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Examining climate-related indices and landscape connectivity to understand mangrove fragmentation in Campeche, Mexico

Abstract

Megadiverse countries such as Mexico face significant challenges in safeguarding their ecosystems and species due to environmental and anthropogenic changes. Coastal biodiversity in the Gulf of Mexico, particularly within mangrove ecosystems, is especially vulnerable yet critical for understanding the impacts of global climate change. This study aims to evaluate the factors contributing to the ongoing chronic changes in and around mangroves. We focused on the Yucatán Peninsula in the western Caribbean Sea, utilizing satellite images from 1981 to 2020 to analyze decadal variations in mangrove coverage. Our findings revealed a high ecological index score of 0.71, underscoring the area's considerable natural value, alongside an anthropogenic index score of 0.46, which highlights the significant impact of human activities. To enhance biodiversity connectivity and preservation, we propose a GIS-based spatial biological corridor technique, establishing protection zones. Urgent action is needed to promote improved forest management and restoration efforts, facilitating climate change adaptation for mangrove and adjacent ecosystems.

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1 Introduction

Mangroves play a vital role in coastal ecosystems, providing essential ecological and social services. However, they face significant threats from socio-economic development, particularly in Southeast Asia and Mexico. In the Sundaic region, threats such as agriculture, aquaculture, and hydrological changes from dam construction have led to severe fragmentation and loss of mangrove habitats (Ng et al., 2022; Kanniah et al., 2021). This region is a global hotspot for mangrove loss, with over 50% of mangroves being deforested or fragmented due to land conversion for aquaculture and rice plantations (Bryan-Brown et al., 2020). Research has highlighted the importance of mangrove connectivity, which facilitates species adaptation and genetic diversity through propagule dispersal influenced by ocean currents (Van der Stocken et al., 2019; Gouvêa et al., 2023). However, declining connectivity, particularly in regions like the Andaman Sea, adversely affects associated ecosystems, such as seagrass meadows, which rely on healthy mangrove habitats for their survival (Mishra & Apte, 2020). In Mexico, mangrove ecosystems are crucial for maintaining coastal biodiversity and supporting local economies through fisheries, flood protection, and carbon sequestration (Harishidayat et al., 2022; Allgeier et al., 2010). Despite their recognized value, significant gaps remain in understanding the local impacts of human activities on mangrove health and connectivity. In Veracruz, for example, mangroves have experienced an alarming 86% loss between 1986 and 2016, largely due to increasing human settlements and industrial development in the lower basin of the Coatzacoalcos River (Cuevas, 2020). Human activities such as land clearing and industrial expansion have notably impacted environmental components, with soil, flora, and water resources being among the most affected (Adame et al., 2020).

The overall aim of this study is to evaluate the current condition of mangrove ecosystems in Mexico, particularly in the context of ongoing anthropogenic pressures, and to develop evidence-based conservation and restoration strategies. This study contributes to the “Mangrove Restoration as a Nature-based Solution in Biosphere Reserves in Latin America and the Caribbean” (MangRes Project), an initiative by UNESCO supported by the Government of Flanders of Belgium and the Organization Autonomous National Parks of Spain. To achieve this aim, the following specific research objectives have been established:

a. Assess historical changes in mangrove cover due to human activities in Laguna de Términos.
b. Calculate the bioclimatic corridor index using spatial and climatic data in the Yucatán Peninsula.
c. Identify ecological indicator for mangrove health using remote sensing data in local communities in the Yucatán Peninsula.
d. Combine ecological and bioclimatic indices to emphasize the need for conservation of mangrove patches in Laguna de Términos and their integration into the ecological corridor system

2 Materials and methods

2.1 Study area

The location of the mangrove forests is indicated on a general map of mangrove habitats in Mexico (Figure A1). The study area includes mangrove forests located along Laguna de Términos in the state of Campeche. Land cover is dominated by reed beds and mangroves, with many vegetation types present (Figure A2). This region is characterized by humid and semi-humid climates and features various soil types, primarily dominated by gley soils with poor drainage and significant peat development on the surface (Figure A3). It comprises geological structures from Tertiary and Quaternary formations (Figure A4). To determine the attributes of the study area, data was collected from the Geoportal website and downloaded from the CONABIO database (Portal de Geoinformación, Sistema Nacional de Información sobre Biodiversidad). The mangrove district in Laguna de Términos was analyzed using land cover data (protection area, core and buffer zones) and vector format data was processed to delineate vegetation boundaries (Figure A5).

2.2 Ecological and anthropogenic indices

Ecological (Figure 1) and anthropogenic (Figure A6) indices are essential for assessing environmental conditions and are available for download in raw format. These indices encompass factors such as habitat fragmentation, human disturbance, and land use change. To derive the ecological index for the municipalities, a modeling approach was employed. The ecological indicator is calculated based on theoretical relationships among key variables, including human influence (the effects of urban development, agriculture, and pollution), trophic structure (the feeding relationships among organisms), and ecosystem stability (the ability to maintain structure and function over time). After normalization, the resulting data are presented according to Mexico's administrative units.

The modeling process involved integrating various environmental and ecological parameters, such as land cover, soil type, topography, and climatic conditions. These parameters were analyzed using a spatial analysis tool and assigned values based on their relative contributions to the overall ecological health of the area (Figure A7). The resulting index provides a quantitative measure of the ecological status of the municipalities, which can guide management and conservation efforts. We downloaded the data, processed the indices, and recomputed them. The studied area is protected by Biological Corridors, established as a conservation system. To assess the impact of human-induced changes on terrestrial biodiversity in Mexico, an index of human impact was derived based on the theoretical framework of the Global Biodiversity Model (GLOBIO3). Developed by Alkemade et al. in 2009, the GLOBIO3 model evaluates temporal changes in conservation status and establishes cause-and-effect relationships between various pressures and threat factors based on information from scientific literature. The model considers land use, infrastructure, fragmentation, climate change, and nitrogen deposition as the main pressures and threat factors. In Mexico, the model was adjusted to a resolution of one square kilometer and included land use, road infrastructure, and fragmentation as pressures and threat factors, using data from the National Institute of Statistics and Geography (INEGI). The ecological indicator ranges from 0 to 1. In QGIS, we use administrative units (communities) to illustrate the value range and add biological corridors to highlight the gaps between all designated areas (Figure 2). Each variable was normalized to a scale from 0 to 1 using the formula:

Normalized score = (raw value - min value) / (max value - min value)

The impacts associated with land use categories, such as cultivated grassland and primary scrub, were adjusted accordingly (Figure A8). The anthropogenic indicator estimates impacts on biodiversity on a scale from 0 to 1, where 0 signifies no impact from human pressure and threat factors, and 1 indicates maximum impact. In QGIS, we reclassified the quantile range for this value. For mangrove forests, a score of 0.1 to 0.3 is preferable, suggesting minimal anthropogenic pressure. In contrast, a higher score for the ecological indicator is desirable, ideally ranging from 0.5 to 1.

2.3 Calculation of the bioclimatic corridor index

To mitigate extreme climatic deviations, climatic variables such as temperature and humidity were integrated. Ecological corridors with varying degrees of continuous primary vegetation were identified, focusing on southwestern Mexico. The analysis considered constraints from large shifts in climatic gradients on organisms' mobility and dispersion. Data were sourced from Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) under the CC BY-NC 2.5 MX license. The bioclimatic corridor was calculated by determining climatic gradients, human influence, and Euclidean distances between native vegetation fragments, reflecting their preservation state (Sarukhán and Jiménez 2016). Human influence and recent evapotranspiration rates were included in the corridor analysis. Fragments of primary native vegetation larger than 1000 ha were identified, and corridors were recognized from these fragments (McGuire et al., 2016). Annual average actual evapotranspiration from 1980-2009 was calculated (Cuervo-Robayo et al., 2014), and all data were processed in raster format with a 1 x 1 km pixel size. Values ranged from -1 (primary vegetation fragment) to 200 (most threatened areas), with 0 indicating optimal corridor conditions. The cost (Dc) in the equation represents the total expense of moving from one cell to a neighboring cell within a landscape grid, incorporating both distance and temperature changes. It is calculated as follows (McGuire et al., 2016):

$$D_c = \left[\frac{C_o + C_n}{2} \right] D_e + |T_0 - T_n|\ W$$

where:

C_o is the cost of the origin cell,

C_n is the cost of the least-cost neighbouring cell,

D_e is the Euclidean distance between the cells,

T_o–T_n represents the difference in temperature between the origin cell (where the movement starts) and the neighbouring cell (where the movement ends), W is 50 km per 1 °C.

These data were downloaded in a format suitable for QGIS Firenze 3.28 and processed for the scope of the research aims.

2.4 Areas for biological conservation

The information on which areas need biological conservation in the Yucatán Peninsula, Mexico, can be compared over time with maps from 1981, 2005, 2010, and 2015. These maps are publicly available on the Internet and can be downloaded. The index of connectivity, specifically relative connectivity, of Campeche mangroves in 2020 was calculated using the Conefor program (version 2.2 released under the GNU GPL). These data were available on the CONABIO website and implemented in the form of a map for our results. This program quantifies the importance of habitat areas and linkages for maintaining or improving connectivity and assesses the impact of habitat and landscape changes on connectivity. The information provided by this analysis can be used as a tool to analyse spatial ecology and support conservation planning decisions, such as restoration efforts, by identifying and prioritizing critical sites for mangrove connectivity. Spatial and temporal changes in the fragmentation patterns of mangrove were measured to identify bioclimatic corridor indices using climatic and spatial parameters, calculate ecological indices for mangrove sites based on remote sensing data, and assess the historical changes in mangrove cover under the influence of anthropogenic pressure. The measurement of biodiversity in the region is based on the coexistence of ecosystems and species with high levels of diversity. To understand the spatial and temporal changes in fragmentation patterns of mangroves, measurements were conducted. The map identifies mangrove sites of biological importance and ecological restoration needs at the national level, as identified by CONABIO (Conabio 2022).

The identification of these mangrove sites was based on the results of the “Second Consultation Workshop on the Mangrove Monitoring Programme in Mexico” held in September 2007 and the “Consultation Meeting on the Identification of Biologically Important Mangrove Sites and Sites in Need of Ecological Restoration in the Region of the Yucatán Peninsula and the State of Tamaulipas” held in September 2008. Biologically important mangroves and core zones were identified and prioritized on the map.

3 Results

3.1. Changes in mangrove forest cover using satellite imaging.

The mangrove forest neighbourhoods were divided into three zones. The study found a low proportion of buffer zones in the study area (Figure A5). The results showed a high rate of land cover change, with about half of the mangroves in Campeche, Yucatán Peninsula, affected since 1981. The mangrove area decreased by an average of 0.34% per year. Over the last 40 years, mangrove coverage has gradually declined (Table 1).

The information provided details the status and changes in mangrove coverage in Mexico. According to the national mangrove surveying system, there was a decline in mangrove coverage from 1981 to

Table 1. The mangrove cover changes in the state of Campeche on the Yucatán peninsula.

Year	Area of original forest patch	Growth in relation to the base year	Percentage of change
	ha	ha	%
1981	216.969	-	-
2005	199.662	-17.307	-7.98
2010	197.623	-19.346	-8.92
2015	198.853	-18.116	-8.35
2020	200.279	-16.690	-7.69

Source: own elaborations based on CONABIO 2022

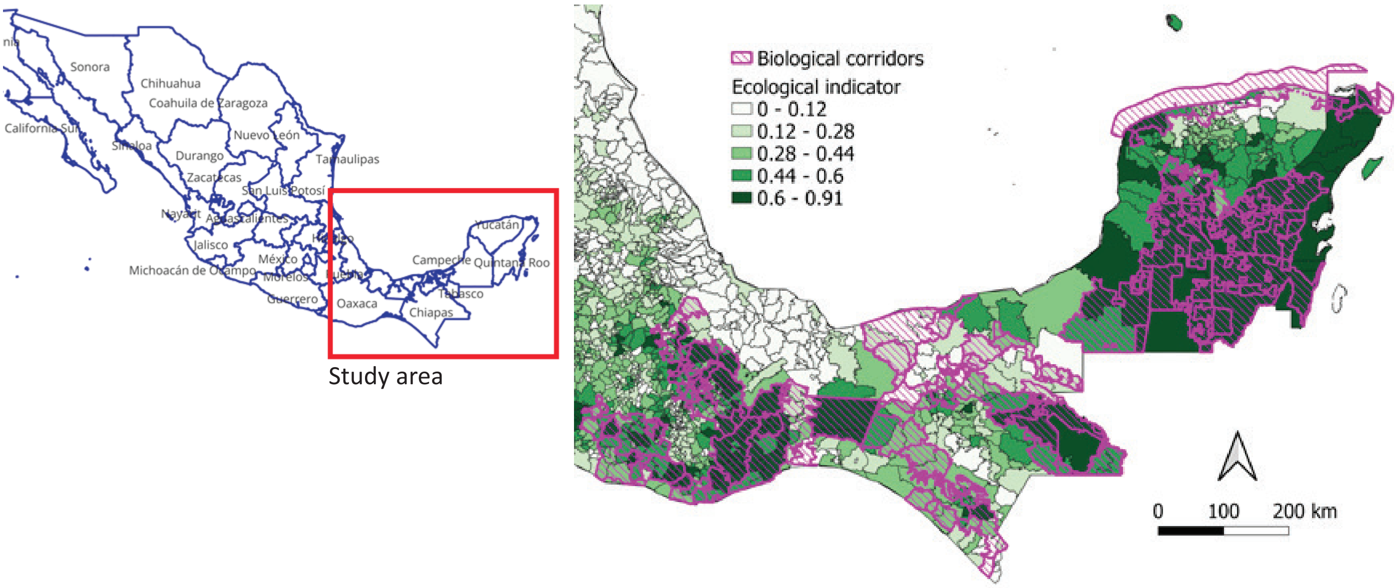

Figure 1. Ecological indicator per municipality in southeastern Mexico. Own elaborations based on CONABIO 2022.

2010, followed by a recovery trend starting in 2015. The study area, divided into three zones, showed a significant land cover turnover with an 8.92% net loss of mangroves from 1981 to 2010 (Figure A5). However, since 2015, mangroves have been recovering, with a net gain of 1.22% of the original area. Given the ongoing decline in mangrove forests within the study area (Table 1), protection measures are necessary. Although biological corridor boundaries are adjacent, they do not encompass this area. The study suggests that the forests around Laguna de Términos are suitable for inclusion in the ecological corridor system (Figure 2) and should be integrated into the existing protection scheme.

Additionally, the study highlights that the coastal zone with numerous lakes, coastal systems, and bays likely maintains high biodiversity and should be safeguarded. The GLOBIO3 model indicates low human impact on biodiversity, with anthropogenic indices ranging from 0.3 to 0.7 and an average of 0.46 (Figure A6). However, mangroves near industrial activities, such as energy production, aquaculture farms, and livestock operations, experience higher anthropogenic pressure. The comparison of mangrove cover every 5 years to the 1981 baseline shows that the largest increase in mangrove area occurred in 2015 (Table 2).

Table 2. Coverage variability of mangroves in the study area.

Year	Area of original forest patch	Growth in relation to the base year	Percentage of change
	ha	ha	%
1981	85408.29	-	-
2005		+74.12	0.09
2010		+68.82	0.08
2015		+699.46	0.82
2020		+155.84	0.18

Source: own elaborations based on CONABIO 2022

3.2. Application of ecological indicator per municipality

We used an ecological indicator with values ranging from 0 to 1 to assess the biodiversity impacts of various pressures and threats in the study area. A value of 0 represents a low impact, while a score of 1 indicates the highest impact. According to Figure 1 the mean ecological index for the study area was 0.71, which suggests that the area has high natural values and is less impacted by human activities.

3.3 Results of the bioclimatic corridor index extent and for biological conservation

This paper proposes connecting fragments of the mangrove to expand the protection area system, which has increased from 85,000 to 86,000 ha over the years. The connectivity index used in this study ranges from -1 to 200, with -1 representing the primary vegetation fragment and 0 indicating optimal conditions within the corridor. A score close to 200 is considered a threatened area, indicating fragmenta-

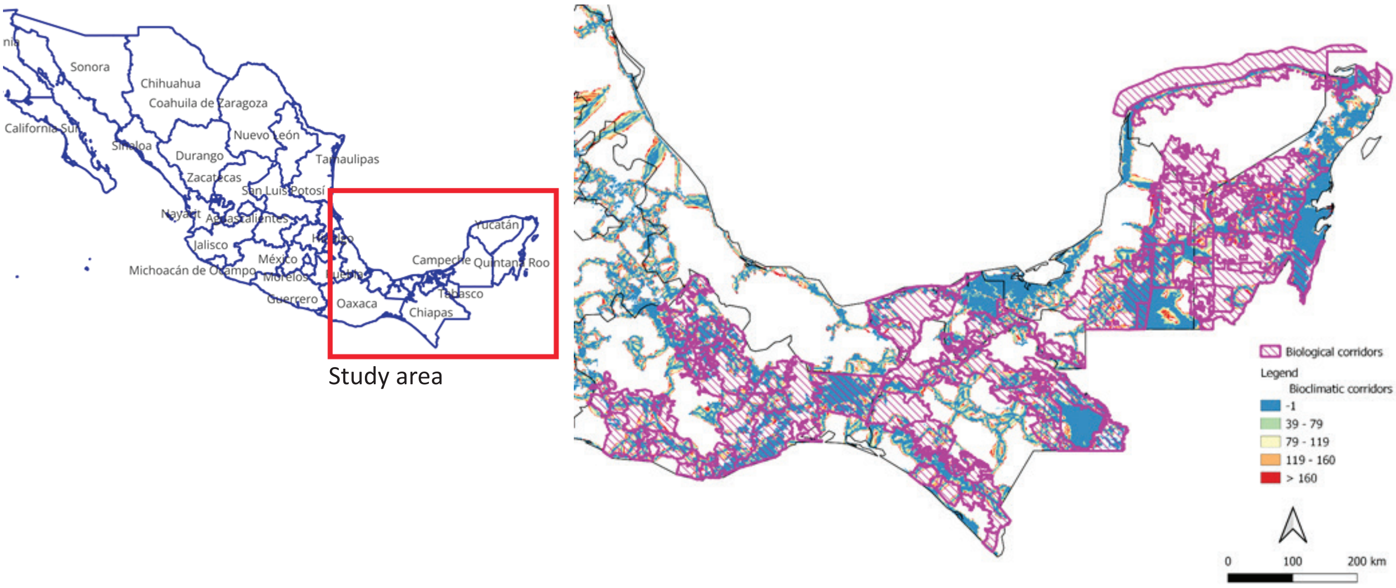

Figure 2. Bioclimatic corridors in southeastern Mexico. Own elaborations based on CONABIO 2022

tion and loss of connectivity. Based on our findings, we recommend including this section of mangroves in the ecological system (Figure 2).

4 Discussion

4.1 Impact of land use changes on mangrove ecosystems

Land cover changes and fragmentation were analyzed using SPOT5 remote sensing imagery. The results showed significant land cover turnover, with nearly half of the mangroves impacted between 2004 and 2014. Mangrove loss averaged -0.34% annually, with fragmentation affecting about 35.4% of core mangrove forests in Ngoc Hien (Hauser et al. 2017). In addition, land use can modified nutrient exports with negative impacts on adjacent seagrass meadows and coral reefs. This underscores the strong and persistent ecological and biogeochemical changes associated with mangrove conversion in tropical estuaries (Herbeck et al 2020).

Forest zones with different regulatory regimes play a significant role in shaping the changes in protection zones in the research area (Figure A5) around mangroves. Deforestation of mangroves in Chocohuital, Chiapas, Mexico from 2000 to 2019 was analyzed using Landsat imagery and the Markov Chain model. The study found a 51-hectare reduction in mangrove cover, with land transitioning primarily to settlements and pastureland. Future scenarios predict a high probability of mangrove areas converting to agriculture or pastureland, emphasizing the need for effective conservation strategies (Cigarroa et al. 2023). Mangrove forests in Tabasco, Mexico, cover 41,498.5 hectares and are crucial for conservation, utilization, and rehabilitation. Soil and hydrocarbon contamination analyses revealed that 55% of these mangroves need protection, 5.8% are polluted and require restoration, and 39.2% are suitable for sustainable use (Domínguez-Domínguez et al. 2019).

Recent studies showed that mangroves can be slightly resilient to human pressures. Findings from China's southeast coast indicated that small, edge-rich mangrove patches are particularly vulnerable (Zhang et al., 2021). Our results, based on ecological (Figure 1) and anthropogenic indices, highlighted the urgent need for conservation efforts. It is important to include the small mangrove patches in Laguna de Términos, which are vulnerable to human impact, in bioclimatic corridors in southeastern Mexico (Figure A6). Effective management is needed to improve ecological connectivity for these small patches. Satellite imagery analysis reveals a 3.75% decline in mangrove areas in the Indian Sundarbans from 1975 to 2018, with deforested mangroves converting to wetlands and water bodies. Canopy density decreased from 42% to 36%, and forest fragmentation increased (Kundu et al. 2023). The use of Landsat satellite images has been shown to be useful for monitoring deforestation and fragmentation in mangroves (Worthington et al., 2020)

The study found no change in mangrove coverage in the examined part of Mexico from 1981 to 2005, with the relationship between urbanization and mangrove habitats still unclear. In Pakistan's Indus Delta, mangrove coverage was assessed using Landsat imagery, revealing an increase from 477.22 km² in 1990 to 1463.59 km² in 2020, reflecting a 3.74% annual growth due to planting and conservation efforts (Gilani et al., 2021). Few indices use biodiversity as a parameter to determine mangrove status, although environmental status at selected spatial scales and using diverse information resources exist. Our study found that the protection zone is appropriate to preserve the mangroves (Figure A5). The dominant types of vegetation were sedge vegetation and semi-deciduous tropical forest with secondary trees, which were found near mangrove forests. In the core zone, mangrove forests were prevalent, while in the buffer zones, there were semi-evergreen seasonal tropical forests with secondary shrubs, trees, herbaceous plants, and cultivated pastures (Figure A8).

The integration of biodiversity loss indicators provided a common score for evaluating mangrove management plans. Accurate assessment of land cover dynamics in West Africa is urgent, with Landsat data revealing a 500 km² net loss of mangroves in the Niger Delta and nearly doubling built-up areas from 1,990 km² in 1988 to 3,730 km² in 2013 (Nababa et al. 2020). Our study provides valuable techniques for appraising land cover dynamics and accurately estimating fragmentation (Figure A7). In recent years, mangroves have become consistently more fragmented. Removing shade from mangrove cover can change the thermal regime of the microclimate and other temperature-dependent parameters (Zabbey et al. 2021).

4.2 Mangrove loss: The role of fragmentation and regulations

Less fragmented forests globally have lower mangrove loss rates. However, pressure and management responses' effectiveness on mangrove losses varied among countries (Turschwell et al. 2020). Higher population density led to greater mangrove loss in countries with poor regulations. From 2000 to 2019, Iskandar Malaysia lost 2,907.29 hectares of mangroves at a 1.12% annual rate. National regulations influence mangrove loss, while fragmented patches showed increased GPP, likely due to edge effects (Kanniah et al. 2021). The type, size, edge complexity, and shape of patches affect the fragmentation effect. Mangrove loss is caused by urban development, crop plantations, and aquaculture (Figure A2). Statistical analysis showed distinct coastal cape differences between the Caribbean and Pacific basins. The Caribbean had more artificial surfaces (0.172) than the Pacific (0.033), while the Pacific had more forest and semi-natural areas (0.766 vs. 0.610). In the Caribbean, Urabá (0.92) and Morrosquillo (0.85) had higher forest cover, whereas Cartagena had more artificial surfaces (Blanco and Ramírez 2021). Developing solutions that address differences in pressure effects and cumulative impacts based on the national context will protect mangroves (Figure A5).

The study found that mangrove forests experienced significant decline between 1977 and 1991 due to deforestation from development programs, particularly shrimp farming. However, from 1991 to 2010, mangrove extent increased due to afforestation and conservation efforts. The fragmentation model showed a strong correlation with observed changes in non-modeled areas, and local biodiversity trends (primarily birds) were consistent with fragmentation patterns. The study also evaluated two decades of global mangrove deforestation data using a hierarchical Bayes model to measure changes over time and assess national regulatory quality standards' impact on mangrove loss (Hermansen et al. 2017). Results indicated that protected zones had less fragmentation and associated loss, and cumulative impacts, population density, mangrove fragmentation, and management responses (e.g., protected areas) were linked to mangrove loss. The impact varied based on biodiversity levels.

The Galapagos Islands saw minimal loss or even expansion of mangrove forests, contrasting sharply with severe fragmentation along Ecuador's mainland coast, primarily due to conversion to shrimp farms. Agriculture, accounting for less than 15% of deforestation, had a weak correlation with mangrove fragmentation. Effective management of deforestation drivers is crucial, as focusing only on deforestation rates may overlook the impacts of fragmentation on ecosystem functions (Jaramillo et al. 2023). The proposed management strategies outlined in this study will serve as a valuable tool in achieving this goal, helping to guide decision-making processes and promote sustainable practices that support the long-term health and resilience of these important ecosystems.

4.3 Using landscape indicators to assess ecosystem health and sustainability

In the past 20 years, mangrove forest fragmentation has increased in the Canaanong-South Vietnam transition zone, likely due to human activities (Do et al. 2022). Landscape indices were used to evaluate these changes and support the conservation of endangered plant species like *Piñuelo rhizophorae* and *Piñuelo benthamii*. Landscape metrics were used to compare the coastal structure and mangrove spatial configuration, revealing a higher proportion of artificial surfaces and urbanization intensity in the Caribbean basin, especially in Cartagena and Urabá (Blanco-Libreros and Ramírez-Ruiz 2021). The greatest specific richness is found in the extensive coastal lagoons of southern Veracruz, Tabasco and Campeche, areas with high rainfall and temperatures never less than 14 °C, which correspond to the study area (Chi-Espínola 2022).

We present a method for assessing climate change impacts and monitoring land cover using satellite imagery. This approach, applicable to other regions like Vietnam, helps analyze the fragmentation of mangrove forests, which contributes to biodiversity loss and ecosystem degradation from human activities (Seto and Fragkias 2007). Consequently, increased protected area goals can be achieved in areas with minimal human impact. These studies have shown significant variation in terms of landscape connectivity between ecoregions and continuity of the bioclimatic corridor (Figure 2).

Protected areas are the primary response to this challenge and are the cornerstone of biodiversity conservation efforts. However, the world's species, ecosystems, and related services are in poorer condition than previously reported (Jacobson et al., 2019). China has lost 50% of its mangroves since the 1950s, and the remaining mangroves are increasingly fragmented. The 10-meter resolution mangrove maps from this study can help manage and protect China's mangroves, especially the small, fragmented mangrove patches scattered along the coast (Zhao and Qin, 2020). China's mangrove landscapes have seen significant changes over the past 40 years, though micro-scale changes remain less understood. This study, using remote sensing data with 99.3% accuracy (as of 2018), found that while mangrove areas recovered after 2000, fragmentation also increased (Zhang et al., 2021). Both the study area and the entire state of Campeche showed temporal and spatial changes in land cover over 40 years (Table 1). From 1990 to 2017, mangroves in Peninsular Malaysia mainly transformed into secondary forests (43%) and plantations, with changes concentrated in northern Kelantan and the west coast. In East Malaysia, 62% of mangroves were converted to secondary forests and plantations, with secondary forests in north-eastern Sabah and plantations on Sabah's north-central coast and Sarawak's west coast (Yan et al. 2020). By 2020, little change was occurring in the area. The results of the anthropogenic map show that human impact is increasing (Figure A6).

The study explores mangrove cover changes in two subtropical estuaries on Brazil's southeast coast, leveraging Landsat imagery from 1985 to 2014. By integrating spectral, spatial, and temporal data through a GIS framework, it identifies and characterizes mangrove fragments. This hierarchical spatial database model offers a versatile tool for similar analyses in other regions (Conti et al. 2016). Habitat destruction and fragmentation caused by natural and anthropogenic factors are contributing to severe reductions in mangrove biodiversity and ecosystem functioning worldwide (Paling et al. 2008; Melalih 2023). Therefore, even small fragments of mangroves should be protected to enhance functional and taxonomic coastal biodiversity. The study shows that the dynamics of mangrove areas are constantly changing, as demonstrated by the observed variations in mangrove areas due to natural and anthropogenic factors (Figure A6). The study by Paling et al. (2008) quantified the change in mangrove area in the eastern part of Exmouth Bay over six years following Cyclone Vance, using Landsat TM satellite and aerial imagery. The results suggested that the majority of the loss was due to long-term consequences of sedimentation or fill, rather than direct wind or wave action. However, the cause and rate of loss and restoration remain largely unknown. In contrast to the displacement of other mangroves around the world, the mangrove forest on the Guangxi coast has been moving seaward, as the rate of change in sediment height on mangrove mud flats has exceeded the rate of change in relative sea level. However, landward migration has been prevented by human land cover (Jia et al. 2014). As the landscape becomes more fragmented due to habitat loss, individual patches become smaller and more isolated, making it less likely that a local population can be sustained (Jansen et al. 2008). The regions with the greatest habitat loss were not necessarily the regions with the greatest loss of metapopulation capacity. Huang et al. (2020) proposed several methods that managers can use to assess and prioritize landscapes for metapopulation sustainability. Mangrove forests, crucial for carbon absorption and habitat provision, have uncertain total coverage in the Arabian Gulf. Fragmented mangroves are common in developed UAE regions, where plantation efforts have boosted their cover. While Kuwait's mangroves are rare, those in Bahrain, Qatar, and Saudi Arabia have remained stable or slightly increased. In contrast, Iran's mangroves are declining (Almahasheer et al. 2018). It also assesses the ecological value of ecosystems at different regional scales, including ecoregions, states, and municipalities (Figure A2). The conservation status of Campeche is high, and there is a need to establish ecological corridors to protect the surrounding area. The study revealed changes in the mangrove forests, and the impact of human activities on natural vegetation degradation and land use changes were taken into account while developing the ecoclimatic corridor model. Therefore, protecting biodiversity in this part of Mexico can mitigate the effects of the aforementioned threats and pressures (Figure 2). The region is well-preserved, and in the context of declining mangrove forests globally, it could serve as a crucial biodiversity reservoir.

The impact of human activities on estuarine resilience is unclear, though hurricanes naturally affect mangroves. Areas with limited connectivity had significantly fewer red mangrove seedlings, indicating that habitat fragmentation may delay forest restoration by limiting seed supply or seedling production (Milbrandt et al. 2006). Therefore, managing various factors of deforestation can increase or decrease fragmentation, and large-scale monitoring of mangroves should also take fragmentation into account (Table 1). Mexico has introduced legislation, such as the general climate change law and the energy transition process, which are of great importance to biodiversity conservation, in an effort to reduce the ecological footprint and protect Mexico's biodiversity. Mangrove forests are at risk of being converted to large-scale pond aquaculture, which threatens biodiversity and ecological functions (Flores-Cárdenas et al., 2018). The Conefor program can assess the importance of habitat areas and their linkages for maintaining or improving connectivity, which is critical for conservation planning (Nuñez et al., 2013). However, forest restoration remains low and reforestation is mostly passive due to reduced land use intensity in southern Mexico (Vaca et al., 2012). Several connectivity models identify areas that have been less modified by humans, enabling colonization by organisms (Revuelta-Acosta et al., 2022). While the impacts of global change drivers on mangroves can be complex and multifaceted, it is essential to implement strategies that use restoration and conservation to enhance the adaptive capacity of these vital ecosystems to the effects of climate change (Wróbel 2023). However, with the emergence of GIS tools and other scientific advancements, it is now possible to create precise and comprehensive global datasets that capture the extent, structure, and health of mangroves. This information can be used to evaluate ecosystem services and promote greater conservation and restoration efforts. Such measures will help minimize mangrove loss and support their expansion, contributing to the preservation of critical ecological services.

4.4 The limitations of the study and research needs.

This study's reliance on satellite imagery from 1981 to 2020 may overlook short-term changes and localized disturbances affecting mangrove coverage. Additionally, the spatial resolution of the images limits the detection of smaller-scale ecological dynamics, and the proposed GIS-based biological corridor technique requires further validation and stakeholder engagement for practical implementation. The results of this study underscore the critical role of mangroves and their adjacent ecosystems in addressing the challenges of climate change. Immediate action is essential to protect and restore these vital ecosystems for long-term sustainability. Effective management strategies and sustainable practices must be adopted to promote biodiversity conservation and enhance ecological resilience. The findings of our study indicate that the studied mangrove ecosystem is relatively stable, reinforcing the effectiveness of our conservation and management approach. Therefore, we recommend incorporating this forest region into the protective boundaries of a well-designed biological corridor system.

Habitat fragmentation remains a significant factor contributing to ecosystem degradation, diminishing the capacity of ecosystems to provide essential services. The provision of services by mangrove forests, in particular, relies heavily on the size and distribution of patches. However, there is limited understanding of the overall scale of coastal fragmentation. Lastly, findings may not be directly applicable to other megadiverse regions due to unique ecological and socio-economic contexts. In light of these findings, it is recommended to implement precise and sustainable management practices that consider the unique characteristics of local ecosystems. This approach requires close collaboration among stakeholders, including government agencies, local communities, and conservation organizations, to develop and execute management plans prioritizing the protection and restoration of mangroves and their neighboring ecosystems.

5 Conclusions

The present study sought to examine the impact of fragmentation on regional conservation priorities, particularly in developing countries' mangroves. This investigation holds significant value in elucidating the dynamics of these ecosystems. The implications of our findings for policies aimed at reducing deforestation and promoting forest cover growth are particularly noteworthy. Mangrove trees have the unique ability to reproduce and disperse widely, but their resistance and dispersal mechanisms can be disrupted by anthropogenic activities such as forest fragmentation and afforestation. Our investigation has revealed divergence in the forest boundaries of the Campeche state mangroves under scrutiny. Moreover, our bioclimatic index analysis established that these forests are ecologically well-suited. Based on satellite remote sensing data, we recommend the incorporation of portions of the mangroves into a conservation system in the form of biological corridors. Our findings, from a temporal and spatial perspective, have valuable implications for the management and protection of mangroves in this region of Mexico.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

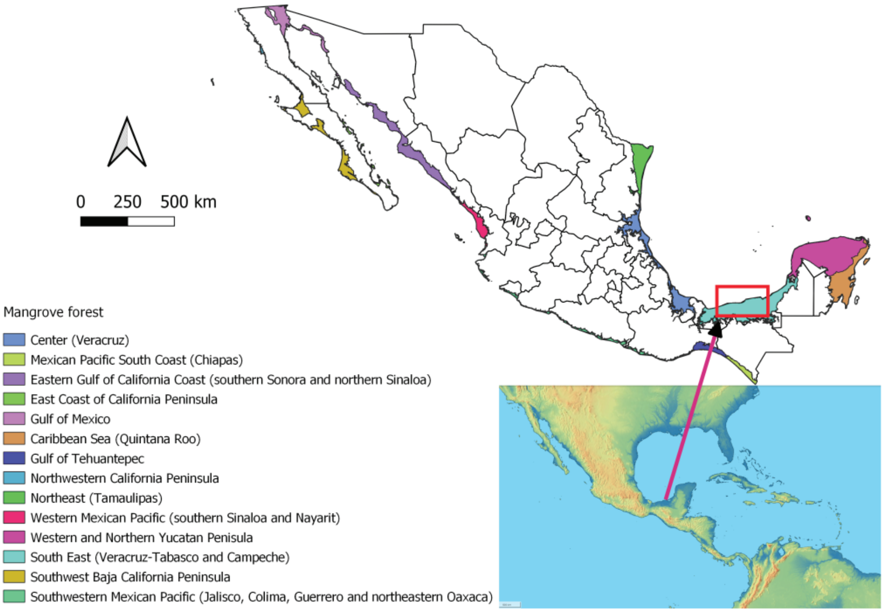

Figure A1. Location of all mangroves in Mexico and the boundaries of the research area in the South East district. Source: CONABIO 2022.

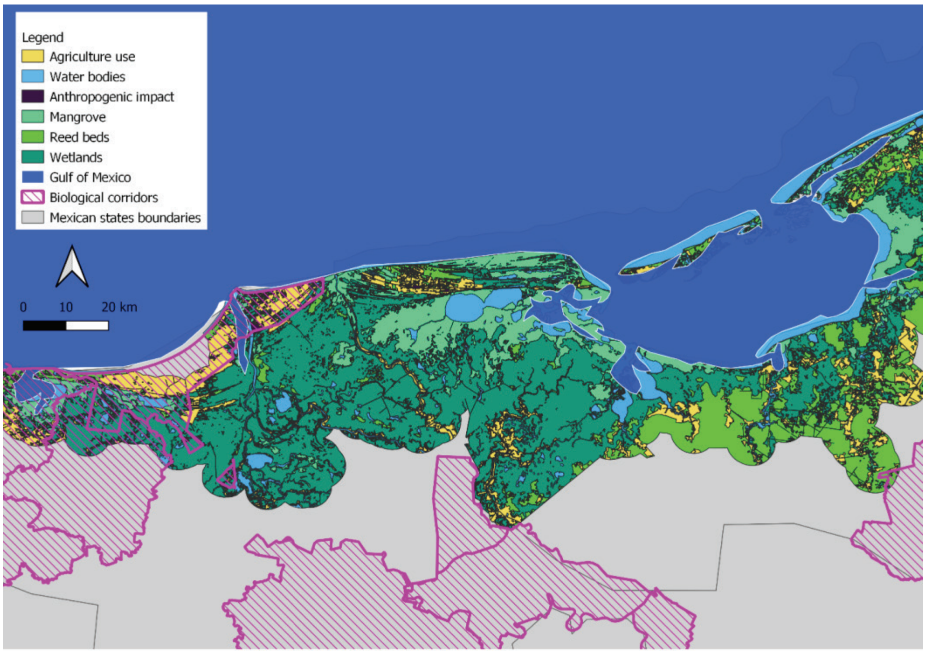

Figure A2. Land cover of the study area in the mangrove district of Campeche, Mexico. Source: CONABIO 2022.

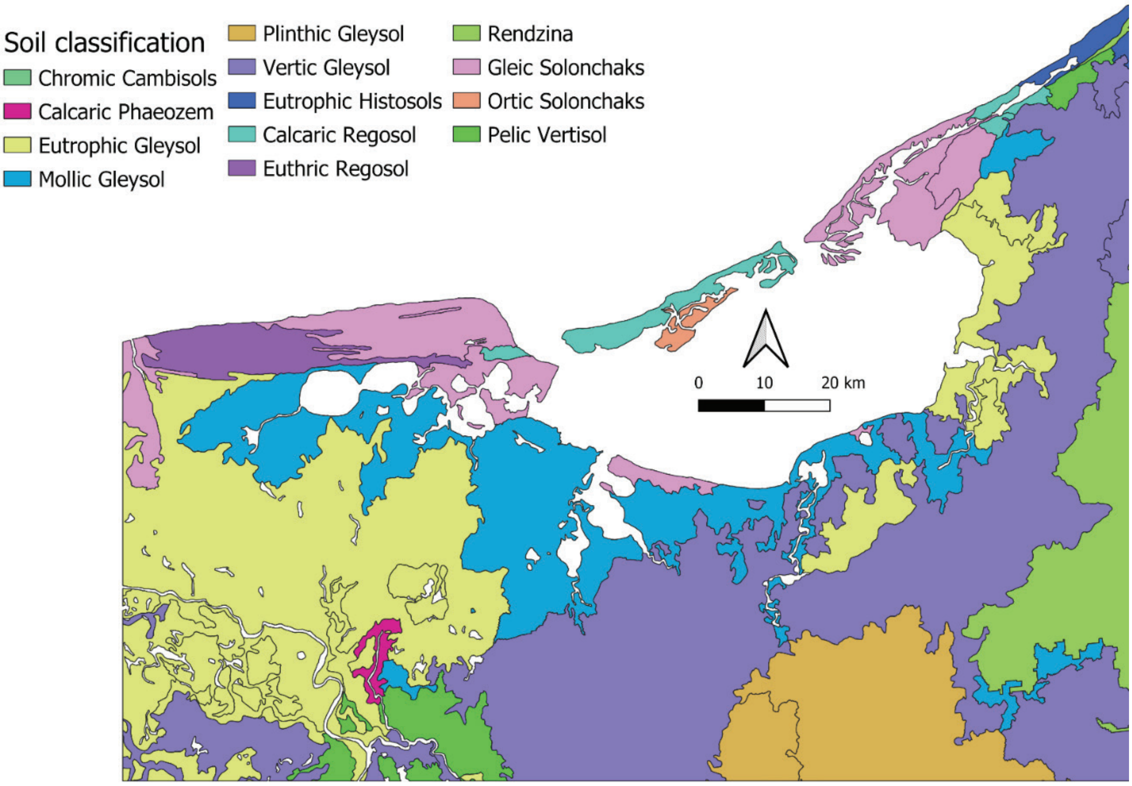

Figure A3. Soil classification map of the study area. Source: CONABIO 2022.

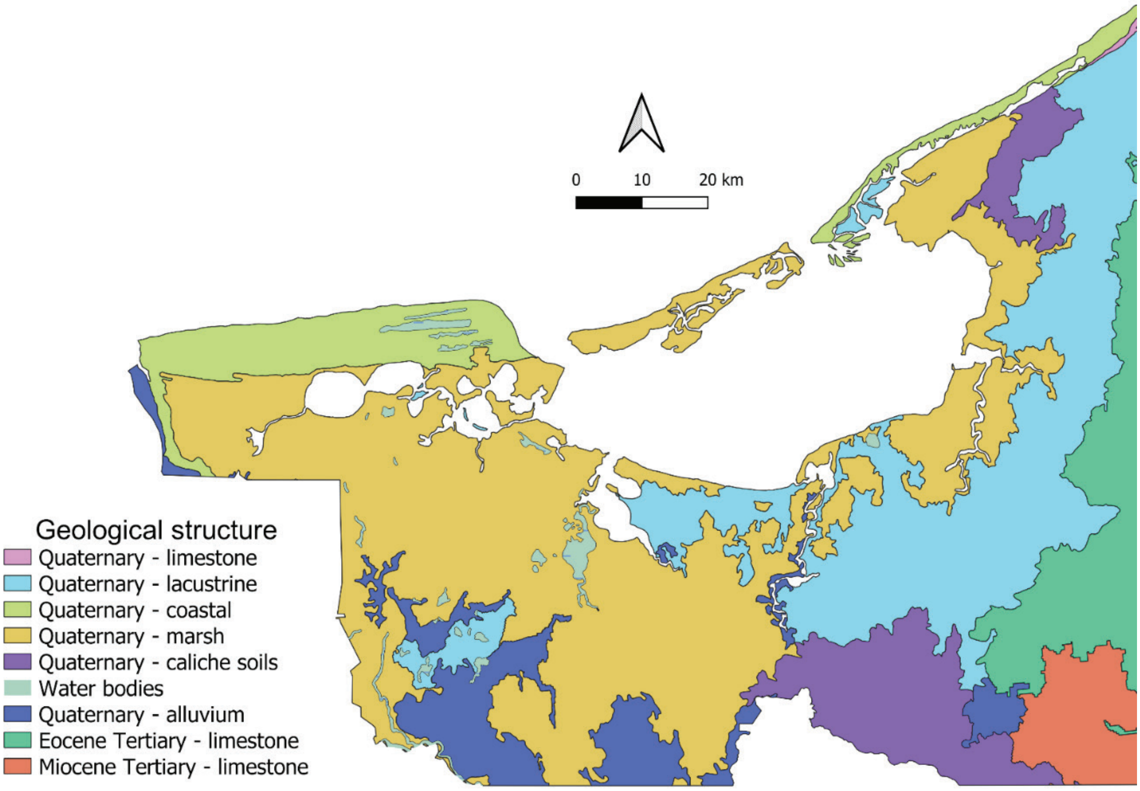

Figure A4. Geologic map of the study area. Source: CONABIO 2022.

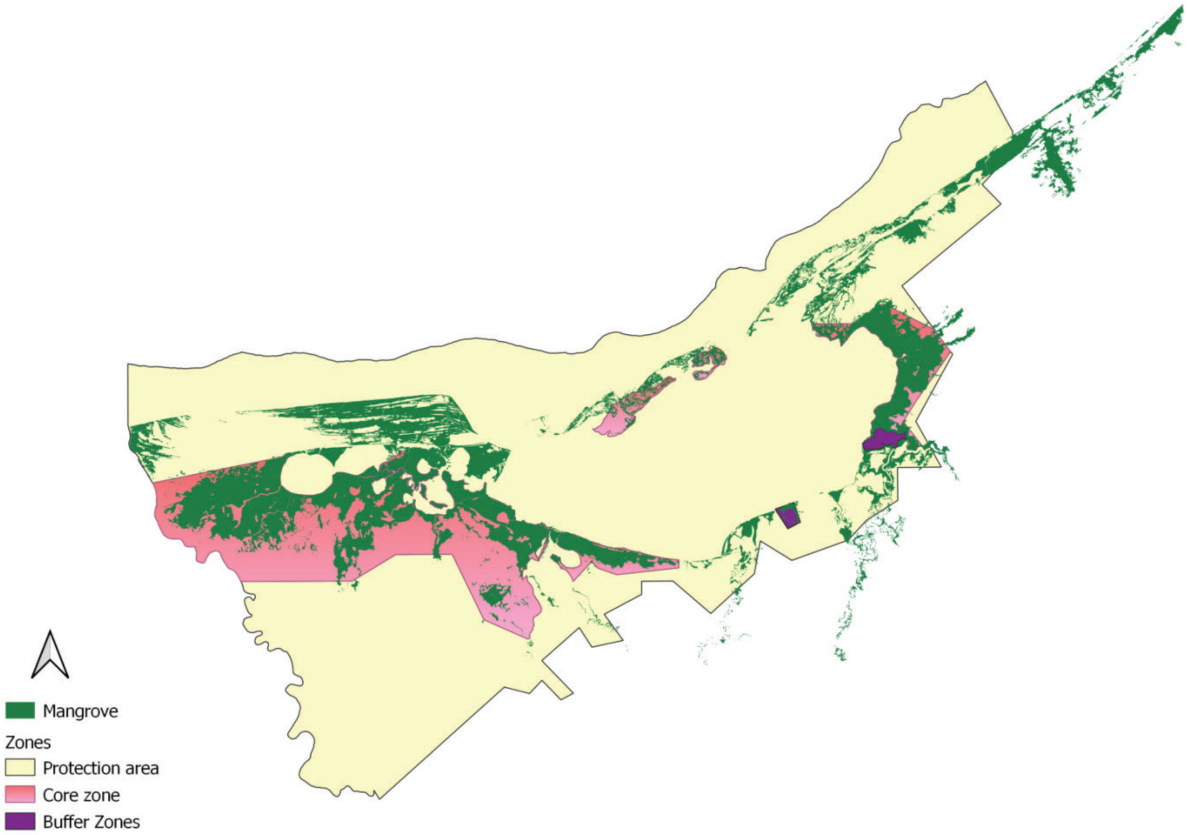

Figure A5. Mangrove zonation in the study area. Source: CONABIO 2022.

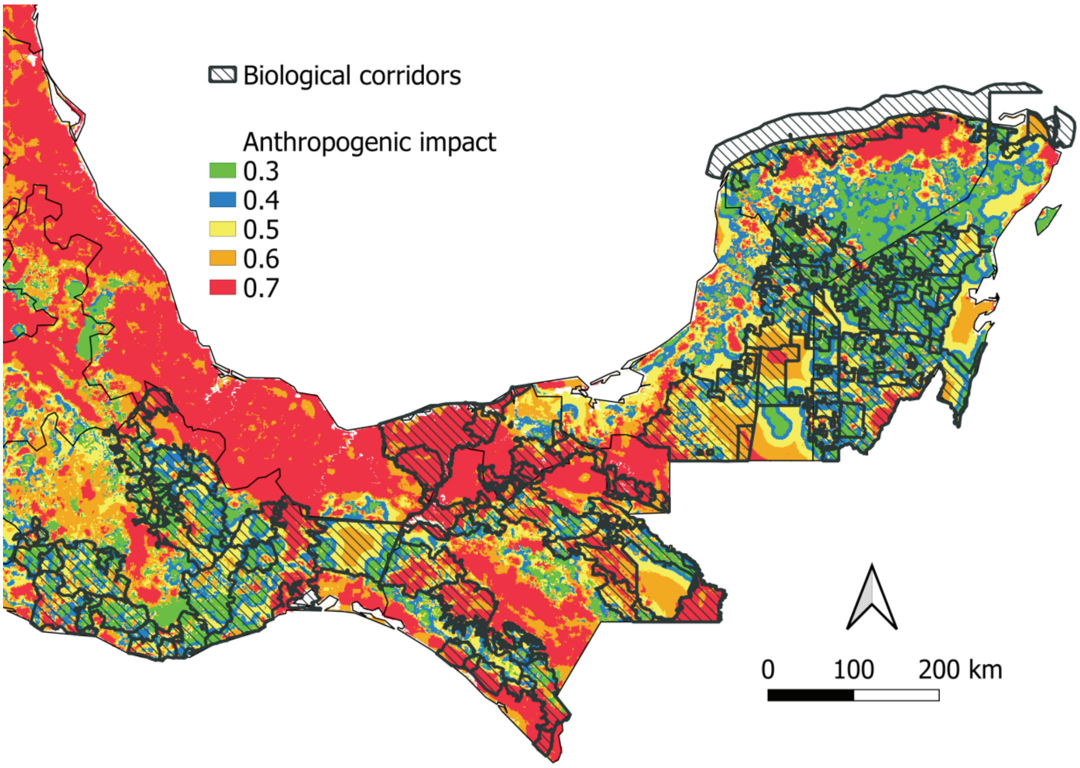

Figure A6. Anthropogenic impact index in south-eastern Mexico. Source: CONABIO 2022.

Figure A7. A satellite image of the study area shows the places most likely to change each year. A) the coastal zone B) a section on the spit.

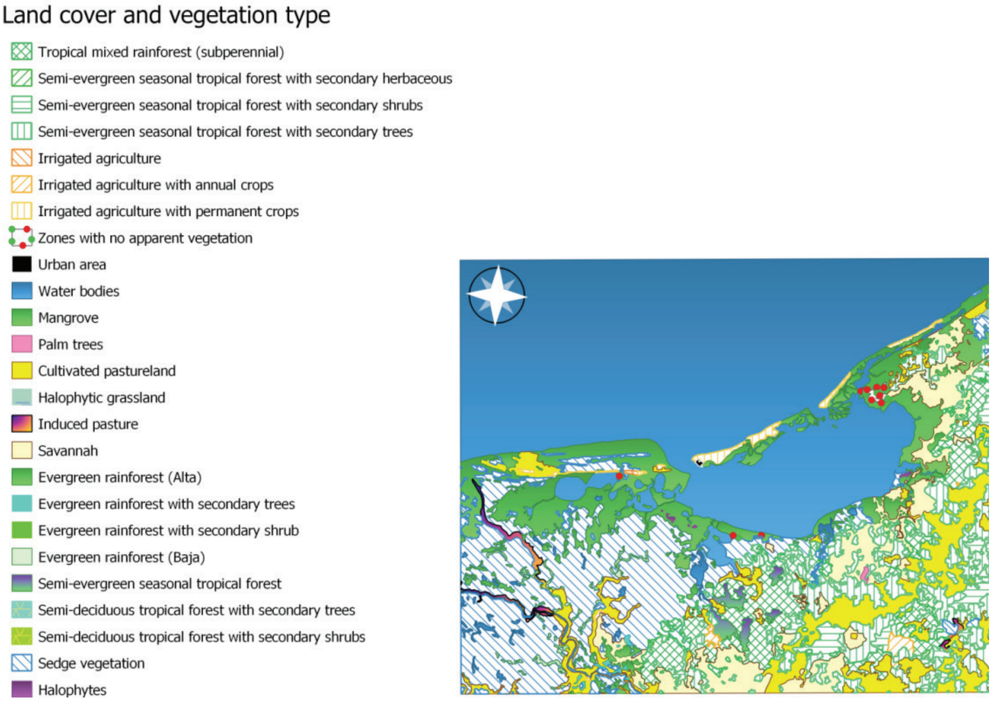

Figure A8. Vegetation type in the research area. Source: CONABIO 2022.