processes, and feedbacks (Martínez et al., 2017). When ecosystems are resilient, the adaptive capacity of society to the increasing risk from natural hazards is increased (Jones, Hole, &

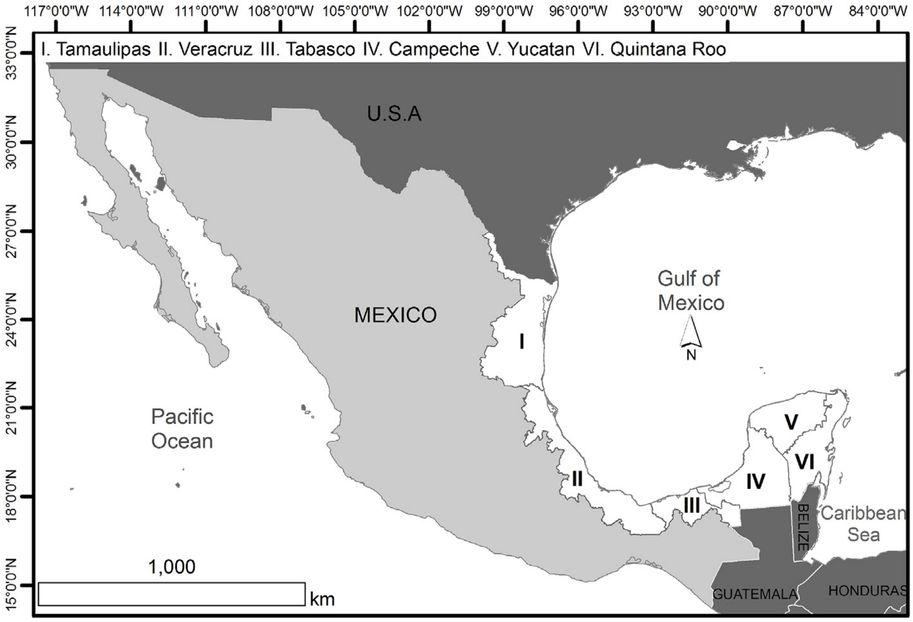

Fig. 2. Mexican Gulf and Caribbean coasts, showing the six states analyzed.

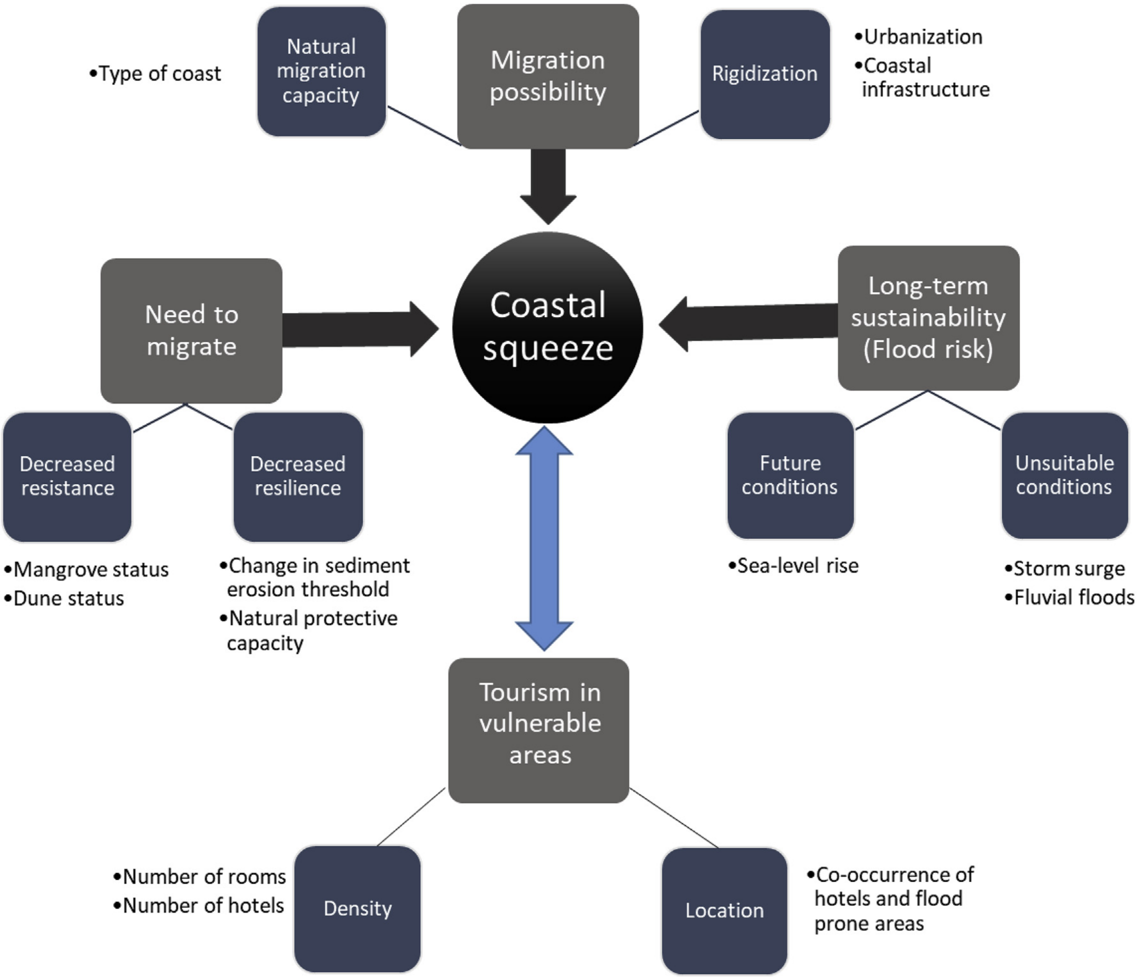

Fig. 3. Flow-diagram showing the variables used to assess the co-occurrence of coastal tourism and coastal squeeze.

Zavaleta, 2012; Reid, 2016). Because sediment dynamics play a key role in the natural dynamics of coastal ecosystems, we measured resilience in terms of changes in the sediment erosion threshold, based on previous studies.

Table 1
Summary of the variables used to estimate coastal squeeze. The variables were collected from secondary and/or primary data sources.

	Variable			Rank (1–5)
Tourism	Tourism intensity Occupation intensity (Image analysis; INEGI, 2015; National Atlas of Tourism, 2016)			1) No hotels; possible camping areas with no facilities; 2) 1–50 hotels, less than1000 rooms in the coastal area of the municipality; 3) 51–150 hotels or more than 1000 rooms in the coastal area of the municipality; 4) 151–700 hotels in the coastal area of the municipality; 5) More than 700 hotels in the coastal area of the municipality
Migration necessity (Need to migrate	Decreased resistance	Level of perturbation of dunes Martínez et al. (2014b),		1) Minimal human intervention; 2) Dunes crossed by roads or small localities built on fixed dunes; 3) Fragmented by highways, occupied by agriculture or cattle ranching; 4) Medium sized urban areas growing on the dunes; 5) Urbanized dunes or massive infrastructure
		Level of perturbation of mangroves CONABIO (2016)		1) Arboreal vegetation having one or more species of mangrove; 3) Patches of regenerating mangrove or infrastructure interrupting hydro-sedimentary dynamics; 5) Areas previously of mangrove and patches of perturbed or dead mangrove
	Decreased Resilience	Change in sediment erosion threshold (Silva et al., 2014)		1) Stable or very slow changes; 3) Slowly erosive or slowly prograding; 5) Very erosive or rapidly prograding
		Natural protective capacity	Geomorphology Liquete, Zulian, Delgado, Stips, and Maes (2013)	1) Hard-rock cliff; 2) Soft-rock cliff; 3) Low cliff or mixed coast; 4) Estuary, lagoon or alluvial plain; 5) Beach, barrier, tidal flat, delta
			Habitat resistance Silva et al. (2014)	1) Mangrove; 2) Secondary dunes; 3) Primary dunes; 4) Reefs and seagrasses; 5) No natural elements
Migration possibility	Natural migration capacity	Type of coast Silva et al. (2011)		1) Accumulative; 3) Stable; 5) Erosive
	Rigidization	Urbanization intensity (rural/moderate/urban), area (km^2), settlements over coastal dunes (yes/no) (INEGI, 2015)		1) No invasion of dunes; 2) Rural areas on fixed dunes or towns behind fixed dunes; 3) Rural areas on mobile dunes or towns growing on dunes; 4) Towns on dunes or urban areas growing on dunes; 5) Urban areas on dunes
		Density of coastal infrastructure per sediment cell (Image analysis, classification from Pranzini, Wetzel, and Williams (2015)		1) No infrastructure or small roads; 2) Roads and breakwaters without evidence of erosion; 3) Highways, breakwaters with sediment dynamics modification; 4) Small ports or groins; 5) Commercial or touristic ports
Long-term sustainability	Future conditions: SLR vulnerability SLR vulnerability for low lying coasts, area affected by SLR scenario of 1 m (Ortiz-Pérez & Méndez-Linares, 2004)			1) Areas over 1 m.a.s.l. or not identified as vulnerable to 1 m SLR; 5) low-lying areas vulnerable to 1 m SLR
	Unsuitable conditions: Flood vulnerability type (coastal/fluvial); occurrence (yes/no) of flood-prone areas and flat areas where floods have been recorded historically (Ortiz-Pérez & Méndez-Linares, 2004)			1) Coastal areas with no evidence of flooding; 3) Fluvial or coastal flooding; 5) Fluvial and coastal flooding

Note: 1) Very low, 2) Low, 3) Medium, 4) High; 5) Very High.

2.2.5. Changes in sediment erosion threshold

This variable refers to changes in sediment erosion threshold owing to the impact of badly-planned infrastructure on the natural hydrosedimentary dynamics of the coast. Ortiz-Pérez and Méndez-Linares (2004) used multi-temporal information from satellite images (LIDAR 1986 to 2013) and field verification to classify Mexican coasts according to their geodynamic behavior and vulnerability to erosion. The authors defined the instability tendency of the Mexican coastline as a function of internal geodynamic processes (tectonic characteristics, vertical movements of ground) and external geodynamic processes (hydrological and hydrographic characteristics of the fluvial and estuarine network). Then, Ortiz-Pérez and Méndez-Linares (2004) proposed a classification of the Mexican coasts as follows: erosive, mixed or accumulative. That classification was modified by Silva et al. (2014), who added further external geodynamic processes (wave height, period, extreme wave heights, grain size, sediment supply, bathymetry), anthropogenic actions (hydrosedimentary interruption), the interactions among these factors and their relationship with erosion trends and velocity. Silva et al. (2014) used aerial photographs (from 1975 to 2014) to analyze historical coastline position, satellite images to identify hydrosedimentary interruptions, mathematic models to describe national wave climate and field work to validate the information. The new coastal geodynamic classification of Mexico (Silva et al., 2014) includes the velocity of coastal changes and considers five categories in response to natural and artificial drivers: slowly prograding, rapidly prograding, stable, slowly erosive, and very erosive (Table 1). We thus used the velocity of coastal changes (slow, none, fast) as a measure of resilience: faster changes were assumed to represent a reduced resilience. Obviously, when shoreline evolution is negative (erosion), it is hazardous for human infrastructure.

2.2.6. Natural protective capacity

Natural coastal ecosystems attenuate waves in normal conditions and during storm events, reduce storm surge waves and promote sediment deposition and retention. In consequence, coastal ecosystems help to protect the coasts from flooding and erosion. The effectiveness of such protection depends on coastal geomorphology and the type of ecosystem (depending on physical attributes such as the surface roughness or the frictional resistance, related with the degree of conservation, the size of the ecosystem, the vegetation density and stiffness).

Coastal geomorphology: The occurrence of erosion and flooding largely depends on coastal geomorphology. This information was gathered from topographic and geological maps by Silva et al. (2014). The natural protective capacity of each geomorphological type found on the coast was classified following Liquete et al. (2013) which was modified to better fit our study sites (Table 1).

Coastal habitat resistance: This variable reflects the physical resistance of each coastal ecosystem to any potential environmental change in sediment or wave energy dynamics (e.g. waves during actual and future storm events) attributed to its ecological attributes. We classified the Coastal habitat resistance according to the frequency and level of exposure to energy (wave and flooding) under prevailing and extreme conditions. In addition, the condition of the fragility of each ecosystem was considered to generate the ranking in resistance (Table 1).

b) Migration possibility

Migration possibility was assessed based on the premise that coastal ecosystems can migrate inland when they are well preserved and functional, and there are no physical obstacles (natural or human-induced) that interrupt such processes. In consequence, we considered that the inland migration of an ecosystem depends on the type of coast (with cliffs totally blocking any inland migration) and is negatively affected by coastal infrastructure and urban growth. Therefore, the variables used for this assessment included type of coastline (see Table 1) (Silva et al., 2011) and the occurrence of rigid barriers that could either directly block migration or disrupt hydro-sedimentary dynamics and increase erosion (Rangel-Buitrago, Williams, & Anfuso, 2018).

Type of coast was used as a proxy of migration capacity based on the theory of environmental filtering, which states that environmental stress factors (sand movement, soil salinity, etc.) are filters that determine the presence of tolerant or non-tolerant species in a specific site, given the predominant environmental conditions. These species are gathered, according to their tolerances, into functional traits that are useful to predict community behavior and possible responses to changes (Gallego-Fernández & Martínez, 2011). It was thus assumed that plants growing on naturally erosive beaches are usually adapted to salinity and burial by sand and can even be dispersed by sea-water. Hence, it is expected that these plants will have a high natural capacity for landward migration as the salinity increases inland owing to SLR. In turn, when the beach is eroding artificially and rapidly, non-tolerant and mainly inland species are present, and the possibility of migration is reduced.

For each sedimentary cell, and from the shoreline up to 100 m inland, image analyses using Arc Map 10.2 was used to map the occurrence of coastal infrastructure (rigid barriers, perpendicular to the shoreline or located on the waterfront), considering their spatial location, number, and type (breakwaters, groins, and ports). Finally, the degree of rigidity of each sedimentary cell was estimated by combining the type of coast and the occurrence of coastal infrastructure on the beach, on top of, or behind the dune systems, according to Pranzini et al. (2015).

c) Long-term sustainability (Flood risk and SLR)

The long-term sustainability of a coastal site is largely affected by sea level rise and flood risk (caused by heavy rains and storm surges). The location of such flood-prone areas was based on previous work by Ortiz-Pérez and Méndez-Linares (2004), who performed a geomorphological analysis of the Mexican coasts. First, they divided the coasts of Mexico into geomorphic units, and then they performed a coastal zonation with aerial imagery (1943, 1975, 1986 and 1997), a videography, ~1 m ground resolution (1997), and topographic maps (1: 10,000) from the National Institute of Statistics and Geography (INEGI) and terrain data from ground surveys. The zoning was based on variables that considered internal geodynamic processes (tectonics and subsidence; local subsidence), external geodynamic processes (historical shoreline variations), hydrometeorological factors (mean significant wave height), and vegetation zones. The authors assumed that belts of different vegetation types (e.g. herbaceous wetland, mangrove, etc.) result from differences in flooding tolerance and hence, flood permanence. Maps showing the vulnerability to fluvial and coastal flooding were generated by combining the above-mentioned geomorphological zoning with slope, elevation and historical flooding events (by storm surges and surface runoff). The flood vulnerability was completed by including low-lying lands that are normally dry, but which had been flooded in the past by either seawater or surface runoff. Finally, we uploaded all the information in a GIS-based model with which the map of potentially inundated areas exposed to 1 m of SLR was generated. To achieve this, we combined the coastal zoning of flood-prone areas with a Digital Elevation Model (DEM) following the same methods as Villatoro et al. (2014). The coastal flooding map that we used combined both sea level rise and flood risk (caused by heavy rains and storm surges).

To characterize the probability of flooding by storm surge for the states of Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan and Quintana Roo, Arriaga, Durán, Posada, Silva, and de Brye (2010), used the hybrid model Mato-HURAC (Posada, Silva, & de Brye, 2008) and the database of the Atlantic Mexican Atlas of maritime climate (Silva et al., 2008) modeled numerically the 117 hurricanes that arrived at the Mexican coasts between 1949 and 2009.

Following Villatoro et al. (2014), for all the entire Mexican Atlantic coast we obtained the maximum storm surge per year. Flood-prone areas were delineated based on estimated storm surge and using the same method Villatoro et al. (2014) used in which the authors explored the vulnerability to flooding and erosion using a range of variables (topography, bathymetry, climate) in the model projections and risk analysis tools. The data thus obtained was ordered annually from highest to lowest and a Weibull type probability adjustment was used. For the present study, the data corresponding to a storm surge with a 100-year probability of occurrence were used.

2.3. *Calculating coastal squeeze: criteria followed for normalization and aggregation of variables*

The analysis of the indicators to be included in the coastal squeeze index depend on the data resolution availability and the spatial operations rely on the nature of the data. The spatial analysis to extract each indicator included the homogenization of geographic projection in each dataset, the transformation of raster information to polygons and the intersection of those polygons with each littoral cell polygon. Hence, a single value, per indicator per littoral cell, was obtained. Then, for each littoral cell, the score of each variable described in Table 1 was normalized by using the max-min method, as shown in Equation (1).

$$Standarized\ variable\ score\ = \frac{actual\ value - minumum\ value}{maximum\ value - minimum\ value} \tag{1}$$

These normalized indicators were aggregated within each criterion (*i.e.* importance of tourism, need to migrate, migration possibility and long-term sustainability) using arithmetic means (Eq. (2)).

$$Criterion\ x = \frac{1}{n}\sum_{i=1}^{n} f_i \tag{2}$$

Then, the four criteria scores were aggregated into the coastal squeeze index (*i.e.* across criteria) with a geometric mean (Eq. (3)).

$$Coastal\ Squeeze\ = \sqrt[4]{\alpha\cdot\beta\cdot\gamma\cdot\delta} \tag{3}$$

where Tourism Importance (α); Need to Migrate (β); Migration Possibility (γ) and Long-term Sustainability (δ) are the four criteria calculated by the aggregation of the standardized values for the variables listed in Table 1, namely: Occupation intensity (a_1); Resistance (b_1); Resilience (b_2); Natural migration (c_1); Rigidization (c_2); Future conditions (d_1) and; Unsuitable conditions (d_2).

$$Coastal\ Squeeze\ = \left(\frac{a_1}{1}\right)^{\frac{1}{4}}\cdot\left(\frac{b_1+b_2}{2}\right)^{\frac{1}{4}}\cdot\left(\frac{c_1+c_2}{2}\right)^{\frac{1}{4}}\cdot\left(\frac{d_1+d_2}{2}\right)^{\frac{1}{4}}$$

Finally, coastal squeeze values were normalized into a zero – one range, with the higher scores representing more intense coastal squeeze.

3. Results

3.1. *Tourism intensity*

Our results show that the Mexican coastal states that we studied are very heterogeneous. Tamaulipas has the largest surface, but the coastal zone area is greater in Veracruz (Table 1). Quintana Roo and Veracruz are the most important states in terms of tourism, and, together, they account for more than 80% of the hotels found in the study area. Veracruz is the state with the largest number of hotels located on the coast, but the largest number of hotel rooms was found along the coasts of Quintana Roo (Table 2); almost twice as many as in Veracruz. In contrast, less than 1% of the hotels were located in the states of Tabasco and Yucatan (around 25 hotels in each). The number of hotels in the Caribbean (63.18%) was almost double the number in the Gulf of Mexico (36.82%).

Tourist activities were found along the entire coast of the six states but were mostly concentrated in twelve locations: eight in the Gulf of Mexico and four in the Caribbean (Fig. 4). Of these, one is in Tamaulipas (Tampico), three in Veracruz (Costa Esmeralda, Port of Veracruz and Coatzacoalcos), one in Tabasco (Ceiba), two in Yucatán (Celestún and Progreso) and three in Quintana Roo (Cancún, Cozumel and Chetumal).

3.2. *Coastal flooding*

The total area exposed to flooding by rainfall, storm surge and SLR is relatively high in Veracruz, Tabasco and Campeche (Table 2). Campeche is the state with the greatest area likely to be flooded by storm surge and SLR is, but the largest area of potential flooding was calculated for Veracruz. Because of the relative sizes of the states, Tabasco has the largest percentage of land exposed to flooding. In all cases, our estimates show that the percentage of coastal area likely to be flooded varies from 38% (Yucatán) to 94% (Tabasco). Nonetheless, it is high in all cases.

We found that 30% (8308) of tourist destinations were exposed to flooding (Fig. 5). Tabasco (in the Gulf of Mexico) and Yucatan (in the Caribbean) had the fewest hotels, yet most of these are located in areas prone to flooding. Meanwhile, 38% of the hotels in Tamaulipas, 33% in Campeche, and 27% in Veracruz are in flood-prone areas. Similarly, nearly 30% of the hotels along the Caribbean coast were in areas vulnerable to flooding.

3.3. *Tourist destinations exposed to coastal squeeze*

Sixty two percent of the total study area had a moderate or severe degree of coastal squeeze (Fig. 6), and 66% of the hotels were on squeezed beaches. On the Gulf of Mexico, the highest values of coastal squeeze were found in the cities of Veracruz, Coatzacoalcos and Campeche; on the Caribbean, the highest values were found along the Riviera Maya, on the northernmost coasts. Veracruz showed the highest contrast in coastal squeeze values: some coastal segments had a very high degree of coastal squeeze, while others experienced almost none. In turn, because floods, subsidence, and erosion affect 80% of the Tabasco coast, our results show that this state is exposed to coastal squeeze along a large portion of its coast. In the state of Campeche, approximately 50% of the coastal area had a medium to high degree of coastal squeeze; the most squeezed areas were the city of Campeche and Isla del Carmen. In both areas, more than ten coastal structures were found to be modifying the current hydro sedimentary flux of the coastline. Accordingly, 80% of the hotels in Campeche were located in areas experiencing coastal squeeze. Yucatan had the lowest proportion of areas experiencing coastal squeeze, yet all the 26 hotels along its coastline were located in areas with some level of coastal squeeze. Also, the infrastructure in Puerto Progreso has caused erosion in neighboring Campeche. Finally, 60% of the coastline of Quintana Roo was affected by a coastal squeeze. Over the last 40 years, massive tourist resorts have been built on top of dunes on the barrier island where Cancún stands, interrupting the dynamic equilibrium of the beach-dune system (Escudero, Mendoza, Silva-Casarín, & Villatoro, 2014). The negative sediment balance has led to chronic erosion problems that have been tackled by installing armoring along the coast. However, the uncoordinated measures to protect private property have triggered further armoring adjacent and downdrift of these constructions. At present, there are more than 50 coastal structures (such as breakwaters, groins, and ports) in the area but the erosion problem is still not under control. The highest degree of coastal squeeze was recorded in Cancun, where two artificial nourishment projects and the construction of breakwaters have failed to control the chronic erosion of their beaches (Escudero, Felix-Delgado, Silva, Mariño-Tapia, & Mendoza, 2018).

Table 2
Summary of hotels, rooms and flood prone areas per state, along the Gulf of Mexico and Mexican Caribbean.
Sources:Tourism: INEGI, 2015.

Variable	Tamaulipas	Veracruz	Tabasco	Campeche	Yucatán	Quinta Roo
State surface (ha)	8,024,900	7,182,000	2,473,100	5,750,700	3,952,400	3,420,500
Coastal zone [10 km wide]	474,654	682,575	188,304	391,469	335,408	653,470
# Hotels	683	1427	461	335	474	941
# Rooms	26,818	41,932	12,479	8973	12,466	90,048
# Rooms/municipalities with coastline	7739	23,554	1424	7764	1342	89,958
# Rooms/municipalities in the coastal zone	13,152	24,041	10,829	7874	1368	89,958
Coastal flooding (ha)	598,858	994,771	946,634	1,066,142	176,642	1,097,007
% Coastal area with flooding	58%	42%	94%	46%	38%	64%
Total flooding area per state (ha)	742,106	1,111,760	946,634	1,066,142	176,642	1,097,008
% State with flooding	9%	15%	38%	19%	4%	32%
Flooding 10 km inland (ha)	258,903	225,258	77,278	172,389	126,666	394,433

Flooding: Ortiz-Peréz & Méndez-Linares, 2004; Rosete, Enríquez, & Aguirre Von Wobeser, 2013.

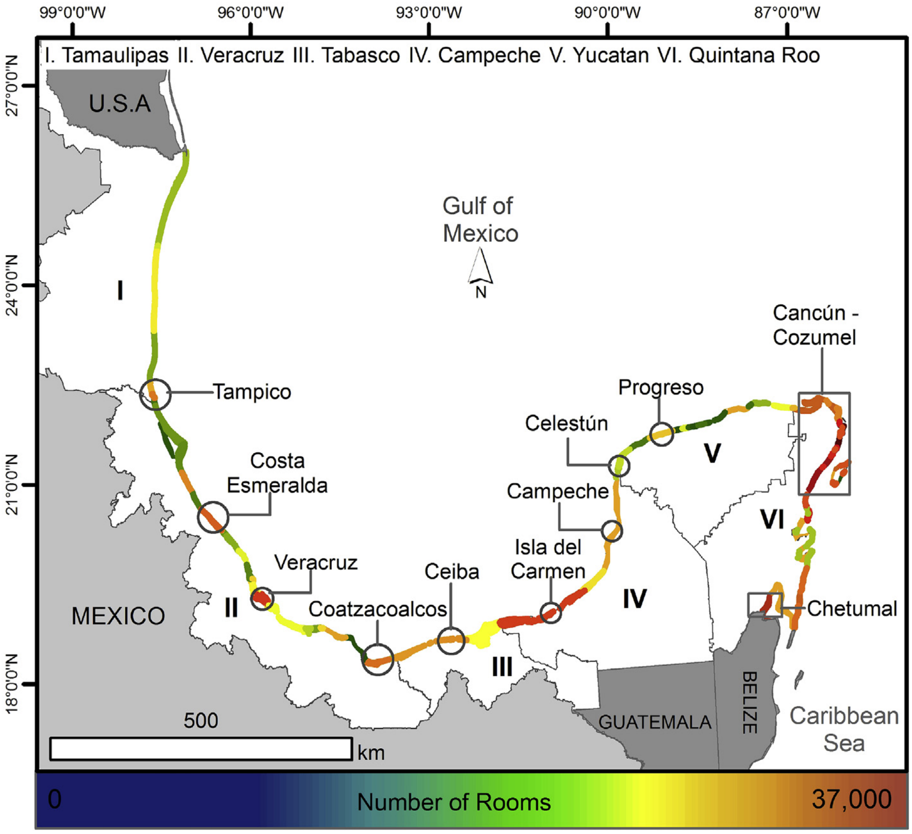

Fig. 4. Municipal tourism infrastructure along the Gulf of Mexico and Caribbean coastlines of Mexico.

3.4. *Tourist destinations in areas prone to flooding or coastal squeeze*

Most tourist destinations undergoing coastal squeeze are in areas prone to flooding (Fig. 7). Overall, less than 10% of tourist locations are in coastal areas with neither coastal squeeze nor flooding. The highest proportion of these locations (without coastal squeeze and without flooding) are in Veracruz, while the lowest proportion were found in the Cancún-Cozumel area (Riviera Maya). However, some states are more vulnerable to flooding than others. For example, in Tamaulipas, only 16% of hotels faced this situation while around 70% of the hotels in Veracruz, 89.6% in Tabasco, and 91.66% in Campeche were located in flooding prone areas.

4. Discussion

During the last decade, it has been increasingly acknowledged that beaches are trapped in a ‘coastal squeeze’, with sea level rise and increased storminess on the ocean side, and the impacts of urbanization on the terrestrial side (Schlacher et al., 2007). Thus, with growing urbanization and human-induced modifications of the coastal zone, the resilience of the beaches and the ability to change shape and extent in response to storms and sea level rise is hindered (Nordstrom, 2000). Although studies on coastal squeeze abound, they have seldom been linked to increasing coastal tourism activity.

4.1. *Tourism, flooding and coastal squeeze*

In this study we found that most tourist destinations in sites undergoing coastal squeeze were also located in areas prone to flooding. There were local variations in the intensity of this trend, but, overall, a coincidence between tourism development, coastal squeeze and flooding was observed along the coasts of the Gulf of Mexico and the

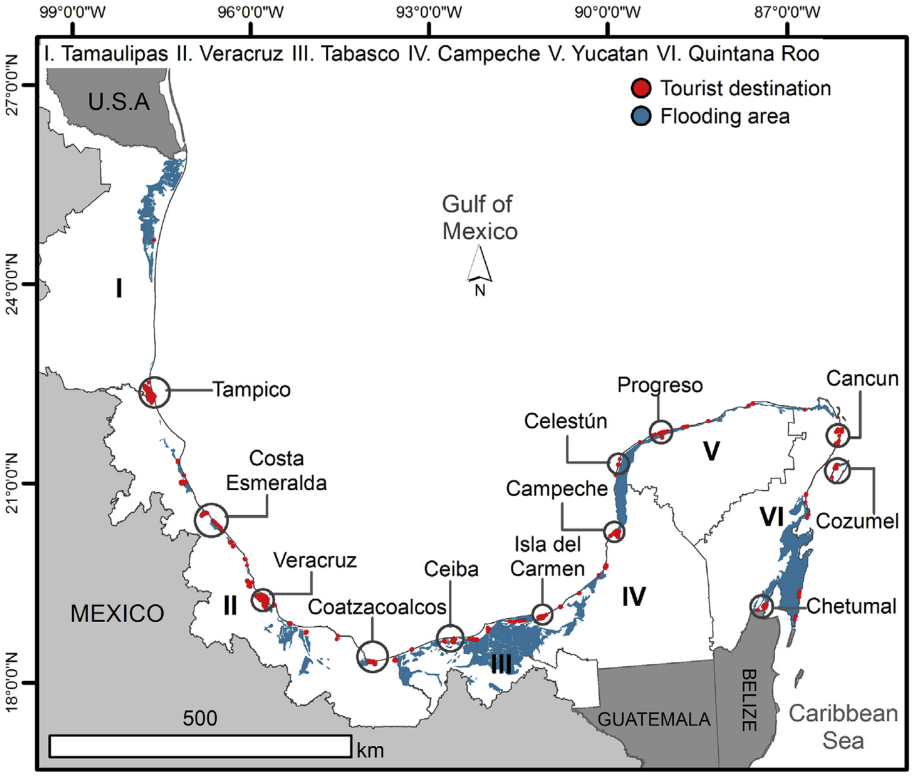

Fig. 5. Tourist destinations located in flood-prone areas along the Gulf of Mexico and Caribbean coastlines of Mexico (flooding includes SLR plus areas that are prone to flooding by storm surge and heavy rainfall, as defined by Ortiz-Pérez and Méndez-Linares., 2004 and explained in Methods).

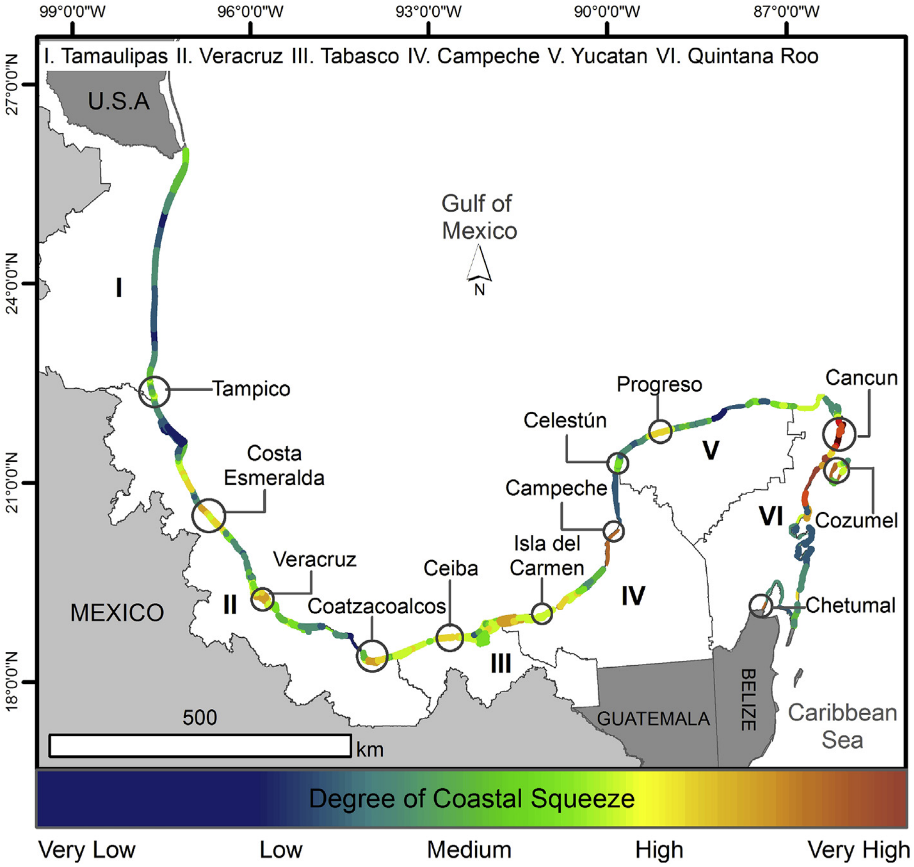

Fig. 6. Different levels of coastal squeeze along the Gulf of Mexico and Caribbean coastlines of Mexico.

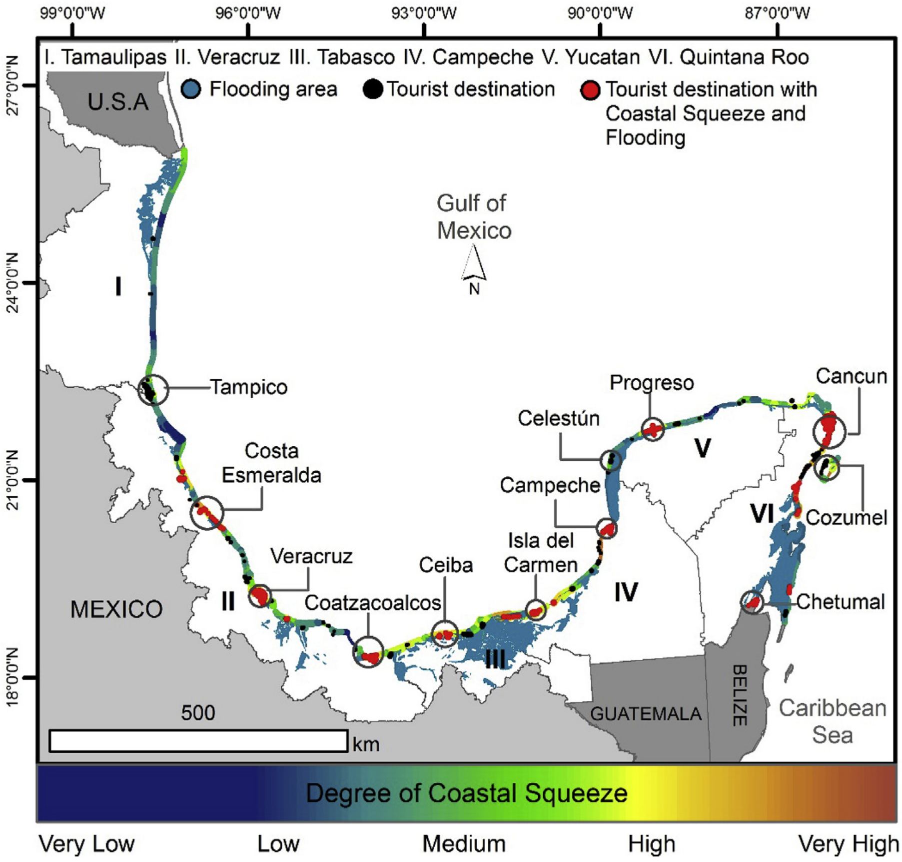

Fig. 7. Tourist destinations exposed to flooding and coastal squeeze along the Gulf of Mexico and Caribbean coastlines of Mexico.

Mexican Caribbean. Coastal squeeze results from a rigidization process owing to urban encroachment. Additionally, in the highly urbanized locations such as the port of Veracruz, Coatzacoalcos and Cancún, natural ecosystems have almost been totally eliminated, although sparse fragments of beach vegetation still remain (Lithgow, Martínez, & Gallego-Fernández, 2015). Indeed, the high proportion of hotels that coincides with coastal squeeze indicates a relationship between them, because the urbanization and rigidization of the coast can disturb sediment supply from the dunes to the beach during storms and induce shoreline erosion, as occurs in Cancun (Escudero et al., 2018; Silva et al., 2017).

Our results are similar to those of earlier studies. Do, de Vries, and Stive (2018) observed that tourist resorts built on top of the dunes have caused coastal squeeze in addition to sediment transport blockage updrift, in Cua Dai Beach, Vietnam. Similarly, Simpson (2013) found that the coastal margin habitats of the United Kingdom have declined by about 10% due to development, which includes tourism. In other areas with relevant coastal tourism activities (i.e. Jamaica, Martinique, nations of the Caribbean Community, and Spain) it has also been observed that coastal squeeze is one of the drivers causing beach erosion and this may, consequently, have a negative impact on the revenues derived from the tourist industry (McDougall, 2017; Schleupner, 2008; Scott, Simpson, & Sim, 2012; Toimil, Díaz-Simal, Losada, & Camus, 2018). Finally, in the state of Veracruz, Martínez, Mendoza-González, Silva-Casarín, and Mendoza-Baldwin (2014a) showed that urbanization and tourism development along the coasts are inducing a coastal squeeze in which native plant species are becoming locally extinct.

The likely damage to coastal communities, tourist infrastructure and transport, will result in high economic losses owing to beach erosion and damage to built infrastructure (King, McGregor, & Whittet, 2011; Stanton & Ackerman, 2007). Furthermore, the diminished attractiveness of coastal areas to tourists can be an additional side-effect of beach erosion and coastal squeeze, exacerbating losses in the tourism industry. For instance, in the coasts of the state of Veracruz, Mexico, Mendoza-González et al. (2018) found that hotel room prices increased by 8–57% depending on the ocean view and proximity to the beach, respectively. Simpson (2013) also observed that changes in the marine climate have already modified the coastal environment, which may affect the attractiveness to some tourists.

4.2. Overcoming the challenge of the coincidence of tourism and coastal squeeze

The future scenario of coastal tourism with increasing storminess, SLR, coastal squeeze and loss of natural ecosystems in the Gulf of Mexico and Caribbean (and elsewhere) could be devastating for tourism and highlights the urgency of acting promptly and effectively. Increasingly, new alternatives are necessary. For instance, ecosystem-based coastal protection has been proposed as a strategy that integrates the potential conflicts between development and conservation (Barbier et al., 2008; Duarte, Losada, Hendriks, Mazarrasa, & Marbà, 2013; McDougall, 2017; McLeod, Lubchenco, Palumbi, & Rosenberg, 2005; Temmerman et al., 2013; Salgado & Martinez, 2017), by reducing the impact of sea-level rise and erosion (i.e. coastal squeeze) (Silva, Martínez, Odériz, Mendoza, & Feagin, 2016). Thus, economic damage and casualties are reduced (Costanza et al., 2008; Pérez-Maqueo, Martínez, Sánchez-Barradas, & Kolg, 2018) through the remarkable capacity of natural ecosystems (seagrass beds and coral reefs) to generate sediments and accumulate them on the beach (coastal dunes). By these means, coastal ecosystems reduce waves and storm surges, as well as limiting erosion and sea-level rise (Duarte et al., 2013; Temmerman et al., 2013) and assisting in mitigating climate-change effects (Fernandino, Elliff, & Silva, 2018). Indeed, an ecosystem-supported coastal protection scheme may seem like a complex and unachievable goal, but recent studies have demonstrated that low-to medium-density tourism can be compatible with the preservation of beach and dune vegetation (Pérez-Maqueo, Martínez, & Nahuacatl, 2017; recent observations in the Yucatan peninsula, Mexico).

5. Conclusions

The accelerated growth and intense expansion of the tourism industry, especially in Quintana Roo and Veracruz, have had a positive impact on the economy of the region. Nevertheless, the environmental costs have been very high as urban encroachment and tourism development have led to coastal squeeze in flood prone areas. This poses an increased safety risk to coastal and marine recreation activities and may reduce the attractiveness of some coastal areas for tourism. Therefore, sustainable protection measures, combined with proper management and prevention of coastal squeeze, are urgently needed to adapt to a changing climate. Finally, we conclude that besides mitigating the coastal squeeze problem, it is fundamental to reduce human pressure on the coast by moving populations landward, or at least promoting new developments further inland. We need to be better prepared to deal with climate change and coastal squeeze challenges that will affect the tourism industry in the very near future.

Author contributions

Debora Lithgow.- She suggested the idea, performed the literature review, gathered the data, analyzed the data and wrote a first draft of the ms.

M Luisa Martínez.- Performed the literature review, corrected the ms and wrote different sections. Discussed the results.

Juan B. Gallego-Fernández.- Proof-read the ms. and helped with the discussion and interpretation.

Rodolfo Silva.- Provided information and data bases, helped reviewing the ms. and helped with the discussion of the results.

Debora L. Ramirez-Vargas.- helped gathering information and organizing the databases. She participated in the discussion.

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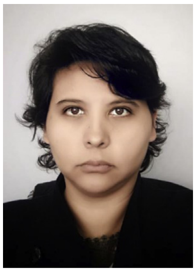

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