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ORIGINAL ARTICLE

Prediction of mangrove recovery in natural protected areas of the Yucatan Peninsula

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Abstract
Natural protected areas (NPAs) in the Yucatan Peninsula favour the conservation of mangrove forests, which are valuable ecosystems for their provision of ecosystem services. However, mangroves are vulnerable to destruction due to natural and anthropogenic pressures. Therefore, it is important to assess their spatial and temporal dynamics and the potential for deforestation and recovery of cover. In this study, we analyse and model mangrove forest cover change in six NPAs of the Yucatan Peninsula by 2025. Predictions were made using the cellular automata method (CA-Markov) based on attributes that drive rates of change (obtained Kappa coefficients between 0.78 and 0.91). Anthropogenic development was the most dominant potential driver of land use and land cover change in all NPAs except the Flora and Fauna Protection Area-Yum Balam. During the period 2005–2015, the Biosphere Reserves-Petenes and Celestún showed the greatest mangrove loss, followed by the Flora and Fauna Protection Area-Nichupté. These processes changed for the simulated period (2015–2025), where an increase in mangrove cover is projected in these protected areas. Flora and Fauna Protection Area-Términos is the only protected area where a projected transition of mangroves to anthropogenic development has been identified. Therefore, it should be considered an area vulnerable to mangrove transformation and loss.

Keywords Mangrove · Land cover change · Molusce · Predictive modelling

Introduction

Mangrove forests comprise a vegetation type that is restricted to the land-sea interface between latitudes of approximately 30° N and 30° S (Giri et al. 2011; López-Angarita et al. 2018). Globally, these are highly valuable ecosystems for their provision of ecosystem services by supporting coastal fisheries (Wang et al. 2021), shoreline stabilization through flood and storm prevention (Chowdhury and Hafsa 2022; Jadin and Rousseau 2022), atmospheric carbon sequestration (Hutchison et al. 2014; Hu et al. 2020; Jadin and Rousseau 2022), favourable habitat for estuarine, coastal and terrestrial fauna (Jia et al. 2018) and the support of millions of coastal livelihoods (López-Angarita et al. 2018).

Mangroves are some of the most vulnerable ecosystems in the world. They are largely threatened by anthropogenic disturbances such as the development of aquaculture ponds and the construction of tourism infrastructure (Zhu et al. 2021). Furthermore, natural (e.g. hurricanes) and climate change disturbances (e.g. sea level rise) have drastically altered their coverage (Chowdhury and Hafsa 2022; Zimmer 2022). Globally, since the mid-1990s, mangrove extent

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has been reduced by more than 40% (Luom et al. 2021) with an annual rate of loss of 0.4% (Hamilton and Casey 2016).

Mexican mangroves constitute the fourth largest national extent on the planet, representing 5.4% of the world's mangroves (Giri et al. 2011). Of these, 60% is distributed in the Yucatan Peninsula (YP) (Velázquez-Salazar et al. 2021). Previous assessments at the national level suggest a reduction in mangrove area of 9.6% for the period 1981–2005 and 1.2% for the period 2005–2010 (Rodríguez-Zúñiga et al. 2013). For the YP, a loss rate of 1.8% was estimated between the period 1976–2000 and more recently between the period 2005–2020, a mangrove recovery rate of 1.7% has been observed (Velázquez-Salazar et al. 2021), with a higher recovery inside protected areas (Osorio-Olvera et al. 2023).

Considering the worldwide recognition of mangroves, spatially explicit research on these ecosystems has focused on understanding land use and land cover patterns (Faruque et al. 2022). Generally, land cover refers to the physical properties that characterize land cover, while land use represents the use of land by humans (Kafy et al. 2021a). The abbreviation LULC (land use and land cover) is commonly used as they are evaluated in combination and cannot be separated from each other (Faruque et al. 2022). The study of LULC change involves the replacement of natural cover by artificial surfaces such as conversion to other land uses such as agriculture, fisheries and expansion of arable and urban land, leading to a loss of biodiversity and irreversible consequences on the function and integrity of ecosystems (Foley et al. 2005; Huang et al. 2020).

LULC change models have been employed to assess the dynamics of wetland cover change, as these areas are influenced by environmental changes and historical and current human activities (Faruque et al. 2022; Mubako et al. 2022). These types of studies are some of the most accurate techniques to detect spatiotemporal change in coastal system (Lopes et al. 2023). Furthermore, LULC change analyses have been employed to predict future spatiotemporal trends to guide land-use planning, population livelihood food security (Qiao and Yuan 2021) and evaluation of the effectiveness of current conservation policies (López-Angarita et al. 2018). Therefore, these types of models can determine where (location of change) and at what rate changes are likely to occur (amount of change) (Sakayarote and Shrestha 2019). Although several studies have shown interest in the dynamics and prediction of LULC changes (Hu et al. 2020; Rahman and Ferdous 2021; Fan et al. 2023), scenario studies on the future distribution of mangroves are still limited (Zimmer 2022). This is particularly important for the YP, where to our knowledge, no studies have addressed future mangrove coverage scenarios. Predicting mangrove coverage change allows to prepare plans for land use management considering patterns of coverage change and spatially explicitly identify regions for prioritization and the variables that influence processes such as deforestation and recovery (Kafy et al. 2021b; Chopade et al. 2023).

In this paper, we analyse and model mangrove forest cover change in the YP, especially considering deforestation and recovery. We focus on generating scenarios of mangrove cover change for the year 2025, considering the federal natural protected areas (NPAs) in the region where mangrove forests are distributed and the adjacent area outside of the NPAs. Furthermore, attributes of the NPAs (location, inside/outside the protected area, time of decree) and the distance to roads, which are known to drive mangrove coverage change rates in the region (Osorio-Olvera et al. 2023), are incorporated.

Methods

Study area

This study was carried out in the YP, between 18° and 21°30′ N latitude, in the states of Campeche, Yucatán and Quintana Roo. The area of analysis considered six of the ten federal NPAs of the YP in the states of Yucatan, Campeche and Quintana Roo that contain mangrove forests (Fig. 1). The main anthropogenic activities in the area are related to the oil industry, tourism, fishing and urban development (Herrera-Silveira 2006; Rioja-Nieto et al. 2015; Cinco-Castro and Herrera-Silveira 2020). The main tourism activities occur in Cancun and the Riviera Maya, in the Mexican Caribbean (Rioja-Nieto et al. 2019). Oil industry activities are mainly located in the southwest of the YP, in Campeche (De la Lanza Espino et al. 2010). The region has been developed since the early 1970s with limited enforcement of regulations, which has affected coastal ecosystems such as mangroves and coral reefs (De la Lanza Espino et al. 2010). Some areas in the region have shown an increase in mangrove coverage for the period 2005–2020. However, mangrove losses have also been recorded, mainly in the western region of the YP (Rioja-Nieto et al. 2019; Velázquez-Salazar et al. 2021; Osorio-Olvera et al. 2023).

The NPAs where the analysis was conducted comprise three biosphere reserves: Los Petenes (BR-Petenes), Ría Celestún (BR-Celestún) and Ría Lagartos (BR-Lagartos) and three flora and fauna protection areas: Yum Balam (FFPA-Yum Balam), Manglares de Nichupté (FFPA-Nichupté) and Laguna de Términos (FFPA-Términos). Four NPAs were not considered for the analysis: Sian Ka'an, Uaymil, Pantanos de Centla and Tulum National Park. The mangrove maps on the first two NPAs present uncertainty, related to the spatial resolution of the satellite images used for the construction of the thematic maps and the criteria to differentiate between mangrove and other wetlands categories (Velázquez-Salazar et al. 2021), which would reduce the reliability of the models and their predictive capacity. In Pantanos de Centla and

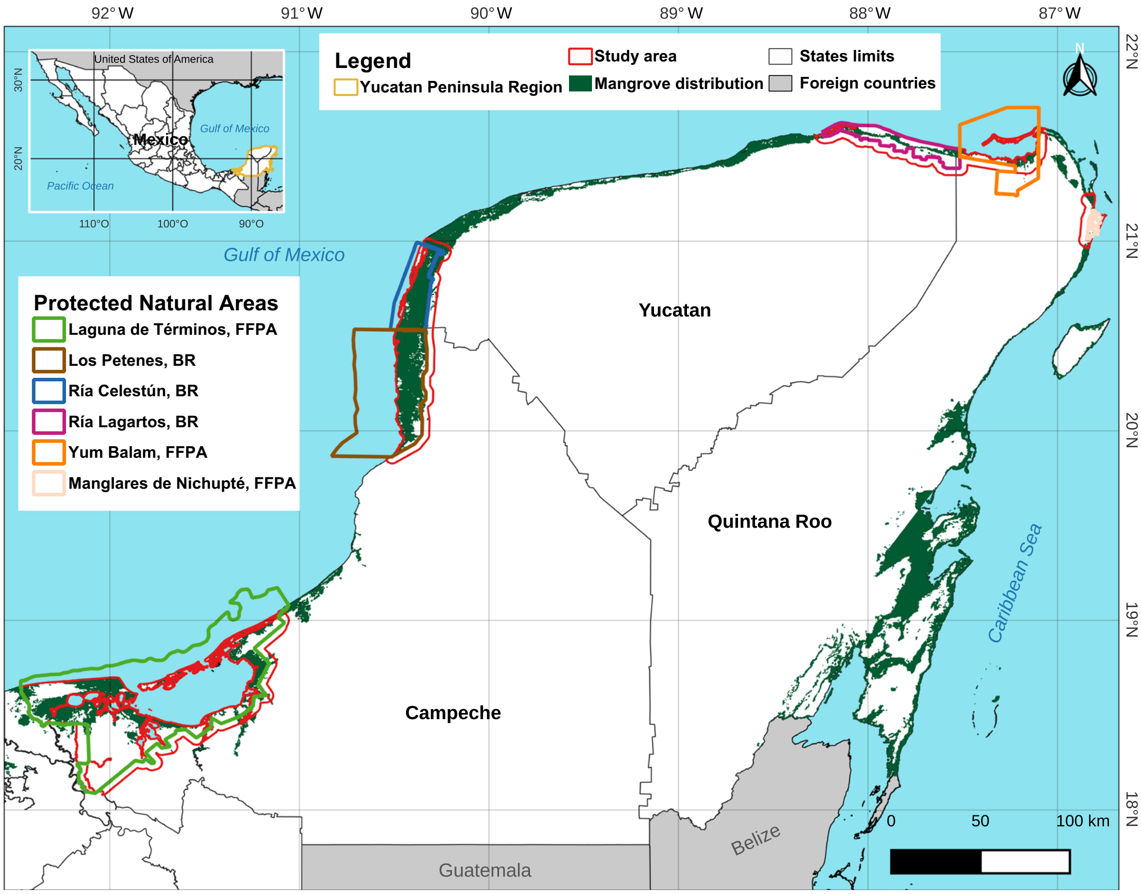

Fig. 1 Yucatan Peninsula, Mexico. The study area considered six federal NPAs and an adjacent 4-km zone (transition area) in the states of Yucatan, Campeche and Quintana Roo

Tulum National Park, the area with mangrove coverage was too small for analysis.

Analysis of land use and land cover change processes

Mangrove cover was obtained from land use and vegetation maps of the coastal zone associated with mangroves in the YP region generated by the National Commission for the Use and Knowledge of Biodiversity (CONABIO, for its acronym in Spanish). The maps used correspond to the years 2005, 2010, 2015 and 2020, which are at a scale of 1:50,000. According to the metadata of the spatial information, the mangrove cover maps for the first assessments were constructed from SPOT 5 satellite images. However, the maps produced for 2020 were constructed from Sentinel-2 images. The overall accuracies of the maps were as follows: 90.5% for the 2005 map, 81.8% for the 2010 map, 85.9% for the 2015 map and 94.2 for the 2020 map (CONABIO 2013, 2016, 2021).

The maps present a classification system composed of eight land use and vegetation classes. These classes were regrouped into fewer categories to improve the performance of the model (Moreno-Mateos et al. 2017): (1) anthropogenic development (agriculture, human settlements and areas without vegetation), (2) mangrove (mangrove and disturbed mangrove) and (3) other vegetation types (wetlands, dry tropical forest and water bodies). In this way, we produced a transition probability matrix using the LULC change data for each period of analysis.

The analysis of changes was performed using the modules for LULC change assessment (MOLUSCE) of QGIS 2.18.8 software (Gismondi 2013). Spatio-temporal changes were estimated, and the LULC transition was calculated between the 2005–2015 research intervals. Subsequently, scenarios for the periods 2020 and 2025 were generated.

Drivers of mangrove cover change

The analysis of the LULC change drivers included in the modelling was based on Osorio-Olvera et al. (2023). A grid with 4×4 km cells for the processing of cover change and data collection was generated. The analysis included cells where mangroves were located inside NPAs and the transition area (defined as the surrounding adjacent area of 4 km bordering the polygon of each NPA, hereafter referred to as the transition zone). The choice of cell size considers the spatial heterogeneity of the area of study, is similar to the spatial extent used in other studies that assess protected area effects (Hua et al 2022; Osorio-Olvera et al. 2023) and facilitates data processing.

From the centroids of each grid cell, the values of vegetation and land use classes for the years 2005, 2010 and 2015 and a set of variables (distance to roads, inside NPA, transition zone and NPA age) were obtained. Subsequently, the rate of change of mangrove cover was calculated for each cell in the analysis grid by the least squares method using mangrove cover data for 2005, 2010 and 2015 (Rioja-Nieto et al. 2017; Osorio-Olvera et al. 2023).

$$y = a + bx \quad (1)$$

where y is the mangrove cover for a given year, a is the y-intercept, b is the slope (rate of change) and x is time.

The polygons of the NPAs were downloaded in shapefile format from the CONABIO website (http://www.conabio.gob.mx/informacion/gis/). The distance to roads was obtained from the geographic information layer of the National Road Network, 1:50,000 scale, for the year 2018 (INEGI 2018). This was calculated as the Euclidean distance to the nearest major road from each cell in the study area. The editing of shapefiles, the generation of the grid and the calculation of the distance to roads analysis were performed with the ArcMap 10.4.1 program.

Linear regressions were performed with the stat package in R version 4.0.5 (R Core Team 2021). Finally, a generalized least square (GLS) model was used to evaluate the effect of NPA (inside the protected area and transition zone), NPA age and distance to roads in the change rate of mangrove cover. The selected GLS model showed significant interactions ($p < 0.05$) between location (within the protected area or transition zone), distance to roads and time since establishment. These variables were incorporated into the modelling and scenario generation process.

Modelling of mangrove forest cover change processes

For the modelling of the transition potential, we used the variables that were previously determinant in the dynamics of mangrove LULC change in the YP during the period 2005–2015. The prediction scenarios of change to 2020 and 2025 were performed using the cellular automata method (CA-Markov), as it is one of the most widely used approaches for predicting future LULC and for modelling large-scale systems, especially for short-term projections (Baker 1989; Gao et al. 2011; Waseem et al. 2015). This model uses evolution from past changes to project probabilities of future changes, assuming that a landscape will move from one mutually exclusive state to another (Rahman and Ferdous 2021). It is based on images from different dates, integrating the spatial rules of the cellular automata with the Markov chain transition (Sang et al. 2011), which is a stochastic model that allows LULC changes to be simulated by a transition matrix and information about the current state (Fernandes et al. 2020). In this way, transition power maps of each class are generated through the assumption that the pixel closest to an existing LULC class is most suitable for each class (Fernandes et al. 2020).

The simulations of the 2020 and 2025 maps were generated following the Markov chain pattern, based on previous simulations for the periods 2005–2010 and 2010–2015. The spatial analyses were performed in the MOLUSCE (module for land use scenarios) add-on of the QGIS 2.18.8 platform, as it is designed to analyse, model and simulate future LULC changes (Kafy et al. 2021a).

Model validation

The validation process consists of verifying the results found in the cellular automata (CA) simulation after the simulation run. This process is carried out using reference data close to the past to verify the simulated results (GIS-Lab 2018). First, the simulation was based on the temporal feed map 1 (2005–2010), while the validation is the comparison between the simulated and observed maps of 2015 (t2). Then, the simulated 2020 map was based on feed map 2 (2010–2015), while the validation is the comparison between the simulated and observed 2020 maps (t3). Finally, the 2015 map is compared with the 2020 map, to produce a simulated 2025 map (t4) in MOLUSCE. In this way, the MOLUSCE model provides a comparison between the actual and the projected LULC. The validation of the simulated LULC maps is performed by calculating the overall Kappa coefficients, which reflect the difference between the actual agreement and the expected agreement by chance.

Based on the incorporation of land use and vegetation maps of the coastal zone associated with mangroves from 2005 and 2015 and incorporating attributes of the NPAs (the location of the NPAs, inside/outside of the protected area and time since establishment) and the distance to roads, it was possible to generate the simulated maps for the year 2020 and 2025.

Results

The validation results for the six natural protected areas revealed an accuracy above 78%, which is considered a very robust predictive simulation (Fernandes et al. 2020; Kafy et al. 2021b; Roy 2021; Ziaul and Pal 2021; de Oliveira Barros et al. 2022). The results of the 2015 simulation validation process are as follows:

The BR-Celestún, BR-Petenes and the FFPA-Yum Balam showed kappa coefficients above 0.91. The lowest kappa coefficient obtained was for the BR-Lagartos (0.79), and FFPA-Términos and FFPA-Nichupté showed coefficients between 0.82 and 0.89. A similar pattern was observed for the 2020 validation process: The BR-Celestún, the BR-Petenes and the FFPA-Yum Balam showed kappa coefficients between 0.93 and 0.97, FFPA-Términos 0.88, Nichupté 0.82 and the lowest kappa coefficient was observed in BR-Lagartos (0.78). Based on the validation results for the 2015 and 2020 simulations, the 2025 simulated map is considered to be valid.

Land use and land cover maps and deforestation rates

The transition potential modelling stage in MOLUSCE produced statistics of annual rates of change and loss and gain of mangrove coverage for each of the analysed NPAs.

The results showed that in the first period (2005–2015), the NPAs that registered a decrease in mangrove area were BR-Petenes, which lost 990 ha (annual rate of – 0.17%), FFPA-Nichupté with a decrease of 12 ha (annual rate of – 0.03) and BR-Celestún with a decrease of 103 ha (annual rate of – 0.02). However, these protected areas showed an increase in the projected period of analysis (2015–2025), with an increase of 1239 ha (annual rate of 0.21%), 1236 ha (annual rate of 2.36%) and 1482 ha (annual rate of 0.29%), respectively (Figs. 2 and 4).

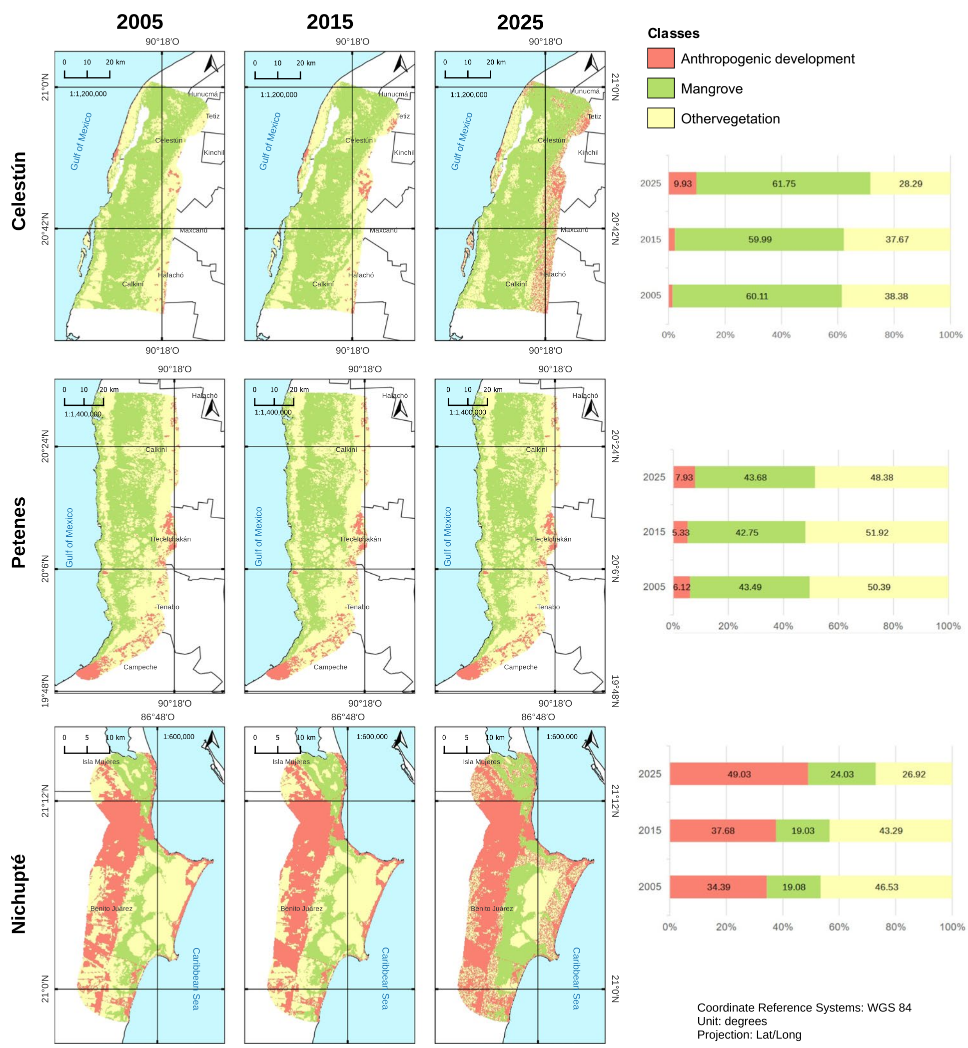

Fig. 2 Land use and land cover change maps and scenarios for the NPAs: BR-Celestún, BR-Petenes and FFPA-Nichupté for the years 2005, 2015 and 2025. The 2025 map corresponds to the simulated map. The bars on the right show the percentage of land use and land cover for each NPA for the years analysed

The NPAs that showed a mangrove recovery in both periods of analysis were FFPA-Yum Balam, FFPA-Términos and BR-Lagartos (Figs. 3 and 4). A reduction in the other vegetation types class is projected for all the NPAs analysed.

Transition matrixes

The NPAs that showed a negative trend on the cover of other vegetation types to an increase of the anthropogenic development class in both periods of analysis were BR-Celestún and FFPA-Nichupté. However, a recovery of mangroves from the other vegetation type class is predicted for the period 2015–2025.

Specifically, BR-Celestún showed a recovery trend in the simulation period (2015–2025) in the eastern zone. However, in the western zone of the FFPA-Nichupté, the first period (2005–2015) revealed a large loss of mangrove but with a positive trend of recovery in the eastern zone of the NPA. The FFPA-Yum Balam in the first period showed a high loss of other types of vegetation, and in the simulation period, a gain of mangrove forest was detected in the north, south and southeast zones. Similarly, in the FFPA-Términos, in the first period, particularly in the south-eastern region, there was a significant loss of other vegetation types but a gain of mangrove forest in the north-western, south-eastern and south-western sections of the NPA. BR-Lagartos did not show a significant trend of mangrove loss or recovery.

The NPAs that went from having a positive trend of recovery of other vegetation types in the first period to an expected pattern of loss in the second period were BR-Lagartos and BR-Petenes. In the FFPA-Términos, a

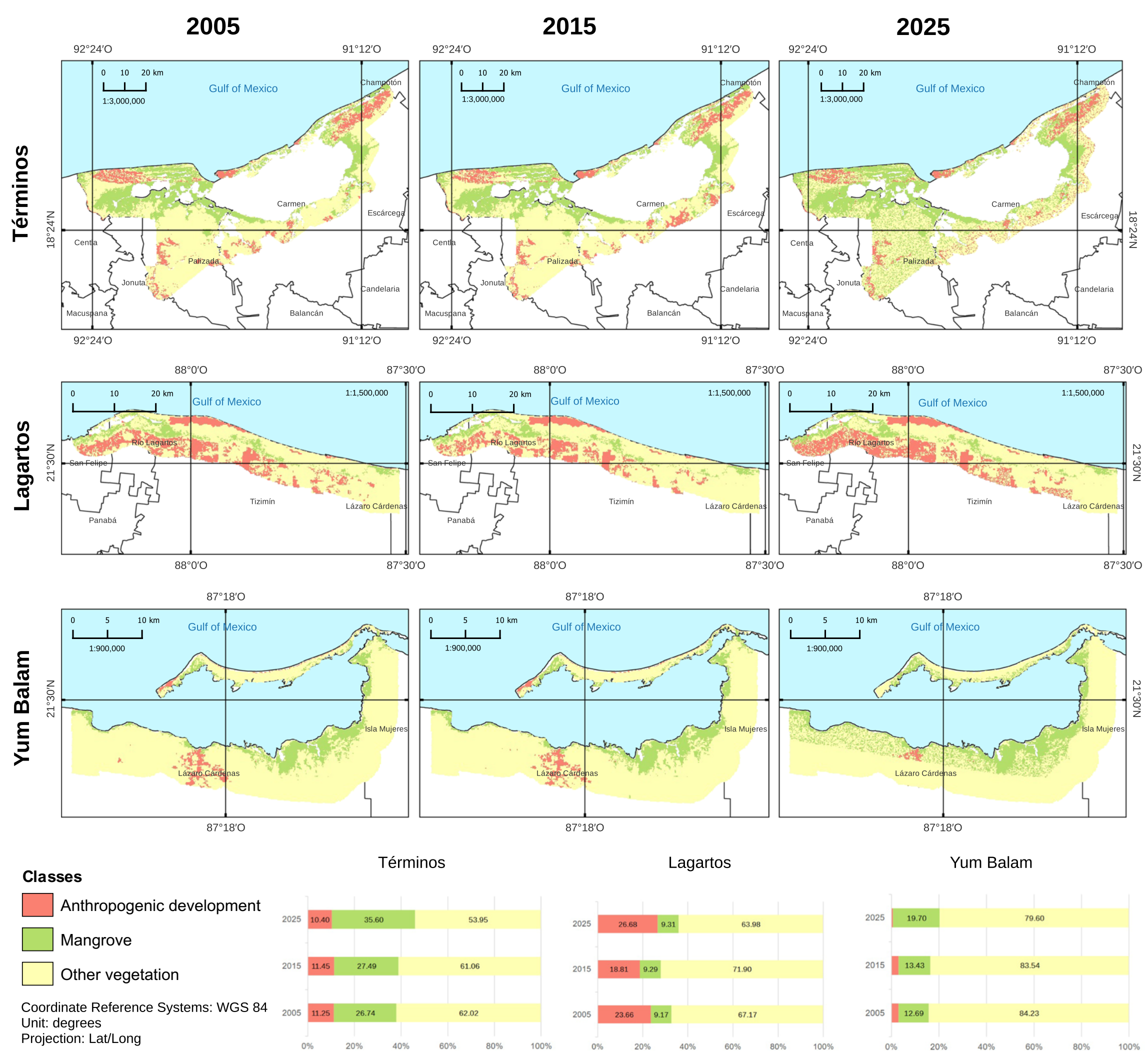

Fig. 3 Land use and land cover change maps and scenarios for the NPAs: FFPA-Términos, BR-Lagartos and FFPA-Yum Balam for the years 2005, 2015 and 2025. The 2025 map corresponds to the simulated map. The bars at the bottom show the percentage of land use and land cover for each NPA for the years analysed

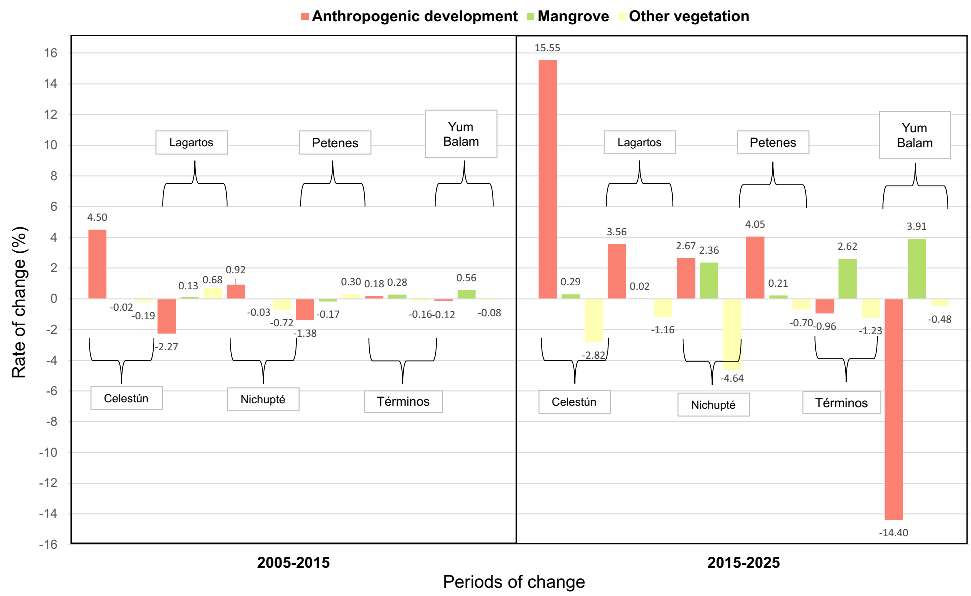

Fig. 4 Observed (2005–2015) and simulated (2015–2025) rate of change for the anthropogenic development, mangrove and other vegetation classes in the six NPAs analysed

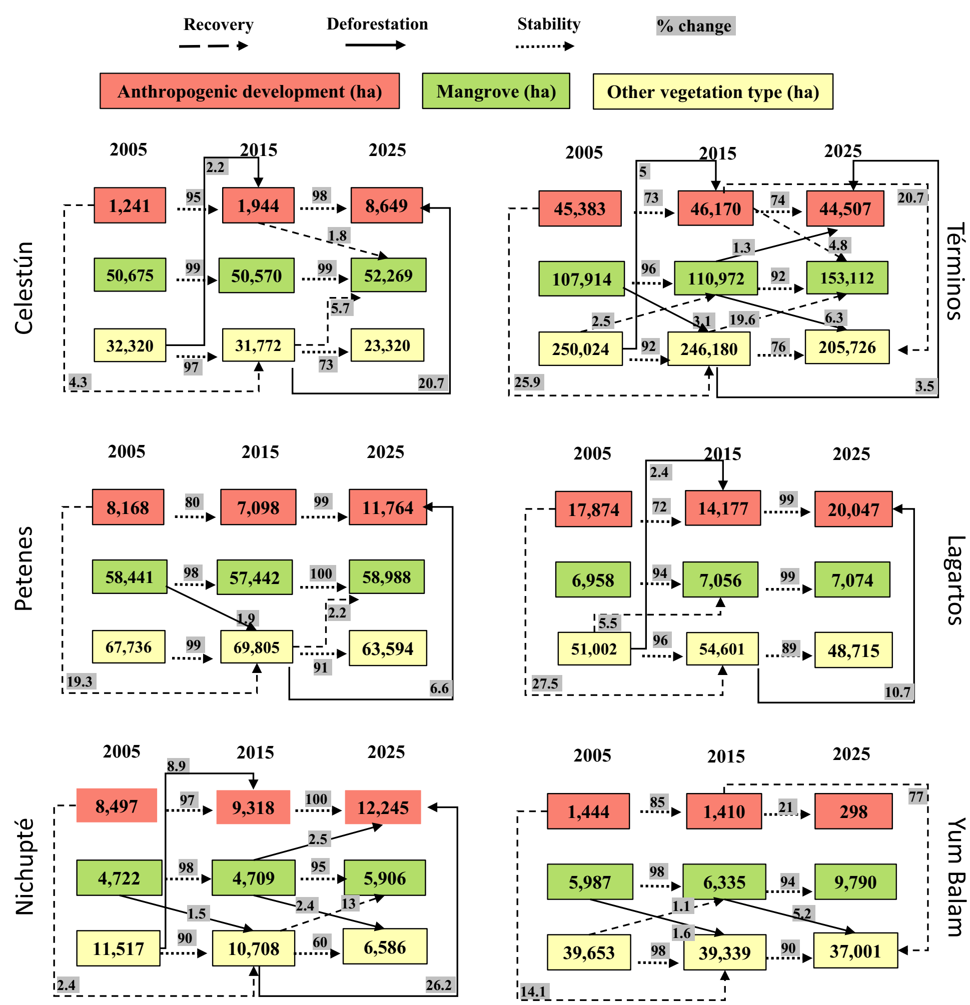

Fig. 5 Transitions of land use and land cover classes and main processes of change for the years analysed. The dashed line indicates recovery, the continuous line indicates deforestation and the dotted line indicates stability processes. The area of each class is shown within the coloured boxes. The percentage of the transition process is indicated within the grey boxes

considerable loss of cover that transformed into anthropogenic development in both the first period and the simulated period was observed. Finally, FFPA-Yum Balam is the only NPA that maintains a trend of mangrove and other vegetation-type recovery in both periods (Fig. 5).

Our analysis has revealed that anthropogenic development (agriculture, human settlements and unvegetated areas) was the most dominant potential driver of LULC change within all NPAs, except in FFPA-Yum Balam. The transition from anthropogenic development to other vegetation types that occurs in all NPAs during the first period and shows a recovery is also noteworthy. This pattern is maintained in the NPAs FFPA-Nichupté and FFPA-Términos.

In the 2005–2015 period, a conversion of other vegetation types to mangroves was observed in the following NPAs: BR-Lagartos (2805 ha), FFPA-Yum Balam (436 ha) and FFPA-Términos (6250 ha). In the simulated period (2015–2025), transitions from other vegetation types to mangroves are predicted for the following NPAs: BR-Celestún (1811 ha), FFPA-Nichupté (1392 ha), BR-Petenes (1535 ha) and FFPA-Términos (47,512 ha). The areas that showed changes in mangrove recovery were in the east of BR-Celestún, in the central area of BR-Petenes and FFPA-Nichupté, in the west and southeast area of FFPA-Términos and southeast of FFPA-Yum Balam. The NPA FFPA-Términos is expected to show a transition from mangroves to anthropogenic development (1442 ha). Therefore, this area is vulnerable to mangrove transformation and loss.

Discussion

The coastal LULC change assessment is one of the most accurate techniques for detecting spatio-temporal change in coastal systems (Lopes et al. 2023). LULC change has been widely used for the identification and prediction of anthropogenic factors promoting cover transformation (Wang et al. 2021). Here, we obtained reliable information to monitor the spatial and temporal progress of mangroves in the YP. The simulated maps showed a high agreement of the 2020 and 2025 simulated maps, as overall reliabilities above 78% were obtained, which are considered highly robust predictions (Fernandes et al. 2020; Roy 2021; Talukdar et al. 2021; Kafy et al. 2021a; de Oliveira Barros et al. 2022). Therefore, our study reveals that from the incorporation of land use and vegetation maps of the coastal zone associated with mangroves from 2005 and 2015 and incorporating attributes of the NPAs (location of the NPAs [inside/outside the NPA] and time since their establishment) and distance to roads (Osorio-Olvera et al. 2023), it was possible to generate accurate change statistics and simulated maps for the year 2020 and 2025.

In the NPAs studied, during the period 2005–2015, the BR-Petenes and BR-Celestún showed the greatest mangrove loss, followed by the FFPA-Nichupté. In the case of the first two, this loss might be associated with the fact that these mangrove areas have been subjected to strong anthropogenic pressures derived from the constant extraction of wood for construction, illegal logging for the maintenance of houses, charcoal production and the artisanal use of salt (salt mines) by the communities surrounding the reserve (RAMSAR 2004; Ceballos et al. 2009; Vázquez-Lule et al. 2009). For the case of FFPA-Nichupté, mangrove reduction is related to the impact of tourism and urban infrastructure in the Mexican Caribbean (Ellis et al. 2017; Rioja-Nieto et al. 2019; Cinco-Castro and Herrera-Silveira 2020). These processes changed for the simulated period (2015–2025), where an increase in mangrove cover is projected in these protected areas. An increase in mangrove cover is recognized for the periods of analysis in the FFPA-Yum-Balam, FFPA-Términos and BR-Lagartos areas. These NPAs maintain the trend of decreasing deforestation rates and increasing recovery that has been previously described (Ellis et al. 2017). Particularly, in the FFPA-Yum Balam, mangrove cover gains have been registered in the period 2005–2015, which coincides with its incorporation, since 2004, in the list of RAMSAR Wetlands of International Importance (Maldonado-Navarro 2022). In the same period, FFPA-Términos showed high recovery rates, which may be due to the implementation of restoration programmes for degraded mangrove areas through the participation of government institutions (CONAGUA, CONABIO, CONANP) and the incorporation of local communities in related activities such as ecotourism and hydrological rehabilitation to promote natural regeneration and strengthen mangrove resilience (Zaldívar-Jiménez et al. 2017); this might be also the case in BR-Lagartos. The recovery of mangrove cover in the YP is also related to other factors. For example, after the impact of hurricanes, the speed of mangrove cover recovery varies depending on the intensity of the event, the impact on the lagoon system, the environmental conditions of each site, tree density and hydrological and sediment dynamics (Velázquez-Salazar et al. 2021). Climatic factors such as annual cumulative precipitation and annual maximum temperature have been also related to the dynamics of mangrove change in the northern YP (Rioja-Nieto et al. 2017). Furthermore, local characteristics such as soil type, hydroperiod and flood level are also important in influencing mangrove dynamics. Therefore, mangrove recovery is related to both site-specific and regional climatic factors (Adame et al. 2014; Castellanos-Basto et al. 2021).

In BR-Celestún, mangrove recovery in the simulation period might be related to the location and extent of the protected area, which insulates mangroves against the destructive effects of anthropogenic encroachment along the edges (Cissell et al. 2018). However, this might change in the future, as different studies have shown that infrastructure development accompanying population increase often leads to increased rates of deforestation in adjacent coastal locations (Valiela and Bowen 2009). Mangrove extraction in BR-Celestún has been reported to occur at very localized points, such as along the roadside leading to Celestún (Vázquez-Lule et al. 2009). Furthermore, the results of transitions showed high transitions from other vegetation cover to anthropogenic development. One of the main disturbances faced by BR-Celestún is the removal of cover for the expansion of salt activity, land use change for the expansion of tourism activity and possible infrastructure construction (Wojtarowski et al. 2021).

Another case of interest in the modelling is observed in FFPA-Nichupté. In this protected area, there is a positive probability of transition towards mangrove recovery, but with a significant loss of other vegetation types (tropical dry forest and other wetlands). This scenario could be viable considering that road construction and the demand for tourism and urban infrastructure in the city of Cancún could impact mangrove cover and other vegetation types (Cinco-Castro and Herrera-Silveira 2020). Analyses reflect that mangroves continue to regenerate, while other vegetation types (e.g. tropical dry forest, other wetlands) are vulnerable to transformation in the NPAs of the Yucatan Peninsula. The vulnerability of other vegetation types with respect to mangroves within protected areas might be associated with the implementation of policies that directly benefit the maintenance of mangroves. For example, Mexico's General Wildlife Law in Article 60 TER prohibits activities that affect the hydrological flow of mangroves (LGVS 2021). This condition has led infrastructure developers to ensure that they maintain hydrological connections in mangrove areas by promoting the presence of canals that maintain mangroves. However, the lack of planning promotes incipient canals that could have two contrasting consequences: (1) they could cause mangrove decline in the medium term in areas where the connection is interrupted, (2) and/or they could favour sediment accumulation in certain areas. Mangrove recovery may also be associated with the availability of new environments with soft sediments that allow the settlement and establishment of new mangrove individuals (Zimmer 2022).

In addition to the particular pressures associated with YP economic development, mangroves and other coastal ecosystems face the impact of climate change and global mean sea level rise (IPCC 2021), which will cause coastal flooding around the world (IPCC 2022). This rise keeps mangroves in a dynamic of spatial displacement of their intertidal habitat (Zimmer 2022), which has favoured the development of two mechanisms to adapt to global mean sea level rise: (1) a vertical adjustment related to feedbacks between plant growth, inundation and sediment deposition (McKee 2011; Krauss et al. 2014) and (2) a process called landward migration that favours the occupation of adjacent uphill ecosystems (Doyle et al. 2010; Langston et al. 2017), such as tropical dry forests in the area. These mechanisms might explain the transformation of other vegetation types towards mangroves and need to be further explored.

Our results allow us to detect spatio-temporal changes in the coastal ecosystems contained within NPAs. Spatial variables related to NPA attributes were able to identify and predict future LULC changes for the years 2020 and 2025. Each NPA has a unique historical, socioeconomic and political context (Figueroa et al. 2009). Also, each NPA is subject to environmental and anthropogenic pressures that determine its LULC change dynamics. While coastal LULC change prediction tools can assist in land use planning and conservation, they could also help policy makers to plan for sustainable coastal landscape management (Lopes et al. 2023). These types of models can determine where (location of change) and at what rate land use change (amount of change) is likely to occur (Wang et al. 2021), based on the incorporation of drivers (e.g. location, Euclidean distance to roads). These models can provide a better understanding of how drivers govern deforestation, generate scenarios of future deforestation/recovery rates, predict the location of forest clearing and support the design of policy responses to deforestation (Mas et al. 2004; Hu et al. 2020; Gong et al. 2023).

In the institutional context, several national environmental policies have been established to promote mangrove conservation. Compliance with institutional regulations could have a positive effect on the projections of mangrove recovery in the NPAs studied. Mexican legislation establishes as a policy the establishment of natural protected areas and indicates, through zoning, the activities allowed within them, which favours the conservation of ecosystems and ensures their maintenance (LGEEPA 2023). The NPAs studied have a management programme that favours the planning and regulation of their activities, a relevant situation since 35% of NPAs in Mexico do not have a management programme. The four main mangrove species (*Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus*) are included in the official Mexican standard, NOM-059-SEMARNAT-2010, which identifies species at risk, favours their conservation and limits harvesting activities in their areas of distribution (SEMARNAT 2010). Furthermore, Article 60 TER of the Mexican General Wildlife Law prohibits any activity that affects the hydrological flow of mangroves (LGVS 2021). Therefore, the correct implementation of institutional measures could allow the reduction of mangrove loss and favour their recovery.

The mangroves present in the NPAs of the YP show a trend of recovery of coverage, mainly in the NPAs of BR-Celestún, BR-Petenes, FFPA-Nichupté, FFPA-Términos and FFPA-Yum Balam. However, they are not exempt from transformation to other types of vegetation (e.g. other wetlands) and anthropogenic development. Protected areas in the YP are expected to keep diminishing in the short term the worldwide trend of forest loss and contribute to mangrove conservation. Therefore, the establishment of NPAs continues to be a strategy for the recovery and reduction of deforestation in mangrove ecosystems.

The LULC data used for the modelling are based on thematic maps with a high accuracy constructed by CONABIO. Uncertainty of the thematic maps can be reduced by incorporating more field data. However, this is expensive and logistically challenging, as mangrove forests are commonly located in areas with difficult access. Furthermore, the uncertainty of the models could be reduced by the incorporation of field data on the LULC changes (Brun et al. 2015; Roy 2021). We produced predictions that allow us to locate areas susceptible to recovery and deforestation processes (Rahman and Ferdous 2021; Mohammad et al. 2022) that can be compared with the data that is expected to be produced in 2025 by CONABIO.

These results provide decision makers with explicit information on the spatial boundaries of priority conservation sites to enhance biodiversity (Hu et al. 2020) and reduce external disturbances such as LULC change. Nevertheless, sufficient support (e.g. funding and personnel) to protected areas needs to be maintained, as this has decreased in the last decades (Rioja-Nieto and Álvarez-Filip 2019).

Conclusions

Mangrove cover modelling is a robust method for predicting changes in LULC and making decisions for maintaining cover. Our study reveals that drivers related to NPA attributes including the location of the analysis area (inside and outside NPAs), the time since the establishment of the protected area and the distance from mangroves to roads were able to influence the dynamics of deforestation and mangrove forest recovery in the YP during the period 2015–2025. BR-Petenes, BR-Celestún and FFPA-Nichupté show mangrove loss rates in the period 2005–2015, but mangrove recovery rates are projected for the period 2015–2025. FFPA-Yum Balam, FFPA-Términos and BR-Lagartos show mangrove recovery in both periods analysed, even establishing in areas with no previous distribution. The FFPA-Términos is the only protected area where a projected transition of mangroves to anthropogenic development has been identified, and this needs to be considered by the local stakeholders and the authorities responsible for mangrove's conservation. Each NPA is subjected to environmental and anthropogenic pressures that determine its LULC change dynamics. Prediction tools can assist in land use planning and conservation, and they could also provide important policy recommendations for sustainable coastal landscape management.

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Data Availability Data sets generated during the current study are available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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