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Research article

Spatial modeling of the conservation state and future scenarios in Eastern *Tabasco*, Mexico

Modelación espacial del estado de conservación y escenarios futuros en el Oriente de Tabasco, México

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Abstract

Land use change in Eastern *Tabasco* (ET) was modeled using the Land Change Modeler (LCM) for the ecological sustainability module of the TerrSet liberaGIS® software, covering the period 2000-2019. In addition, a probabilistic and spatial scenario (2030) was created using Markov chains and Cellular automata. The results indicated that during 2000 and 2019, agricultural and forest uses dominated, together accounting for 60 %. The rest of the land cover types covered a small area: water bodies and wetlands (7.9 %), evergreen rain forest (5 %), medium evergreen and semi-evergreen forest (2.4 %), lowland floodplain forest (2.6 %), and fallow lands (14.8 %). The spatial projection to the year 2030 pointed to a slight increase in agricultural use (60.3 %), human settlements (1.5 %), and oil palm plantations (2.1 %). Although productive activities will continue to dominate, high, medium, and low forests will remain stable at 5.2, 2.8, and 2.6 %, respectively, contrary to the situation of water bodies and wetlands, which will continue to lose significant areas, as indicated by the spatial projection. In order to preserve the remaining forests and those wetlands that still exist, it is important that ecological zoning plans have clear criteria for ecological regulation and a vision of sustainable development. Likewise, conservation, restoration and sustainable use of the *Usumacinta* Canyon Flora and Fauna Protection Area and the *Wanhá* Biosphere Reserve must be strengthened.

Key words: Agricultural activities, cellular automata, Markov chains, land use change modeler, forest plantations; evergreen rain forest.

Resumen

Se modeló el cambio de uso del suelo en el Oriente de Tabasco (OT) con el módulo *Land Change Modeler* (*LCM*) *for ecological sustainability* del *software TerrSet liberaGIS*®, durante el periodo 2000-2019. Además, se creó un escenario probabilístico y espacial (2030) mediante Cadenas de *Markov* y Autómatas celulares. Los resultados indicaron que durante 2000 y 2019 dominaron los usos agropecuarios y forestales, que en conjunto representaron 60 %; el resto de las coberturas cubrieron poca superficie: cuerpo de agua y humedal (7.9 %), selva alta perennifolia (5 %), selva mediana perennifolia y subperennifolia (2.4 %), selva baja inundable (2.6 %), y acahual (14.8 %). En la proyección espacial a 2030, se observó un ligero crecimiento de los usos agropecuarios (60.3 %), el aumento de los asentamientos humanos (1.5 %), y de la palma de aceite (2.1 %). No obstante que, las actividades productivas continuarán siendo dominantes; sobresale que las selvas altas, medias y bajas permanecerán estables con 5.2, 2.8 y 2.6 %; contrario a la situación de los cuerpos de agua y humedales, que seguirán perdiendo superficies importantes, tal como lo indica la proyección espacial. Para conservar los remanentes de selvas y humedales que aún existen, es importante que los ordenamientos ecológicos tengan criterios claros de regulación ecológica y la visión de desarrollo sostenible. Asimismo, se debe fortalecer la conservación, restauración y aprovechamiento sostenible del Área de Protección de Flora y Fauna Cañón del Usumacinta, y de la Reserva de la Biosfera *Wanha'*.

Palabras clave: Actividades agropecuarias, autómatas celulares, Cadenas de *Markov*, modelador del cambio de uso de suelo, plantaciones forestales, selva alta perennifolia.

Introduction

The degradation of ecosystems threatens the maintenance of biodiversity, particularly because it negatively affects the function and dynamics of ecological systems at different spatial and temporal scales (Pérez-Vega et al., 2020). Among the consequences of land use change in tropical areas are biodiversity loss, climate change, desertification, air pollution, soil degradation, and food shortages (Castellanos-Navarrete et al., 2021).

In Mexico, deforestation and the loss of wetland cover have magnified the fragmentation of ecosystems, and together with climate change, will cause water shortages and sporadic, early rainfall in arid and semi-arid regions (Rodríguez-Moreno et al., 2017).

Tabasco is a biologically diverse state with different natural ecosystems that are intricate and complex due to their agroclimatic characteristics (Palma-López et al., 2011). During the 20th century, the state experienced the deterioration of its natural vegetation cover due to the deforestation of tropical rainforests and the loss of wetlands for agricultural uses derived from the *Chontalpa Plan* and the *Balancán-Tenosique Plan* (Pinkus-Rendón & Contreras-Sánchez, 2012). In addition, the oil boom in the 1970s caused more than a 50 % reduction in lake and marsh wetlands (Landgrave & Moreno-Casasola, 2012).

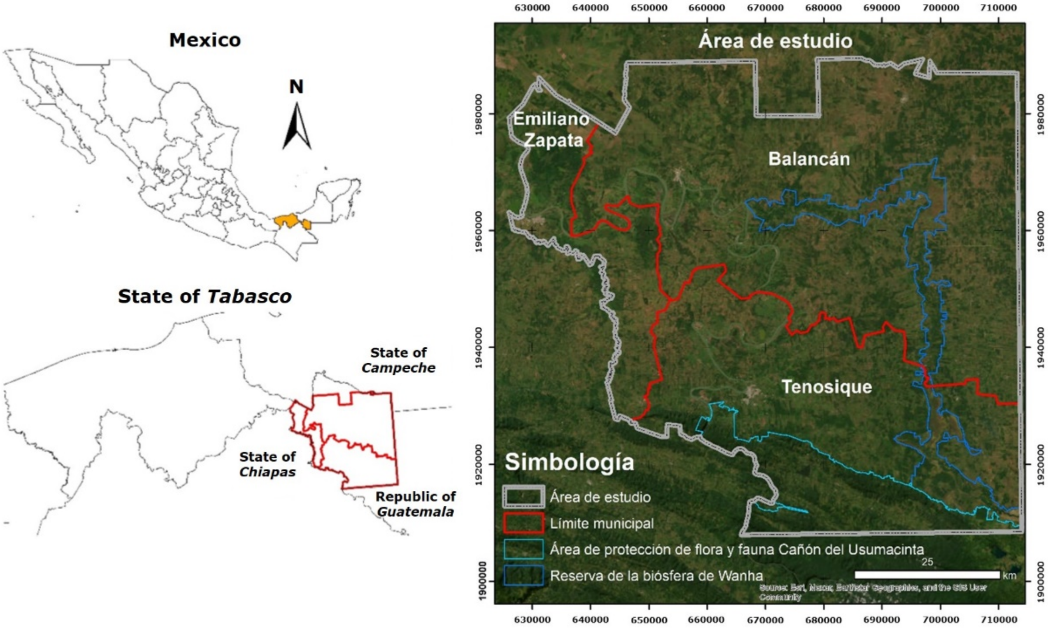
In 1947, the *Los Ríos* region of *Tabasco* had the highest coverage of natural vegetation (82.3 %), predominantly consisting of tall evergreen forest in the mountainous and hilly areas, while lowland floodplain forest (61.5 %) prevailed in the plains (Ramírez-García et al., 2022). However, the widespread devastation of the tall evergreen forest began in the first decade of the 20th century with agricultural activities and cattle ranching, which intensified after the banana crisis in the mid-20th century (Manjarrez-Muñoz et al., 2007). In 1984, grasslands already covered more than half of the region (54.3 %) (Gallardo-Cruz et al., 2019). The tall evergreen forest and fragmented forest were estimated to occupy only 12.9 % (Ramírez-García et al., 2022).

This study employs land use and vegetation analysis, and trend prediction as useful information for planners and decision-makers to propose sustainable development and land-use planning actions in response to land degradation (Ramírez-García et al., 2022). Therefore, the objectives were: (1) To model land use change in Eastern *Tabasco* for the 2000-2019 period using such tools as Land Change Modeler (LCM) for Ecological Sustainability; and (2) To design a probabilistic and spatial scenario for the year 2030 based on the use of Markov chains and Cellular automata.

Materials and Methods

Study Area

Eastern *Tabasco* (ET) comprises the *Balancán*, *Emiliano Zapata* and *Tenosique* municipalities, in Southeast of Mexico (Figure 1), covering a surface area of 6 234.2 km^2, which represents 24.7 % of the state. The region borders the state of *Campeche* to the North, shares an international border with the Republic of *Guatemala* to the East and South, and borders the state of *Chiapas* to the Southwest. From North to South, warm subhumid climates with summer rainfall (Aw), warm humid climates with abundant rainfall in summer (Am), and warm humid climates with abundant rainfall throughout the year (Af) prevail. The average annual precipitation varies from 1 600 to 2 000 mm, and the average annual temperature ranges from 26 to 28 °C (Aceves-Navarro & Rivera-Hernández, 2019). The territory features geomorphological regions of coastal terraces, karst terraces, active river plains, and sloping karst mountains (Zavala-Cruz et al., 2016).



Área de estudio = Study area; *Emiliano Zapata* = *Emiliano Zapata* municipality; *Balancán* = *Balancán* municipality; *Tenosique* = *Tenosique* municipality; *Simbología* = Key; *Área de estudio* = Study area; *Límite municipal* = Municipal border; *Área de Protección de Flora y Fauna Cañón del Usumacinta* = *Usumacinta* Canyon Flora and Fauna Protection Area; *Reserva de la Biosfera de Wanha* = *Wanha'* Biosphere Reserve.

Figure 1. Geographical location of the municipalities covering Eastern *Tabasco*, Mexico.

Acquisition of satellite images

Multispectral satellite images ranging from visible to mid-infrared were obtained from the website of the United States Geological Survey (USGS, 2019). The first image, for the year 2000, was taken on December 5th, 1999, with the Landsat 5

Thematic Mapper (TM) and had a spatial resolution of 30×30 m. The second image, with a spatial resolution of 30×30 m, was taken with the Landsat 8 Operational Land Imager-Thermal Infrared Sensor (OLI-TIRS) on July 5th, 2019.

Description of land cover and land use

Short-cycle crops: their vegetative cycle lasts less than a year, like those of corn, beans, etc.; annual crops: crops with a vegetative cycle lasting 12 to 24 months, like the sugar cane; oil palm: an agro-industrial oilseed crop for oil production; grassland: naturally occurring or induced herbaceous communities of grasses; forest plantation: species cultivated for timber or resin production; wetlands: aquatic, rooted, and floating plant communities; fallow lands: the successional phase of removed or disturbed vegetation; lowland floodplain forest: vegetation less than 15 m tall that grows on temporarily or permanently flooded soils; medium-sized evergreen and semi-evergreen forest: tree associations in tropical climates, 50-75 % of whose species lose their leaves during part of the year; tall evergreen forest: tropical plant associations, more than 75 % of whose species retain their foliage throughout the year; bodies of water: rivers, lakes, lagoons, etc.; bare ground: areas devoid of vegetation; human settlements: establishment of a demographic conglomerate (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2017).

Classification of satellite images from 2000 and 2019

To obtain the 2000 and 2019 land cover and land use maps (Figure 2), the supervised classification technique was applied, based on prior knowledge of the study area and a review of historical cartography. Multispectral satellite images were processed using the Semi-Automatic Classification plugin of the open-source software QGIS 3.8.3 (QGIS Development Team, 2025), using the maximum likelihood algorithm, which examined the probability function of each class and assigned each pixel to the class with the highest probability. The spectral signatures used were combinations of RGB bands 3-2-1 and 4-3-2.

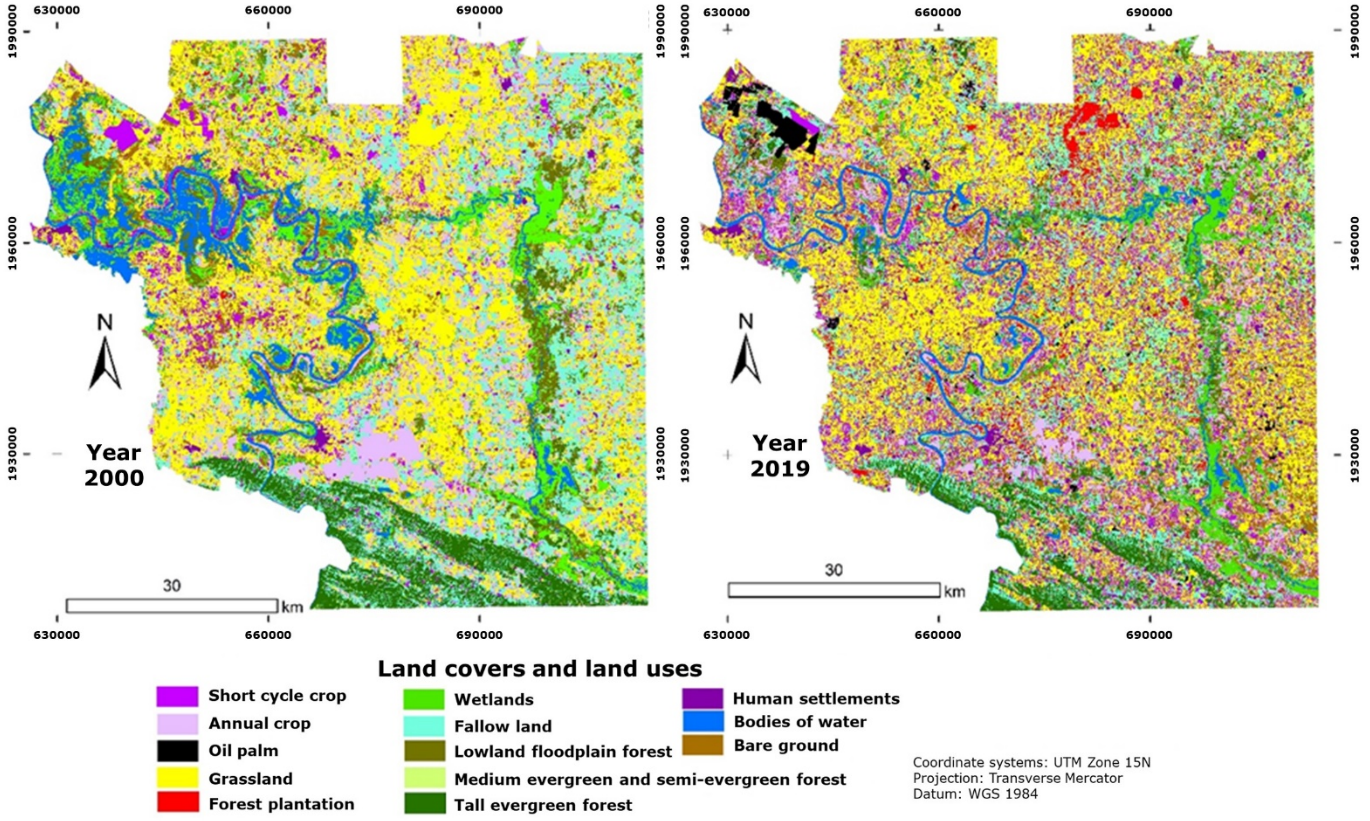


Figure 2. Map of land cover and land use in 2000 and 2019.

Modeling of land use change in 2000-2019

To perform the spatiotemporal analysis for the 2000-2019 period, the raster images were cross-referenced using the Land Change Modeler (LCM) for Ecological Sustainability module integrated into TerrSet liberaGIS® (Eastman, 2024). The CrossTab command was used to validate the probability matrix (Eastman, 2024). The cross-referencing of images between 2000 and 2019 (Figure 2) was generated using a matrix and an Overall Kappa statistic of 0.89, which demonstrated that the cross-referencing of the two time periods was reliable for the analysis of land use change in the territory (Eastman, 2024). The results included a summary of the matrices with the surface area of each category, compared to others.

Probabilities of change with Markov chains 2030

A transition probability matrix was created using the Markov command in TerrSet liberaGIS® (Eastman, 2024). The method involved cross-referencing land use maps from two time periods, with a margin of error of 15 %, to generate a probability matrix of the changes that may occur in a third period (Eastman, 2024). The Markov matrix was created using images from 2000 and 2019. The results were a matrix of probability of change (2030) and a collection of images of suitability/aptitude areas (2030) containing the number of pixels expected to change from one land use class to another over a period of time (Eastman, 2024).

Creating scenarios with Cellular automata 2030

Cellular automata were used with the CA-Markov command in TerrSet liberaGIS® (Eastman, 2024) to simulate a potential scenario of vegetation and land use for the year 2030. The spatial scenario for 2030 (Figure 3) was constructed based on the 2019 land cover and land use image, the probability matrix of changes (2030), and the collection of images of suitability/aptitude areas (2030). The VALIDATE command was used to validate the accuracy of the projection for the year 2030. This command calculated the Kappa statistic (*K*) to indicate the degree of agreement between two maps, both in general terms and on a per-category basis (Eastman, 2024). The spatial projection (2030) presented an overall accuracy Kappa: *Kstandard*=0.76 %, *Kno*=0.78 %, *Klocation*=0.78 %, and *KlocationStrata*=0.78 %.

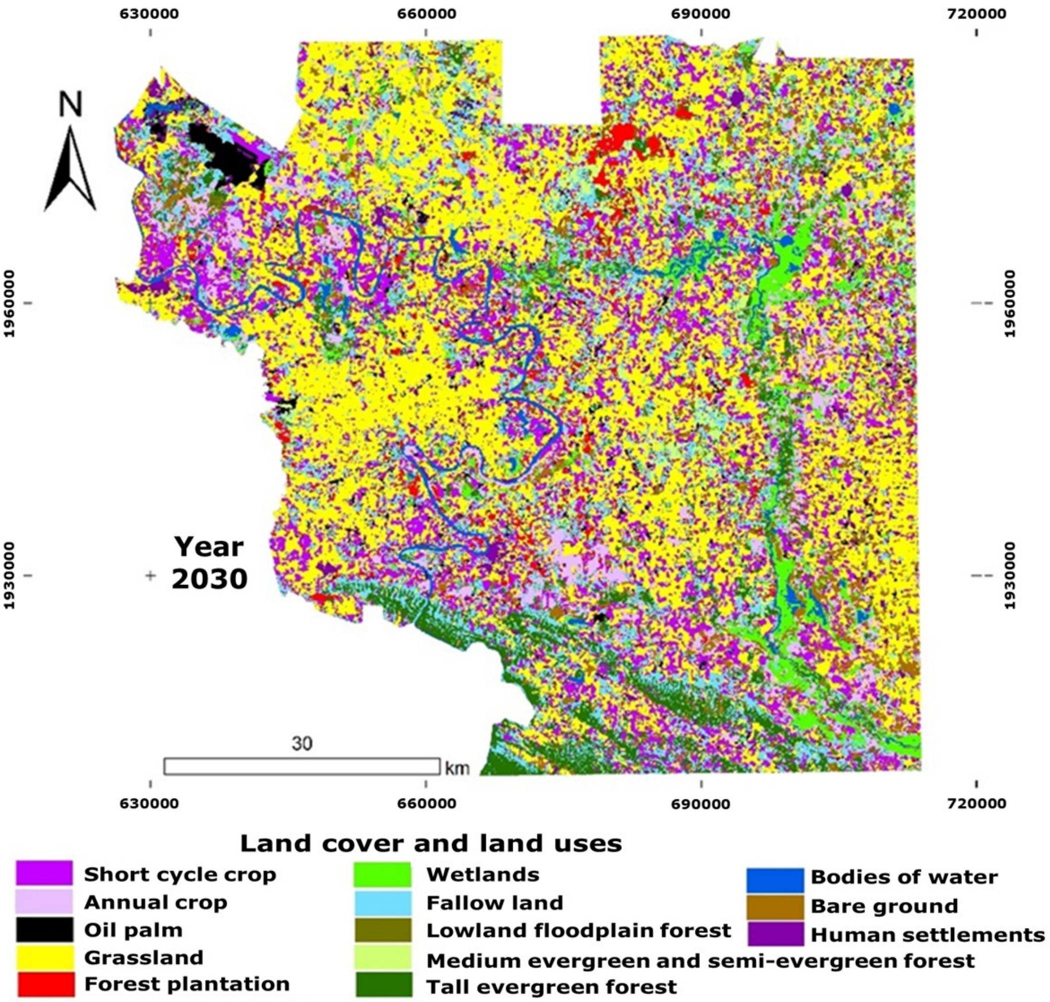


Figure 3. Scenario resulting from land cover and land use for the year 2030.

Modeling of land use change in 2019-2030

The 2019 land cover and land use image was superimposed onto the 2030 projection using the Land Change Modeler and CrossTab modules to obtain the change matrices and the Kappa statistic (K)=0.76 (Eastman, 2024).

Calculation of exchange rates

According to the work of Palacio-Prieto et al. (2004), land use change rates are calculated using the following formula:

$$d = \left[\left(\frac{S2}{S1}\right)\frac{1}{n-1}\right]100$$

Where:

d = Annual change rate (in percentage)

S1 = Surface area covered by a specific land use at the beginning of the period

S2 = Surface area covered by a specific land use at the end of the period

T = Number of years in the analysis period

n = Number of years in the analysis period

Results and Discussion

Land use change in 2000-2019

The predominant land cover and land use in 2000 were: grasslands, annual crops (sugar cane), fallow lands, wetlands, lowland floodplain forests, and water bodies (Table 1). In 2019, the dominant categories were: grasslands, short-cycle crops (corn, beans, squash, etc.), fallow land, and annual crops (Table 1). It is clear that the main activities in ET are livestock farming, agriculture (Ramírez-García et al., 2022), and forestry, mainly involving introduced species (Trujillo-Ubaldo et al., 2018). Likewise, small remnants of natural vegetation were observed, especially forests that were once the dominant cover and have been affected by deforestation due to agricultural use (Palomeque-de la Cruz et al., 2019).

Table 1. Quantification of land cover and land use during 2000-2019.

Land cover and land use	2000 (km^2)	%	2019 (km^2)	%	Rate of change
Bodies of water	330	6	169	3.1	-3.4
Bare ground	263	4.8	292	5.3	0.6
Human settlements	51	0.9	64	1.2	1.2
Wetlands	402	7.3	264	4.8	-2.2
Fallow land	823	15	812	14.8	-0.1
Lowland floodplain forest	323	5.9	141	2.6	-4.3
Medium evergreen and semi-evergreen forest	71	1.3	132	2.4	3.3
Tall evergreen forest	314	5.7	275	5	-0.7
Short-cycle crop	301	5.5	864	15.8	5.7
Annual crop	884	16.1	357	6.5	-4.7
Oil palm	0	0	93	1.7	0.0
Grassland	1 690	31	1 754	32	0.2
Forest plantation	6	0.1	241	4.4	21.2
Total	5 478	100	5 478	100	

The most notable land use changes between 2000 and 2019 were the increase in short-cycle crops from 5.5 to 15.8 %, with a positive change rate of 5.5 % (Table 1). This was mainly encouraged by the "*Sembrando Vida*" (Sowing Life) program in the municipalities of *Balancán*, *Tenosique*, and *Emiliano Zapata* (Gutiérrez-San Pallo et al., 2019), which has led to an increase in the agricultural area devoted to staple crops such as corn, beans, squash and *chigua*.

Forest plantations are implemented through private initiative and government programs. These grew from 0.1 to 4.4 %, with a positive rate of change of 21.2 % (Table 1). Noteworthy are the plantations of eucalyptus (*Eucalyptus grandis* W. Mill *ex* Maiden), teak (*Tectona grandis* L. f.), melina (*Gmelina arborea* Roxb. *ex* Sm.), Australian cedar (*Toona ciliata* M. Roem.), African mahogany (*Khaya ivorensis* A. Chev.), and, to a lesser extent, plantations of native species such as cedar (*Cedrela odorata* L.) and mahogany (*Swietenia macrophylla* King).

The development of oil palm cultivation is one of the main activities that has expanded in ET (Hernández-Rojas et al., 2018; Trujillo-Ubaldo et al., 2018), with an increase of 1.7 %, similarly to what happened in Southern Thailand, where this crop increased from 0.04 to 6.84 % (Srisunthon & Chawchai, 2020). This has had a direct impact on the few remaining forests and fallow lands in ET (Table 1). In the municipality of *Tenosique*, there is a remnant of tall evergreen forest within the *Usumacinta* Canyon Flora and Fauna Protection Area, which between 2009 and 2016, this vegetation cover experienced a cumulative loss of 1 625 ha as a result of land-use change. Of this area, approximately 1 231 ha were transformed into land for agricultural activities, while only 394 ha evolved into secondary vegetation (Palomeque-de la Cruz et al., 2025). Although the landforms are not suitable for these production activities, as they are located in areas with steep slopes, they continue to be exploited (Gutiérrez-San Pallo et al., 2019; Palomeque-de la Cruz et al., 2019).

Land uses that decreased in surface area in ET were annual crops, which diminished from 16.1 to 6.5 %, with a negative rate of change of 4.7 % (Table 1). Wetlands decreased by 7.3 to 4.8 %, with a negative rate of change of 2.2 %, and water bodies decreased by 6 to 3.1 %, exhibiting a negative rate of change of 3.4 % (Table 1). These ecosystems are mainly located in the *Wanha'* Biosphere Reserve and are being affected because their margins are losing territory due to encroachment by agricultural practices, particularly during the dry season (Ramos-Reyes et al., 2021; Srisunthon & Chawchai, 2020).

Major transitions in land use changes in 2000-2019

Agricultural uses underwent transitions mainly in grassland areas, land sown with annual crops, and fallow lands, which gave way to short-cycle crops (Figure 4). As indicated, this was facilitated by the federal "Sowing Life" program, because those responsible for registering producers required them to have clean, cultivable land, rather than fallow land. Therefore, clearing, digging, and burning practices were carried out in order to clean up and enter the program, as was the case in other states that benefited from this federal program (Cortez-Egremy et al., 2022; Gutiérrez-San Pallo et al., 2019).

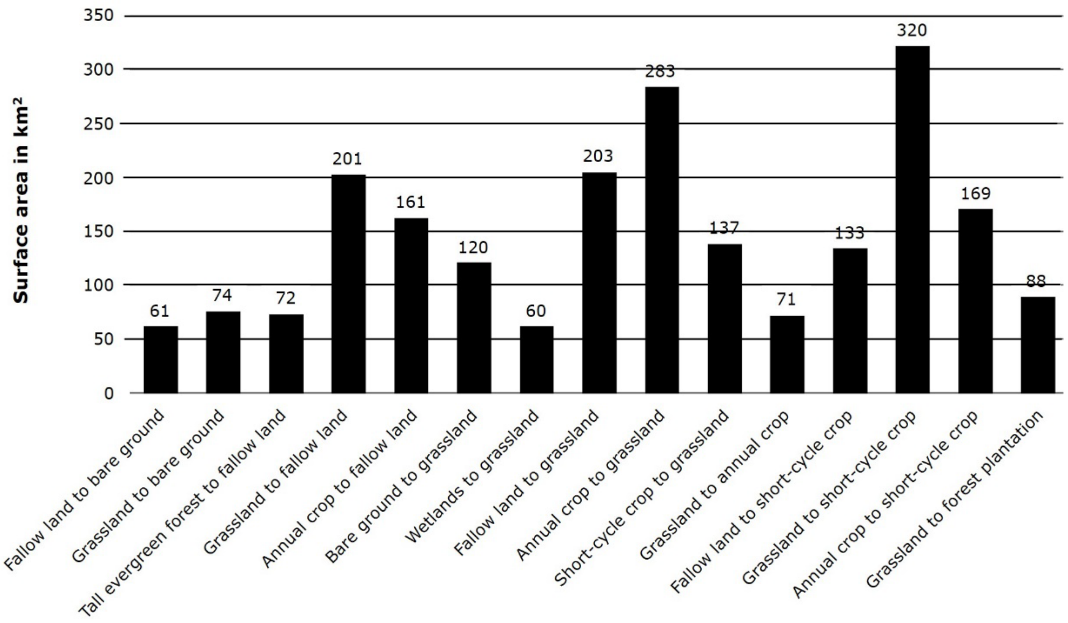


Figure 4. Main transitions in land use changes in the 2000-2019 period.

Annual crops, fallow lands, short-cycle crops, wetlands, and bare soil were converted to grasslands (Figure 4), which is used for extensive cattle ranching, still an important economic activity in ET (Manjarrez-Muñoz et al., 2007; Ramírez-García et al., 2022). Over time, this activity has continued to grow dynamically over the decades, to the detriment of other land uses and natural vegetation cover (Rodríguez-Medina et al, 2017; Srisunthon & Chawchai, 2020).

Grassland areas are being converted into forest plantations (Figure 4), a recent activity in ET that seeks to meet the demand for wood as a raw material to supply the forestry industry, reduce pressure on the remaining forests, increase the income of rural families by creating jobs (Trujillo-Ubaldo et al., 2018), and provide the ecosystem services that have been lost due to deforestation. Other abandoned agricultural areas have regenerated naturally and formed areas of fallow land (Palomeque-de la Cruz et al., 2019; Ramos-Reyes et al., 2021).

The tall evergreen forest is being transformed into fallow land (Figure 4). As in many other parts of the world, many issues associated with biodiversity loss related to the decline of tree species and of this type of ecosystem are caused by anthropogenic processes, such as the extraction of primary trees or precious woods for the illegal trade in timber used for construction, furniture, firewood, among others (Cabrera-Pérez et al., 2013; Sari et al., 2023).

Land use change projections for 2019-2030

The dynamics of land use change during 2019-2030 predict that water bodies will tend to decrease steadily (3.1 to 2.3 %) and, as a direct consequence, wetland ecosystems will also be reduced (4.8 to 4.1 %) in ET. Similar results are documented for the rest of the state of *Tabasco* due to the increase in agricultural uses (Ramos-Reyes & Palomeque-de la Cruz, 2023) (Table 2).

Table 2. Quantification of land cover and land use during the 2019-2030 period.

Land coverage and use	2019	%	2030	%
Bodies of water	169	3.1	123	2.3
Bare ground	292	5.3	283	5.2
Human settlements	64	1.2	82	1.5
Wetlands	264	4.8	221	4.1
Fallow land	812	14.8	768	14.1
Lowland floodplain forest	141	2.6	140	2.6
Medium evergreen and semi-evergreen forest	132	2.4	150	2.8
Tall evergreen forest	275	5	284	5.2
Short-cycle crop	864	15.8	855	15.7
Annual crop	357	6.5	321	5.9
Oil palm	94	1.7	116	2.1
Grassland	1 754	32	1 873	34.3
Forest plantation	241	4.4	242	4.4
Total	5 479	100	5 458	100

Wetlands in Mexico are subject to similar pressure from the same activities, compounded by urban growth, oil extraction, and tourism (Rodríguez-Arias et al., 2018). The decline of wetlands is causing concern due to the loss of various ecosystem services, which leads to ecological vulnerability (Assefa et al., 2021; Srisunthon & Chawchai, 2020). Fallow lands also tend to decrease in the projection for the period 2030 (Table 2). The loss of wetlands contributes significantly to climate change. When drained or destroyed, they release large amounts of carbon stored in their soils, which increases greenhouse gases and reduces their ability to regulate the climate (Mei et al., 2024). Annual crops suffer losses (Table 2) due to the abandonment of sugar cane cultivation (Ramírez-García et al., 2022).

The land uses most likely to increase, according to the CA-Markov model, are human settlements (1.2 to 1.5 %) (Table 2), due to the continuous expansion of human populations (Girma et al., 2022). Oil palm cultivation is an agro-industrial activity that has grown in terms of surface area and will continue to increase in ET, according to the model's predictions for the coming years (Hernández-Rojas et al., 2018); this crop has been promoted in border areas as a way to modernize rural areas (Castellanos-Navarrete et al., 2021; Srisunthon & Chawchai, 2020) (Table 2).

For grasslands, an increase from 32 to 34.3 % is predicted (Table 2), and this is the predominant land use in most studies of land use change carried out in *Tabasco*, nationwide, and in other tropical areas (Assefa et al., 2021; Palomeque-de la Cruz et al., 2019; Sari et al., 2023). However, it may change depending on the agricultural and forestry activities practiced, as pointed out by Girma et al. (2022), who project a drastic decrease in this use by 2050 as a result of the impact of other land uses. Land cover and land use types that show no apparent significant changes are lowland floodplain forest, medium-altitude evergreen and semi-evergreen forest, high-altitude evergreen forest, forest plantations and short-cycle crops (Table 2).

Transitions projected for 2019-2030

ET abounds in agricultural land; other notable land uses include oil palm cultivation and forest plantations, which constitute recent practices. Thus, land use transitions for the 2019-2030 period are dynamic, and a transformation from short-cycle crops to grassland and forest plantations can be observed (Figure 5). Grasslands will be converted into areas for short-cycle crops, forest plantations, and oil palm plantations (Figure 5), with the latter showing an upward tendency. These dynamics are similar to those mentioned at the national level and in other tropical countries (Castellanos-Navarrete et al., 2021; Ramos-Reyes & Palomeque-de la Cruz, 2023; Sari et al., 2023).

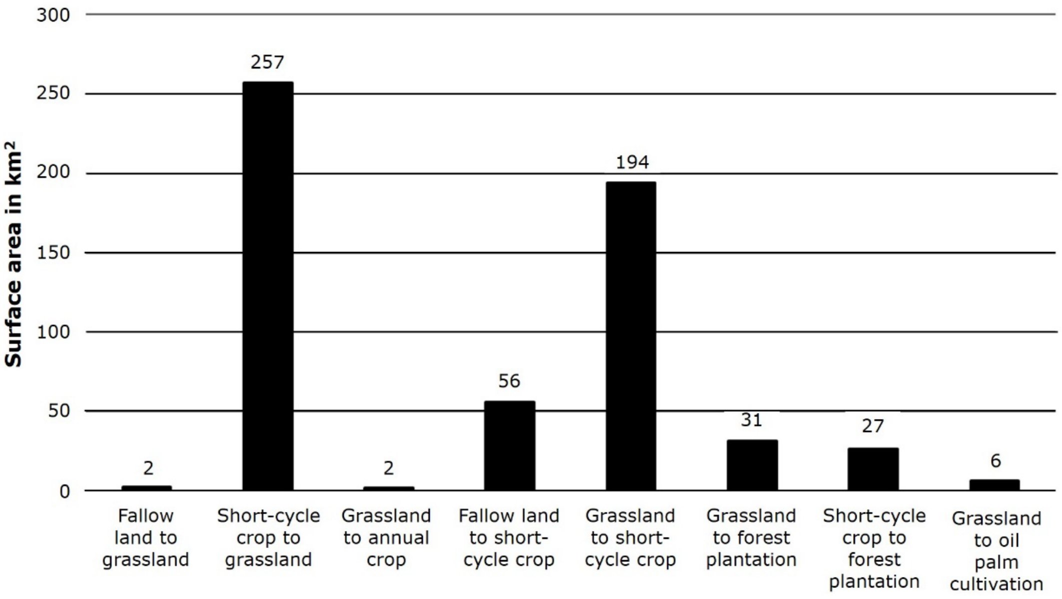


Figure 5. Transitions forecast for the period 2019-2030.

Fallow lands tend to be converted into short-cycle crops and grassland (Figure 5). It is important to note that fallowing is one of the cultural practices of producers in ET, which involves allowing the land to rest (for the fallow land to develop) during a certain period of time, so that the soil may recover its fertility and regain favorable conditions for agriculture to be practiced (Licona & Estupiñan, 2019).

The integration of transition-based geomatic models: Land Change Modeler, Markov chains, and Cellular automata (CA-Markov) helps to understand trends and directions in land cover and land use. These results are useful for preventing problems such as drought, flooding, and soil erosion, and they contribute to the understanding of the causes of major environmental issues and assessment of the future impact of land use change, in order to propose the sustainable use of natural resources as a strategy to mitigate climate change (Principi, 2022).

Conclusions

Modeling of land use change in Eastern *Tabasco* for the 2000-2019 period highlights the dominance of agricultural and forestry land uses, which account for 60 %, while the cover of tall evergreen forests, medium evergreen forests, semi-evergreen forests, and lowland floodplain forests accounts for only 10 %. Agricultural uses are undergoing dynamic changes. Grasslands are losing land as they are converted to short-cycle crops, annual crops, forest plantations, and fallow land, unlike short-cycle crops, which are increasing in surface area over annual crops, grassland, and fallow land. The evergreen high forest cover is transformed into fallow land, and the wetlands become grasslands.

The probabilistic and spatial scenario for the year 2030 allowed for the detection of land use change, showing potential spatial distributions for Eastern *Tabasco*. In fact, water bodies can be seen to have covered 6 % of the surface area in 2000 are projected to cover only 2.3 % by the year 2030, which means that they will shrink by 3.7 %, representing a loss of 61.6 % of ET's water. Consequently, wetlands will also be affected, decreasing in surface area from 7.3 % in 2000 to 4.1 % in the projection for 2030, which implies a decrease of 43.8 %.

The use of the Land Change Modeler (LCM), combined with Markov chains and Cellular automata, is an essential scientific tool for analyzing and projecting future land use changes. It also allows for the assessment of potential impacts on the vegetation cover and ecosystem services. The synergy between these methods enhances territorial planning, promotes conservation policies, and helps mitigate the effects of urban growth or agricultural expansion. Taken together, this approach provides a scientific basis for promoting strategies aimed at ecological resilience and rational land use within the context of climate change.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Alex Ricardo Ramírez García: development of supervised classifications and data analysis; Miguel Ángel Palomeque de la Cruz: land-use change modeling and manuscript writing; Victorio Moreno Jiménez: identification of land cover types and land uses in the study area; Santa Dolores Carreño Ruiz: identification of land cover types and land uses in the study area; Abisag Antonieta Ávalos Lázaro: identification of land cover types and land uses, analysis of results, writing and style; Tania Gudelia Núñez Magaña: support with the final draft.

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