WETLAND CONSERVATION

Natural Protected Areas effect on the cover change rate of mangrove forests in the Yucatan Peninsula, Mexico

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Abstract

Mangrove forests provide important ecosystem services that support the maintenance of coastal socio-ecological systems. Strategies such as the establishment of Natural Protected Areas (NPAs) have been encouraged worldwide to promote their conservation. However, mangroves are still being lost as a consequence of anthropogenic disturbance and environmental variation. In here, we determine the change rate in mangrove cover, between 2005–2015, in eight coastal NPAs and the corresponding four km adjacent transition area in the Yucatan Peninsula (YP), and assess the relationship with location (inside or outside the protected area), their time since establishment and distance to roads. In general, we observed higher positive rates of change in mangrove cover inside the protected areas than in the adjacent transition zones ($p < 0.05$). Change was related to both the distance to roads and the time since establishment of the NPAs ($p < 0.05$). Higher (positive and negative) mangrove rates of change were observed in areas closer to roads, and more stable areas were detected as the distance to the roads increased. The positive rate of change also increased with the age of the protected area. These patterns were more evident inside the NPAs. The continuous monitoring of mangrove change dynamics in protected areas in this important region and their drivers, is necessary to establish effective management strategies considering the spatial and temporal variability of environmental and anthropogenic disturbances.

Keywords Mangrove cover · Change rates · Natural protected areas effect

Los bosques de manglar proporcionan importantes servicios ecosistémicos que contribuyen al mantenimiento de los sistemas socioecológicos costeros. Para promover su conservación, se utilizan estrategias como el establecimiento de Áreas Naturales Protegidas (ANP). Sin embargo, los manglares siguen perdiéndose como consecuencia de las perturbaciones antropogénicas y la variación ambiental. En este estudio determinamos la tasa de cambio en la cobertura de manglar, entre 2005-2015, en ocho ANP costeras y su área adyacente de 4 km, en la Península de Yucatán (PY), y evaluamos su relación con la ubicación (dentro o fuera del área protegida), el tiempo de establecimiento de el ANP y la distancia de los manglares a las carreteras. En general, observamos mayores tasas positivas de cambio en la cobertura de manglar dentro de las áreas protegidas que

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en las zonas adyacentes (p < 0.05). El cambio se relaciona tanto con la distancia a las carreteras como con el tiempo transcurrido desde el establecimiento de las ANP (p < 0.05). Se observaron tasas de cambio del manglar más altas (positivas y negativas) en las zonas más cercanas a las carreteras, y se detectaron zonas más estables a medida que aumentaba la distancia a éstas. Las tasas de cambio positivas también incrementaron con la edad del área protegida. Estos patrones fueron más evidentes dentro de las ANP. El monitoreo continuo de la dinámica de cambio de los manglares en las áreas protegidas de esta importante región y de las variables que la determinan, es necesario para establecer estrategias de manejo efectivas considerando la variabilidad espacial y temporal de las perturbaciones ambientales y antropogénicas. Palabras clave: cobertura de manglar, tasas de cambio, efecto de las áreas naturales protegidas

Introduction

Mangrove forests are one of the most biologically important ecosystems in coastal areas (Aburto-Oropeza et al 2008). These ecosystems are located in intertidal zones of tropical and subtropical regions, and can thrive in fresh and hypersaline water (Romañach et al 2018). Mangrove forests provide important ecosystem services, such as coastal protection (Giri et al 2011; Lee et al 2014, 2021; Veettil et al 2018) and blue carbon areas (Mace et al 2012; Lee et al 2014; Kelleway et al 2017), provision of breeding and nursing grounds for ecologically and commercially important wildlife species (Giri et al 2011; Kelleway et al 2017; Lee et al 2021), sources of food and wood for local communities (Alongi 2008; Mace et al 2012; Veettil et al 2018; Lee et al 2021; Velázquez-Salazar et al. 2021), climate regulation and waste bioremediation (Lee et al 2021), recreational and cultural uses (Kelleway et al 2017), and water purification and regulation (Mace et al 2012), among others. The cover of mangrove forests is affected by natural disturbances such as storms and hurricanes (Liao et al 2019; Goldberg et al 2020; Lee et al 2021), anthropogenic activities including population migration toward coastal areas, infrastructure construction, and agricultural development (Rioja-Nieto et al 2017; Friess et al 2019), and rising sea levels and increasing hurricane intensity and frequency (Feller et al 2017; Liao et al 2019; Cinco-Castro and Herrera-Silveira 2020; Pakmehr et al 2020). These have led to a worldwide reduction of mangrove cover (Mandal and Bar 2013). According to Giri et al., (2011), globally, mangrove forests occupy a total area of c.a. 137 760 km^2, with an annual deforestation rate of c.a. 0.13% (Goldberg et al 2020). In America, a 3.6% annual deforestation rate was estimated for the period 1980–1997. However, a decrease between 0.16–0.22%, which seems to be related to more accurate

systematic assessments and good biological conservation practices, was recently estimated (Bryan-Brown et al 2020). Mexico is home to 5.4% of the world's mangroves, ranking fourth worldwide, based on mangrove cover (Giri et al 2011). The Yucatan Peninsula (YP) contains c.a. 55% (544,169 ha) of the mangrove cover in Mexico (Velázquez-Salazar et al. 2021), of which approximately 82% is located within a protected area (Rodríguez-Zúñiga et al 2013).

Protected Areas are considered the primary tool for maintaining ecological integrity and the conservation of ecosystems (Teh et al 2012; Rodrigues and Cazalis 2020), sustaining ecosystem services and the livelihoods of local communities (Kelleway et al 2017; Lee et al 2021). According to the World Database on Protected Areas (WDPA), approximately 15% of land areas have a conservation scheme (269, 643 NPAs) (UNEP 2022). Despite their importance for the conservation of biodiversity, NPAs are affected by human activities such as land-cover and use change, pollution, overexploitation of hydric resources, and fragmentation, which can cause severe ecosystem disruption (Carey et al 2000; Figueroa et al 2009). The approaches used to assess the effect of protected areas effectiveness are diverse, but in general evaluate ecological and governance indicators (Cruz-Vázquez et al. 2019). Local spatially explicit studies on effects of protected areas containing mangrove forests are still limited, and consider different spatial extents for analysis, ranging from a few km to several ha (Rioja-Nieto et al 2015; Jayanthi et al. 2018; Guerra-Martínez et al. 2019; Hua et al 2022).

Considering the importance of mangrove forests for the environmental services they provide, their extension in the region and the importance of NPAs for their conservation, in this study we determined the change rate in mangrove cover in coastal areas of the Yucatan Peninsula from 2005 to 2015, and assessed the relation with NPAs', their time since establishment, and distance of mangrove areas to roads. The later are characteristics that have been recognized as important for successful protected areas.

Materials and Methods

Study Area and Research Approach

The YP is located in southeastern Mexico between 18º and 21º30' North latitude, and includes the states of Campeche, Yucatán and Quintana Roo (Fig. 1). Based on its environmental characteristics, it is classified as the PY physiographic province, a region with a flat relief and altitudes below 400 m above sea level. In fact, most of the region have an altitude below 50 m above sea level (Vidal-Zepeda 2005; Bautista and Palacio 2012).

In the YP, economic activities 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), which have caused eutrophication, loss of habitats and pollution (Herrera-Silveira 2006). The region has been developing since the early 1970s with limited regulations, affecting coastal ecosystems such as mangrove forests and reef systems (De la Lanza Espino et al. 2017; Rioja-Nieto et al 2019). Main tourism activities occur in Cancun and the Riviera Maya region, in the mexican Caribbean. Oil industry activities are mainly localized in the southwest of the YP, in Campeche.

This study was conducted considering eight of the 10 federal NPAs in the YP (states of Yucatan, Campeche and Quintana Roo), and the adjacent surrounding or transition area that contain mangrove forests (Fig. 1). Four of the considered NPAs (the year of establishment and size is indicated between parenthesis) are Biosphere Reserves (BR): Los Petenes (1999; 280,247 ha), Ría Celestún (2000; 80,707 ha), Ría Lagartos (1999; 59,807 ha), and Sian Ka'an (1986; 525,051 ha); and four area Areas of Flora and Fauna Protection (AFFP): Uaymil (1994; 88,753 ha), Yum Balam (1994; 152,685 ha), Manglares de Nichupté (2008; 4,222 ha), and Laguna de Términos (1994; 703,803 ha). The BR Pantanos de Centla and Tulum National Park, also located in the YP, were excluded from analysis as their mangrove cover is too small for analysis. The NPAs are part of the national protected areas system managed by the National Commission of Natural Protected Areas (CONANP) — the main government agency responsible for the management and conservation of ecosystems in Mexico.

Mangrove Cover 2005–2015

Mangrove cover was estimated from land-use and vegetation maps of the coastal zone issued by the National Commission for the Use and Knowledge of Biodiversity (CONABIO, for its acronym in Spanish). We used 1:50.000-scale maps corresponding to the mangrove coverage for 2005, 2010 and 2015. The 2005 mangrove map (90.5% overall accuracy) was constructed from SPOT 5 images corresponding to the years 2005 and 2006; the 2010 map (81.8% overall accuracy), from SPOT 5 satellite images from 2010; and the 2015 map (75.6% overall accuracy), from SPOT 5 images from 2015 (and last quarter of 2014), and RapidEye imagery. (CONABIO 2013a, 2013b, 2016). We did not consider CONABIO's mangrove cover maps from 2020 as the criteria to classify mangrove areas in the Sian ka'an and Uaymil region changed from previous assessments, resulting in an increase related to the method of assessment > 80,000 ha of mangrove.
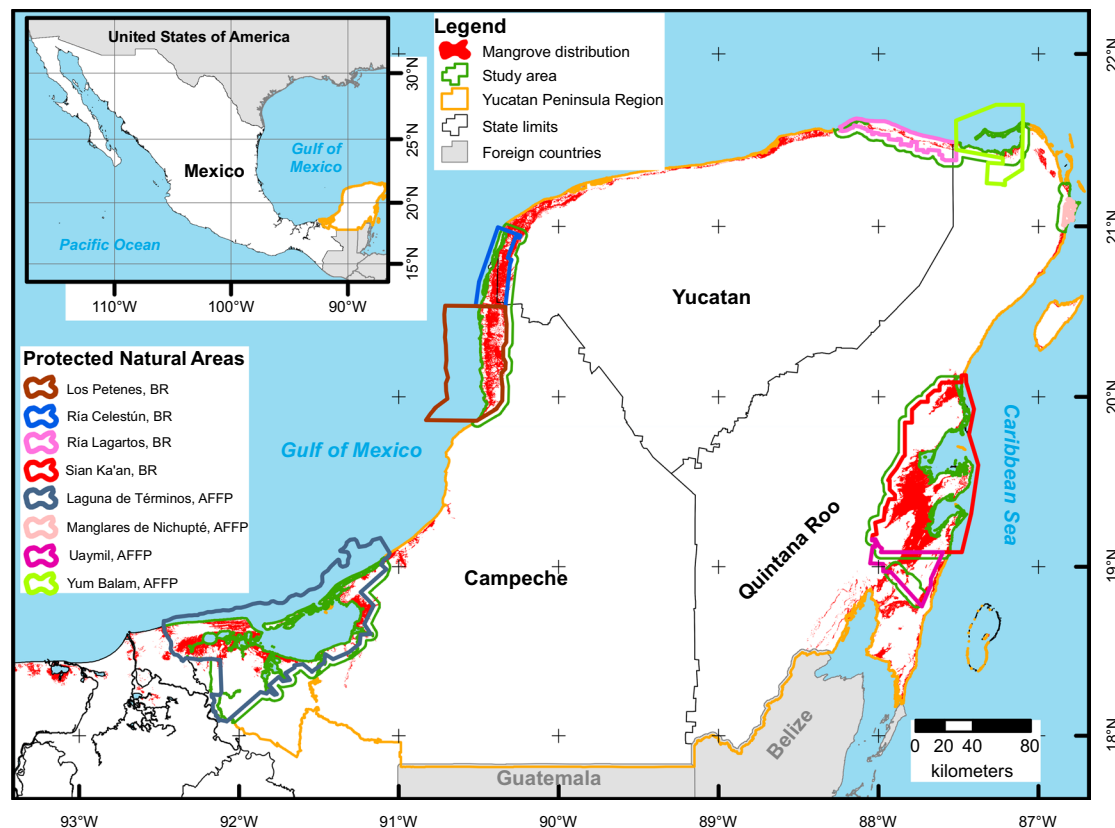
Fig. 1 Yucatan Peninsula, Mexico. The study area considered eight federal NPAs and an adjacent four-kilometer transition zone in the states of Yucatan, Campeche, and Quintana Roo

Considering the mangrove cover in 2005 and the extent of protected areas administered by the federal government in the YP (SEMARNAT-CONANP 2020), a grid with 4×4 km cells was generated for the processing of cover change and data collection. This choice of cell size considered the spatial heterogeneity of the AOI (mangroves are closer to the coast), and it is similar to the spatial extent used in other studies evaluating protected area effects in forests (Guerra-Martínez et al. 2019; Hua et al 2022). The analysis included cells where mangroves were located inside the NPAs and outside the protected areas. For the later a surrounding area of four km adjacent to the polygon of the NPAs was considered. This area is hereafter referred to as the transition zone. The polygons of the NPAs were downloaded in shapefile format from the CONABIO website (http://www.conabio.gob.mx/informacion/gis/).

The rate of change of mangrove cover for each cell in the grid of analysis was calculated using a linear regression (Eq. 1) by the least-squares method using the mangrove cover data for 2005, 2010 and 2015 (Rioja-Nieto et al. 2017).

$$y = a + bx \tag{1}$$

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. Linear regressions were performed with the *stat* package in R version 4.0.5 (R Core Team 2021).

The time since the NPA establishment (hereafter referred to as NPA age) was obtained from the Mexican federal protected areas database in the CONABIO website. 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.

Statistical Analysis

To spatially associate the variables inside NPAs, transition zone (outside the protected area), NPA age, and distance to roads with the cover change rate layer, we used the point-intersect function between the mangrove cover layers for 2005, 2010, and 2015 and the independent variables considered, using the centroids of each cell in the grid. A multiple linear regression was first performed to evaluate the effect of the NPA (inside/transition zone the protected area), NPA age, and distance to roads in the change rate of mangrove cover. However, the visual assessment of residuals showed a non-homogeneous variance. Consequently, a Generalized Least Square (GLS) model was used, which is essentially a weighted linear regression. The GLS allows for variance heterogeneity as this can be modeled. In this sense, we evaluated different variance structures to fit the model and evaluate the effect of the explanatory variables. Seven GLSs were conducted (see supplementary information), and we selected the model with the lowest value of the Akaike Information Criterion according to the protocol suggested by Zuur et al (2009). The assumptions of the selected model were evaluated visually using the standardized residues. GLSs were fitted with the *nlme* package (Pinheiro et al 2022) and the *a-posteriori* tests were carried out with the *rstatix* package (Kassambara 2020) in R version 4.0.5 (R Core Team 2021).

Results

Mangrove Cover Change Rate

In 2005, we identified 301,692.9 ha covered with mangrove forests in the area of interest (AOI), equivalent to approximately 72.05% of the total mangrove cover reported for the YP by CONABIO in the same year. About 87.7% (264,470.04 ha) of the AOI was located within the protected areas, and 12.3% (37,222.83 ha) in the transition zones.

The AOI was composed by 662 cells of 4×4 km associated with the eight federal NPAs and their respective transition areas (Fig. 2). Of these cells, 37.6% showed negative rates of change of mangrove cover, with slopes between -12 and -0.01, where only 2.56% of cells showed slopes < -5 ha year^{-1}. Around 24.6% of the cells showed no change of mangrove cover for the period of study (rates of change of 0 ha*year^{-1}). On the other hand, around 37.6% of cells showed positive rates of change, of which 10.4% were > 5 ha*year^{-1}. The positive rates of change were common for the regions of Yum Balam and Laguna de Términos. However, for the later several areas also showed high rates of mangrove cover loss. Cells with no change and a small increases in mangrove cover dominated in the Sian Ka'an, Uaymil, Manglares de Nichupté, Ría Lagartos and Celestún regions. Cells with mangrove loss were mainly observed in the region of Los Petenes and as previously mentioned, some areas of Laguna de Términos (Fig. 2).

Drivers of Mangrove Cover Change

In general, between 2005–2015, we observed higher positive rates of change in mangrove cover inside protected areas than in the adjacent transition zones (W = 45,470, p < 0.0406) (Fig. 3).

The GLS with the lowest AIC value (2414.5), considered a combined variance structure where residuals were allowed to scatter according to the distance to roads depending on the zone (within NPA/transition zone) and according to the NPA age depending on the zone.
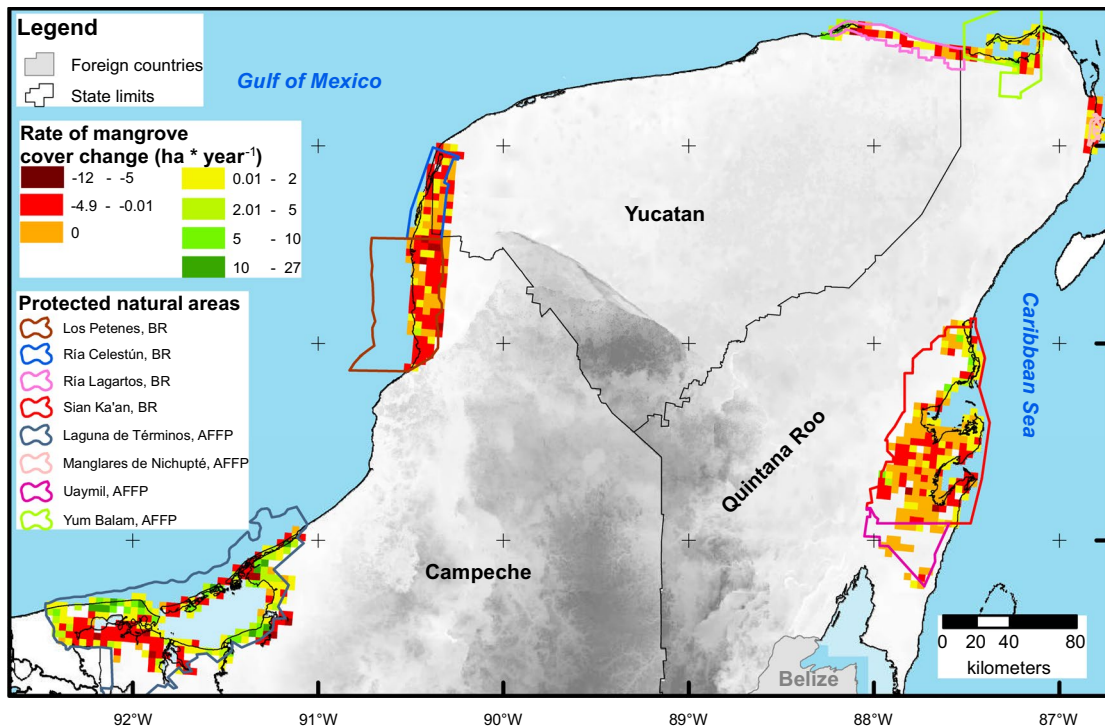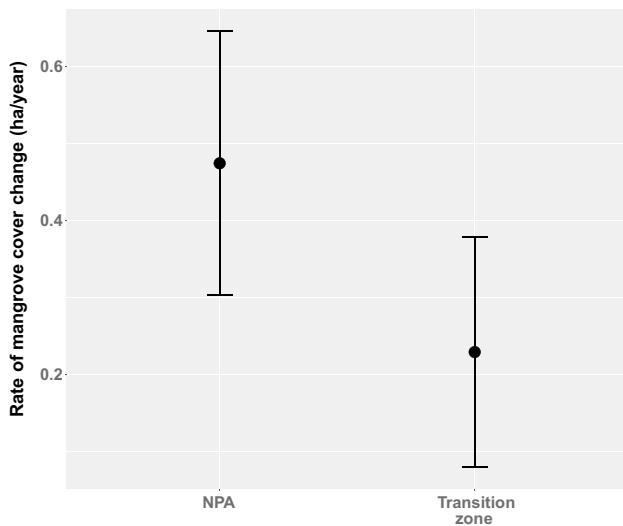
Fig. 2 Rate of mangrove cover change (2005–2015) in eight Natural Protected Areas and the associated transition zones in the Yucatan peninsula. The rate of change in a 4×4 km grid was estimated with a linear regression using 2005, 2010 and 2015 mangrove cover maps published by CONABIO

The GLS model selected showed significant interactions (p < 0.05) between location (inside the protected area or transition zone), distance to roads and time since the establishment


Fig. 3 Rate of mangrove cover change (2005–2015) inside protected areas and transition zones (outside protected areas) in the Yucatan Peninsula. Horizontal lines show the median, box height marks the first and third quartiles, and whiskers indicate the minimum and maximum values

of the protected area with the rate of mangrove cover change. This implies that at shorter distances to roads, there are higher rates of mangrove cover change and as the distance increases, the effect is reduced for both the protected areas and the transition zones (Fig. 4a and 4b). Higher positive rates of mangrove cover are observed inside the protected areas. In older protected areas, the positive rate of mangrove cover change increases both inside and in the transition zones, with more evident changes inside the protected areas (Fig. 5a and 5b).

Discussion

Mangrove cover in the NPAs and transition areas in the Yucatan Peninsula increased by approximately 3,120 ha between 2005 and 2015. Positive rates were observed inside the protected areas and to a lesser degree in the adjacent transition zones. This seems to indicate that the protected areas administered by CONANP, and to some extent in their area of influence, are having a positive effect on the cover of mangrove forests in the region. The spatial heterogeneity on mangrove cover change observed inside the protected areas and the adjacent transition zones can be related to several attributes such as environmental characteristics, type of anthropogenic disturbance, differences in management capacity and enforcement of regulations, the protected areas

Fig. 4 Effect of distance to roads on the rate of mangrove cover change (2005–2015) inside the protected areas (a) and the adjacent transition zones (b) in the YP
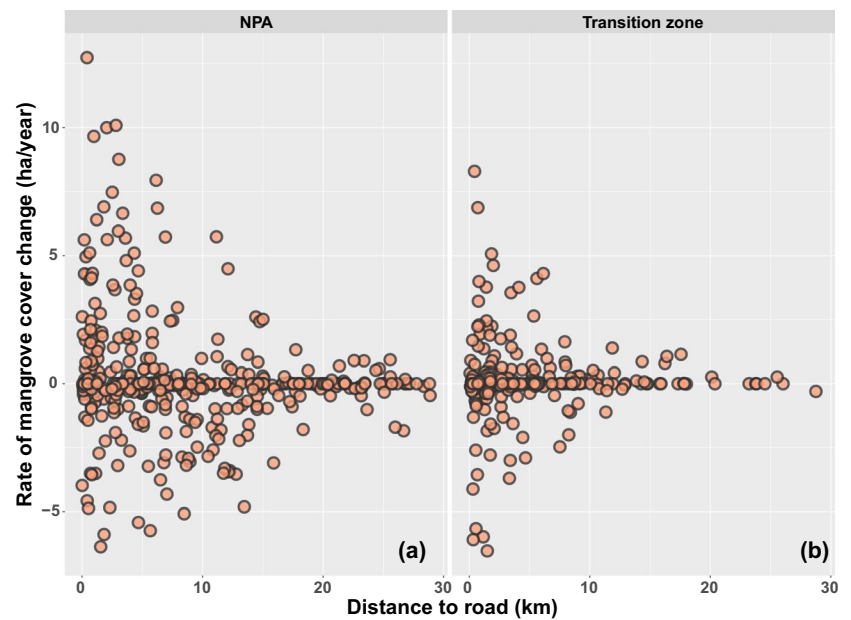

size and isolation, edge effect between the protected areas and the transition zones, among others.

Air temperature and annual precipitation are known to be important drivers for mangrove cover change in the region (Rioja-Nieto et al. 2017), where the South of Quintana Roo and Campeche have higher mean annual precipitation values than the North of Yucatán (Daniel et al 2020). The level and frequency of inundation and salinity are also important (Krauss et al 2008). Given the karst characteristics of the YP, this is mainly controlled by groundwater discharge (Enriquez et al 2010).

A greater distance from urban populations and infrastructure (Ervin 2003), and a bigger size of the protected area (the

smallest NPA analysed contains 4222 ha), favour isolation and support the conservation and recovery of ecosystems (Mora et al 2006; Joppa and Pfaff 2009). This has been previously observed in mangrove forests and tropical dry forests (Sánchez-Azofeifa et al 2009). Furthermore, anthropogenic driven ecosystem degradation in protected areas with a buffer zone surrounding the core zone (such as in Los Petenes, Ría Celestún, Ría Lagartos and Sian Kaan), is known to be low or non-existent (Ohayon et al 2021), well administered protected areas with effective enforcement of regulations are known to reduce deforestation rates (Ferraro et al 2013), and changes in forest cover are lower within protected areas (Hu et al 2021).

Fig. 5 Rate of mangrove cover change (2005–2015) inside protected areas (a) and adjacent transition zones (b) in the YP, in relation to the time since establishment of the protected area
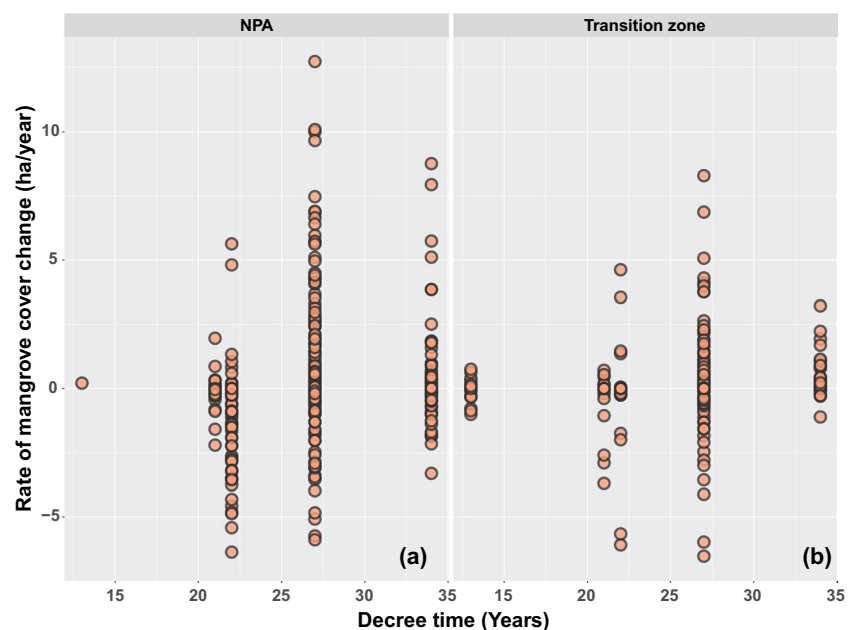
However, it is important to consider that in the early twenty-first century, the area in the country under protection that is administered by CONANP has increased considerably, but funding and personnel in charge of enforcing regulations have decreased (Rioja-Nieto et al 2019). Therefore, the federal government capability to enforce regulations is limited, and the positive effect of the protected areas that we observed in here over the period of time assessed, might have been affected.

The lower rates of change observed in the transition zones could be related to the effect that the protected areas have in their surroundings, and the anthropogenic pressure occurring outside. In tropical forests, effects on successional stages are strongly related to forest coverage within a 4 km radius (Arroyo et al. 2023). Also, positive edge effects of protected areas on vegetation cover and other characteristics such as vegetation greenness and productivity, have been previously reported (Hua et al 2022). On the other hand, in mangrove forests, the negative edge effect of human activity has resulted in mangrove areas closer to the edge showing less development in structure and diversity, as well as higher mortality and reduced tree diameter and height. In the transition zones, human land uses are increasingly expanding and intensifying, producing changes in ecological functioning and biodiversity. The zones considered here as transition zones are defined as an area of influence in the mexican legislation, whose objective, according to Hansen and DeFries (2007), is to minimize the impact of adverse influences at the borders of NPAs. Our data suggest that in general, this is happening in the borders of the protected areas in the YP, considering the lower but positive rates of mangrove cover change observed in the transition zones.

For both, inside the protected areas and the transition zones, we observed higher (positive and negative) mangrove rates of change in areas closer to roads, and more stable areas as the distance to the roads increased. Several studies have associated roads with negative effects, as they facilitate forest access and disturbance (Hirales-Cota et al 2010; Jaramillo et al 2018; Hayashi et al 2019; Liu et al 2022). Road construction restrains tidal exchange in wetlands, reduces the supply of fresh water, and increases the influence of salt water, all of which impact mangrove productivity and increase forest degradation (Aljahdali et al 2021; Keat-Chuan Ng and Cyril Ong 2022). However, higher positive mangrove cover change rates were also observed in areas closer to roads. This might relate to the cofounding effect of management in the protected areas (i.e., limiting mangrove deforestation), their influence on the transition zones, and adequate environmental conditions in the YP that favor mangrove growth. Our results also showed a positive increase on the rate of mangrove cover change related to the maturity (age) of the NPA. In tropical forests, age of the protected area seem to have no effect on cover dynamics such as deforestation (Van Der Hoek 2017; Zhao et al 2019; Castillo et al 2021). However, in temperate forests, results are contrasting, where in some regions older protected areas perform better, but in other regions younger areas are more effective (Geldmann et al 2014; Butsic et al 2017). It is well known that by removing anthropogenic disturbances, ecosystems tend to recover (e.g. Newbold et al. 2015; Moreno-Mateos et al. 2017). Therefore, our observations indicate that the longer anthropogenic disturbances cease or are reduced within protected areas, mangrove positive rates of change increase.

A clear spatial pattern on the rate of mangrove coverage changes in relation to the main anthropogenic activities and their differentiated capability to affect mangroves, was not observed in the region. Since the early 1970s, the oil industry in the southwest (Romo 2015) and tourism in the east (Rioja-Nieto et al 2019) of the YP, have been the main economic activities. In the North of the study area, fishing and urban development are the main activities (Cinco-Castro and Herrera-Silveira 2020).

Monitoring mangrove cover in different regions is important because the temporal dynamics of losses and gains in a given site vary, even within NPAs (Castillo et al 2021). Similarly, human expansion and infrastructure construction, particularly in coastal zones, involves changing pressures on mangrove forests which impact their spatial dynamics (Osland et al 2018; Keat-Chuan Ng and Cyril Ong 2022). Therefore, large scale studies on mangrove dynamics within protected areas, which are the main strategy for their conservation, need to be continuous.

Conclusions

Our study provides evidence on the positive effects that NPAs, on a spatially explicit context, have on mangrove dynamics in the Yucatan Peninsula. In general, mangrove coverage in the area of study and over the period of time (2005–2015) evaluated increased, which corresponds with previous assessments (e.g. CONABIO). Inside protected areas, higher positive rates were observed, a pattern that was maintained when evaluating the relation to roads and the age of the NPA. Considering that in the adjacent transition zones, positive rates dominated but with lower values, suggest that the protected areas also seem to have a positive edge effect on these areas. This supports the evidence that links the amount of coverage of surrounding forest with succession trajectories at a landscape scale. However, further studies considering greater distances from the protected areas need to be performed. Age is considered a key feature for successful marine protected areas (Edgar et al. 2014). This seems to be also the case on protected areas containing mangroves. The continuous assessment of NPAs effects is necessary, considering the spatial and temporal variability of environmental and anthropogenic disturbances, the limitations that NPAs enforce on human activities, and the difficulties to maintain their funding. It is important to keep and if possible, improve the functioning (e.g. increase of funding) of protected areas in the region, in order to keep them effective for the conservation of mangrove forests.

Declarations

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