System of Environmental Economic Accounting

NATURAL CAPITAL ACCOUNTING AND VALUATION OF ECOSYSTEM SERVICES PROJECT

Pilot testing the SEEA-EEA framework in Mexico: Coastal protection by mangrove ecosystems

Report of the NCAVES Project

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0. Preamble

The *Natural Capital Accounting and Valuation of Ecosystem Services Project* is a three-year (2017-2020), global project launched jointly by United Nations Statistics Division (UNSD), United Nations Environment Programme, and the United Nations Convention on Biological Diversity (CBD), with financial support from the European Union. Brazil, China, India, Mexico, and South Africa were chosen as the initial countries to pilot test the project.

The project aims to advance the knowledge agenda on environmental-economic accounting, particularly ecosystem accounting, by initiating pilot testing of the *UN System of Environmental Economic Accounts-Experimental Ecosystem Accounting* (SEEA-EEA; see UN, 2014b) framework in select countries where biodiversity is at stake, with a view to:

- Improving the measurement of ecosystems and their services (both in physical and monetary terms) at the national/subnational level;
- Mainstreaming biodiversity and ecosystems in national/subnational level policy-planning and implementation;
- Contribute to the development of internationally agreed methodology and its use in partner countries.

The *Natural Capital Accounting and Valuation of Ecosystem Services in Mexico* (NCAVES-Mexico) project was officially launched in June 2017 and implementation began in September 2017 when the project consultant was contracted. The Programme of Work 2018 for the NCAVES-Mexico project was submitted to and approved by the *Interinstitutional Working Group on Experimental Ecosystem Accounting* in February 2018; it included two major tasks:

- conducting a <u>country assessment</u> of natural capital accounting and valuation of ecosystem services in Mexico, based on desk study and visits to relevant organisations. The assessment report would serve as an input to develop a national plan for advancing environmental-economic and ecosystem accounting in Mexico, and
- compiling <u>pilot accounts</u> —in physical and, whenever possible, monetary terms— of select ecosystem services based on existing data and using the UN-SEEA-EEA framework.

The *Country Assessment on Natural Capital Accounting and Valuation of Ecosystem Services in Mexico* was completed in December 2018. The report describes the current situation in Mexico with regard to: a) environmental-economic accounting; b) valuation of ecosystem services; c) mechanisms for payment for environmental services; d) inclusion of ecosystem services concepts in public policy, planning and regulatory instruments; and e) the country's participation in international initiatives for valuing ecosystem services. The report also identifies opportunity areas where adoption of the SEEA-EEA framework in Mexico might be useful. The report is currently being edited for separate publication.

In a first report on *Pilot testing the SEEA-EEA framework in Mexico*, I described the data sources, data compilation processes, and analytical methods used in, as well as the main findings from, the pilot studies on Carbon sequestration, surface water supply, and food crop production carried out under the NCAVES-Mexico project. This second and final report describes the data and analytical methods used in, as well as the main findings from, an initial analysis of the coastal protection services provided by mangrove forest ecosystems. Despite the paucity of data available, I decided to also include coral reefs and seagrass beds in this analysis in order to have a more comprehensive —albeit still incomplete— view of the key, complementary role that these ecosystems play in coastal risk protection (see Guannel *et al.*, 2016).

A technical exchange meeting was held on the 8th of November 2019 to submit the source data and methods that I intended to use in this study to the consideration of technical experts from CONABIO, Comisión Nacional del Agua, CONANP, INEGI and other relevant institutions. They all concurred with the methodological approaches proposed and, in fact, mentioned that the same methods and much of the same data sets are being used in other, local-level studies.

1. Introduction and justification

Coastal regions are constantly subject to the action of ocean waves and storms and, thus, naturally experience erosion and flooding over a range of temporal (daily, seasonal, decadal) and spatial scales. However, coastal erosion and flood impose risks to human populations and activities, their infrastructure and assets. In Mexico and other developing countries. these risks have been increasing over the last decades due to the continued, rapid growth of coastal populations and the development of coastal zones for tourism and other economic activities and infrastructure. Add the sea level rise and higher frequency of strong hurricanes that climate change scenarios project (Wong *et al.*, 2014), to more fully comprehend the critical importance of coastal erosion and flood, and their potentially severe consequences for coastal populations around the world.

Protection of coastal populations has traditionally been approached by constructing seawalls, bulkheads, rock revetments, levees and other structures to rise or harden shorelines (Arkema *et al.*, 2013; Cheong *et al.*, 2013; Ondiviela et al., 2014; Hopper and Meixler, 2016). Although such solutions might be adequate in some cases, evidence shows that their construction may have unintended negative impacts on recreational use, water quality, fisheries production and even on erosion itself (Defeo *et al.*, 2008; Peterson & Lowe, 2009; Cheong *et al.*, 2013; Marchant, 2017). Rather recent but abundant evidence shows that oyster and coral reefs, as well as coastal vegetation such as mangrove forests, tidal saltmarshes and seagrass beds buffer coastlines from waves and storm surge, reducing their impact and the ensuing risks for coastal communities and infrastructure (*e.g.*: Das and Vincent, 2009; Feagin *et al.*, 2009; Mukherjee *et al.*, 2009; National Academies, 2010; Barbier *et al.*, 2008; Barbier *et al.*, 2011; Gedan *et al.*, 2011; Jones *et al.*, 2012; Arkema *et al.*, 2013; Cheong *et al.*, 2013; Schmitt *et al.*, 2013; Ondiviela *et al.*, 2014; Guannel *et al.*, 2016; WorldBank, 2016; Elliff & Silva, 2017; Losada *et al.*, 2017; Harris *et al.*, 2018; Hochard *et al.*, 2019).

The ability of coastal ecosystems to influence (ameliorate/attenuate) these processes and thus protect people and infrastructure from storm, wind, and wave damage is now recognized as a coastal protection ecosystem service (Barbier *et al.*, 2011; Liquete *et al.*, 2013; Ondiviela *et al.*, 2014; Guannel *et al.*, 2016; Nordlund *et al.*, 2016; Beck *et al.*, 2018; CICES, 2018), providing additional impetus for the conservation of coastal habitats. Coastal protection services are classified as regulation and maintenance ecosystem services in the CICES v.5.1 classification scheme (see Table 1 below).

Table 1. Coastal protection services evaluated in the NCAVES-Mexico project, classified according to the Common International Classification of Ecosystem Services v.5.1 (CICES, 2018).

Section	Division	Group	Class	Code	Class type
Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	By depth/volumes

Despite this and other valuable services they provide, coastal habitats have long been neglected, often overexploited, polluted and clear-cut to devote the land to other uses through drainage, dredging and filling (Defeo *et al*., 2008; Barbier *et al*., 2011; CEC, 2016; Hopper & Meixler, 2016; WorldBank, 2016; Beck *et al*., 2018; Hochard *et al*., 2019). Being situated at the margin of land and sea, coastal ecosystems are sensitive to, and affected by, natural and anthropogenic impacts from both sides which can easily impair their ability to provide protection for coastal human populations. And yet, degradation and loss of coastal ecosystems seems to continue worldwide; the value of the coastal protection —and other— services they provide has not yet been fully perceived (Barbier *et al*., 2008; Pinsky *et al*., 2013; Ondiviela *et al*., 2014; WorldBank, 2016; Losada *et al*., 2017; Horchard *et al*., 2019). If ecosystem services are to be integrated into conservation programmes, their supply in the local landscape must be credibly quantified and the way such supply would be affected by modifications of the physical/biological environment or by different management scenarios should be properly considered. Coastal protection has been one of the most contentious ecosystem services in part because the amount of protection provided by ecosystems is highly context dependent: Not all coastal ecosystems provide protection —or the same level of protection— in all circumstances (Barbier *et al*., 2011; Ondiviela *et al*., 2014; Guannel *et al*., 2016). The extent to which a given coastal ecosystem can protect a given stretch of coastline is very difficult to evaluate in objective, quantitative terms because the many (geomorphologic, ecological, and hydrodynamic) factors involved vary greatly among locations, times, and scales and field information on the key parameters (*e.g*., wave height and length, water depth, tidal height, wind velocity, beach slope, ecosystem extent, species composition, etc.) for different locations or conditions is seldom available (Barbier *et al*., 2008; Barbier *et al*., 2011; Pinsky *et al*., 2013; Ondiviela *et al*., 2014; Guannel *et al*., 2016).

Several methods and models have been developed to evaluate, in quantitative terms, the vulnerability of coastal regions to erosion and inundation and the risk reduction afforded by natural ecosystems, based on geophysical measurements (*e.g.*, waves, storm surges, currents, tides, etc.) and analyses of coastal processes (*e.g*., sediments transport, interactions between waves and structures, etc.) (*e.g*., Vo-Luong & Massel, 2008; Bosom and Jiménez, 2011; Suzuki *et al*., 2011; Pinsky *et al*., 2013; Guannel *et al*., 2016; Volvaiker *et al*., 2017; Harris *et al*., 2018; Reguero *et al*., 2018; see reviews in Ondiviela *et al*., 2014 and WorldBank, 2016). Those methods/models, however, have been applied on a rather few real-world cases (usually at a local level), due to the amount of detailed field data necessary to fit the complex, computationally demanding mathematical models involved (WorldBank, 2016; Reguero *et al*., 2018).

Alternatively, a number of indices or indicators have been constructed with the intention of assessing, in relative terms, the vulnerability of a coast, as well as the role that natural ecosystems play in coastal protection and risk reduction. Such methods are based on qualitative or semi-quantitative assessments of hydrodynamic, geophysical, and socioeconomic features, which are then combined into a unique metric or index (WorldBank, 2016). These include, among others, the USGS's Coastal Vulnerability Index that yields a relative measure of the coastal system's vulnerability to the effects of sea-level rise (Hammar-Klose & Thieler, 2001); the CLIMADA tool to assess risks from wind and storm surge, assess economic losses from coastal hazards, and evaluate the role of natural habitats in reducing such losses (Reguero et al., 2014); the Coastal Capital Project Framework, a detailed framework to analyze and qualitatively estimate the role that natural habitats play in shoreline protection (WRI, 2009); the Coastal Vulnerability Module of the Integrated Valuation of Ecosystem Services and Tradeoffs system (InVEST), which produces a spatially-explicit qualitative index of coastal exposure to erosion and flooding, based on risk rankings of seven individual bio-geophysical variables (Sharp et al., 2018); the Coastal Flood Regulation Module of the Artificial Intelligence for Ecosystem Services (ARIES) system aims to model the risk reduction from coastal flooding that is afforded by coral reefs and mangroves, based on historical data from which statistical relationships between wave exposure, coastal habitats and the impacts on people and infrastructure are constructed (Villa *et al*., 2014); and others (e.g., Liquete *et al*., 2013; Sousa *et al*., 2013, etc.).

Recently, the World Bank Wealth Accounting and Valuation of Ecosystem Services (WAVES) Programme reviewed the various approaches available for assessing and valuing the coastal protection services afforded by mangroves and coral reefs. The resulting guidance note recommends using process-based —rather than index-based— approaches for this purpose (WorldBank, 2016). However, the lack of detailed historical observations and data necessary to fit those process models has seriously limited their use in practice (Beck *et al.*, 2018). Instead, the less data-demanding index-based approaches have been more often used at the local (*e.g.*, Guerry *et al.*, 2012; Kumar and Kunte, 2012; Sousa *et al.*, 2013; Hopper & Meixler, 2016; Elliff & Kikuchi, 2017; Marchant, 2017), country-wide (Arkema *et al.*, 2013; Cabral *et al.*, 2017), regional (Liquete *et al.*, 2013) and even global (Chaplin-Kramer *et al.*, 2019) level. Although no unified approach has emerged yet (which makes it difficult to compare the results from different studies), many of these studies have focused on assessing the level of coastal exposure as per the coastal protection module of the InVEST system.

In this study, I aim to assess, in relative terms, the vulnerability (exposure) of Mexico's coastal zones to erosion and flooding, identify the areas that are most vulnerable, and assess the role that coastal ecosystems play in reducing such vulnerability. Distinctive features of this study are that coastal vulnerability and the reduction of vulnerability are assessed in a spatially explicit manner using, whenever possible, moderate-resolution, local data for two time periods and following, as much as possible, the SEEA-EEA framework.

2. Ecosystem extent

The first step in the SEEA-EEA workflow consists in estimating the ecosystems' extent at different points in time. For the ecosystems examined in the pilot studies on Carbon sequestration, surface water supply, and food crop production, ecosystem extent accounts were compiled based on INEGI's Vegetation and land use, scale 1:250 000, charts. However, the spatial resolution of INEGI's charts is too coarse for the narrow distribution and small extent of mangrove forests in Mexico. Moreover, INEGI's charts only encompass the terrestrial portion of Mexico's territory and do not include coral reefs and seagrass meadows. For this reason, for the pilot study on the coastal protection services provided by Mexico's coastal ecosystems (*viz*., mangrove forests, coral reefs and seagrass meadows) other, higher-resolution data sources had to be utilized.

In 2005 the National Commission for the Knowledge and Use of Biodiversity (CONABIO, for its acronym in Spanish) launched a major effort specifically devoted to map and monitor the geographic distribution and extent of mangrove forests in Mexico and their changes over time. The *Sistema de Monitoreo de los Manglares de México* (Mexican System for Mangrove Monitoring, SMMM for its acronym in Spanish), began operating in 2005 analysing and processing remote sensing data (satellite imagery plus aerial photography), supported by extensive field work, to produce high-resolution maps (scale 1:50,000) depicting the extent and geographic distribution of mangrove forests in Mexico as of 1970/1980, 2005, 2010 and 2015 (CONABIO, 2009; Rodríguez-Zúñiga *et al.*, 2013; Valderrama-Landeros *et al.*, 2017). The country-wide, repeated mapping being carried out by the SMMM allows evaluating, in a highly accurate, spatially explicit manner, the extent of Mexican mangrove ecosystems and its changes over time.

The importance of coral reefs and seagrass meadows had been historically overlooked until relatively recently. In addition, the logistic and technical difficulties that their field study involves have made data on their extent, geographic distribution and condition to be very scarce and incomplete. There have been recent efforts by the Commission for Environmental Cooperation of North America to map the extent of these ecosystems in North America, mainly in relation to their important role for climate change, as they happen to be some of the world's most efficient carbon sinks (North America's blue carbon; CEC, 2016). In fact, the term "blue carbon" was recently coined in recognition of the valuable role that seagrasses, salt marshes, and mangroves play in sequestering carbon dioxide from the atmosphere. At the global level, the UN-Environment World Conservation Monitoring Centre, through its Ocean+ Habitat Atlas programme, has been compiling data from various authoritative local and international sources to make them available to the public in the form of digital maps through their on-line Ocean Data Viewer. Having been compiled from various sources with observations made at different points in time, neither the CEC nor the WCMC datasets can be assigned to one particular date and cannot be properly used to track changes over time. Nevertheless, these are the best data sets currently available on these key ecosystems; hopefully, these monitoring efforts will be maintained so that, in the coming years we will data suitable for monitoring these ecosystems will become available.

Thus, to compile ecosystem extent accounts for Mexican mangrove forests I used the SMMM digital maps available at http://www.conabio.gob.mx/informacion/gis/. For seagrass meadows and coral reefs, I had to content myself with the partial information contained in the WCMC's data sets on the global distribution of seagrass beds and warm-water coral reefs, respectively. I segmented the WCMC data sets as per Mexico's Exclusive Economic Zone to identify the seagrass meadows and coral reefs present in the country's coasts and waters. Each of these WCMC data sets actually includes two files: One file contains polygons fully documenting the location and spatial extent of areas covered by seagrass/reef that have been properly mapped based on remote sensing (aerial photographs or satellite imagery) data. The second file contains point data showing the location of areas where the occurrence of these ecosystems has been documented, but their spatial extent has not been mapped yet. For these analyses, only the polygon data were included which resulted in an underestimate of the extent of these ecosystems (*e.g.*, seagrass meadows along the Pacific coast of Mexico have not been mapped yet).

Fig. 1 shows the geographic distribution of mangrove forests in Mexico as of 1970/1980, 2005, 2010 and 2015. As can be seen, mangroves are present on all the coastal states of the country, but the three states of the Yucatán peninsula hold over half of Mexico's total area. On the Pacific coast, the northernmost presence of mangroves is on the coast of Baja California. The changes in the extent of the country's mangrove forests over time are summarized in Fig.2 below.

As can be seen in Fig.2, the protection that the Mexican System of Protected Areas has afforded to coastal ecosystems, preventing their conversion to other land uses, has been extremely important. Up to the 1980s, only a very small fraction of Mexican mangrove forests was protected; between the 1980s and 2005, over 82,000 ha of those were converted to other land uses. By 2005, some 45% of the remaining mangrove forests had been included in protected areas and, since then, their extent has remained essentially constant and even increased slightly from 2010 to 2015. The major drivers of mangrove loss have been land-use changes associated with shrimp and fish-farming, agriculture, port infrastructure, tourism, and urban development. Despite Mexican regulations aimed at protecting mangroves, there are several areas where they face risk of loss due to coastal development (*e.g*., in the States of Jalisco, Colima, Nayarit, Michoacán, Guerrero, Baja California Sur, Quintana Roo and Yucatán). In addition, most of Mexican mangrove areas are threatened by high nutrient loads and low turbidity and, in many areas (*e.g*., in the States of Jalisco, Colima, Quintana Roo and Yucatán) they are threatened by coastal squeeze. In the Gulf of Mexico region, mangroves are threatened by oil spills and oil and natural gas extraction whereas in the North Pacific are threatened by the expansion of aquaculture activities (CEC, 2016; Valderrama-Landeros *et al*., 2017).

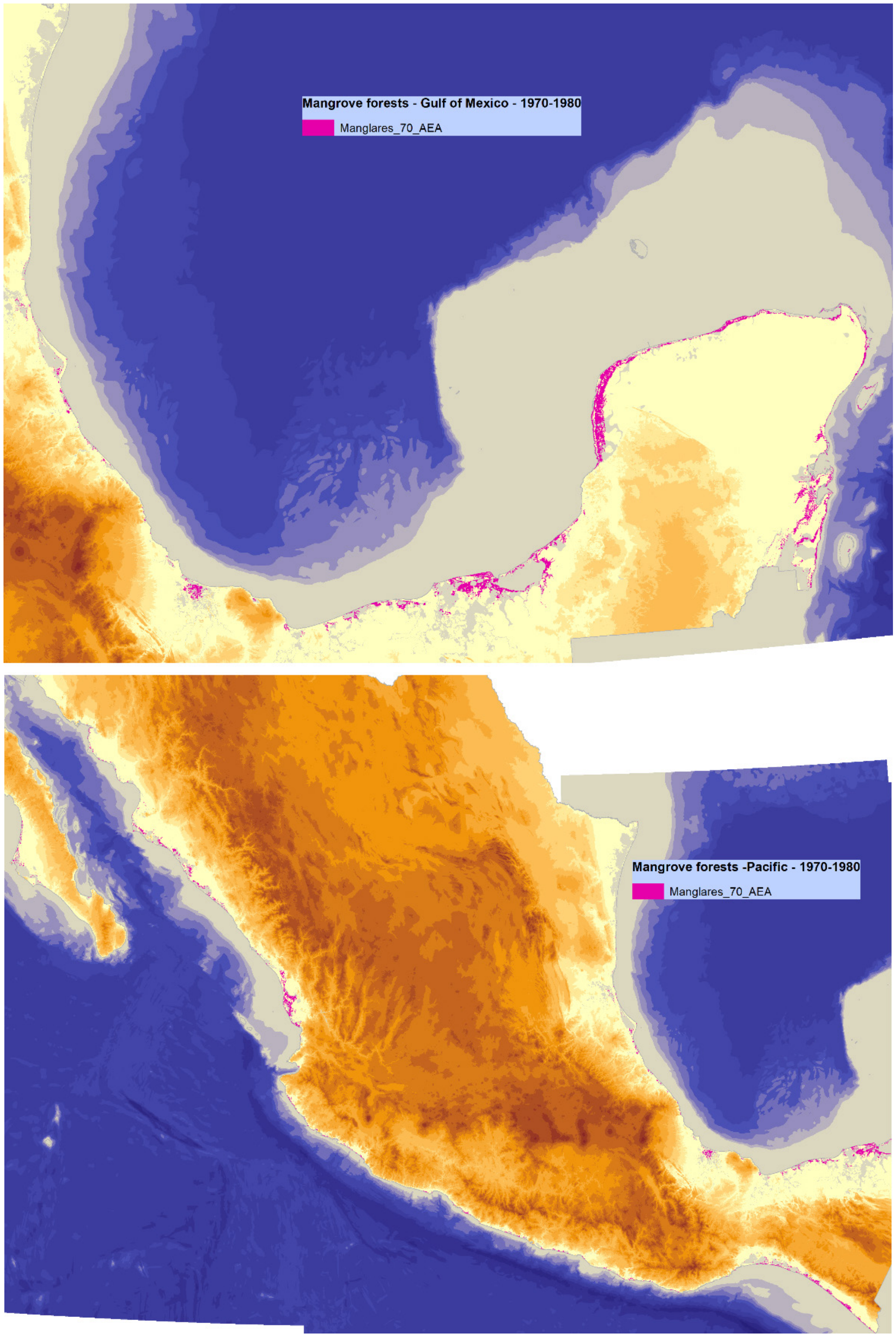


Fig. 1a Geographic distribution of mangrove forests in Mexico as of 1970/1980. Upper panel: Gulf of Mexico coast; bottom panel: Pacific coast.

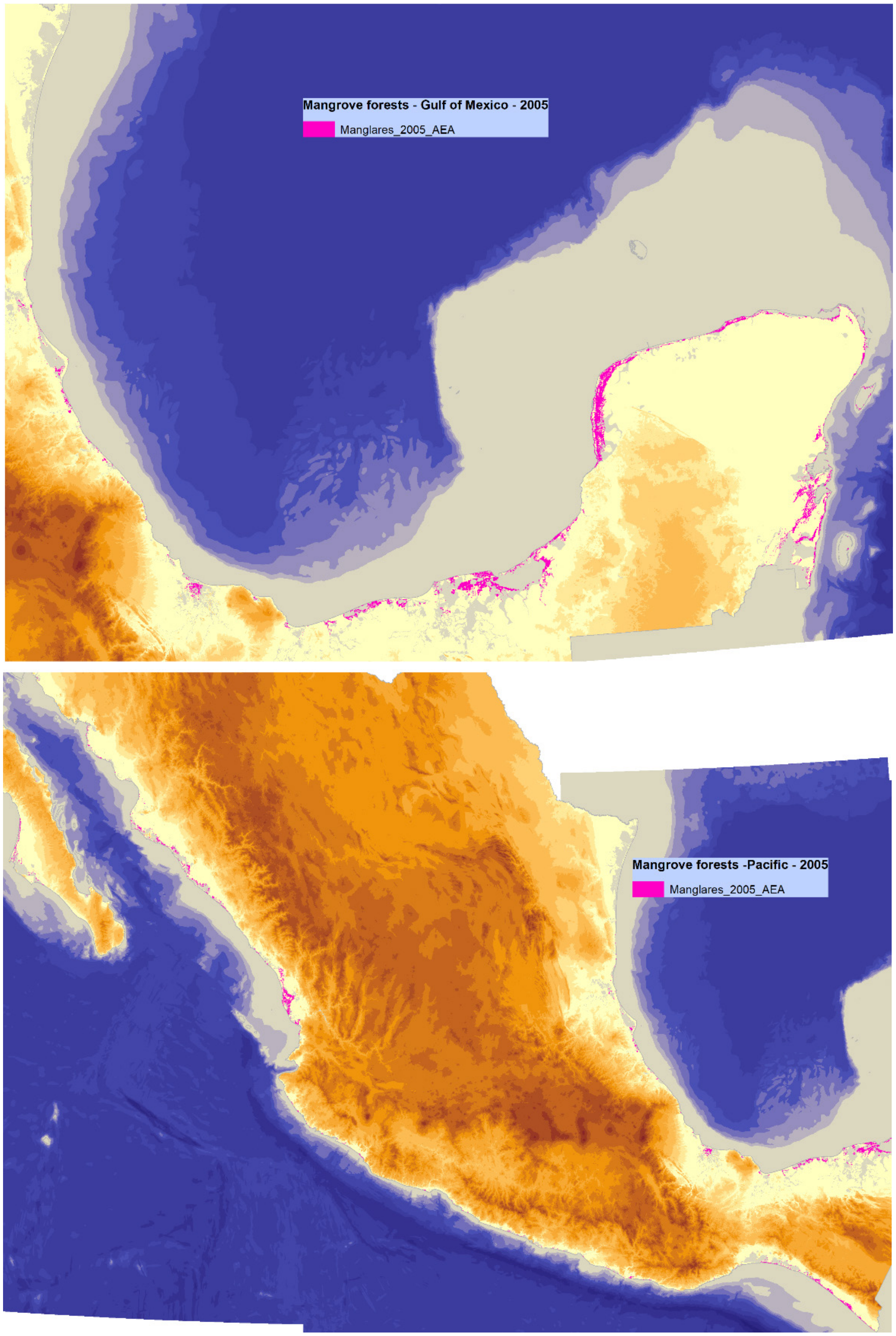


Fig. 1b Geographic distribution of mangrove forests in Mexico as of 2005. Upper panel: Gulf of Mexico coast; bottom panel: Pacific coast.

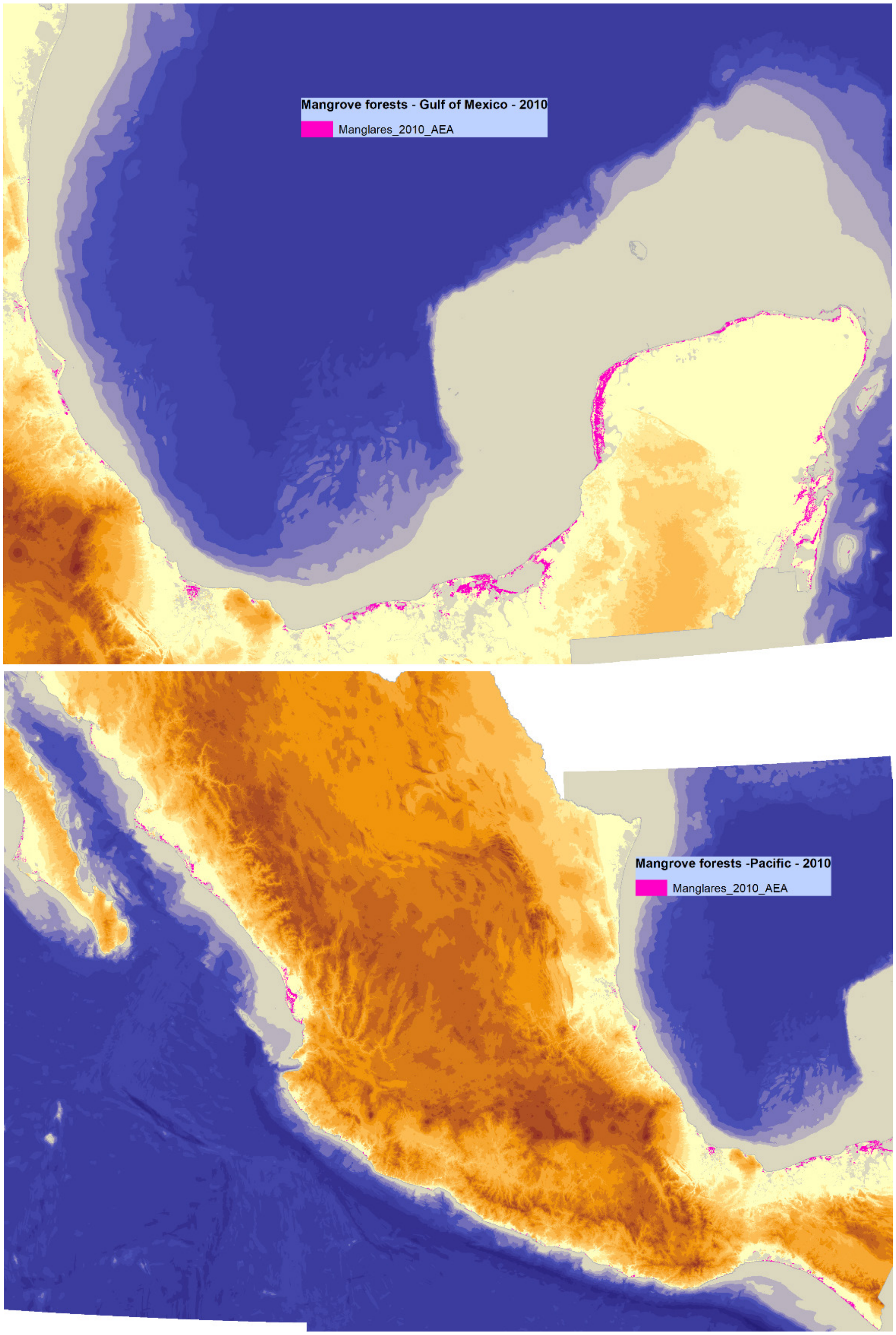


Fig. 1c Geographic distribution of mangrove forests in Mexico as of 2010. Upper panel: Gulf of Mexico coast; bottom panel: Pacific coast.

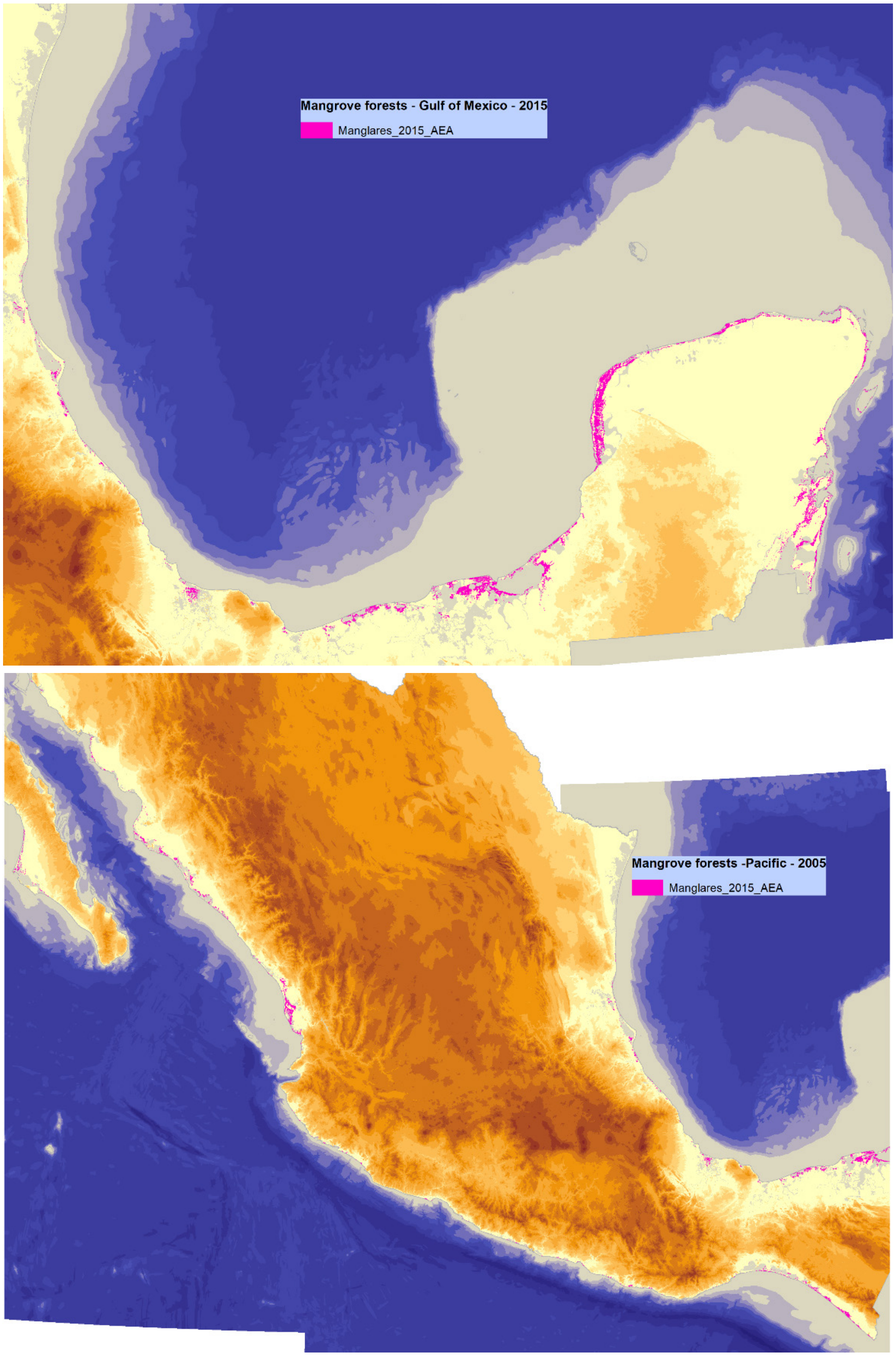
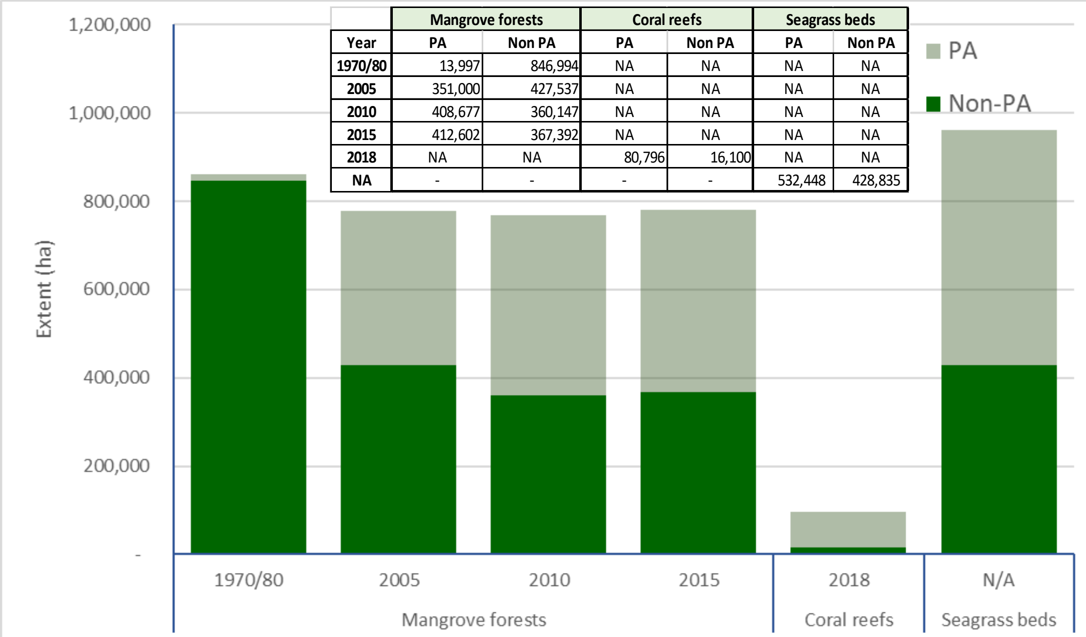


Fig. 1d Geographic distribution of mangrove forests in Mexico as of 2015. Upper panel: Gulf of Mexico coast; bottom panel: Pacific coast.



	Mangrove forests		Coral reefs		Seagrass beds	
Year	PA	Non PA	PA	Non PA	PA	Non PA
1970/80	13,997	846,994	NA	NA	NA	NA
2005	351,000	427,537	NA	NA	NA	NA
2010	408,677	360,147	NA	NA	NA	NA
2015	412,602	367,392	NA	NA	NA	NA
2018	NA	NA	80,796	16,100	NA	NA
NA	-	-	-	-	532,448	428,835

Figure 2 Changes in the extent (in ha) of Mexico's mangrove forest ecosystems over time and approximate extent of coral reefs and seagrass beds. PA: Protected areas.

Fig.3 shows the approximate geographic distribution of seagrass beds in Mexico. This map shows only the largest patches of this ecosystem type, as smaller patches are known to occur in many other localities (particularly on the Pacific coast), but their spatial extent has not been mapped yet. As can be seen, extensive seagrass meadows exist in the Yucatan peninsula and the coast of the Gulf of Mexico. Vast seagrass beds are also known to occur in the temperate Gulf of California and other parts of the Pacific coast of Mexico but most of those have not been mapped, largely due to the logistic challenges involved in surveying this submerged habitat. In particular, additional mapping efforts have to be made along the Gulf of California and the Pacific coast, where point data are available documenting presence of seagrass but no areal mapping has been done (CEC, 2016).

The approximate extent of seagrass beds is also shown in Fig.2. Some 9,613 km^2 of seagrass meadows have been mapped along Mexican coasts but, as stated above, these figures do not reflect their actual, present day extent as the occurrence of many patches has been recorded but their extent has not been estimated. Seagrass beds are one of the major data gaps in the knowledge of coastal habitats worldwide, and their spatial extent is largely underrepresented in the data available (CEC, 2016; Ruiz-Frau *et al.*, 2017). It is estimated that about half of the seagrass beds occurring in North America have not been surveyed for spatial distribution and extent (CEC, 2016). In addition, these figures come from a compilation of results from various different studies and surveys conducted at different points in the past so that their present-day status cannot be ascertained.

Seagrass beds are among the world's most threatened ecosystems; their extent has been declining steadily and, yet, those impacts are poorly known because of the logistic difficulties for monitoring these ecosystems (Orth *et al.*, 2006; Waycott *et al.*, 2009; Barbier *et al.*, 2011; Ondiviela *et al.*, 2014; CEC, 2016; Nordlund *et al.*, 2016; Nordlund *et al.*, 2018). Vast expanses of seagrass meadows have been lost in North America as a direct or indirect consequence of coastal development and anthropogenic pressures such as pollution, land-cover change, and direct physical impacts. In Mexico, the Gulf of California has extensive seagrass meadows, many of which are under threat from agricultural run-off and lack of management. In the Yucatan peninsula and the Gulf of Mexico coast, extensive seagrass habitat is being lost rapidly. In addition, North American seagrass meadows are threatened by high water turbidity and phytoplankton concentration, driven in part by nutrient loading. Nitrogen over-enrichment results in proliferation of phytoplankton blooms, which decrease water clarity and prevent light from reaching seagrass beds on the sea floor. In near-shore areas, excess Nitrogen-loading often derives from human sources such as wastewater treatment facilities, watershed runoff, agriculture, etc. Climate change is also adversely affecting seagrass distribution and health world-wide, via bleaching, storms, temperature stress, and species migration (CEC, 2016). As Fig.2 shows, a significant portion of Mexico's seagrass meadows occur outside of protected areas.

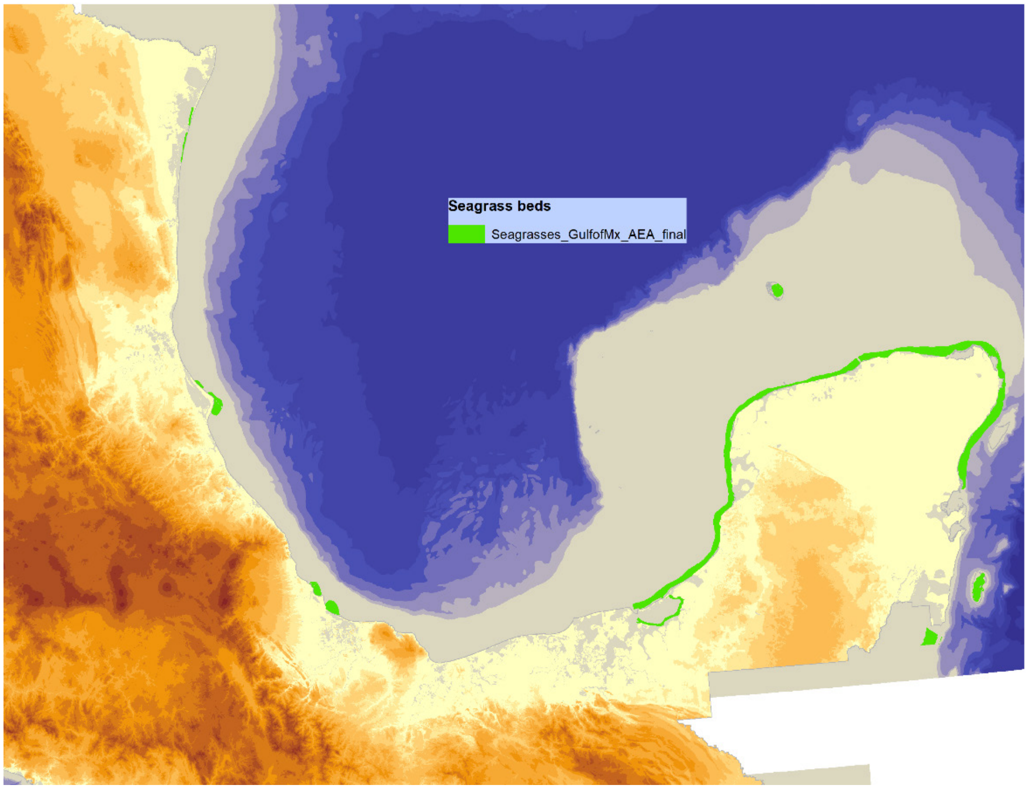


Fig. 3. Approximate geographic distribution of seagrass beds in Mexico. Other smaller patches of seagrasses also occur along the Pacific coast but their extent has not yet been documented.

Fig.4 shows the approximate geographic distribution of coral reefs in Mexico. These are concentrated in four main areas: The Campeche Bank and the Caribbean Sea (Fig.4a); the nearshore reefs between Tampico and Veracruz in the Gulf of Mexico (Fig. 4b); and the Gulf of California (Fig.4c). The most extensive reef development in the country is in the state of Quintana Roo on the east coast of the Yucatan Peninsula. Cozumel Island is a relatively large island with a number of reefs on both windward and leeward shores.

The approximate extent of coral reefs is also shown in Fig.2. Some 97 thousand hectares of coral reefs have been mapped along Mexican coasts but, as stated above, these figures do not reflect their actual, present day extent as these figures come from a compilation of results from various different studies and surveys conducted at different points in the past so that their present-day status cannot be ascertained.

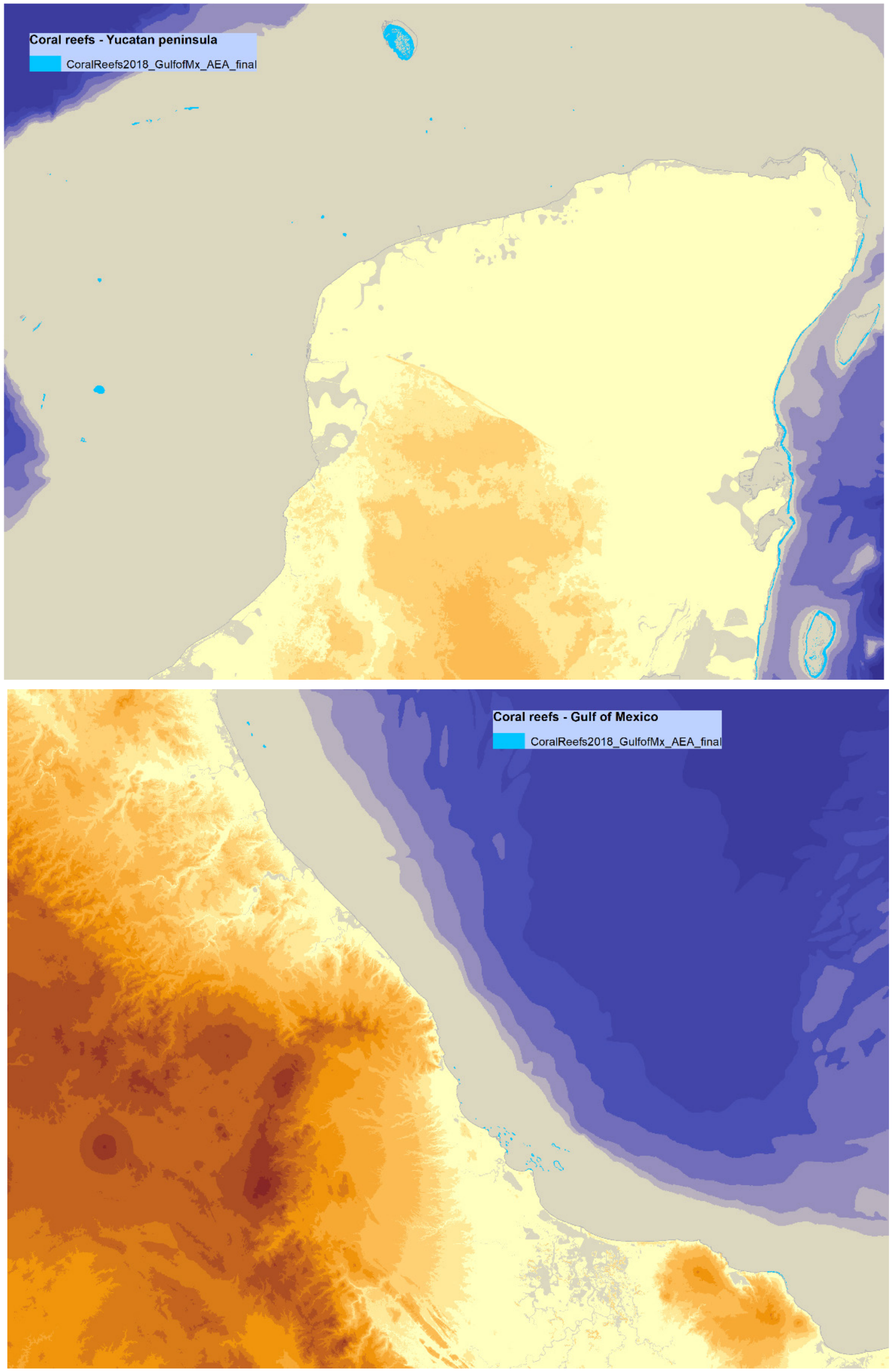


Fig. 4. Geographic distribution of coral reefs in Mexican coasts. 4a) Upper panel: Campeche Bank and the east coast of the Yucatan Peninsula; 4b) Bottom panel: Gulf of Mexico.

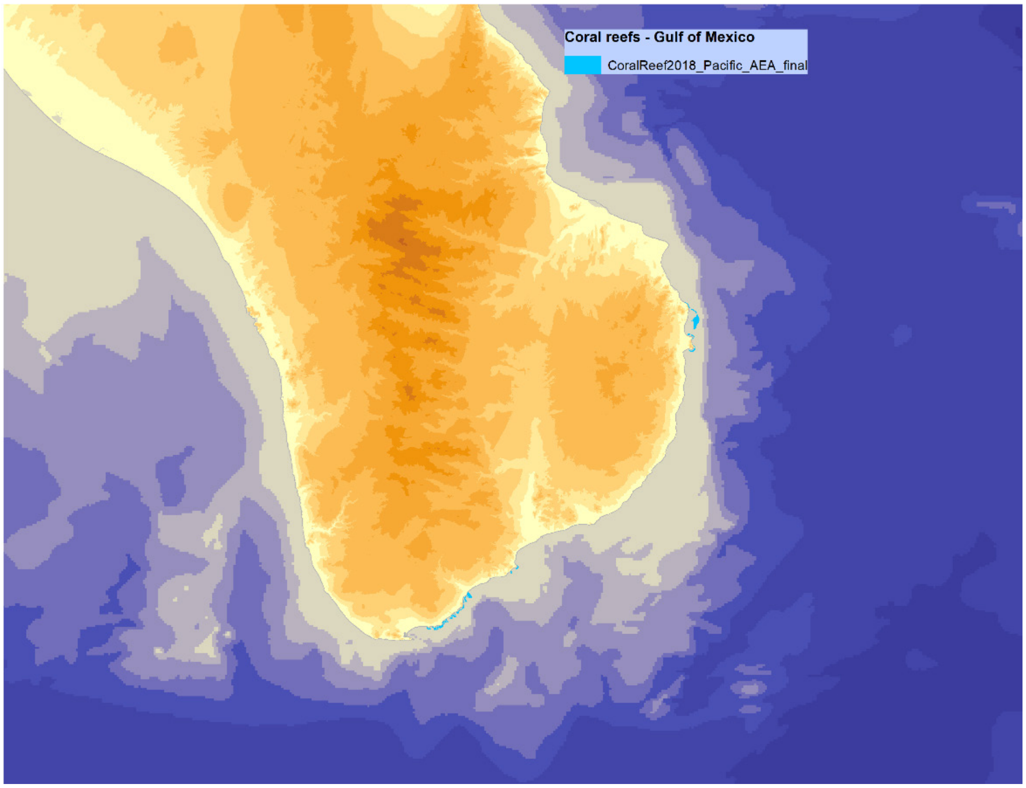


Fig. 4 (cont.). Geographic distribution of coral reefs in Mexican coasts. 4c) Southern end of the Baja California peninsula.

Despite the numerous benefits that coral reefs provide, deterioration of these ecosystems due to human activities is intense and increasing worldwide; some 30% of coral reefs have been either lost or degraded worldwide (UNEP, 2006; Barbier *et al*., 2011; Burke *et al*., 2011; Elliff & Kikuchi, 2017; Elliff & Silva, 2017; Beck *et al*., 2018). The major threats to Mexican coral reefs also derive from human activities, compounded by natural disturbances, although no recent assessment of their condition seems to be available. Over a decade ago, the GEF/World Bank Mesoamerican Barrier Reef System Initiative identified 1) inappropriate coastal development and unsustainable tourism; 2) inappropriate inland resource and land use and industrial development; 3) over-fishing and inappropriate aquaculture; 4) inappropriate port management, shipping and navigation practices; and 5) natural oceanographic and meteorological phenomena as the main threats to the coral reefs of Belize, Guatemala, Honduras and Mexico (World Bank, 2007). Coral reefs in the Mexican Caribbean have suffered from intense fishing activities since the 1960s and increasing pressure from tourism since the mid 1970s. Arrivillaga and García (2004) pointed out that anthropogenic impacts derived from tourism development include boat groundings, alteration of the coastal fringe, loss of mangroves, direct damage and pressures from tourist divers, and the resulting loss of protection from storms. Reef patches at Isla Mujeres have been affected by tourism-related activities and similar damages are spreading elsewhere (*e.g.*, to Akumal, Puerto Morelos, Mahahual and Cozumel). Shallow reefs at Cancun, Sian Ka'an and Banco Chinchorro have been affected by boat-related damage. The reefs just off the northern tip of the Yucatan Peninsula and immediately westward (Punta Mosquito, Boca Nueva, Piedra Corrida) have very little (<2%) live hard coral cover (Garcia-Salgado *et al*., 2008). Fortunately, as Fig.2 shows, most of Mexico's remaining coral reefs have become recently included in protected areas.

3. Ecosystem condition

Unfortunately, no data are available to assess the condition of Mexican coastal ecosystems and its changes over time. During the course of their latest inventory of mangrove forests in Mexico (as of 2015), the SMMM made an additional effort to also distinguish and map degraded from well-preserved mangrove forests. However, these data are not entirely comparable with data for previous years and were not included in this analysis. Hopefully, the next iteration of the mangrove monitoring programme will produce updated data that will allow, for the first time, assessing how the extent of well-preserved and degraded mangroves in Mexico changes over time.

No similar data are available for coral reefs and seagrass beds, unfortunately. As mentioned above (and references therein), the health of coral reefs has been deteriorating over the last decade due to numerous factors including increasing temperature and water acidity (leading to coral bleaching and decalcification, respectively), invasive species (such as lion fish in the Caribbean), diffuse contamination from inland agriculture, etc. Even less information is available about the condition of seagrass meadows and how this has changed over time, not only in Mexico but worldwide. It would be most important to count on data describing how the health of these key coastal ecosystems is changing over time.

4. Mapping and assessing the role that Mexican coastal ecosystems play in reducing coastal vulnerability

As discussed above in section **1. Introduction and justification**, the vulnerability of coastal zones to erosion and flood caused by storms, wind and waves is a complex phenomenon resulting from various geomorphologic, ecological, and hydrodynamic characteristics and processes that vary greatly among locations, times, and scales. This complexity makes modeling coastal vulnerability —and the role that natural ecosystems play in attenuating it— in quantitative, spatially-explicit terms, inherently technically difficult. This is further compounded by the amount of field measurements and data (time series data on wave height and length, water depth, tidal height, wind velocity, beach slope, ecosystem extent and structure, etc.) that are necessary for fitting the models and which are seldom available for different locations or conditions.

For this pilot study, I initially tried to follow the five-step approach recommended by the WAVES programme (WorldBank, 2016) for estimating coastal protection benefits afforded by natural coastal ecosystems. My extensive (although by no means exhaustive) search for relevant data showed that no local data are available for properly fitting the models (*e.g.*, SWAN, DELFT3d, etc.) aimed to estimate the effect of natural coastal ecosystems on the nearshore hydrodynamics (third step in the WAVES modelling approach). In fact, I was able to find only a couple of studies in which the full WAVES modeling approach has been implemented in practice, one on mangroves in Philippines (Losada *et al.*, 2017) and another one on coral reefs worldwide (Beck *et al.*, 2018). For this reason, in the end I limited the scope of this pilot study to assessing, in relative terms, the susceptibility (exposure) to erosion and flooding of Mexican coasts using basic geophysical information and, from that, assess in relative terms the role that coastal ecosystems play in reducing such risks. Of the several index-based approaches currently available for this purpose, I chose the Exposure Index (EI) implemented as part of the Coastal Vulnerability Module of the InVEST system (Sharp *et al.*, 2018).

The Exposure Index is, in fact, an expanded modification of the Coastal Vulnerability Index (CVI) and model that was originally developed by the U.S. Geological Survey as an easy-to-implement tool to assess the vulnerability of US coasts to sea level rise (Hammar-Klose & Thieler, 2001). The USGS scheme ranks each segment of the coastline as to its relative vulnerability to sea-level rise with respect to six geophysical variables: Tidal range, wave height, coast slope, erosion rate, coastal geomorphology, and rate of sea level rise. Each of these variables is assessed (in relative terms) at equidistant points along the coastline using a 5-point ordinal scale denoting increasing levels of risk (R_i). The CVI is then computed, for each point along the coastline, as:

$$CVI = \frac{\sqrt{R_{TidalRange} * R_{WaveHeight} * R_{CoastSlope} * R_{Erosion} * R_{Geomorphology} * R_{SeaLevelRise}}}{6}$$

CVI values can then be mapped to show the relative vulnerability to sea level rise of each segment of the coastline.

The CVI assesses coastal vulnerability to sea level rise only, based only on geophysical variables. The Coastal Vulnerability Model of the InVEST system is a modification of the Hammar-Klose & Thieler, 2001 approach. It also includes geophysical variables (viz., coastal geomorphology, relief [local bathymetry and topography], and sea level rise), but also takes into account the effects of storms and hurricanes (by including data on wind and wave forcing associated with storms), as well as the protective role of coastal ecosystems (by including information on the location and extent of such entities). Beyond that, the InVEST's Coastal Vulnerability Model is operationally identical to the USGS's CVI: Each of the variables is assessed (in relative terms) at equidistant points along the coastline using a 5-point ordinal scale denoting increasing levels of risk. The Exposure Index (EI) to flood, erosion and sea level rise is then computed, for each point along the coastline, as the geometric mean of the ranks of the seven variables:

$$EI = \sqrt[7]{R_{Geomorphology} * R_{Relief} * R_{Habitats} * R_{SeaLevelRise} * R_{WindExposure} * R_{WaveExposure} * R_{SurgePotential}}$$

The Exposure Index denotes the exposure to erosion and flood caused by storms, of a given coastline segment relative to all other shore segments in the study area. It is an ordinal index, the values of which range from 1 (lowest risk) to 5 (highest risk). EI values can then be mapped to examine the different levels of exposure along the coastline, differentiate areas with relatively high or low exposure and identify those that would be most at risk to coastal hazards. EI maps can then be coupled with maps showing population distribution, infrastructure, properties, etc. to examine their vulnerability (exposure) and identify those areas where coastal populations, infrastructure, etc. would be more or less threatened by storm waves and surge.

Finally, the relative role that coastal habitats/ecosystems play at reducing exposure to flood and erosion can be examined by assessing EI with the presence of coastal ecosystems (Scenario0) and then repeating the assessment in the (simulated) absence of coastal ecosystems (Scenario1). The difference between Scenario0 and Scenario1 provides a spatially explicit assessment, in relative terms, of the exposure reduction that coastal ecosystems provide. Results from these analyses can shed light on how the conversion or development of coastal habitats and ecosystems would increase the exposure of human populations and assets to flood and erosion; can then be used to inform development plans and permitting criteria; and, by explicitly highlighting the protective services that natural ecosystems provide to coastal populations, would help to better appreciate these ecosystem services.

Despite the obvious shortcoming of being a qualitative —and, to some extent, subjective— approach, the EI (and other similar index-based approaches) can be applied in those cases where detailed, relevant data are not available or sufficient, as is the case of many developing countries (Cabral *et al*., 2017). The InVEST Coastal Vulnerability Model has been recently used in a number of studies ranging from the local (*e.g.*, Guerry *et al*., 2012; Hopper & Meixler, 2016; Elliff & Kikuchi, 2017; Marchant, 2017), country-wide (Arkema *et al*., 2013; Cabral *et al*., 2017), to the worldwide (Chaplin-Kramer *et al*., 2019) level. In fact, the InVEST Coastal Vulnerability Model is, nowadays, perhaps the approach most widely used for assessing coastal vulnerability and the coastal protection services provided by ecosystems.

Data and procedure

Shoreline.- Mexico's shorelines were extracted from INEGI's Physiography - topoform system, scale 1:1'000,000, map. To accurately model coastal risk, I generated shoreline sampling points every 1km along the Pacific and the Atlantic (encompassing the Gulf of Mexico and the Mexican Caribbean) coasts of the country. The two coasts were separately analyzed.

Geomorphology.- To describe the susceptibility of Mexico's shoreline to erosion and flooding, I ranked the relative exposure of the different coastal topoforms recorded in INEGI's Physiography - topoform system, scale 1:1'000,000, map in terms of a 5-point ordinal variable ($R_{Geomorphology}$) where 1 denotes "very low risk" and 5 "very high risk". Ranks were assigned following the exposure scheme proposed by Hammar-Klose & Thieler, 2001, as modified in the InVEST system (Sharp *et al.*, 2018).

Relief.- Mexico's relief was described using INEGI's 15m resolution Digital Elevation Model (Continuo de Elevaciones Mexicano) and INEGI's 400m resolution Digital Bathymetry Models for Mexico's Exclusive Economic Zone. These raster files were first reprojected from their native Coordinate Reference System to the one used for this project (Albers Equal-area conic projection), resampled to a common 100m resolution, and mosaicked to produce a continuous, single raster file (R_{Relief}) describing (in terms of elevation/depth values) the relief of the country's terrestrial and marine territory.

Coastal habitats.- Coastal ecosystems ($R_{Habitats}$) included in these analyses were mangrove forests as mapped (as of 2010 and 2015) by CONABIO's mangrove monitoring system, and seagrass meadows and coral reefs as mapped in WCMC's data sets on the global distribution of seagrass beds and warm-water coral reefs, respectively. I segmented the WCMC polygon data sets as per Mexico's Exclusive Economic Zone to identify the seagrass meadows and coral reefs present in the country's coasts and waters.

To assess the exposure risk offset that the presence of coastal ecosystems provide, a risk offset score and a maximum effect distance should be assigned to each ecosystem type. The offset score denotes, in relative terms, the exposure reduction or protection that the presence of the ecosystem provides, whereas the distance denotes how far the ecosystem can offset exposure risk from the edge of its extent. Following previous, similar studies (Guerry *et al.*, 2012; Arkema *et al.*, 2013; Hopper & Meixler, 2016; Cabral *et al.*, 2017; Elliff & Kikuchi, 2017; Marchant, 2017; Chaplin-Kramer *et al.*, 2019), I assigned the following scores and distances: Mangrove forests: 1, 1500m; coral reefs: 1, 1000m; seagrass meadows: 4, 500m.

Sea level rise.- Sea level rise ($R_{SeaLevelRise}$) was not considered in this pilot study.

Wind exposure.- In the InVEST system, the relative level of risk due to wind exposure is assessed in terms of the Relative Exposure Index (REI) proposed by Keddy, 1982. In simple terms, REI is the product of the average wind speed, wind duration and the distance over which wind blows uninterruptedly over water to the sampling point on the shore. The wind speed and wind duration data are derived from the US-NOAA's WaveWatchIII wave prediction model; WaveWatchIII data for the period 1999-2007 have been compiled and pre-processed and are supplied as part of the InVEST system installation. Distance values are dynamically derived during process by tracing 16 rays from each sampling point in different cardinal directions until they intersect with land or travel more than 12km. Once the REI values for the entire study area have been calculated, they are converted to a 5-point ordinal variable ($R_{WindExposure}$), where 1 denotes the least exposure due to wind and 5 the most exposed.

Wave exposure.- In the InVEST system, the relative level of exposure of a coastline segment to storm waves (an indicator of the potential for coastal erosion) is estimated as a function of the average power of oceanic and locally wind-generated waves. The power of oceanic waves is estimated from wave height and wave duration data, while that of locally wind-generated waves is estimated from wind speed and wind duration data; these estimations are made using data from the NOAA's WaveWatchIII wave prediction model. WaveWatchIII data for the period 1999-2007 have been compiled and pre-processed and are supplied as part of the InVEST system installation. Once the exposure-to-waves values for the entire study area have been calculated, they are converted to a 5-point ordinal variable ($R_{WaveExposure}$), where 1 denotes the least exposure due to wave erosion and 5 the most exposed.

Surge potential.- Storm surge (*i.e.*, the abnormal rise in seawater level during a storm) is determined by wind speed and direction but is also affected by how long the wind can blow over shallow areas before reaching the shore —the longer the distance, the higher the potential for storm surge. In the InVEST system, the surge potential at a given shoreline sampling point is estimated based on the distance from the shore point to the nearest edge of the continental shelf (hereby defined as where the bathymetry drops below 200m). Once all the surge potential distances for the entire study area have been calculated, they are converted to a 5-point ordinal variable ($R_{SurgePotential}$), where 1 denotes the least risk of surge due to a relatively short distance and 5 the most risk.

Population exposed.- Following previous studies, I considered the population most at risk for exposure to coastal hazards to be people living within 5 km of the coast. The Population Density ver. 4.11 data sets for 2010 and 2015 contained in NASA's 30 arc-second resolution Gridded Population of the World ver.4 collection were used for these analysis. This raster file was first reprojected from its native Coordinate Reference System to the one used for this project (Albers Equal-area conic projection) and clipped to the country's boundaries using INEGI's Physiography - topoform system, scale 1:1'000,000, map.

Role of coastal ecosystems to reduce exposure to flood and erosion.- The InVEST Coastal Vulnerability Model was run with and without coastal ecosystems. As described by Chaplin-Kramer *et al.*, 2019, the Exposure Index (EI) values calculated without coastal ecosystems represent the exposure from physical factors only and can be interpreted as the maximum potential coastal risk; EI values calculated with coastal ecosystems denote the remaining coastal risk that is not mitigated by the ecosystems; and the difference between the two is the fraction of the coastal risk that is reduced by the presence of coastal ecosystems…an indication of the coastal protection service they afford.

Results

Fig.5 shows the distribution of the Exposure Index along Mexico's coasts, comparing the currently existent (as of 2015) scenario with a hypothetical scenario without coastal ecosystems. As can be seen (Figs. 5a, c, e and g), in the absence of coastal ecosystems most of the Mexican coasts would be subject to high levels of exposure to flood and erosion, due to their physical (*e.g.*, wave and wind exposure) and geomorphologic features (*e.g.*, sandy beaches). The only exceptions to this pattern are the eastern and western coasts of the Yucatan peninsula (Fig.5c) and the eastern coast of the Baja California peninsula (Fig.5e) which would have moderate (Yucatan peninsula) or even low (Baja California peninsula) levels of exposure.

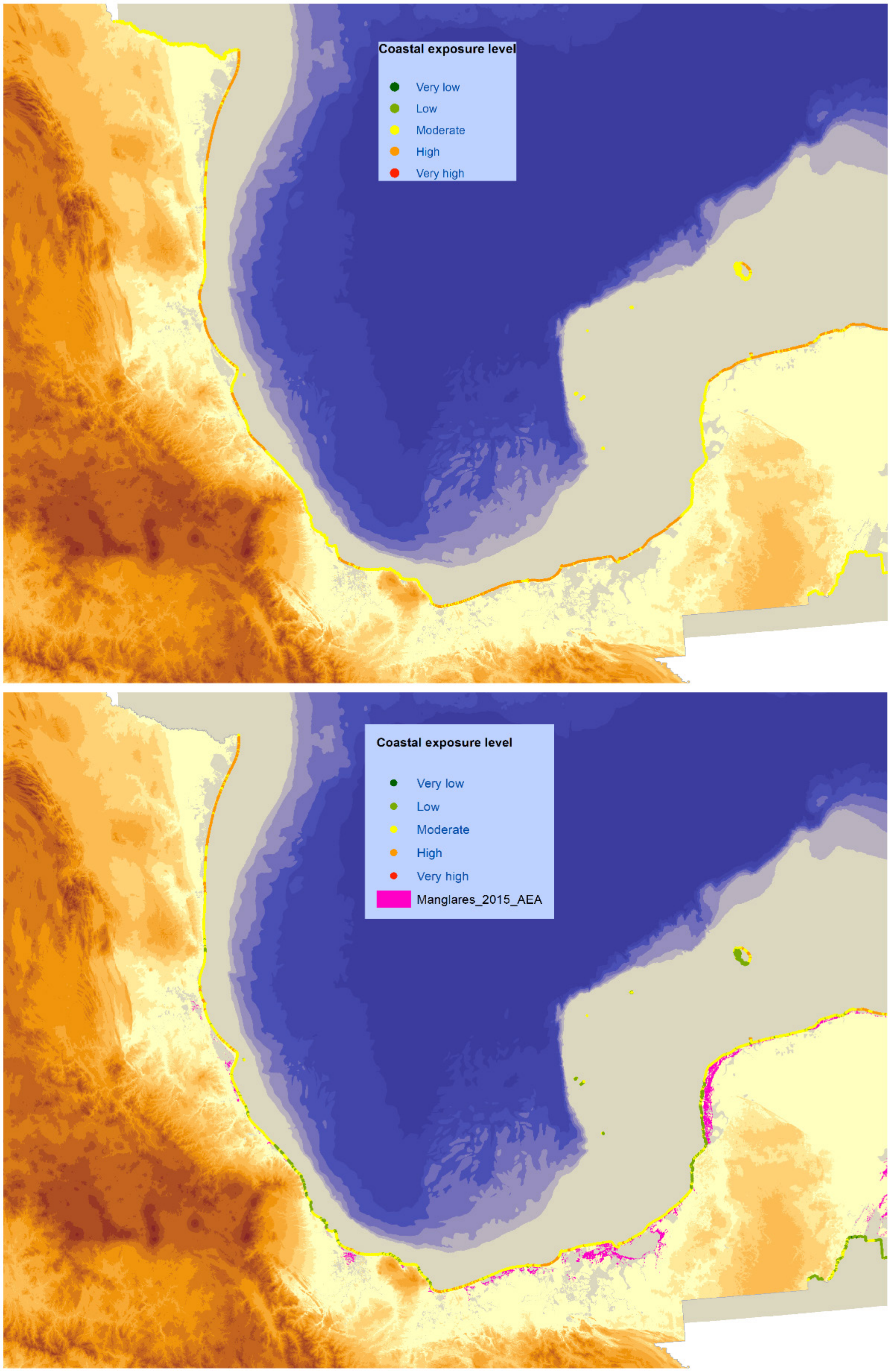


Fig.5. Relative levels of coastal exposure to flood and erosion along the Gulf of Mexico coast a) under a hypothetical scenario without coastal ecosystems (upper panel), and b) with currently existent (as of 2015) ecosystems (bottom panel). See explanation in the text.

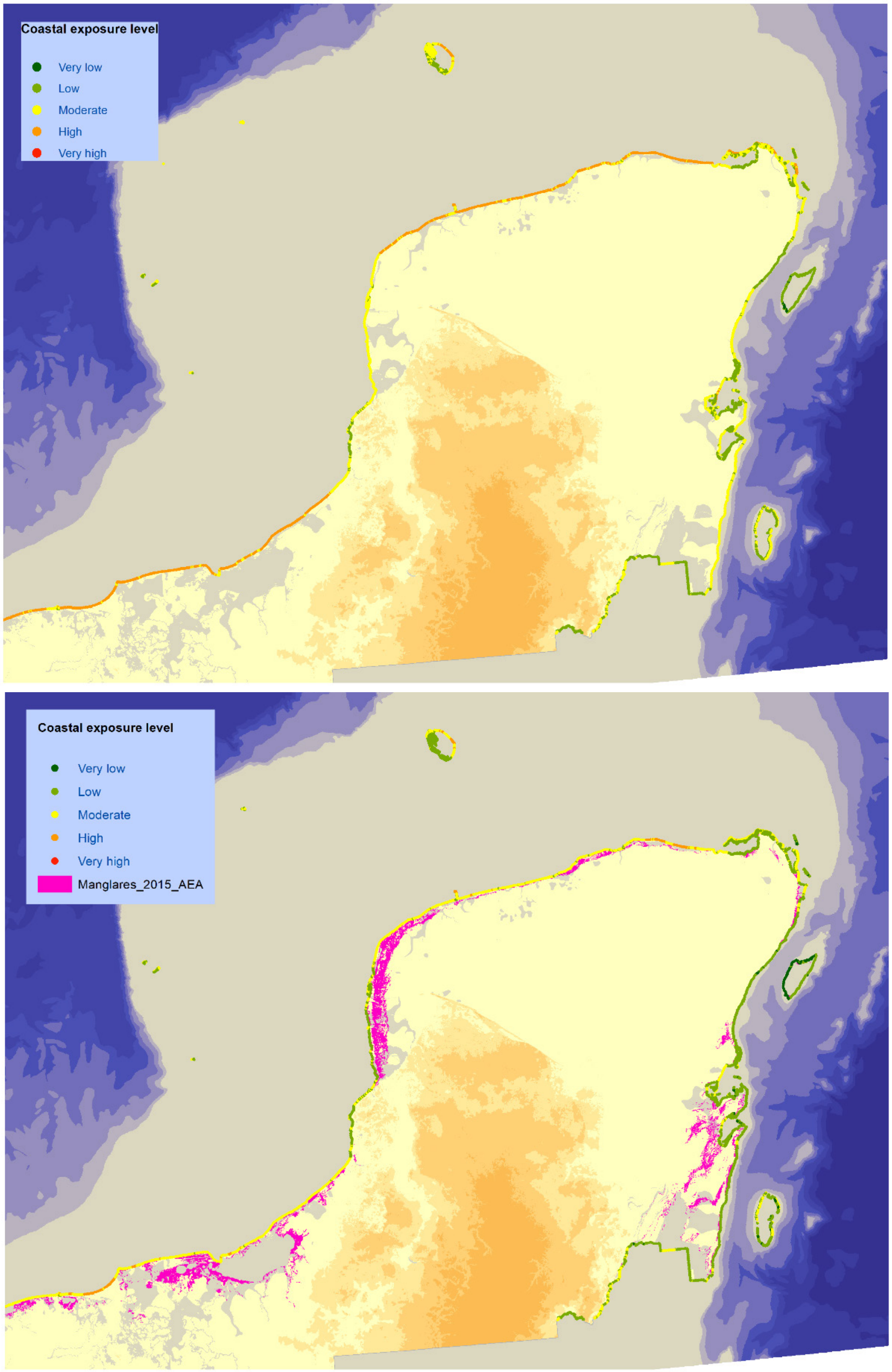


Fig.5 (cont.) Relative levels of coastal exposure to flood and erosion along the coast of the Yucatan peninsula c) under a hypothetical scenario without coastal ecosystems (upper panel), and d) with currently existent (as of 2015) ecosystems (bottom panel). See explanation in the text.

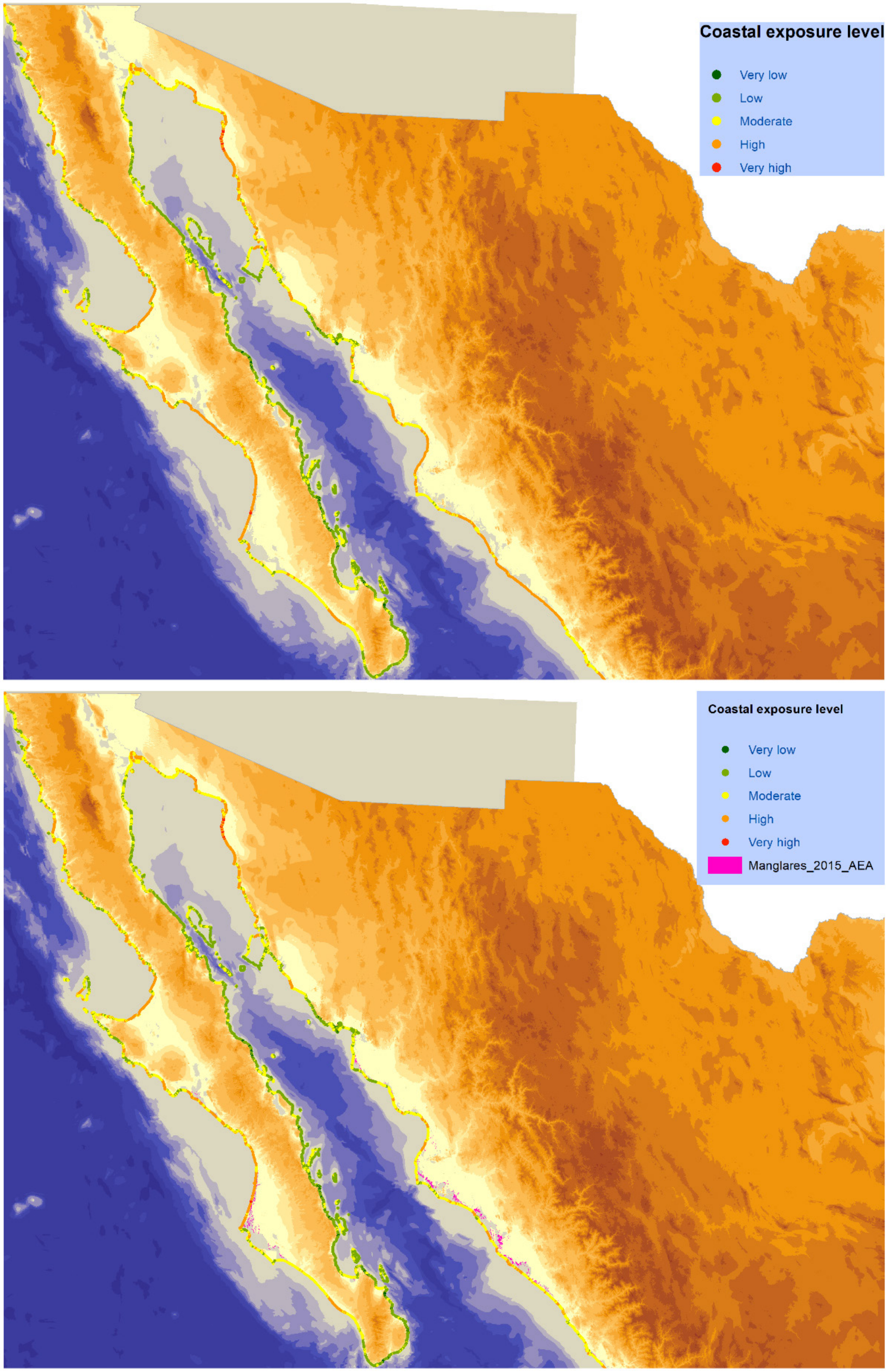


Fig.5 (cont.). Relative levels of coastal exposure to flood and erosion along the northern half of the Pacific coast, e) under a hypothetical scenario without coastal ecosystems (upper panel), and f) with currently existent (as of 2015) ecosystems (bottom panel). See explanation in the text.

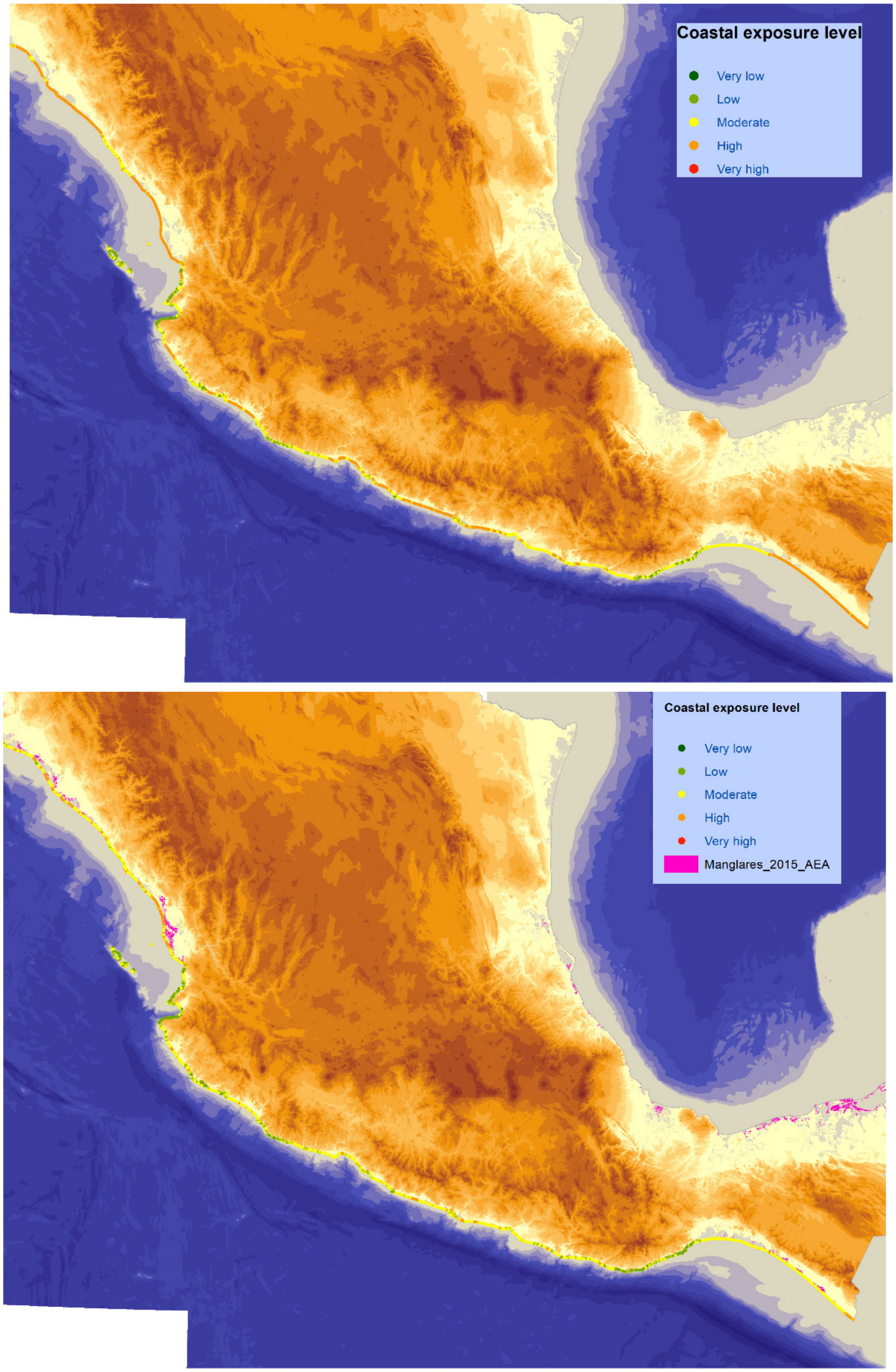


Fig.5 (cont.). Relative levels of coastal exposure to flood and erosion along the southern half of the Pacific coast, g) under a hypothetical scenario without coastal ecosystems (upper panel), and h) with currently existent (as of 2015) ecosystems (bottom panel). See explanation in the text

The role that coastal ecosystems play in reducing coastal vulnerability is particularly evident in most of the Gulf of Mexico coast, the northern coast of the Yucatán peninsula (Fig.5b), and the southern half of the Pacific coast (Fig. 5h). The high exposure that those zones would otherwise experience (*cf.* Figs. 5a and 5g) is reduced to a moderate level by the presence of mangrove ecosystems (and seagrass meadows in the Yucatán peninsula) and the attenuation of wave and wind exposure that these ecosystems provide. Similarly, the extensive mangrove forests, seagrass meadows and coral reefs present in the eastern and western coasts of the Yucatan peninsula reduce their level of exposure from moderate or low (Fig.5c) to low or even very low levels. These effects are all important as these are the parts of the country that are more frequently hit by hurricanes.

By contrast, the low level of exposure of the eastern coast of the Baja California peninsula (Figs. 5e, f) seems to be due more to its geomorphology and the low levels of wind and wave exposure and surge potential characteristically occurring in the Gulf of California. Only small patches of mangroves occur in this area and, thus, the two scenarios (with *vs.* without coastal ecosystems) do not differ markedly in exposure levels. Numerous small patches of seagrass beds are known to exist in this zone but these were not included in these analyses as they have not been mapped yet (see discussion above in section **2.Ecosystem extent**).

Even with the presence of coastal ecosystems, some parts of the country are subject to a high level of exposure. This is the case of the northernmost shores of the Gulf of Mexico (Fig.5a), the Pacific coast of the Baja California peninsula and the eastern coast of the Gulf of California (Fig.5c). Factors including the absence of protective coastal ecosystems, high wave and wind exposure, and geomorphologic features such as sandy beaches contribute to the relatively high vulnerability of these areas.

Table 2 shows the fractions of Mexico's coasts that are exposed to different levels of vulnerability under both the currently existent (as of 2010 and 2015) and the hypothetical no-ecosystems scenarios. The small changes between 2010 and 2015 are due to the small increase in mangrove coverage that has taken place recently, which translates into a minor reduction in the extent of coastline subject to high levels of exposure. The important role that coastal ecosystems play in reducing the level of exposure is clearly revealed by the hypothetical no-ecosystems scenario: Were it not for the presence of coastal ecosystems, 22.2% of the Gulf of Mexico coast and over 24.2% of the Pacific coast would experience high (and even very high) levels of exposure. The coastal protection effect provided by coastal ecosystems reduces these figures to just about 7% and 13.4%, respectively. The much larger extent of mangrove forests and coral reefs as well as the presence of seagrass meadows along the Gulf of Mexico coast account for the much larger risk reduction there.

Table 2. Fraction (as percentage of the total length of each coast) of Mexico's coasts subject to different levels of exposure to flood and erosion, under the currently existent conditions (as of 2010 and 2015) and a hypothetical scenario without coastal ecosystems.

	Gulf of Mexico			Pacific		
Exposure Index	**2010**	**2015**	**No ecosystems**	**2010**	**2015**	**No ecosystems**
Very low	2.5	2.5	0.3	1.0	1.0	0.7
Low	48.3	48.4	30.8	37.5	37.5	33.6
Moderate	41.9	41.9	46.7	47.9	48.0	41.5
High	7.3	7.1	22.2	13.4	13.3	24.0
Very high	-	-	-	0.2	0.2	0.2

Under the SEEA-EEA framework, benefits derived from ecosystem services are only realized — and enter the economy— when they are actually used (and benefitted from) by economic units (government, business, household, individual person). Therefore, the benefits (in terms of human well-being) and the beneficiaries of the coastal protection services provided by Mexico's coastal ecosystems should be identified and quantified. As discussed above (see section **1. Introduction and justification)**, the ability of coastal ecosystems to ameliorate or attenuate wind and wave exposure benefit human populations by protecting them —and their activities, infrastructure and assets— from coastal erosion and flood caused by storms. Relevant, spatially explicit data on activities, infrastructure and assets present in Mexico's coastal zones is, unfortunately, not available. For this reason, I used population exposed as a rough indicator of the users' demand for coastal protection services. For this purpose, I considered the population most at risk for exposure to coastal hazards to be people living within 5 km of the coast.

Fig.6 shows the density of people living along the Mexican coasts, expressed as the average population density (inhabitants/km^2) within a 5km radius around each sampling point, as of 2010 and 2015. These maps clearly show the location of the highest densities of people but the figures should not be taken at face value as there is significant overlap in the population counted in adjacent 1 km stretches of coastline. The small changes between the two dates are due to population growth and to minor shifts in their distribution. As can be seen, except for the major coastal cities such as Tampico (State of Tamaulipas), Veracruz and Coatzacoalcos (Veracruz State), Ciudad del Carmen (Tabasco State), Campeche (Campeche State), Progreso (Yucatán State) (Fig.6a); Cancún, Playa del Carmen and Cozumel (State of Quintana Roo, Fig.6b); Mazatlán (Sinaloa State, Fig.6c); Puerto Vallarta (Jalisco State), Manzanillo (Colima State), and Acapulco (Guerrero State (Fig.6d), population density in the immediate vicinity of the coastline is generally relatively low (<100 people/km^2). However, the high-density zones that coincide spatially with zones potentially subject to high coastal risks (see Figs. 5a, c, e g) are the places where the highest demand for the coastal protection ecosystem service exists. This is the case of the cities of Tampico, Coatzacoalcos and Ciudad del Carmen, Progreso and Cancún, all of them along the Gulf of Mexico and Mexican Caribbean coasts.

Table 3 shows the distribution of the coastal populations (separately for the Pacific and Gulf of Mexico coasts) across the different levels of coastal vulnerability under both the currently existent (as of 2010 and 2015) scenario and a hypothetical scenario in which coastal ecosystems are absent. These figures are given in proportional terms as it is impossible to attribute a 1 km stretch of coastline to the risk for people in surrounding areas and, in addition, there is significant overlap in the population counted in adjacent 1 km stretches of coastline. The role that coastal ecosystems play in protecting human populations inhabiting within 5km from the shoreline from coastal hazards is clearly revealed by the hypothetical no-ecosystems scenario: Were it not for the presence of coastal ecosystems, some 17% of the people along the Gulf of Mexico coast and almost 11% of those on the Pacific coast would be exposed to high (and even very high) levels of risk. The coastal protection effect provided by coastal ecosystems reduces these figures to just about 8% and 7%, respectively. The much larger extent of mangrove forests and coral reefs as well as the presence of seagrass meadows along the Gulf of Mexico coast account for the much larger protection benefit there.

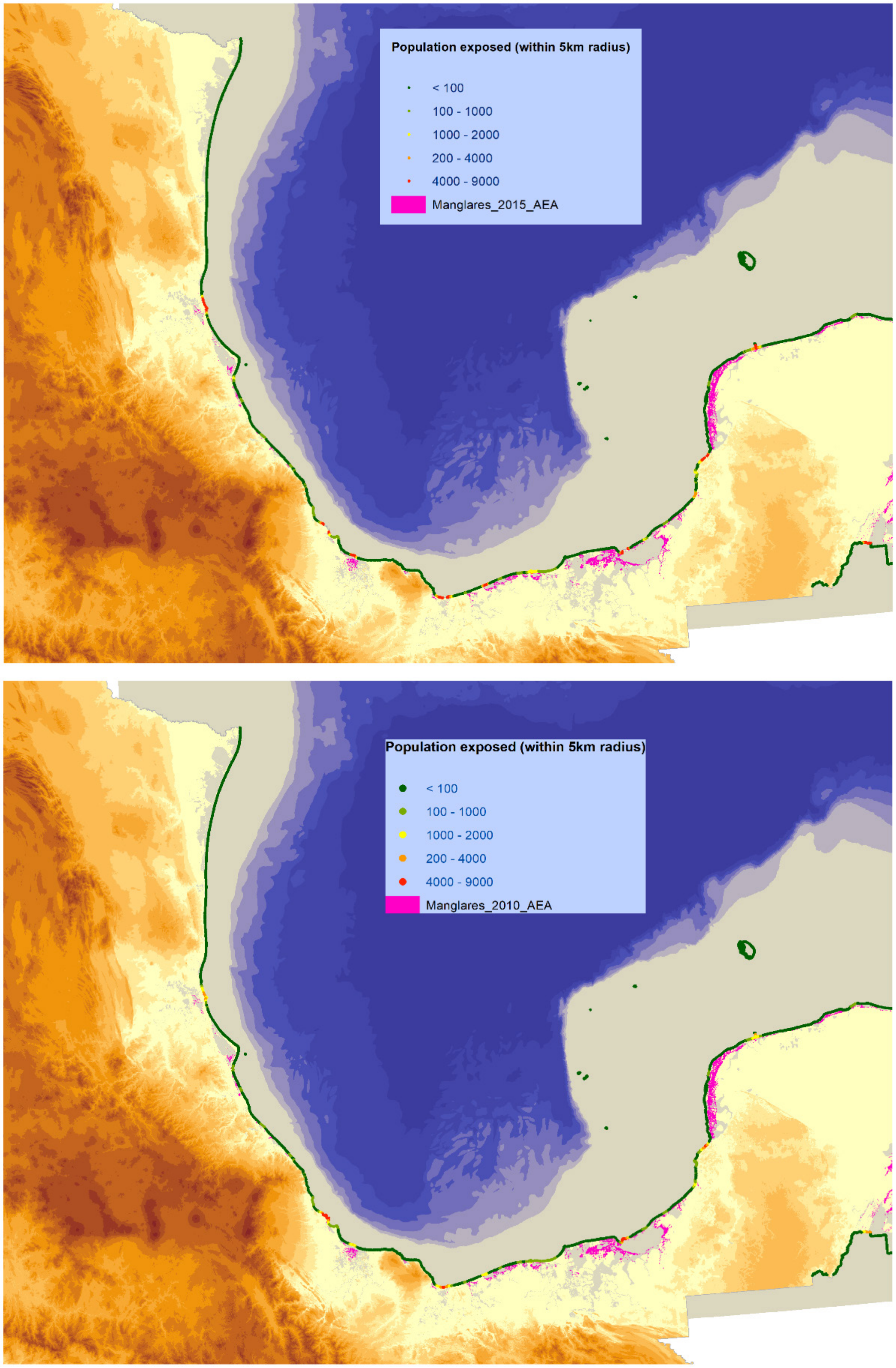


Fig.6a. Relative numbers (population density in the 5km adjacent to each sampling point along the coast) of people along the Gulf of Mexico coast, as of 2015 (upper panel) and 2010 (bottom panel).

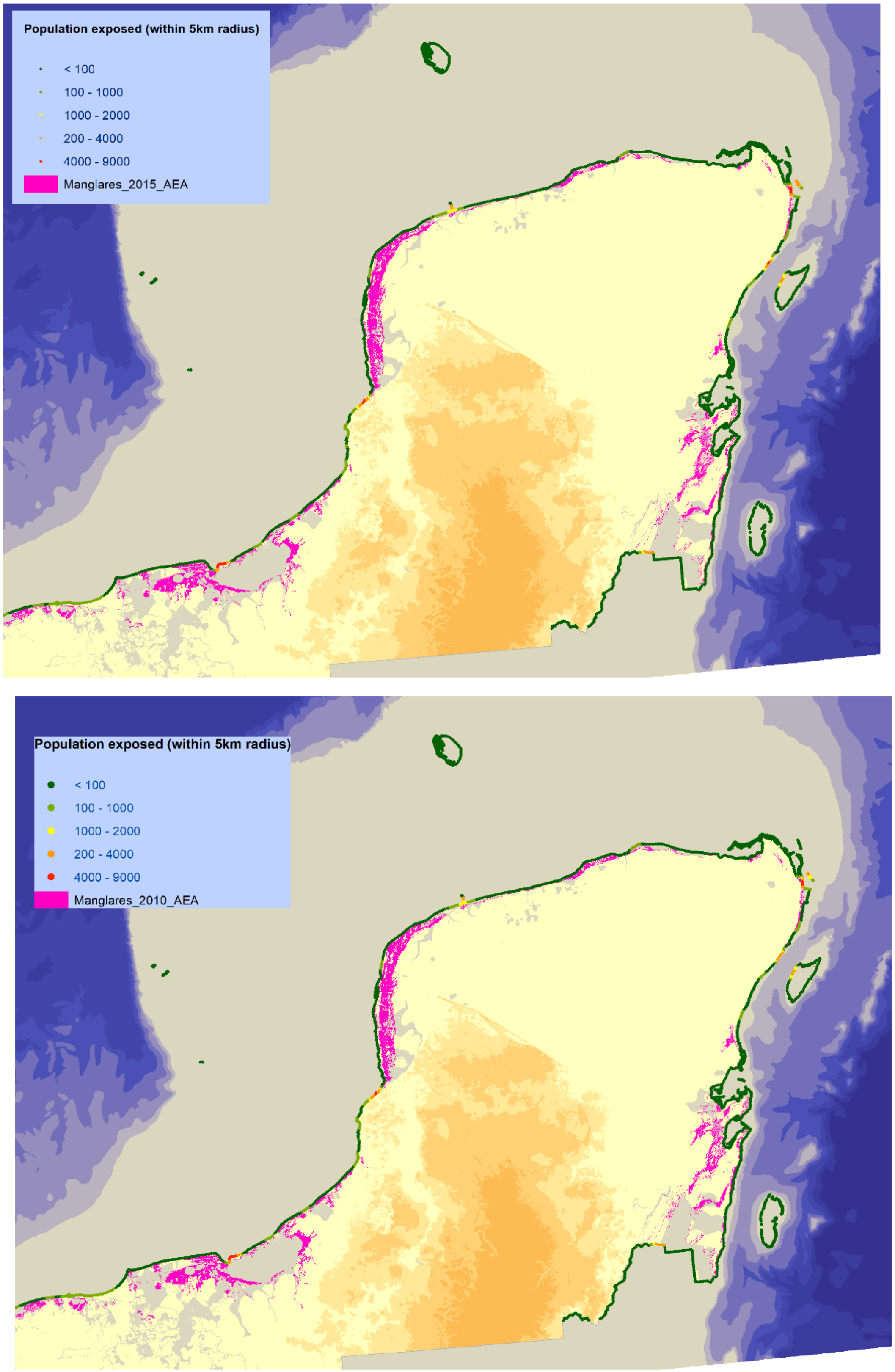


Fig.6b. Relative numbers (population density in the 5km adjacent to each sampling point along the coast) of people along the Yucatan peninsula coast, as of 2015 (upper panel) and 2010 (bottom panel).

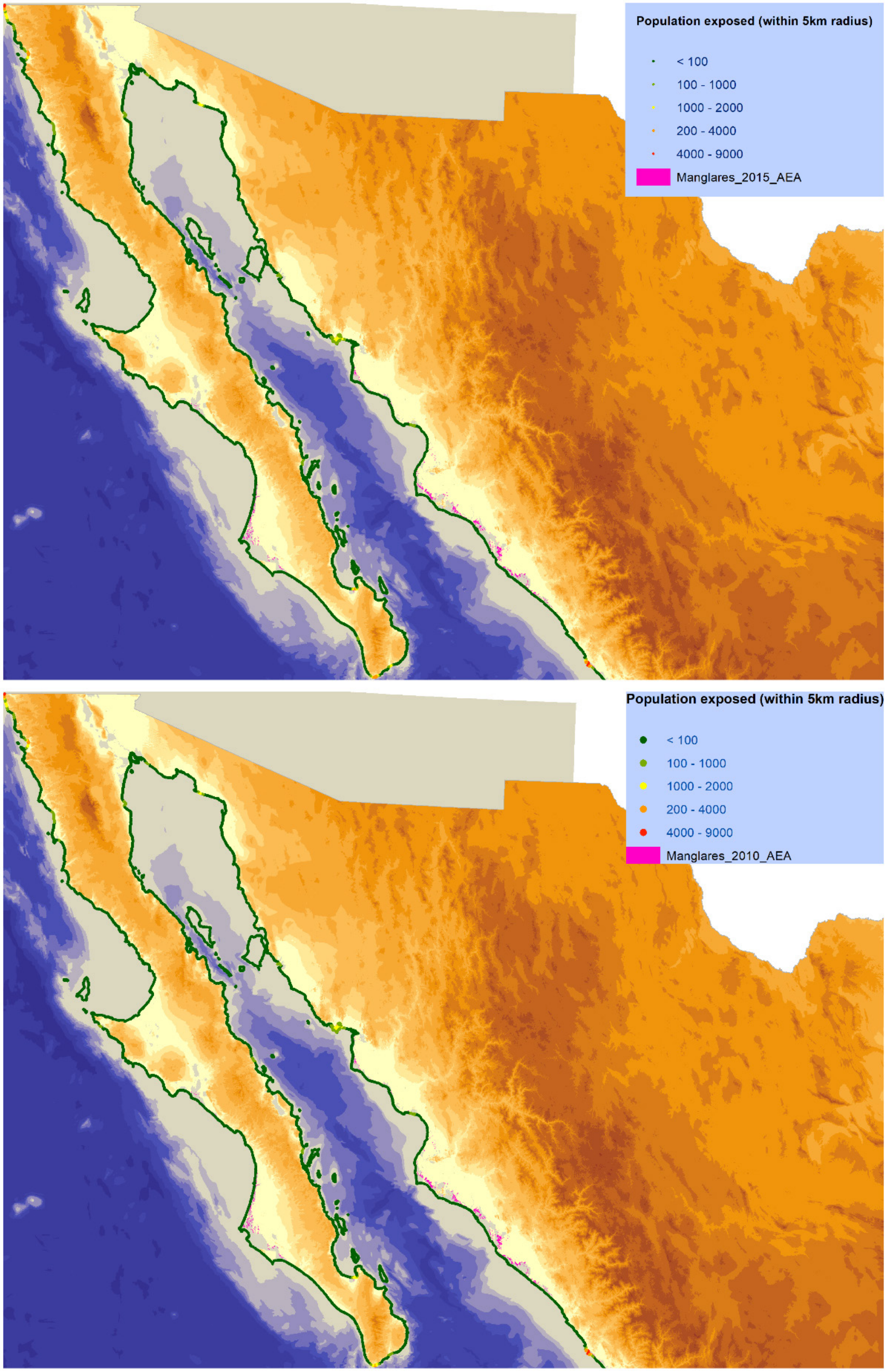


Fig.6c. Relative numbers (population density in the 5km adjacent to each sampling point along the coast) of people along the northern half of the Pacific coast, as of 2015 (upper panel) and 2010 (bottom panel). See explanation in the text.

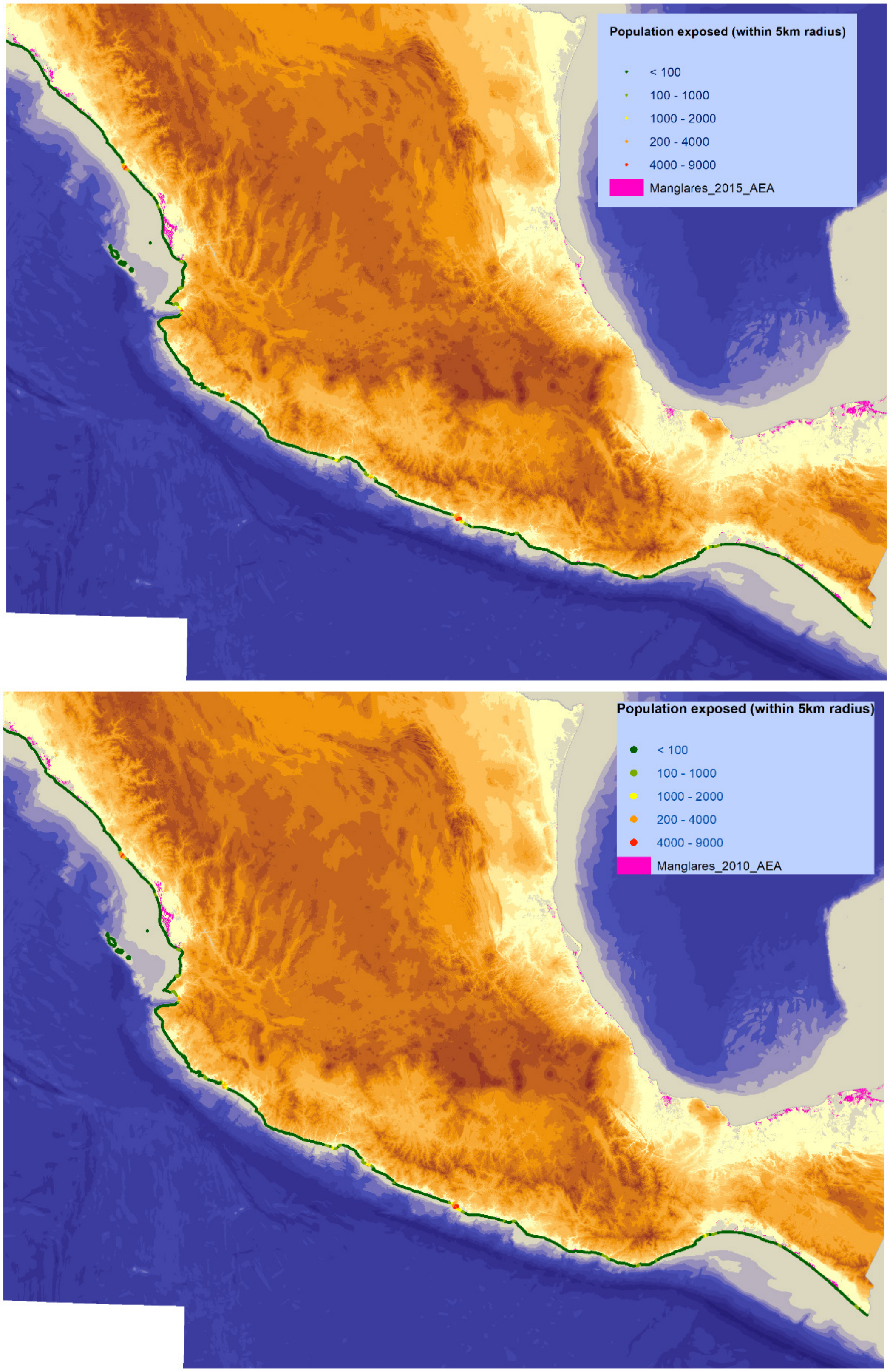


Fig.6d. Relative numbers (population density in the 5km adjacent to each sampling point along the coast) of people along the southern half of the Pacific coast, as of 2015 (upper panel) and 2010 (bottom panel). See explanation in the text.

Table 3. Distribution of coastal populations across the different levels of coastal exposure to flood and erosion, under the currently existent conditions (as of 2010 and 2015) and a hypothetical scenario without natural coastal ecosystems. Figures denote (separately for each coast) the percentage of the total coastal population (defined as people inhabiting within 5km from the shoreline) subject to different levels of coastal exposure.

	Gulf of Mexico				Pacific			
Exposure Index	2010	2010 No ecosystems	2015	2015 No ecosystems	2010	2010 No ecosystems	2015	2015 No ecosystems
Very low	2.7	0.6	2.8	0.6	1.4	0.3	1.3	0.3
Low	49.6	44.0	50.0	44.4	35.1	30.2	35.9	31.1
Moderate	39.5	38.3	39.7	38.0	56.9	58.7	56.4	58.1
High	8.3	17.1	7.6	17.0	6.6	10.8	6.4	10.5
Very high	-	-	-	-	0.0	0.0	0.0	0.0

<u>Possible approaches for valuing, in monetary terms, the coastal protection services supplied by Mexican coastal ecosystems</u>

Only a few studies have aimed to estimate the monetary value of coastal protection services provided by Mexican ecosystems. Most of those studies has been conducted at the local level and used some form of benefit transfer approach for the valuation. Vázquez-Navarrete *et al.*, (2011) mapped the ecosystems (including mangrove forests) present in nine municipalities of the State of Tabasco and used a benefit transfer approach to estimate the monetary value of a suite of 16 ecosystem services (including protection against hazards and natural disasters and erosion control) that, according to the literature, these ecosystem types provide. Mendoza-González *et al.* (2012) mapped and quantified land use changes that took place from 1995 to 2006 in three localities in the central part of the State of Veracruz, and estimated the loss of both natural ecosystems/habitats (including mangrove forests and beaches) and a suite of nine ecosystem services that, according to the literature, these ecosystem types provide. The value of the ecosystem services lost was estimated, in most cases, using a benefit transfer approach; coastal protection by beaches was valued using the direct market price of building an artificial foredune made of concrete; coastal protection services by mangroves were somehow not included. Camacho-Valdez *et al.* (2013) mapped and assessed the distribution and extent of coastal wetlands (including mangrove forests) in the southern part of the State of Sinaloa using remote sensing techniques. They used a value transfer approach to value 11 ecosystem services (including flood and storm buffering) that these wetland types have been reported to provide. CONANP-GIZ (2017) used the benefit transfer approach to value four ecosystem services (including coastal protection from flooding and extreme weather events) provided by the mangrove forests and coral reefs of Cozumel Island in the State of Quintana Roo.

A couple of recent studies have used different methodological approaches. Pérez-Maqueo *et al.* (2018) used regression models to estimate economic damages caused (at the State- and Municipality-level) by extreme hydrometeorological events using land-use cover and socio-economic data as predictors. Their country-wide, non-spatially explicit analyses did include coastal ecosystems and showed that these play a significant role in storm protection reducing economic damages caused by hurricanes and other extreme weather events. Beck *et al.* (2018) conducted a global-level, spatially-explicit valuation of the flood protection services provided by coral reefs. They used process-based flooding models to estimate the coastal protection benefits provided by coral reefs and constructed an expected damage function to value them.

While all these studies do provide valuable information, the technical shortcomings of the benefit transfer approach (discussed in the *Country Assessment on Natural Capital Accounting and Valuation of Ecosystem Services in Mexico*) reduce the usefulness of their results and make them incompatible with the SEEA-EEA framework. A particularly important deficiency of these benefit transfer studies is the fact that the flow or supply of ecosystem services is not actually measured/estimated —as required by the SEEA-EEA framework— but it is implicitly assumed that a given ecosystem delivers the services that have been documented elsewhere for the same ecosystem type under roughly similar conditions. But, as it has been admitted by even some of the same authors (*e.g*., Vázquez-Navarrete *et al*., 2011), not all ecosystems of the same type are able to supply the same ecosystem services; factors such as climate, geology, location, land-use history and human influence affect their functioning and their capacity to supply ecosystem services. Moreover, this approach also assumes that a given ecosystem asset supplies services at the average rate documented for the same ecosystem type so that the service supply is then estimated as the product of the average supply rate and the ecosystem asset's extent. However, detailed studies (*e.g.*, Barbier *et al*., 2008) have clearly shown that coastal ecosystem services such as wave attenuation do not respond linearly to changes in ecosystem extent.

Perhaps due to these shortcomings is that some of these studies have produced results that are inconsistent with each other. For example, Mendoza-González *et al.* (2012) did not include coastal protection as one of the services supplied by mangroves in the central part of the State of Veracruz. Camacho-Valdez *et al.* (2013) did not include Carbon sequestration among the services provided by coastal wetlands in the southern part of the State of Sinaloa. And the value obtained by CONANP-GIZ (2017) for the coastal protection services provided by mangrove forests in Cozumel Island was much lower (US$414/ha/yr) than those calculated by Camacho-Valdez *et al.* (2013) for the State of Sinaloa (US$2,957/ha/yr) or by Vázquez-Navarrete *et al*., (2011) for the State of Tabasco (US$3,402/ha/yr). Finally, monetary values estimated using the benefit transfer approach are, ultimately, averages of various estimates in turn obtained using different valuation methods. Therefore, it is unlikely that they are compatible with the exchange value required by the SEEA-EEA framework.

The WAVES programme (WorldBank, 2016) commissioned an in-depth review of the literature on economic valuation of coastal protection services provided by mangrove forests and coral reefs. The study found that, of the several different approaches that have been tested for valuing coastal protective services, the one more often used was the replacement cost method (*i.e*., estimating the protective value based on the cost of building human-made storm barriers), followed by avoided cost and direct market pricing. While the study recognizes that each method may be well suited for some particular conditions and data availability situations, production function methods, especially the Expected Damage Function approach, are especially informative and yield more reliable estimates of the value of protection services by mangroves and coral reefs (Barbier, 2016). In the Expected Damage Function approach, ecosystems are thought of as producing services (*e.g.* the protection of economic activity, property and human lives) that benefit individuals by reducing damage. The method first constructs an Expected Damage Function that describes the likely value of the assets damaged under different conditions (*e.g.*, storm frequencies or return periods). The method then uses a "with/without" approach, projecting the expected damages in the presence of the ecosystem service and in its absence; the difference represents the value of the coastal protection benefits. An important consideration is that monetary values estimated with this approach are compatible with the concept of exchange value used in the SEEA-EEA framework.

The review commissioned by the WAVES programme (WorldBank, 2016) concludes by recommending a five-step approach for estimating and valuing coastal protection benefits provided by mangrove forests and coral reefs: 1) Estimate offshore hydrodynamics, 2) Estimate nearshore hydrodynamics, 3) Estimate effects of coastal ecosystems on hydrodynamics, 4) Estimate extent and level of flooding or erosion, and 5) Assess expected and averted damages and value coastal protection benefits.

It further recommends that steps 1-4 be evaluated by means of geophysical, process-based models and an Expected Damage Function approach be used for valuing the coastal protection benefits in terms of damages averted. Each of the first four steps poses a different type of problem that can be solved based on time series of geophysical, climatic, vegetation and oceanographic data/measurements, and using dedicated mathematical models and pieces of software that have been developed and tested not only for mangrove forests and coral reefs but also for seagrass meadows and other coastal ecosystems (see Vo-Luong & Massel, 2008; Bosom and Jiménez, 2011; Suzuki *et al.*, 2011; Pinsky *et al.*, 2013; Guannel *et al.*, 2016; Volvaiker *et al.*, 2017; Harris *et al.*, 2018; Beck *et al.*, 2018; Reguero *et al.*, 2018; see reviews in Guannel *et al.*, 2014; Ondiviela *et al.*, 2014 and WorldBank, 2016). Data necessary for valuing coastal protection benefits (step 5) include property value, past damages, and an estimate of the potential/expected damages. Spatially explicit data on the distribution of people and assets are necessary to estimate the expected damages but, lacking these, a commonly used approach for estimating the distribution of coastal assets is to spatially allocate a country's GDP based on population density (see, for example, Beck *et al.*, 2018).

To date, however, this highly systematic, process-based approach seems to have been applied in only a few cases. Losada *et al.*, (2017) used the WAVES 5-step approach to value the protective services provided by mangrove forests in the Philippines. They estimated flooding exposure, the extent and depth of flooding, the resulting damages to people and property, and the risk and probability based on event return periods, for each of three mangrove cover scenarios (current mangrove extent, historical mangrove extent as of 1950 and no mangroves), at national and local scales. They estimated the population, population below poverty level, residential stock, industrial stock, and length of roads in the country and combined this information with empirical damage curves for population, stock and roads to estimate the damage from flooding under different return periods. The differences in damages across the three mangrove cover scenarios give the benefits of mangroves for risk reduction in terms of both annual expected monetary benefits and number of people protected. The risk reduction benefits were then annualized so that the benefit values could be included in national accounts.

Beck *et al.*, (2018) valued the flood protection savings provided by coral reefs at the global level also following the WAVES 5-step approach. Using process-based flooding models, they estimated the annual expected benefit of coral reefs for protecting people and property globally. They compared flooding for scenarios with and without (actually, a 1m reduction in the height and roughness of coral reefs) reefs for four storm return periods. They estimated (indirectly) the built capital exposed based on population density data and the correlation between this and GDP. They finally estimated the land, population and built capital that would be flooded across all coastlines with coral reefs and derived the annual expected benefit of coral reefs for flood damage reduction.

No economic valuation of the coastal protection services provided by seagrass meadows seems to have been completed yet.

Uncertainties and possibilities for future improvement

The main technical and theoretical limitations of the Exposure Index, in general, are already recognized and described in the InVEST system documentation. These include, among others:

- The oversimplification of complex coastal processes (*e.g.*, wind and wave exposure, etc.),
- interactions between coastal processes and features are omitted,
- the presence of coastal ecosystems is considered but their extent and condition are not factored in,
- coastline segments with the same geomorphology class are assumed to behave in a similar way

and to suffer the same level of exposure throughout the study area,

- as a result of the above, exposure ranking is the same throughout the study area, without taking into account any possible interaction between variables. For example, the relative exposure to waves and wind will have the same weight whether the coastline segment under consideration is a sandy beach or a rocky cliff.
- the potential protective effect of coastal ecosystems is always included, even in those coastline segments that have a low exposure by virtue of their geomorphology or are little exposed to winds, waves or surge potential.

From the user's viewpoint, the main limitations of the Coastal Vulnerability model include the following:

- The model only produces a qualitative index of coastal exposure to erosion and inundation but does not value directly any ecosystem service. The model simply ranks coast segments as having a relatively low, moderate or high risk of erosion and inundation and thus provides a qualitative representation of coastal hazard risks;
- the model outputs cannot be used to quantify shoreline retreat or the extent/level of erosion/inundation of a specific coastal location, which are essential pieces of information for evaluating potential damages caused by coastal erosion, flood, waves, etc.;
- the assessment of the role of coastal ecosystems is, to some extent, tautological. The model assumes that the presence of one or more of these ecosystems would imply a reduction (additive, when more than one ecosystem is present) of exposure compared to the lack thereof. However, as discussed in section **1.Introduction and justification**, the amount of protection provided by ecosystems is highly context dependent: Not all coastal ecosystems provide protection —or the same level of protection— in all circumstances, and the extent to which a given coastal ecosystem protects a given stretch of coastline has to be evaluated in objective terms due to the many (geomorphologic, ecological, and hydrodynamic) factors involved which vary greatly among locations, times, and scales.

On top of the above-mentioned shortcomings — which affect, in general, any application of the InVEST's Coastal Vulnerability model—, additional particular limitations were faced when I implemented the model to assess the role of coastal ecosystems in reducing coastal vulnerability in Mexico. These include:

- The insufficient thematic, temporal or spatial resolution of the data available. For example, to describe the susceptibility of Mexico's shoreline to erosion and flooding, I used INEGI's Physiography - topoform system, scale 1:1'000,000, map. This map displays the various relief forms present in the Mexican territory, describing them in terms of their geological and lithological origins. While this map provides a reasonable description and classification of inland geomorphology, its spatial and thematic resolution are rather insufficient to adequately describing the country's coastal geomorphology. Compare, for example, with the level of detail found in NOAA's Environmental Sensitivity Index maps which describe the entire USA coastline in terms of 28 types of shoreline, mapped at scale 1:24,000 —and which were used by Arkema *et al.*, 2013 to assess the InVEST index of coastal exposure for the US coastline.
  The only information available on coral reefs and seagrass meadows is clearly insufficient. Lacking adequate local data, I used the digital maps compiled by the UN-Environment WCMC's Ocean+ Habitat Atlas programme. In addition to being incomplete (see discussion above in the **Data and procedure** section), those datasets include data from various sources, with observations made at different points in time (some of them duplicated) and with different spatial resolution, that cannot therefore be assigned to one particular date nor be properly used to track

changes over time. But these are the best data sets currently available on these key ecosystems. Information on seagrass beds and coral reefs comparable to that being produced by CONABIO's Mexican System for Mangrove Monitoring would be highly desirable.

- Lack of data. To examine the coastal protection benefits provided by coastal ecosystems I simply used the population density maps included in NASA's Gridded Population of the World ver.4 collection. While those data are consistent with national censuses, a general procedure is used for disaggregating and spatializing the census' point-data; however, the resulting maps have not been validated in the field. Moreover, finer resolution mapping of demographic information such as data disaggregated by age-classes and/or by marginalization or income level would help to make a better assessment of vulnerability to coastal hazards. But such data are not yet available in Mexico.

  In fact, to properly examine the coastal protection benefits provided by coastal ecosystems, spatially explicit data on population, built capital (*e.g.*, infrastructure, property), economic activity, property value, etc. are necessary. But this sort of information is not yet available in Mexico either.

Although the above-listed shortcomings clearly limit the usefulness of the results obtained in this first country-wide assessment of the coastal protection services supplied by Mexican coastal ecosystems, they do not render them invalid. In fact, the InVEST Coastal Vulnerability model has been applied in many different studies worldwide and its results have proved to be useful at least in relative terms. For example, Arkema *et al.*, 2013 applied the InVEST model to the entire US coastline and validated the results by correlating the EI values with the number of fatalities across 21 US states. They found that the EI values accurately predict total population exposed to the greatest levels of coastal hazard. Cabral *et al.*, 2017 used the model to assess the exposure of Mozambique coasts to coastal hazards and erosion and found that districts with higher EI values suffered nearly twice as many coastal disaster-related fatalities than districts with a lower hazard index, according to a national database.

Nevertheless, it would be highly desirable to implement in Mexico the full 5-step approach recommended by the WAVES programme to quantify and value, in a spatially explicit manner, the coastal protection benefits provided by coastal ecosystems as has been done for mangrove forests in the Philippines (Losada *et al.*, 2017) and for coral reefs globally (Beck *et al.*, 2018). In order to implement this approach in Mexico, two major challenges have to be addressed:

- Lack of data. On the one hand, in order to estimate offshore and nearshore hydrodynamics; the effects of coastal ecosystems on nearshore hydrodynamics; and the extent and level of flooding or erosion (steps 1-4 in the WAVES approach) by means of geophysical, process-based models, time series of geophysical, climatic, vegetation and oceanographic data/measurements are required. For medium- to small-scale studies (*e.g.*, country-wide), some of these requirements can be met —after suitable pre-processing— with data from global sources such as the NOAA's WaveWatchIII wave prediction model. But for some others, *e.g.*, structural characteristics of vegetation at the site, drag coefficients for different surface types, etc., site-specific data and estimates are necessary as these are highly variable and highly dependent on the site's characteristics and the models being used (Guannel *et al.*, 2014).

  On the other hand, in order to value the coastal protection benefits in terms of damages averted by constructing an Expected Damage Function (step 5 in the WAVES approach), spatially explicit data on population, population structure, built capital (*e.g.*, infrastructure, property), economic activity, property value, etc. are necessary.

  None of these data/measurements are currently available in Mexico. It would be, therefore, important to launch concerted country-wide efforts to meet these data gaps.

- Technically complex, computationally demanding models.- As discussed above, steps 1-4 in the WAVES approach can be solved (given the necessary data/measurements) using dedicated specific, process-based mathematical models and pieces of software that have been developed and tested for all the major coastal ecosystems (*viz.*, mangrove forests, coral reefs, coastal marshlands, seagrass meadows, etc.) and can be neatly integrated into a coherent modelling framework (see Guannel *et al.*, 2014 and WorldBank, 2016). Such models, however, are all technically complex, computationally demanding and not easy to implement; although these are not insurmountable obstacles, they do limit the range of users/institutions that are capable to use them and would make communicating the results to decision-makers more difficult.

Potential policy relevance

Despite the shortcomings of the data and the methods used in this initial pilot study, its outputs can be used —and can prove to be useful— from both the coastal risk and the ecosystem conservation viewpoints:

- First, in general terms, identifying the locations that may be more or less exposed (even if only in relative terms) to coastal hazards is, by itself, important/useful information that can give an indication of where physical changes may occur and their impact on coastal communities. This can help decision makers to protect and improve the coastal communities' preparedness to address coastal risks by implementing appropriate management or adaptation strategies. On the other hand, such information can help to better inform development plans and permitting schemes. The Coastal Vulnerability model produces an easy-to-understand and easy-to-communicate qualitative index of coastal exposure to erosion and inundation as well as an estimate of human population density in the immediate vicinity of the coastline. It is not only simple to use but can be also applied even in data-scarce situations.

  Many countries, particularly developing countries, are currently working toward developing national coastal risk maps, as they constitute a critical first step for risk reduction and coastal protection. Until recently, these efforts used to overlook the role that coastal ecosystems might play in this regard. Initiatives such as the World Bank's WAVES programme, the UNSD's SEEA-EEA and others are creating opportunities to also consider protection services provided by coastal ecosystems. Future national risk maps should also identify where and how much risk reduction is being provided by coastal ecosystems and thus discern where the protection and restoration of such ecosystems offer the greatest risk reduction benefits even above artificial measures.
- On the other hand, examining the role that the different variables (geomorphology, wave and wind fields, coastal ecosystems) participating in these models make to coastal exposure in different parts of the coastline helps to identify those areas where coastal ecosystems play a key role in reducing exposure to hazards, thus highlighting their value and the importance of their conservation.

  Coastal ecosystems are facing increasing pressure for conversion to other economic activities not only in Mexico, but worldwide. In many coastal areas/countries where mangrove forests and coral reefs have been degraded or lost, there is high interest in promoting their conservation and restoration. Assessing and valuing the ecological services that these ecosystems provide is key for improving their management and for designing better management and conservation policies. This would help to mainstream the value and importance of these ecosystems into public policies and management programmes that might induce their conversion or degradation and thus, alter, the production of important ecosystem services that benefit human populations.

- Secondly, in particular for the results obtained in this pilot study, the EI values hereby obtained do provide a preliminary, albeit rough but spatially explicit and credible identification of the relative vulnerability of Mexico's coasts. Also, the data compiled and the modelling approaches implemented lay the bases for future, more detailed studies that could then focus on those coastal zones hereby identified as particularly critical.

- Finally, country-wide scale studies (such as the present one) allow identifying the main knowledge and data gaps existent. As discussed in the previous sections, some key actions that could improve the quality of future similar studies include: (a) Improving and enhancing the thematic and spatial resolution of INEGI's topoform system map; (b) Launching a mapping and monitoring effort for coral reefs and seagrass meadows comparable to the one being carried out by CONABIO's mangrove monitoring system; c) Develop a bathymetry map with higher spatial resolution than the datasets currently available (400m); d) Develop spatially explicit socio-economic datasets at least to a level that could be comparable to the available environmental data.