DEFORESTATION DYNAMICS IN BIOSPHERE RESERVE OF MANGROVES: EVALUATION AND FUTURE SCENARIO

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Abstract. Mangroves provide various ecosystem services to society but are affected by deforestation, resource exploitation and land use. This study analyses the dynamics of deforestation of mangroves in Chocohuital, Chiapas, Mexico from 2000 to 2019 and provides a future scenario using Landsat imagery (5TM and 8 OLI) and the Markov Chain model. Results indicate a loss of 51 ha of mangroves from 2000 to 2019. The deforestation rates were -0.11% for mangroves, -0.37% for pastureland and -21.44% for the jungle, from 2000 to 2019. The transitions indicate gains in the surface of new settlements and more pastureland, while the losses were for mangroves, forests, and bodies of water. Future scenarios indicate 0.11 probability of transitioning from mangrove areas to agriculture and 0.5 to pastureland. Therefore, it is imperative to analyse alternative future scenarios of mangroves to optimize their conservation and development through proactive policy planning, especially in protected natural area.
Keywords: *Markov chain, prediction, land use/land cover, Landsat, deforestation*

Introduction

Mangroves are estuarine ecosystems characteristic of tropical areas. Mangroves provide multiple ecosystem services to society. They prevent erosion, stabilise the coastline, act as biological filters and provide shelter, feeding, nesting, and breeding areas. Moreover, wetlands are considered carbon sinks and climate stabilizers globally (Bu et al., 2019). Deforestation, resource explotation and land use change are the main threats to mangroves. Deforestation is associated with economic and social impacts, including reduced biodiversity and hydrological services.

The mangroves of La Encrucijada Biosphere Reserve belong to the RAMSAR sites, wetlands of international importance in the Ramsar Convention (Ramsar site no. 815, since 1996, *Fig. 1*) (The Secretariat of the Convention on Wetlands (Ramsar, Iran, 2022). It is distinguished by the inclusion of two endemic species, *Rhizophora harrisonii* reported by Rico-Gray (1981) and *Avicennia bicolor* (Nettel et al., 2008). Furthermore, anthropogenic activities such as illegal logging, hydrological changes, extraction of species and pollution contribute to the degradation of the forest.

Tropical deforestation increases atmospheric carbon and promotes climate change. For this reason, stopping the deforestation of wetlands, which sequester tons of carbon, is key for preventing global warming and preserving biodiversity. The use of exchange rates to measure mangrove deforestation has therefore been proposed. However, some approaches vary in scale, timing, classification method and inputs. For example, only a few studies have been conducted at local and regional scales on mangrove transformation in Mexico. In addition, only some techniques use statistics to know the causes and predict future deforestation scenarios (Jaimes et al., 2009).

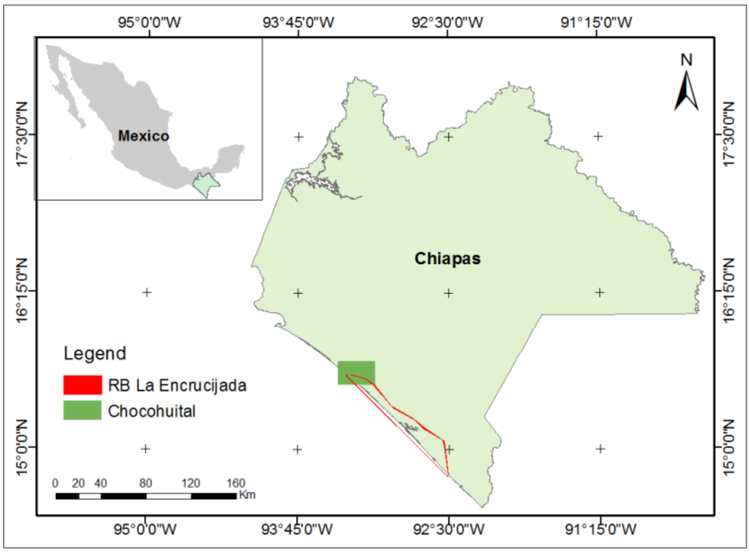

Figure 1. *Location of the study site, Chocohuital, Chiapas, Mexico*

Deforestation studies have focused on quantifying net or total changes, ignoring class transitions. Land use and forest cover dynamics have been studied. However, results vary between regions. For example, Mexico reports mangrove deforestation rates between 0.85% and 1.05%, but information sources vary and spatiotemporal scales are insufficient to detect changes (Hirales et al., 2010; Mendoza et al., 2010; Soto et al., 2010; Leija et al., 2016; Ramos et al., 2019). Therefore, it is essential to improve methods of assessment and prediction to make them more reliable for describing the ecosystem dynamics.

The correct selection of spatiotemporal scale and the quality of satellite imagery is needed to assess the causes and consequences of deforestation and land use change. However, there is no established methodology to determine the dynamics of land use change. Challenges in determining the causes of deforestation may include different classification systems, scales of analysis and information sources.

Conceptual frameworks and tools that allow efficient and accurate assessment of intertidal dynamics at different spatiotemporal scales are needed. Remote sensing and geographic information systems are valuable for monitoring environmental indicators at different spatiotemporal scales (Richards et al., 2016). However, determining mangrove deforestation using GIS and remote sensing limit the actual ecosystem extent. It has not been able to predict future expansion. Simulating the dynamics and getting the probability of changing mangroves require the addition of methods for the analysis of dynamic spatial using Markov Chains (Etemadi et al., 2018; Supriatna et al., 2018). The model can be used to explain and predict future scenarios, allowing us to monitor the changing landscape and serve as a tool for decision-making in the medium term (DasGupta et al., 2019).

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The objectives of this study were to analyze the causes of land use change, determine deforestation rates and model a future deforestation scenario for mangroves. To achieve this, a multitemporal analysis of the Landsat 8 imagery post-classification was carried out for the dynamics of deforestation during the period 2000-2019. Subsequently, Markov chains were used to determine the dynamics of land use change and understand the causes of deforestation. Finally, a Markovian model of the future deforestation scenario was obtained at an appropriate scale. It is imperative to analyze alternative future scenarios for mangroves in order to optimize their conservation and development, especially in protected natural areas.

Materials and methods

Site description

The study area is located coastal Chiapas State, southeastern Mexico (*Figure 1*). It has a warm subhumid climate, with an average annual temperature of 22 °C and an average annual rainfall of 599 mm. The approximate total population is 18352 inhabitants (INEGI, 2020). The Chocohuital estuary belongs to the La Encrucijada Biosphere Reserve Protected Natural Area (ANP). Furthermore, this area is the RAMSAR site no. 815, as it is a wetland of international importance for The Ramsar Convention (The Secretariat of the Convention on Wetlands (Ramsar, Iran, 2022).

Information sources

The images were obtained from the portal http://www.usgs.gov/ with path & row 22; 049, from Landsat-5 TM (February 14, 2000) and Landsat-8 OLI (February 2, 2019). All images have a spatial resolution of 30m and are considered for the dry season with cloudiness of 0%.

The systematic procedure was followed, such as clipping the images by study area shape file and making a composite of the bands RGB (4,5,6). All satellite images were projected to the Universal Transverse Mercator (UTM) cartographic projection system using the WGS84 zone 15N. The maximum likelihood algorithm was used to classify the images and the resulting vectors were converted to raster format. Finally, the maps were filtered with 3x3 pixel windows, using a model as a standardization measure to reduce the effect known as “salt and pepper”, which refers to isolated pixels belonging to a class different from the set. ArcGIS 10.5 was used for cartography processing.

Land use classification

The hierarchical land use and vegetation classification system was adopted from the 1:50000 scale cartography produced by CONABIO (Acosta et al., 2009). This official cartography was prepared using an interdependent classification method that has a geostatistical validation percentage of 93% and is divided into seven categories, as shown in *Table 1*.

Accuracy assessment

The accuracy of the resulting maps was evaluated using error matrices weighted by the proportion of the area of each evaluated class and the Kappa coefficient. A simple random sample of 50 points was generated in ArcGIS.

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Table 1. *Land use and vegetation classification*

Categories	Classification Description
Agriculture	Seasonal and irrigated agriculture, pasture for livestock activity and food production
Urban	Settlements, aquaculture ponds, shrimp farms, roads and highways
Water	Estuaries, lagoons and rivers
Mangrove	*Rhizophora mangle, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus, Rhizophora harrisonii* and *Avicennia bicolor*
Wetlands	Hydrophyte vegetation: popal, tular, palm grove, chaparral and coastal dune vegetation
Pastureland	Induced pastureland, cultivated pastureland and savanna
Jungle	Low deciduous forest, medium sub deciduous forest, low evergreen forest and semi evergreen forest

Based on the classification, an error matrix was created to identify inconsistencies between the verified coverage and the coverage generated by the classification, which was used to calculate the overall accuracy, obtained by dividing the sum of correctly classified units by the total number of drives in the array. The matrix is square, the rows correspond to the referential classes (truth or field verification), while the columns correspond to the classes of the map. The diagonal expresses the number of verification points where both sources (map and field) agree, while the marginal points assume repair errors (Morales et al., 2016).

The Kappa coefficient (k) was estimated to assess whether the reality map classification had a significantly higher accuracy than would have been achieved by a random method (Congalton et al., 2019). It attempts to limit the degree of fit due to the accuracy of the classification alone, ignoring random factors, as described in *Eq. (1)*:

$$\kappa = \frac{N\sum X_{ii} - \sum(X_{ii} * X_{+i})}{N^2 - \sum(X_i * X_{+i})} \quad \text{(Eq.1)}$$

where: N is equal to the total sampled data, X_{ii} indicates the observed agreement and $(X_i{**}X_{+i})$ is the expected agreement (product of marginals). The value obtained represents the percentage in which the classification is better than that expected by chance. If the return value is 0.80, the map is 80% better than expected by chance. Three classes of results are considered: a value of k less than 0.4 represents a poor agreement, a value between 0.4 and 0.8 represents a moderate agreement and a value greater than 0.8 represents strong agreement.

Processes of land use change

The analysis of land use change processes was carried out with a post-classification multitemporal analysis over 19 years. It consists of the superposition of land use and vegetation maps of different dates, 2000 and 2019 (Díaz et al., 2010). Both maps show the same land use and vegetation classification: agriculture, water, urban, wetland, mangrove, pastureland, and jungle.

Change detection matrix

Subsequently, the transition matrix is calculated, which synthesizes the main changes from time t to time t_{+n} of the categories represented in the maps. The diagonal data of

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the matrix represent the area that did not change during the analysis. In contrast, the off-diagonal data indicate transitions from one class to another in the form of losses or gains between the two dates (Vázquez et al., 2009).

Exchange rates

Areas for each land use and vegetation type were obtained and deforestation was calculated using the FAO equation (FAO, 1996) *Eq. (2)*:

$$\delta_n = \left(\frac{S_2}{S_1}\right)^{1/t} - 1 \quad \text{(Eq.2)}$$

where: S_n is the annual exchange rate, S_1 is the coverage area on the initial date, S_2 is the coverage area on the current date and t period analyzed.

The calculation of the net annual loss for each type of vegetation was carried out with *Equation (3)*:

$$P_a = \frac{(S_2 - S_1)}{t} \quad \text{(Eq.3)}$$

where: P_a = annual loss in the area, S_1 = coverage in 2000, S_2 = area of coverage in 2019 and t = period analyzed.

Land use transition dynamics

The transition probability matrix was obtained from the transition matrix by dividing each cell of the transition matrix by the total area of the analysis class. Finally, flow models showing the dynamics between major land uses were constructed from transition matrices. The Markovian transition matrices were generated using the Markov chain package in the R program version 4.1.2. (Spedicato, 2017). The Markov chain package for R provides S4 classes for homogeneous and inhomogeneous Markov chains, which allows for greater flexibility in handling discrete-time Markov chains that other existing solutions do not have (Kumar et al., 2016).

Future scenarios of deforestation with Markov chain

The Marvok chain is an efficient tool to extract probabilities of change (Etemadi et al., 2018). Markov chain modeling has been applied to monitor changes in coverage trends, including future changes and degradation (Hasan et al., 2020). In this study, an integrated Markov chain model was used to predict future scenarios to simulate changes through matrices and spatial information. The transition probability maps were used to generate land use dynamics for the future.

Results

Accuracy assessment

The global accuracy of the thematic map of land use in 2019 was 96%, with a value of the Kappa index equal to 0.95, which indicates a high classification accuracy. A high concordance between the reference data and the classification data is considered (*Table 2*). The discrimination of mangroves and wetlands shows good accuracy. Our

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classification reliability results are within the range used in various studies using spectral and visual criteria for satellite image interpretation.

Table 2. *Classification error matrix for the 2019 map and accuracy assessment*

Category	1.	2.	3.	4.	5.	6.	7.	Total	Accuracy	Kappa
1.Agriculture	10	0	0	0	0	0	0	10	1	0
2.Water	0	10	0	0	0	0	0	10	1	0
3. Urban	0	2	8	0	0	0	0	10	0.8	0
4. Wetland	0	0	0	10	0	0	0	10	1	0
5. Mangrove	0	0	0	0	10	0	0	10	1	0
6. Pastureland	0	0	0	0	0	10	0	10	1	0
7. Jungle	0	0	0	0	0	0	10	10	1	0
Total	10	12	8	10	10	10	10	70	0	0
Accuracy	1	0.8	1	1	1	1	1	0	0.96	0
Kappa	0	0	0	0	0	0	0	0	0	0.95

1. Agriculture; 2. Water; 3. Urban; 4. Wetland; 5. Mangrove; 6. Pastureland; 7. Jungle

Processes of land use change

The distribution of the land use change processes mapped in the Estero Chocohuital is shown in *Figure 2*, corresponding to 2000 and 2019, respectively. In the initial year, few human settlements are observed and the extensive development of forests in the central part of the basin. The dominance of the natural pastureland characteristic of the coastal plain is notorious. The wide distribution of the mangroves and the large estuary allowed the flow of fresh and salt water. It was observed that the process of change that predominated in the study area during the period of analysis was the increase of human settlements and the advance of the agricultural frontier. However, the deforestation of the jungle and wetlands was more pronounced since this process affected 30% of the surface. It is observed that in 2000 seasonal agriculture was developed in compact and dense patches in the middle part of the basin. For 2019 a change from seasonal agriculture to smaller and dispersed patches throughout the area is determined. The new human settlements are observed scattered throughout the coastal plain. According to the map, a new productive activity derived from the establishment of shrimp aquaculture was found, displacing mangrove areas. In addition, at both dates, areas without some types of vegetation were identified, which indicates the high deforestation of mangroves and halophyte vegetation.

Change detection matrix

The change detection matrix was obtained by superimposing the 2000 and 2019 maps (*Table 3*). High transitions from wetland to seasonal agriculture, pastureland and human settlements are observed. Agriculture gains the area of human settlements, wetlands, mangroves, pastureland, and jungles. In addition, high dynamic between the mangroves, wetlands and the water body are shown. In 2000, 719 ha of the jungle prevailed; this condition was modified for 2019 and was reduced by almost 96% in surface area. In 2000 the dominant class was pastureland representing 18.6% of the total area; in 2019

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decreased to 17.5%. Mangroves initially covered about 32.2% of the total area. From 2000 to 2019, 2191 ha of mangrove were maintained, representing 97% of surface stability. The transitions indicate gains in the area of agriculture, new settlements and wetlands, while the losses were for mangroves, pastureland, jungle and water bodies.

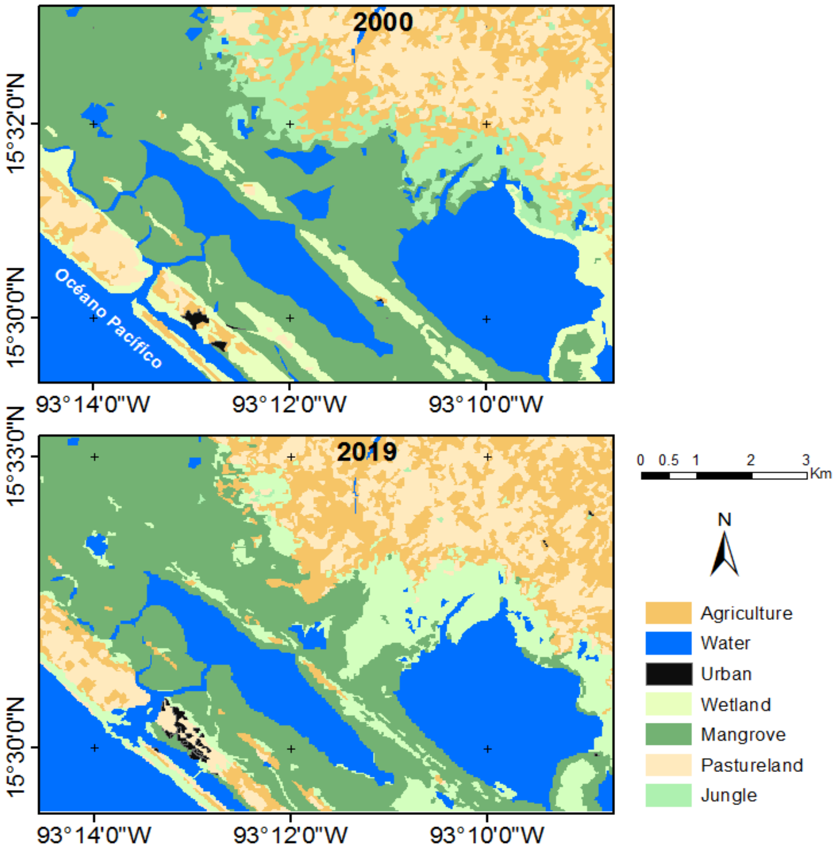

Figure 2. *Map of land uses of the Chocohuital estuary from 2000 to 2019*

Table 3. *Matrix of transition of land uses of the Chocohuital estuary from 2000 to 2019*

2000	2019							Grand Total
	Agriculture	**Water**	**Urban**	**Wetland**	**Mangrove**	**Pastureland**	**Jungle**	
Agriculture	577	8	7	59	4	362	2	1,019
Water	35	1395	0	61	36	2	0	1,529
Urban	1		7	2	1	3		14
Wetland	76	30	10	270	227	40		653
Mangrove	17	15		354	2191	1	1	2,579
Pastureland	549	9	5	22	6	898	2	1,491
Jungle	224	2	1	336	63	91	2	719
Grand Total	1,479	1,459	30	1,104	2,528	1,397	7	8,004

Exchange rates

The exchange rates to land use change mapped for the Estero Chocohuital for the whole study period are presented in *Table 4*. The dominant dynamics of land use change are the expansion of human settlements, agriculture, and wetlands. However, the rate of

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deforestation was more pronounced in low-jungle, pastureland, and mangroves. The highest exchange rate was in the jungle, with -21.63%. Mangroves lost 51 ha from 2000 to 2019, with an exchange rate of -0.11%. The class representing 49% of the changes was agriculture, increasing 460 ha. As for the establishment of new human settlements, the urban area increased to 16 ha. The increase in agricultural areas was 24 ha a year. On the other hand, forests decreased significantly by 37 ha annually.

Table 4. *Exchange rates of land use change in the Chocohuital estuary, during 2000-2019.*

Category	2000		2019		Change total (Ha)	Annual loss (Ha)	Exchange rate %
	Ha	%	Ha	%			
Agriculture	1,029	12.7	1,479	18.5	460	24	1.98
Water	1,529	19.1	1,459	18.2	-70	-4	-0.25
Urban	14	0.2	30	0.4	16	0.84	4.09
Wetland	653	8.2	1,104	13.8	451	24	2.80
Mangrove	2,579	32.2	2,528	31.6	-51	-3	-0.11
Pastureland	1,491	18.6	1,397	17.5	-94	-5	-0.34
Jungle	719	9.0	7	0.1	-712	-37	-21.63

Land use transition dynamics

Figure 3 shows the dynamics of the probability of change between classes during 2000-2019. There are three subgroups of classes: 1. Jungle-mangrove-wetland-agriculture; 2. Mangrove-bodies of water-wetland; 3. Agriculture-pastureland-wetland-human settlements. The dynamics of displacement of forest areas, such as jungles, wetlands and mangroves to agriculture, pastureland and finally, new human settlements. The proximity between mangroves, water and wetlands indicates a strong dynamic between transitional coastal ecosystems and a strong dependence on the influence of water for their connectivity and proper functioning. Mangroves have a 0.07 change of becoming new human settlements, a 0.34 of diminished to wetlands and 0.01 of being deforested for agriculture. Wetlands have a 0.14 chance of being urban and jungles have a 0.12 chance of becoming agricultural. Areas of pastureland have 0.22 to transition to new human settlements. The most worrisome is the high transitions of the mangrove to new human settlements, which prevent its restoration. There are also indications of soil erosion.

Future scenarios of deforestation

In the R program with the Markov Chain package, the maximum likelihood estimators, the Bootstrap estimators, and the confidence intervals were obtained for the transition matrix from the satellite imagery for the years 2000-2019.

Figure 4 shows the graph of the predictions for Estero Chocohuital. The plot indicates high probability of maintaining agriculture (0.5) and pastures (0.5) over time. In comparison, the mangrove has a probability of 0.5 becoming a wetland or disintegrating mangrove. The mangroves have a probability of transition to the agriculture of 0.11 and, wetlands 0.25 probability of agriculture in the future. Areas of agriculture probability of 0.25 transition pastureland. If the same trends of land use change continue, in a few years the mangroves will be eliminated, and the wetlands will be degraded and contaminated.

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There will be extensive areas of pastures and rainfed agriculture where there used to be lowland forests. The urban centers will be larger and built around crops.

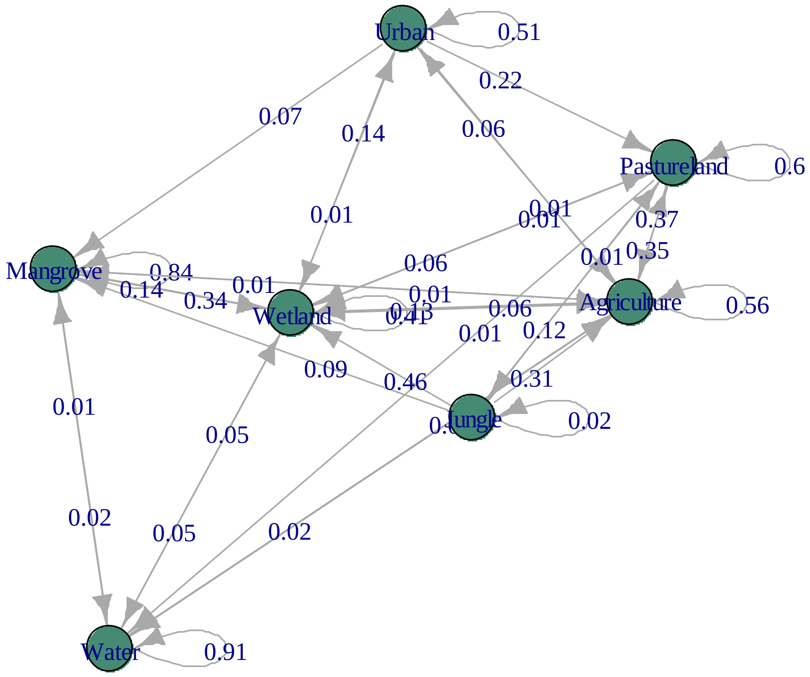

Figure 3. *Probability dynamics of transition between land use classes of Estero Chocohuital, during 2000-2019*

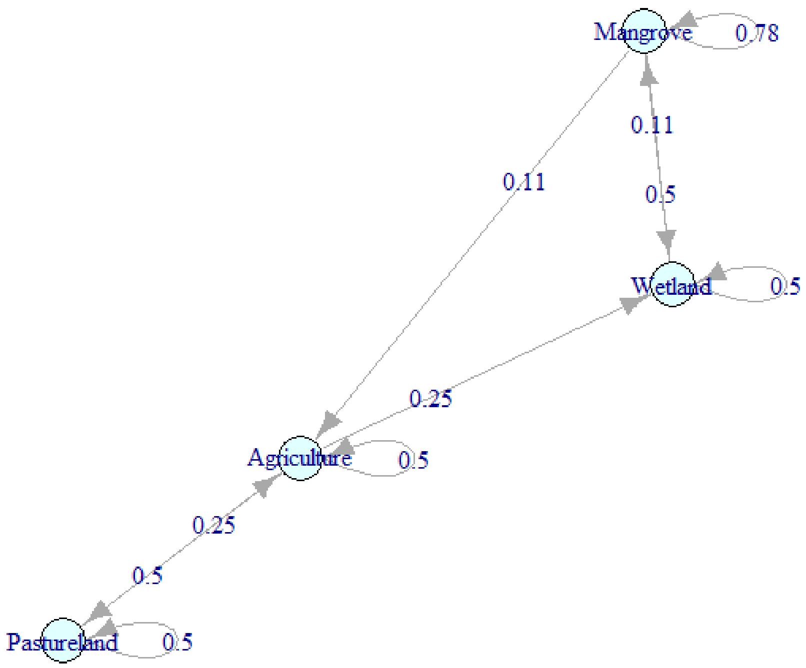

Figure 4. *Future predictions of the probability of transition between land use classes of Estero Chocohuital*

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Discussion

The results of this research were obtained from the analysis of Landsat images to determine the change in land use and deforestation rates from 2000 to 2019. The Markov Chain methodology allowed us to determine future deforestation scenarios for the mangroves in Chiapas.

Processes of land use change

The fragmentation of large areas but the low frequency may indicate the importance and causes of the change processes. The modification of the Chocohuital estuary, the closure channel to divert the water flow, which led to the loss of the mangrove, was identified. Changes in river flow and land use cause negative (erosion) and positive (sediment accumulation, recolonization) effects on mangroves (Godoy et al., 2018). During the rainy season, water quality in coastal areas may deteriorate.

Given the environmental degradation of tropical zones, it is important to know the distribution of land use change in order to assess the environmental conditions in which the changes occur and to identify the areas with the greatest pressure (Ramos et al., 2019). Within the ANP, trends in land use change were evidenced; 33% of the original area has changed due to the expansion of agriculture, with an increase in crops such as oats, wheat, corn and alfalfa (Leija et al., 2020).

The decline in deforestation may not be related to a socioeconomic change, but rather to the fact that there is less and less forest cover that is easily accessible or suitable for agricultural activities. In addition, the remaining forest is located in restricted or protected areas. Agricultural land use has been replaced because by urban growth (Jiménez et al., 2018). The lack of data on the measurement of changes in the cover of tree vegetation and wetlands still subsists, even though this information is relevant to support models of land use change that allow mitigating its loss or seeking its rehabilitation to restore environmental services and benefits. Our research determined an increase in human settlements in areas where mangroves previously existed. This change means a double risk: the loss of natural areas and a high probability of flooding for the people living in these areas. Recurrent flooding is the result of wetland loss and change of use to residential areas (Palomeque et al., 2019). Unplanned urban expansion in areas unsuitable for housing, such as steep slopes or riverbeds, increases the population's risk to natural phenomena.

The lack of analyses that consider multitemporal stages to define the succession time of vegetation in ANPs is evident. It is important to continue with the evaluation and monitoring of land use change patterns in Mexican ANPs (Sánchez et al., 2017). Regional studies should identify the main drivers of change in order to predict the direction of change and promote conservation (Velázquez et al., 2002).

Land use classification

Several studies have reported the urgent need to obtain reliable, accurate and up-to-date spatial information on land cover and the magnitude of its change for the sustainable resource use (Bozkaya et al., 2015). The integration of remote sensing and GIS has been shown to improve the accuracy of spatial modeling of land use change (Pourebrahim et al., 2015; Valdez et al., 2019). Detecting change is important for understanding the current state of land use, patterns of change and the pressures on the mangrove ecosystem. The use of multitemporal Landsat imagery to generate maps of land use change in

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mangrove ecosystems has been recognized (Kanniah et al., 2015; Maryantika et al., 2017). The Landsat image analysis-based approach to mangrove mapping and change detection can provide long-term quantitative information for coastal management. In general, the classification results are good if they have an overall accuracy value of more than 60% (Supriatna et al., 2018). The precision evaluation was determined using a Kappa coefficient of 0.95. Advances in data and detection techniques are favorable for the development of new methods to map mangrove ecosystems in more detail.

Change detection matrix

The advance of the agricultural frontier in the southeastern Mexico implies the tendency to replace mangrove areas and low flood forests with oil palm plantations. In Mexico, oil palm plantations were established in the southeast and this trend is expected to continue. The growth of plantations is due to economic support and is not accompanied by environmental or socio-economic impact assessments (Hernández-Rojas et al., 2018). Oil palm expansion is an important but under-recognized threat in Malaysia and Indonesia (Richards et al., 2016). Coconut plantations and oil palm in mangrove areas have been introduced into a protected area in provincial Indonesia (Eddy et al., 2022).

Our research agrees with Basyuni et al. (2018), that the main drivers of mangrove deforestation are aquaculture, land abandonment and oil palm. Forest fragmentation into smaller patches of secondary forest is evident. This phenomenon, observed in numerous studies, results from the invasion and growth of shrubs due to land abandonment and less human pressure from migration to urban centers (Wingate et al., 2022). Different drivers shape the biophysical landscape and ecosystem services and their impact on the well-being of residents (Nicholls et al., 2016). Mangrove deforestation removes the natural barrier to salinity infiltrating soil for livestock, among other impacts. In addition, changes in land cover have altered the temperature of the radiating surface, justifying that the change in land use can alter the temperature of adjacent areas (Thakur et al., 2021).

Exchange rates

The extent of mangroves has decreased throughout the planet due to changes in land use, overexploitation, pollution, floods, coastal erosion, cyclones, and decreased availability of fresh water. In recent decades, 35% of the mangrove area has been lost, losses that exceed those of tropical forests and coral reefs (Valiela et al., 2001).

There are few studies to detect changes in land use in Protected Natural Areas in Mexico. In 2017, the ANP Altas Cumbres determined a notable expansion of urban areas and a significant decrease in temperate forests and tropical vegetation (Sánchez et al., 2017). However, our results coincide with deforestation in the Los Tuxtlas Biosphere Reserve from 2006 to 2016 riparian strips and the transition from pastureland to crops, suggesting a change in economic activities of the area (Thaden et al., 2020). In the Chamela-Cuixmala Reserve, they indicated an evident and significant slowdown in the annual change rates of plant formations (Flores et al., 2019).

Deforestation rates reported here are like other hotspot regions in Mexico. They are considered high compared to the national average (Leija et al., 2020). An intensification of coastal erosion and an increase in change processes are reported in 66% of the Mexican coastline (Valderrama et al., 2019). In Mahahual, a deforestation rate of 0.85% was determined and the main agents of deforestation are related to tourist facilities, rather than population growth (Hirales et al., 2010). Yucatán and Campeche reported forest cover loss rates between 0.6-0.8%. The change in land use for livestock is the direct cause of

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deforestation in the Peninsula and is promoted by programs and incentives for livestock development such as PROGAN (Ellis et al., 2017). Land use planning policies and agrarian strategies that promote land conversion, especially mangroves, for development or other financial benefits would disturb the ideal human-nature balance (Sannigrahi et al., 2020).

It is important to homogenize spatial and temporal criteria so that the analyzes between regions are compatible with each other. For the state of Chiapas, an annual deforestation rate of 1.1% was reported based on net exchange value (Romero et al., 2013). There is a process of change and replacement of land cover and use, the greatest growth is agriculture, including dynamic processes such as conversion to secondary vegetation, at the expense of forests and jungles (Morales et al., 2016). The deforestation rate may be caused by the conversion of forest lands to seasonal agriculture, when they are unproductive, they give way to urban sprawl. Furthermore, few studies suggest that tropical deforestation is associated with population and poverty (Singh et al., 2018).

Land use transition dynamics

We found that the land use change dynamics in the study area implies the deforestation of forests and mangroves to turn them into temporary or irrigated agricultural sites. When these sites are abandoned, they become human settlements or areas without vegetation. There are few studies of the deforestation process within Protected Natural Areas in Mexico (Sánchez et al., 2017; Thaden et al., 2020). Landscape metrics corroborate a decrease in fragmentation and connectivity in the Maya zone. There was a net loss of forests (-1.6%) associated with pastures and commercial agriculture in Bacalar. The most intense changes during 2011-2018 focused on secondary vegetation (Ellis et al., 2020).

The transitions between categories reveal a forest disturbance-recovery dynamic. Demographic factors at the municipal level are the ones that most affect the loss of vegetation. The greatest loss occurs closer to agricultural areas. The areas with high ecological fragility are those with the greatest susceptibility to being deforested. The loss of mangroves and lowland forests is due to the conversion of the soil to irrigated and seasonal agriculture. In addition, these activities generate agrochemical residues that are dumped into the estuaries, increasing their degradation (Quintero et al., 2021).

Our findings coincide with what has been reported in Vietnam, Brazil and Honduras, degraded mangrove areas were converted into aquaculture ponds (Chen et al., 2013; Hauser et al., 2017; Godoy et al., 2018). Agricultural areas, dense mangroves and water bodies indicate decreasing trends, while areas of farms and aquaculture settlements show increasing trends. The American continent and Asia are the most affected areas by mangrove ecosystems (Grijalva et al., 2022). Rapid urbanization and tourism development in the Caribbean can decrease ecosystem resilience to environmental stressors and undermine the sustainability of tourism development. On the northern and central Pacific coast of Mexico, 66% of mangrove loss was due to the establishment of shrimp ponds (Adame et al., 2018).

Future scenarios of deforestation

The study of land use change allows us to understand the history and the current changes and to anticipate or plan the possible future scenarios of the patterns and processes inherent to the dynamics of the landscape (Thaden et al., 2020). Some works project the predominance of more salt-tolerant mangrove species, indicating a more saline environment that represents a threat to the ecosystem and the economy of local inhabitants

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(Mukhopadhyay et al., 2015). The open mangrove is more susceptible to the edge effect, making it unstable for other types of land uses.

The practice of commercially valuable aquaculture has pushed down native agricultural practices in the region. Human settlements and aquaculture are classes with great potential for expansion in the future. The expansion of aquaculture decreases the quality, density, and condition of dense mangroves. In the Indian Sundarban Delta, four 2030 scenarios were developed based on local policy considerations and arguments. They determined moderate to significant aquaculture expansion for all scenarios. In 3 of 4 scenarios, they indicated a moderate loss of mangroves. They observed an overall decline of 0.31% per year (DasGupta et al., 2019). Our results are in line with the expected predictions for Bangladesh, agricultural land and water bodies will shrink, while rural and urban settlements as well as marshes will increase (Hoque et al., 2020).

The use of Markov chains allows for analyzing the dynamics of land use change and modeling future deforestation scenarios. The integration of Markov chains to determine land use change and future projections is an accurate tool to simulate the internal dynamics of the landscape and obtain change probabilities. It is estimated that by 2025, 37,937 ha of forests, 650 ha of forests and 885 ha of mangroves will have been lost in the coastal region of Oaxaca (Leija et al., 2016). In Villahermosa, a loss of 1171 ha of arboreal vegetation and 247 ha of wetlands is projected between 2008 and 2030 (Palomeque et al., 2019). It is important to highlight the limitations to validate predictive models of land use change. For example, the change in the technologies used between the two dates, in addition, the same types of inputs are not always available. Understanding mangrove dynamics is important to track the effectiveness of current land use practices, management regimes and to inform future mangrove conservation efforts.

Conclusion

This study analyzes the dynamics of mangroves deforestation in Chocohuital, Chiapas, Mexico from 2000 to 2019 and provides a future scenario using Landsat imagery and the Markov Chain model. The results indicate a loss of 51 ha of mangroves, 712 ha of jungle, 94 ha of pastureland and an estuary decrease of 70 ha. The deforestation rates were -0.11% for mangroves, -0.34% for pastureland and -21.63% for the jungle. The transition dynamic indicates the loss of forest areas, including low jungles and mangroves, to agriculture and induced pastures. The mangroves are being displaced by the advance of the agricultural frontier and the development of human settlements. The establishment of new aquaculture farms was found on the banks of the Chocohuital estuary. When fertility decreases, they become human settlements or areas devoid of vegetation. Our results highlight high concordance of the land use classification with the Kappa index of 95%. Future scenarios indicate a probability of 0.11 for mangroves to become agriculture areas and 0.5 for pasturelands. It is essential to create future scenarios of mangrove distribution to optimize conservation and development through proactive policy planning, especially in a protected natural area.

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