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Loss of coastal ecosystem services in Mexico: An approach to economic valuation in the face of sea level rise

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The economic valuation of coastal ecosystem services is a critical step for the design of sound public policies that support the preservation of the services that nature provides to society in the context of climate change. Using the value transfer method, we obtained the economic valuation that represents the loss of coastal ecosystem services caused by sea level rise in Mexico. Using the Bathtub method, digital elevation models and sea level data, we identified the areas in the country prone to flooding and the associated ecosystem impacts. In Mexico, the annual economic loss caused by the disappearance of coastal ecosystem services is estimated at $6,476,402,405 USD, where wetlands represent the greatest economic losses, since they represent the largest affected ecosystem by area. However, beaches and dunes are the most valued ecosystem due to the economic activities that occur in these areas. In the mangroves, the service as habitat, refuge and nursery is the most valued for its positive relationship with fisheries. The states with the most economic losses are Baja California Sur, Sinaloa and Campeche. The protection of the coastal zone in Mexico should be a priority in the development strategies in the country because its loss and/or rehabilitation imply high economic costs and compromises the wellbeing of society.

KEYWORDS

ecosystem services, economic valuation, sea level rise, flooding, Mexico

Introduction

The importance of coastal ecosystems and the services they provided to society are widely recognized (Costanza et al., 1997a; Daily, 1997; Liu et al., 2011; de Groot et al., 2012; Barbier, 2015). People obtain benefits from these ecosystems (Nicholls et al., 2011;

Weiss et al., 2011)through the environmental services they provide to society, divided in four main categories: provisioning, regulating, cultural and supporting services (Reid et al., 2005; Aktürk and Güneroğlu, 2021). Coastal ecosystems, such as sandy beaches, dunes, mangroves, and other wetlands, provide protection against storms and coastal flooding, through their capacity as natural barriers to reduce the energy of the waves and retain sediment, they also provide refuge and nursing habitat for a diversity of species, and support recreational, aesthetic and cultural values for people (Shepard et al., 2011; Arkema et al., 2013; Barbier, 2015). In this sense, coastal ecosystems have been recently proposed as measures of adaptation and mitigation against climate change under the concept of Nature-based Solutions, as long as they remain in a healthy condition (Baustian et al., 2020; Ruckelshaus et al., 2020; Hagedoorn et al., 2021).

The provision of ecosystem services directly depends on the functionality of these ecosystems and on the natural and anthropic impacts that affect them (Mendoza-González et al., 2012); especially in the context of climate change and the continuous and accelerated sea level rise, which represents a threat for coastal ecosystems worldwide (Kopp et al., 2016). The incidence of hydro-meteorological extreme events (such as hurricanes and strong storms) could intensify (Kirezci et al., 2020), exposing coastal ecosystems to flooding and erosion, leading to their degradation and the potential loss of their services, increasing the vulnerability of coastal communities and habitats.

Therefore, the economic valuation of ecosystem services shows that coastal ecosystems are finite and that their depreciation or degradation has associated costs that negatively impact social wellbeing (Instituto Nacional de Ecología y Cambio Climático, 2021). The economic valuation of ecosystem services is the evaluation of compensations (de Groot et al., 2012), that is, the value of these services reflects the value that society is willing to exchange to conserve these natural resources. However, these valuations are not trivial, since most of the ecosystems, especially the coastal ones, do not have established prices from which their value could be derived. For this reason, different economic valuation methods are used, that allow the allocation of a monetary value for ecosystems. The benefit transfer method, also known as value transfer, has been widely used to value ecosystem services in different places and at different scales, because it allows transferring the results of existing valuation studies to other sites with similar ecosystems and beneficiaries, reducing time and costs (Reid et al., 2005; Bishop, 2010; Liu et al., 2011; Mendoza-González et al., 2012; Brander, 2013).

Mexico is a country rich in ecosystems, a reason that has led to the development of diverse studies for the identification, description, prioritization, and economic valuation of its services (Margulis, 1992; Loa, 1994; Barbier Strand Ivar, 1998; Sanjurjo, 2001; Mendoza-González et al., 2012; Camacho-Valdéz et al., 2013; Lithgow et al., 2017; Instituto Nacional de Ecología y Cambio Climático, 2021). However, the valuation of ecosystem services losses that might result from sea level rise in Mexico is practically non-existent. Therefore, in this paper we present an approach to the economic valuation of the loss of ecosystem services provided by mangroves, sandy beaches and dunes, and wetlands in Mexico, in the face of sea level rise by the end of the 21st century. In the results we identify the areas of the Mexican coast prone to flooding associated with sea level rise and an approximation to the economic valuation of this potential loss. We also identify the states most affected by the loss of coastal ecosystems and their services, considering that this information can be used for decision-making in coastal management and for the implementation of actions that could lead to improving their resilience and can in the long term serve as protection options against sea level rise in Mexico.

Materials and methods

Study area

Mexico has a privileged geographic location, with access to the Pacific Ocean, the Gulf of California, the Gulf of Mexico and the Caribbean Sea. The coastal extent in the country is 11,122 km, with 3,149,920 km of Territorial Sea and Exclusive Economic Zone, in addition to a wide continental shelf and insular territory that together provide diverse coastal ecosystems and resources (Instituto Nacional de Ecología y Cambio Climático, 2021). Due to the heterogeneity of the Mexican coast (Silva et al., 2011), we divided the country in four marine regions, hosting 70 coastal and marine priority areas for their high biodiversity, the importance of their resources and the level of threats they face. These regions are: 1) Region I Northern Pacific and Gulf of California, a marginal sea characterized by having a diversity of coastal environments and interior islands, with natural landscapes and conservation status valued worldwide. The Pacific is characterized by the presence of large systems of coastal sand dunes, as well as numerous bays that provide refuge, breeding and nursing habitats for whales. 2) Region II Central Pacific and 3) Region III Southern Pacific harbor an important number of coastal lagoons, estuarine systems, bays, sand bars and sandy beaches. The spatial orientation of the coastline made this region vulnerable to the impact of extreme wave effects and sea level rise. 4) Region IV Gulf of Mexico and Caribbean Sea, some of the largest and most productive coastal lagoons of the country are located in this region, as well as estuarine zones, coastal marshes, mangroves, coral reefs and rocky shoals that provide habitat for priority species (Figure 1).

Of all the coastal ecosystems in these regions, the sandy beaches, coastal dunes, mangroves, and other wetlands are of particular relevance due the ecosystem services they provide,

FIGURE 1
Coastal and marine priority regions in Mexico. Modified from Arriaga Cabrera et al. (1998).

including natural protection against extreme wave action, erosion control, refuge and nursery habitat, aesthetic and recreation values (Reid et al., 2005; Ramsar, 2013). Mexico is one of the countries in Latin America with highest proportion of exposed low coastal zones, which makes it especially vulnerable to sea level rise and degradation of its coastal ecosystems (Romero et al., 2012; Silva et al., 2014; Lithgow et al., 2017). The sea level data measured in tidal stations in Mexico are limited and not very robust, which impairs their reliability to develop future projections for the country. This has led to using scenarios presented by international institutions such as the IPCC, to implement research to assess the adverse effects of sea level rise in the country, as is the case of coastal flooding (Zavala-Hidalgo et al., 2010).

Identifying coastal areas prone to flooding by sea level rise

In the absence of an accepted universal model, we applied the Bathtub or "bucket-fill" method, which is relatively simple and efficient to identify areas prone to flooding (Hansen, 2016; Williams and Lück-Vogel, 2020; de Lima et al., 2021). This method assumes a uniform water level increase over a specific topography, and areas are identified as "prone to flooding" where the elevation is equal or lower than the defined sea level.

Although the Bathtub has a degree of uncertainty because it is a static model and does not consider hydrodynamic effects related to wave propagation and its transformations, it is neither practical nor advisable to use detailed numerical models. given their complexity, high computational cost, and the detailed input data required for the spatial scale of this study (the entire coastal zone of Mexico). In this sense, the Bathtub method provides a good approximation for the identification of flood-prone areas when it comes to large spatial scales (Hansen, 2016). We followed the spatial analysis described by Afanador and Ruíz (2009). We used the USGS 30 m spatial resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) as a topographic base of the entire coastal territory of Mexico. As a flood scenario, we established seawater levels that resulted from the sum of sea level rise of +0.84 m from the long-period SSP5-8.5 (2081-2100), established by the IPCC in its Sixth Assessment Report (IPCC, 2021) and the maximum high tide recorded for 25 coastal regions of Mexico based on their meteorological and oceanographic characteristics (Dirección General de Puertos, 2001). With the results obtained from this analysis, we generated a flood map using geoprocessing tools, thus allowing the identification of areas prone to flooding along the coast of Mexico.

Area of coastal ecosystems flooded by sea level rise

Based on the land use and vegetation maps of the coasts of Mexico (SEDENA, 2015.), we identified that mangroves, wetlands, and beaches and dunes are the ecosystems that have the greatest presence throughout the country. We classified this database into three groups considering the ecosystems mentioned above, where we categorized beaches and dunes in the same group, we categorized mangroves in a group independent of wetlands due to the variety of environmental services they provide, and we categorized all classes related to water bodies, marshes, swamps, and flood zones in the group of wetlands. For the latter we used as a reference the definition of wetland established by the Ramsar Convention (Ramsar, 2013). Finally, based on the results of the flood extent analysis obtained with the Bathtub method, and using geoprocessing tools, we determined the flood areas for each of the three coastal ecosystems in the 17 coastal Mexican states. In this way, we estimated the area of mangroves, beaches and dunes, and wetlands that could be affected by sea level rise. It is important to emphasize that due to the scale of the analysis and the diversity of ecosystems present on the coast of Mexico, we did not consider the dynamism and adaptive capacity to flooding that these ecosystems may initially show in the face of sea level rise.

Economic valuation of coastal ecosystem services loss

We obtained the approximation to the economic valuation of ecosystem loss using the value transfer methodology, taking as a basis standardized economic values of ecosystem services and quantifying the monetary cost per hectare of ecosystems located in flooded areas. We selected the ecosystem services for the assessment based on the environmental and social characteristics of the Mexican coasts and considering what would be the impact of losing these services as a consequence of degradation and/or loss of coastal ecosystems, being of greater importance those that provide protection against storms, erosion control, habitat, refuge and nursery, water supply, aesthetics and recreation (Table 1). The information needed to complete a benefit transfer valuation is available in various environmental valuation databases, including "Environmental Valuation Reference Inventory" (EVRI) and "The Economics of Ecosystems and Biodiversity" (TEEB) (McComb et al., 2006).

We use these databases and previous published research (Mendoza-González et al., 2012; Pérez-Maqueo et al., 2013a) to perform our value transfer. Overall, we found 25 valuation studies of the ecosystem services provided by the beach and coastal dunes, mangroves and wetlands, were performed in countries of Latin America like Mexico, USA, Canada, Costa Rica, Belize, as well as in countries in the European and Asian region, such as Spain, Malaysia, Thailand, Philippines, Sri Lanka, and China (Bennett and Reynolds, 1993; Barbier Strand Ivar, 1998; Lara-Domínguez et al., 1998; Sathirathai, 1998; Bann, 1999; Barbier et al., 2002; Gunawardena and Rowan, 2005; Barbier, 2007; Dissanayake and Smakhtin, 2007; Samonte-Tan et al., 2007; Tong et al., 2007; Aburto-Oropeza et al., 2008; Cooper et al., 2008; Batker et al., 2010; Brenner et al., 2010; Economics Earth, 2010; Janekarnkij, 2010; Liu et al., 2010; Tianhong et al., 2010; Kauffman, 2011; Mendoza-González et al., 2012; Molnar et al., 2012; Camacho-Valdéz et al., 2013; Pérez-Maqueo et al., 2013a; Ballard et al., 2015) (see **Tables 4–6** of **Supplementary Material**). The economic values of ecosystem services correspond to different years and methodologies, so it was necessary to standardize by adjusting them to United States dollars (US$) using the Consumer Price Index (CPI) and the Purchasing Power Parity (PPP) for the year 2020. These indicators were obtained from the World Bank (2021). Finally, we made the adjustment using the following formula (Envalue, 2007; Mendoza-González et al., 2012):

$$ESV = \frac{(value/CPI) \times 100}{PPP} \times USA \quad PPP$$

Where:

ESV: ecosystem services value

Value: is the value in the original year in the original currency.

CPI: is an index of inflation of the source data, with a base year in 2020.

PPP: is the Purchasing Power Parity between the original currency and US$ in 2020.

The proposed methodology for the monetary quantification of environmental loss is illustrated in Figure 2, it mainly consists of 3 steps. First, the terrain heights and ecosystems available in

TABLE 1 Average yearly valuation of coastal ecosystem services for the year 2020.

Coastal ecosystem	Ecosystem services	Average valuation (2020)US$ ha^{-1} year^{-1}
Mangrove	Refuge and nursery habitat	630.75
	Erosion control	83.07
	Storm buffering	335.41
	Aesthetic and recreation	107.82
Wetland	Refuge and nursery habitat	229.04
	Water supply	550.04
	Storm buffering	715.78
	Aesthetic and recreation	155.76
Beach and dune	Storm buffering	27,429.73
	Aesthetic and recreation	9,088.38

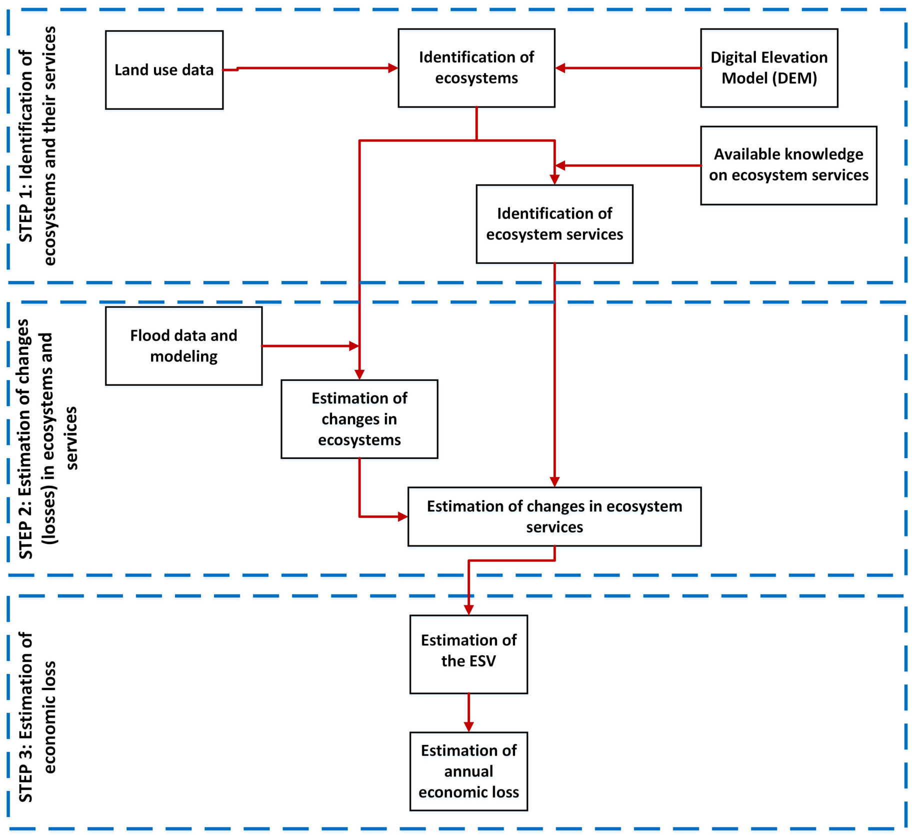

FIGURE 2
Steps of the proposed method for the estimation of economic loss for the ecosystem services losses.

the study area are identified using land and ecosystem data, the main services of each ecosystem are algo identified. Second, the changes for each ecosystem are evaluated incorporating flood data (model). Based on the estimated changes, the areas of flooded ecosystems are identified. Third, estimation of the ESV and the annual economic loss caused by the disappearance of ecosystem services in relation to sea level rise.

Results

A total of 2,715,023 ha on the Mexican coast is prone to flooding under the predicted scenario of sea level rise by the end of the century. The Gulf of California (R-I) and the Gulf of Mexico and the Caribbean Sea (R-IV) represent 46% and 45% of the total area prone to flooding, respectively. The states of Baja California, Baja California Sur, Sonora, Sinaloa, Nayarit, Tamaulipas, Veracruz, Tabasco, Campeche, Yucatán and Quintana Roo are located in these regions and present the largest potential flood extensions (Figure 3 and Table 2). The coasts of the states located in the R-II and R-III have the smallest extensions of potential flooding, with 1% and 8% of the total respectively.

Of the three ecosystems, the largest predicted loss area at the national level corresponds to wetlands, with 2,479,767 ha, which represents 91% of the total potentially affected coastal ecosystems; followed by the loss of 175,099 ha of mangroves, which represents 7%, and the loss of 60,157 ha of beaches and dunes, corresponding to 2%. Campeche, Sinaloa, Baja California Sur, Yucatán and Tabasco are the states that would lose the most mangrove area. Baja California Sur, Sinaloa, Campeche and Tamaulipas are the states that would lose the most wetland area, and Baja California Sur, Sinaloa, Sonora and Baja California would lose more beaches and dunes. On the other hand, Michoacán, Jalisco and Colima are the states with less predicted impacts on these ecosystems (Figure 3).

At the national level, we estimate that the annual economic loss caused by the disappearance of ecosystem services in relation to sea level rise would amount to $6,492,551,964 USD. The loss of mangrove services is estimated at $202,588,949 USD per year, which corresponds to 3% of the national total, where its most valued service, and therefore the one that represents the

FIGURE 3
Predicted coastal flooding areas resulting from sea level rise in Mexico.

greatest economic loss, is that of shelter and nursery habitat for important commercial species. Erosion control is the least valued service (see the Supplementary Material). Campeche, Sinaloa, Baja California Sur, Yucatán and Tabasco are the states that have the greatest potential economic losses due to the effects of sea level rise on this ecosystem.

Regarding wetlands, the loss of their services represents $4,093,153,701 USD per year, corresponding to 63% of the total nationally. Baja California Sur, Sinaloa, Campeche, Tamaulipas, and Quintana Roo are the states with the greatest potential economic losses due to service decreases in this ecosystem. In the case of beaches and dunes, the loss of their services amounts to $2,196,809,314 USD per year, corresponding to 34% of the national total, where Baja California Sur, Sinaloa, Sonora, Baja California, and Campeche are the states with the greatest potential economic repercussions (Figure 4 and Table 3). For wetlands, and beaches and dunes, the most valued service is protection against storms, while the aesthetic and recreation service are less valued (see the Supplementary Material).

TABLE 2 Total area and area by ecosystem prone to flooding for the Mexican coast.

		Mangrove	Wetland	Beach and dune	Area prone to flooding (ha)
R-I	Baja California	1,394	158,772	7,226	167,392
	Baja California Sur	22,362	362,113	17,984	402,459
	Sonora	5,606	198,085	7,969	211,660
	Sinaloa	41,904	345,456	8,310	395,671
	Nayarit	4,721	64,278	781	69,781
R-II	Jalisco	29	1,832	323	2,185
	Colima	64	3,518	315	3,897
	Michoacán	39	71	54	164
	Guerrero	282	19,459	635	20,376
R-III	Oaxaca	3,016	121,258	2,999	127,273
	Chiapas	2,282	76,087	1,386	79,755
R-IV	Tamaulipas	120	262,399	4,197	266,717
	Veracruz	3,403	126,816	1,338	131,557
	Tabasco	11,997	131,256	312	143,566
	Campeche	58,820	340,934	4,607	404,361
	Yucatán	14,795	56,728	916	72,439
	Quintana Roo	4,264	210,704	802	215,770
	Total	**175,098**	**2,479,767**	**60,157**	**2,715,023**

Discussion

Ecosystems provide a large and important range of free services on which we depend. The degradation of coastal ecosystems in Mexico and the potential loss of its services due to sea level rise represents an estimated annual economic cost of $6,492,551,964 USD, corresponding to 0.6% of the country's Gross Domestic Product (GDP) for 2020. This estimated cost has a non-homogeneous distribution among the coastal ecosystems in the country, based on the valuation of their services and the area prone to flooding. Although the projections of sea level rise in Mexico are similar to global estimates, they vary regionally, showing a lower increase in the coasts of regions II and III, and higher effects in the coasts of regions I and IV (Palacio-Aponte et al., 2005; Zavala-Hidalgo et al., 2010).

Our results corroborate these observations, since the states located in regions I and IV present the largest potential flood areas in comparison with the states in regions II and III. One of the main reasons is the heterogeneous morphology of the

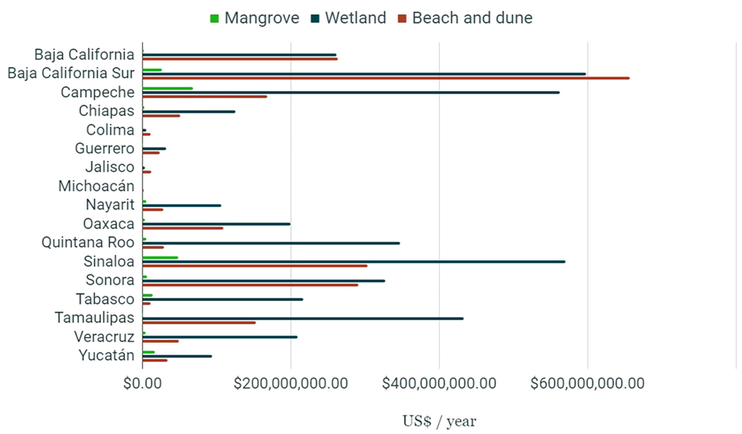

FIGURE 4
Annual economic losses by state due to the disappearance of ecosystem services in Mexico.

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TABLE 3 Estimated monetary cost from the loss of services for each coastal ecosystem in Mexico.

	Ecosystem services	Total value for the loss of ecosystem servicesUS$ year^{-1}	Total national value for the loss of ecosystem servicesUS$ year^{-1}
Mangrove	Refuge and nursery habitat	110,443,370	202,588,949
	Erosion control	14,536,676	
	Storm buffering	58,729,783	
	Aesthetic and recreation	18,879,119	
Wetland	Refuge and nursery habitat	567,965,930	4,093,153,701
	Water supply	1,363,971,272	
	Storm buffering	1,774,967,925	
	Aesthetic and recreation	386,248,574	
Beach and dune	Storm buffering	1,650,082,283	2,196,809,314
	Aesthetic and recreation	546,727,031	
	Total		**6,492,551,964**

Mexican coast (Silva et al., 2014), as a result of the influence of a diversity of processes, including tectonic activity that cause vertical uprising of the earth's crust in the active regions along the Pacific (R-II and R-III) (Zavala-Hidalgo et al., 2010). This represents a critical factor in the potential degradation of ecosystems and the loss of their services.

In this sense, states such as Jalisco, Colima, Michoacán and Guerrero had lower areas prone to flooding, which means a lower probability of ecosystem degradation and lower economic losses. This was not the case of states such as Baja California Sur, Sinaloa and Campeche, located in R-I and R-IV, where vast coastal plains are common and the potential for ecosystem degradation is larger, hence the loss of services is more likely, resulting in higher potential economic costs (**Tables 2**, **4**). Studies focused on assessing the sea level rise vulnerability in Mexico at the end of this century identify severe flooding impacts in all the states along the Gulf of Mexico, as well as for Sinaloa, Baja California Sur and Sonora in the Pacific coast and Gulf of California (Ivanova and Gámez, 2012). This coincides with our results in this study. However, sea level rise maps using the bathtub method are generally only used as a communication tool to assist in illustrating the general risks of sea level rise and should not be relied on solely for decision-making purposes. This is because the maps are simple and do not consider many of the complex processes of coastal inundation. For example, the bathtub approach does not consider existing seawalls, storm surge, erosion or other local factors, which can all influence the extent of erosion from sea-level rise (Geoscience Australia, 2015).

Sandy beaches and dunes are widely distributed along the Mexican coasts. Approximately 70% of the coasts along the Pacific and the Gulf of California are sandy beaches, as is the case of 92% along the Gulf of Mexico and the Caribbean (Silva et al., 2014; CONABIO, 2022). The permanent and intense interaction between dunes and beaches is conducive to consider them as a management functional unit. In this sense, their total extension in the Mexican coasts is 808,711 hama (Martínez et al., 2014). Taking this into account and the results we obtained, the potential loss of this ecosystem due to sea level rise represents 7.5% of the national extent. Even though this ecosystem has the lower estimates of affected area by sea level rise (2%) in comparison with mangroves and wetlands (**Table 2**), their value is very significant, because the loss of their services is estimated at $2,196,809,314 USD annually, which corresponds to 54% of the economic losses of wetlands, with a much larger potential flooded area (91%) (**Table 4**).

This is due to the valuation of the services of beaches and dunes in comparison with the value assigned to other ecosystems. Beaches and dunes are very economically very important for Mexico, since the services of this ecosystem have allowed the development of economic activities associated with tourism and recreation. The arrival of international tourists has increased continuously during the last 60 years, as has the economic income related to this activity, significantly boosting the growth of some regions of the country (Martínez et al., 2014). The coasts of states located in regions I and IV, such as Quintana Roo and Baja California Sur, are the locations that have had the greatest economic growth thanks to tourism (Llamosas-Rosas et al., 2021). In this sense, there are large economic investments that would be affected by the degradation of beaches and dunes and the loss of their valuable services. The potential loss of this ecosystem and its services due to sea level rise should be of particular relevance for Mexico, due to the great economic impact that it can cause

TABLE 4 Estimated total cost caused by potential ecosystem services losses for each coastal state in Mexico.

	Mangrove ecosystem services total lossUS$ year^{-1}	Wetland ecosystem services total lossUS$ year^{-1}	Beach and dune ecosystem servicestotal lossUS$ year^{-1}	Ecosystem servicestotal lossUS$ year^{-1}
Baja California	1,612,838	262,071,490	263,885,146	527,569,474
Baja California Sur	25,872,711	597,710,708	656,748,187	1,280,331,606
Campeche	68,054,441	562,753,261	168,227,430	799,035,132
Chiapas	2,640,522	125,590,338	50,613,417	178,844,277
Colima	73,598	5,806,120	11,520,886	17,400,604
Guerrero	326,207	32,119,392	23,191,947	55,637,546
Jalisco	33,664	3,024,684	11,829,316	14,887,665
Michoacán	44,950	117,909	1,973,885	2,136,744
Nayarit	5,462,728	106,099,297	28,538,008	140,100,033
Oaxaca	3,489,403	200,150,755	109,506,896	313,147,054
Quintana Roo	4,933,325	347,792,324	29,277,467	382,003,116
Sinaloa	48,483,472	570,217,099	303,477,822	922,178,393
Sonora	6,486,229	326,962,733	291,007,124	624,456,086
Tabasco	13,880,951	216,654,438	11,398,861	241,934,250
Tamaulipas	138,912	433,121,385	153,278,162	586,538,459
Veracruz	3,936,907	209,325,422	48,877,021	262,139,350
Yucatán	17,118,091	93,636,344	33,457,740	144,212,175
	202,588,949	**4,093,153,701**	**2,196,809,314**	**6,492,551,964**

derived from the possible limitation of tourist activities and/or the need to invest in conservation measures. protection and adaptation.

However, this ecosystem is highly dynamic and has the potential to respond to changes in sea level, i.e., an upward and landward translation of the active profile in pace with rising sea level and maintaining the shape of the equilibrium profile, which decreases the protection service loss, as long as the beach has enough space to move and is not restricted by coastal infrastructure. In this regard, a sandy beach-dune system can migrate landwards, while maintaining its relative elevation and thus protective function service under sea level rise provided accommodation space and sand are available (López-Dóriga and Jiménez, 2020). Therefore, the magnitude of the physical changes and the impacts on beaches and dunes that could be caused by sea level rise will vary regionally, depending on the type of existing threats and the levels of degradation at each location. A serious and widespread problem that this ecosystem is already facing is that its physical space is becoming smaller, due to human development and other productive activities on the Mexican coastal zone, which seriously compromises its ecological integrity and makes it more vulnerable to sea level rise, increasing consequently the potential economic costs due to the loss of its services.

It is necessary to consider that we do not include shoreline changes other than sea level rise induced, and this should be equivalent to "isolating" the sea level rise component in the long-term behavior of these coastal areas. Other factors such as fluvial sediments and longshore and cross-shore sediment transport patterns would also contribute to their long-term evolution. Thus, our results provide a first approximation of the effects of sea level rise on the beaches and dunes of the Mexican coast.

The magnitude of the physical changes and the impacts on beaches and dunes that could be caused by sea level rise will vary regionally, depending on the type of existing threats and the levels of degradation at each location. However, a serious and widespread problem that this ecosystem is already facing is that its physical space is becoming smaller, due to human development and other productive activities on the coastal zone, which seriously compromises its ecological integrity and makes it more vulnerable to sea level rise, increasing consequently the potential economic costs due to the loss of its services.

Regarding wetlands, the estimated costs for the loss of their services ($4,093,153,701 USD) represent 63% of the total cost at the national level, again placing regions I and IV as the most affected, and highlighting states such as Baja California Sur, Sinaloa and Campeche with the greatest economic losses

(**Table 4**). Lagoons such as Ojo de Liebre and San Ignacio in Baja California Sur, have a high value as refuge and nursery habitat for the gray whale. The wetlands of Sonora and Sinaloa provide critical habitat to millions of migratory birds, a diversity of fish and endemic vegetation of high ecological value. The loss of services of this ecosystem, in addition to the high revenue related to activities such as fishing, aquaculture and tourism, would imply migration to other economic activities or adaptation by implementing protection and/or recovery programs.

The permanence and migration of coastal wetlands in Mexico will depend on the new conditions of salinity, depth and permanence of the water, as well as the conditions of anoxia that this entails in the coastal spaces that will be invaded by the increase in sea level. The anthropic pressure that has been exerted on this ecosystem is a key factor to consider, which might have already impacted its resiliency and might add to its degradation and loss. In states such as Baja California Sur, Sonora and Sinaloa, due to their arid to semi-arid climatic characteristics, wetlands are critical ecosystems for migratory birds and a diversity of species that use them to complete their annual cycles. In this sense, it is essential to generate conservation strategies for these ecosystems in the face of rising sea levels.

As well as beaches and dunes, wetlands have the ability to build up vertically by sediment accretion and the accommodation space, namely the vertical and lateral space available for fine sediments to accumulate and to be colonized by wetland vegetation. The wetlands resilience to sea level rise is primarily driven by the availability of accommodation space, which is strongly influenced by the building of anthropogenic infrastructure in the coastal zone (Schuerch et al., 2018). It has to be noted that we do not include in this approach any adaptive factors that make wetlands respond dynamically to sea level rise. Despite this, our results show an approximation of the Mexican wetland areas that would be most affected by sea level rise and where more specific analyses should be performed leading to actions to enhance resilience. The permanence and migration of coastal wetlands in Mexico will depend on the new conditions of salinity, sediment availability, depth and permanence of the water, as well as the conditions of anoxia that this entails in the coastal spaces that will be invaded by the increase in sea level. The anthropic pressure that has been exerted on this ecosystem is a key factor to consider, which might have already impacted its resiliency and might add to its degradation and loss.

Mangroves are present in all the coastal states of the country, with a coverage of 905,086 ha (CONABIO, 2022). Based on this, the loss of mangroves caused by sea level rise would represent 19% of the national coverage, generating high economic impacts in the states of Campeche, Sinaloa, Baja California Sur, Tabasco, and Yucatan (**Table 4**). In the Mexican Pacific, the most important mangrove forest is located in Marismas Nacionales (southern Sinaloa and northern Nayarit), a site recognized as Wetland of International Importance by the Ramsar Convention (Villanueva-Fragoso et al., 2010). Sinaloa, being the second state with the highest economic losses due to the disappearance of its mangrove services, will face an annual loss of $48,483,472 USD (**Table 4**). Although Nayarit is not listed among the states with the greatest losses, it is important to mention that practically the whole mangrove forest in Marismas Nacionales would be degraded.

In general, the economic loss represented by the degradation of mangroves acquires greater relevance for the refuge and nursery habitat service, due to the close relationship that exists between this ecosystem and the fishing landings of various commercial species, a well-documented phenomenon along region (Aburto-Oropeza et al., 2008). However, mangroves not only benefit commercial species. For example, throughout Mexico, mangroves are critical breeding habitat for the Reddish Egret (*Egretta rufescens*), an endangered species in Mexico and a priority bird at the continental level, and for the Bare-throated Tiger Heron (*Tigrisoma mexicanum*), a species subject to special protection in Mexico (SEMARNAT, 2010). These coastal forests also provide habitat for protected waterbirds, including the Ridgway's Rail (*Rallus obsoletus*, protected as threatened) along Baja California Sur, Sonora Sinaloa and Nayarit, and the Clapper Rail (*Rallus crepitans*, protected as endangered) in the Gulf of Mexico and the Yucatán Peninsula (SEMARNAT, 2010). Similarly, the mangroves of Yucatan are a refuge for various species of resident and migratory waterbirds, and fish and invertebrate species of great commercial value. Local communities in Tabasco use the mangrove as raw material, an activity regulated through extraction programs controlled by the Ministry of the Environment and Natural Resources (SEMARNAT) of Mexico, which allows them to have an economic income.

The estimation of the economic loss of ecosystem services allows us to discuss the importance of valuing ecosystems as first approximation for decision making, as well as allowing us to infer the economic importance for a region or state. The value of this economic loss can be compared to the GDP for each state (**Table 5**).

Regardless of the ecosystem type and the potential area to be lost to flooding, each of these three ecosystems has a unique ecological importance and, as a whole, their health determines the economic development potential and the social well-being of the coastal and marine zones of Mexico. The information presented here allows the identification of the coastal areas of Mexico prone to flooding due to sea level rise and the identification of coastal ecosystems at risk, as well as the economic loss that the degradation of these environmental services would represent. This information is especially relevant in the face of climate change, since the economic valuation of ecosystem services is an essential tool required to guarantee that the services that nature provides to society are quantified and considered in the formulation of sound public policies in the country (Instituto Nacional de Ecología y Cambio Climático, 2021), which will then guide conservation efforts and promote the resilience of these

TABLE 5 Comparison between the GDP of Mexico's coastal states in 2020 (in millions of GDP) and the monetary cost for the loss of ecosystem services.

State	National GDP (%)	GDP nominal (million USD)	Ecosystem servicestotal lossUS$ $year^{-1}$
Jalisco	7.22	77,591	14,887,665
Veracruz de Ignacio	4.51	48,412	262,139,350
Baja California	3.64	39,117	527,569,474
Sonora	3.46	37,155	624,456,086
Tamaulipas	3.09	33,180	586,538,459
Campeche	2.75	29,573	799,035,132
Tabasco	2.54	27,325	241,934,250
Michoacán de Ocampo	2.51	26,988	2,136,744
Sinaloa	2.27	24,345	922,178,393
Oaxaca	1.56	16,809	313,147,054
Yucatán	1.51	16,259	144,212,175
Chiapas	1.5	16,138	178,844,277
Guerrero	1.35	14,518	55,637,546
Quintana Roo	1.34	14,414	382,003,116
Baja California Sur	0.8	8,581	1,280,331,606
Nayarit	0.69	7,361	140,100,033
Colima	0.64	6,903	17,400,604

ecosystems over time. However, we emphasize the need to consider in similar local and regional scale studies, the dynamism of these ecosystems to respond to sea level rise, as well as socioeconomic and socioecological aspects.

Conclusions

This article provides an approximation to the economic valuation of the loss of ecosystem services caused by sea level rise by the end of the century in Mexico. At the national level, the estimated annual economic cost of the potential loss of coastal ecosystem services is $6,476,402,405 USD, distributed non-homogeneously and based on the valuation of different services in the three main ecosystem types: mangroves, wetlands, and beaches and dunes. The impacts on wetlands represent 63% of the estimated loss, mainly driven by the extent and vulnerability of this ecosystem type in the country. Beaches and dunes are extremely valued for their protection services against extreme weather events and as the basis for important economic activities. Mangroves represent a smaller proportion of the national estimate, but it is the ecosystem type that provides the most services as habitat for protected species and for commercially important fisheries. Overall, the states with highest potential economic losses are Baja California Sur, Sinaloa, Campeche, and Tamaulipas.

Although sea level rise represents a greater threat for regions I and IV and to a lesser extent for regions II and III, a broad perspective must be used to guide research and management efforts in the immediate future, to increase the relevance of science in the design of public policies and conservation strategies that can address these threats. It is critical to use a multi-disciplinary approach to define mitigation and adaptation actions to reduce the potential economic losses that are expected by sea level rise. Coastal ecosystems in Mexico should be a national priority in terms of research, protection, management, and restoration, since their loss and/or rehabilitation entails very high economic costs and compromises the well-being of society.

Quantifying the dynamic effects of sea level rise is a great challenge due to the complexity of interactions between coastal processes acting at different scales and over different time periods. In this sense, the main limitation in our analysis is sea level rise as a stable component and the lack of ecosystem dynamism to respond to sea level rise with some degree of adaptation. In this sense, the results presented here should be taken with caution, as they could represent an overestimation of the cost of the loss of the ecosystem services analyzed. Nevertheless, our results provide a first approximation for Mexico and a baseline that should be refined and compared with integrative assessments. Because each state in Mexico has physical variability in its coasts and has different degrees of ecological disturbance and presence of anthropogenic activities, specific integrative studies should be performed considering local physical characteristics, as well as the capacity of the ecosystem to respond dynamically to sea level rise.

Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

Author contributions

VF wrote the first draft, performed analyses and performed, reviewed, and edited the manuscript. RC conceived the manuscript, collected data, performed the analyses, reviewed, and edited the manuscript. AK performed the analyses, reviewed, and edited the manuscript. OH reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.898904/full#supplementary-material

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