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Article

Análisis geomático espacial del cambio de uso del suelo en Huimanguillo, Tabasco (2000-2010-2030)

Spatial analysis and geomatics of land use changes in Huimanguillo, Tabasco (2000-2010-2030)

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Resumen

El cambio de uso del suelo representa uno de los grandes desafíos que se antepone a la sostenibilidad, debido a que contribuye al cambio climático y a la pérdida de biodiversidad. Ante esto, y con base en el desconocimiento de los patrones de cambios de usos del suelo y sus efectos en los ecosistemas de Huimanguillo, Tabasco, se planteó realizar un análisis con *Land Change Modeler* (2000-2010) para estimar la distribución de las coberturas naturales con mayor presión ambiental. A partir de ello se construyó una proyección con Cadenas de *Markov* y Autómatas Celulares (2030). Así, durante 2000 y 2010 se detectaron importantes ganancias en los humedales (39 236 ha) y en la vegetación arbórea (24 773 ha), lo cual es favorable para el mantenimiento de los servicios ecosistémicos. Sin embargo, se registraron aumentos en la zona urbana (1 266 ha) con disminución en la agropecuaria (53 639 ha), aunque esta aún constituye la mayor superficie en el territorio. Además, con el análisis espacial del 2010 contra la proyección 2030, se detectó que continuaron las tendencias de crecimiento de los humedales (7 197 ha), vegetación arbórea (9 937 ha) y uso urbano (1 498 ha); así como la disminución del área agropecuaria (16 433 ha). Este estudio generó información cartográfica útil para la definición de las estrategias y políticas de planificación territorial, que conlleve a la implementación de un modelo de ordenamiento ecológico territorial de desarrollo urbano, y, en su caso, al decreto de áreas naturales protegidas.

Palabras clave: Áreas Naturales Protegidas, Autómatas Celulares, Cadenas de *Markov*, geomática, modelador del cambio de uso del suelo, ordenamiento ecológico territorial.

Abstract

The change of land use represents one of the major challenges that sustainability plans face, because it contributes to climate change and biodiversity loss. In view of this, based on the lack of knowledge of the patterns of land use changes and their effects on the ecosystems of *Huimanguillo, Tabasco*, an analysis with Land Change Modeler (2000-2010) was proposed to estimate the distribution of natural covers with greater environmental pressure. Based on this, a projection was built with Markov Chains and Cellular Automata (2030). Thus, during 2000 and 2010, significant gains were detected in wetlands (39 236 ha) and in arboreal vegetation (24 773 ha) that were favorable for the maintenance of ecosystem services. However, there were increases in the urban area (1 266 ha) in the face of the agricultural decline (53 639 ha) which, despite its losses, still represents the largest area in the territory, due to the permanence of productive activities. In addition, the 2010 spatial analysis against the 2030 projection found that trends in wetland growth (7 197 ha), tree vegetation (9 937 ha) and urban use (1 498 ha) continued in the face of agricultural area losses (16 433 ha). This study generated helpful mapping information for determining environmental planning strategies and policies that may lead to the implementation of an ecological regulatory zoning for urban development and to decreeing Protected Natural Areas.

Key words: Protected Natural Areas, Cellular Automata, Markov Chains, Geomatics, Land Change Modeler, Environmental Planning.

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Introduction

The change of land use is one of the challenges that the sustainability plans face today, as it contributes to climate change and to the loss of biodiversity (Mahmood *et al.*, 2010). The factors that drive this change vary from one region to another as well as through time (Rudel *et al.*, 2009), due to the presence of such phenomena as population growth, globalization and the opening of the export market, which may modify the land conversion scenario in the future (Schmitz *et al.*, 2015).

Since the 1960s, there is a clear tendency in Mexico to transform forests into agricultural lands where rain-fed crops are prevalent (Rosete-Vergés *et al.*, 2014). This is particularly important, because the conversion of rain forests into agricultural areas entails the elimination of carbon sink that contributes to global climate change (Zheng *et al.*, 2013). Land conversion in Mexican territory, particularly due to deforestation, has different causes, according to the region, which are most directly linked to environmental and socioeconomic factors and to public policies (Masera, 1996).

In *Tabasco*, the change of land use has been dramatic in terms of deforestation; Tudela (1992) points out that, in 50 years, almost all the rain forest cover in the state was lost. Toward the 1960s, supported by the oil boom, the federal declaration for the purpose of producing large amounts of basic grains, which was the source of the *Chontalpa* Plan, stimulated the economy through the construction of infrastructure and the resulting population growth that favored the creation of such great urban centers as *Cárdenas, Huimanguillo, Comalcalco, Centla, Paraíso* and *Macuspana* (Pinkus-Rendón and Contreras-Sánchez, 2012).

Today, these effects are more visible because the macroeconomic stimulus through the demand of agricultural products and commercial livestock rearing has favored the rise of their prices in the national and international market, which in turn favors the conversion of vegetal covers into great farming areas. Such is the case of the *Huimanguillo* municipality, where citriculture, stockbreeding and forest plantations (eucalyptus, rubber, and oil palm) have increased their surface area in the last few decades (Palma-López *et al.*, 2011). Without a doubt, the modification of land use in *Tabasco* has been largely driven by the search for economic growth, as has historically been the case of developing countries (Dewan and Yamaguchi, 2009).

The study of the change of land use is central in environmental research, as it is crucial for the assessment of the environmental impact in order to predict environmental and socioeconomic scenarios and establish territorial planning policies (Paegelow *et al.*, 2003). As for the current uses of the land in the *Huimanguillo* municipality, *Tabasco*, the following questions are prevalent: are the land use changes favorable to the environment? Or, do they generate conflicts of interests? For this reason, we suggested a spatial geomatic analysis of the change of land use, utilizing the (2000-2010) Land Change Modeler tool to estimate the distribution of the natural covers subjected to a greater environmental pressure due to the presence of anthropic uses, and, based on the results of this analysis, to build a future scenario (2030) using Markov chains and cellular automata.

Materials and Methods

Study area

The *Huimanguillo* municipality, *Tabasco* (Figure 1) is located in the basin of the *Tonalá* river in Mexico. This territory belongs to the *Chontalpa* region, the seat of whose municipal government is the city of the same name, located at the east of the state, between the parallels 17°49' N and 93°23' W. It borders to the north with the *Cárdenas* municipality; to the south, with the states of *Chiapas* and *Veracruz*; to the east, with *Chiapas*, delimited by the *Mezcalapa* river, and to the west, with *Veracruz*, whose boundary is the *Tonalá* river. The surface area of the municipality is 372.792 ha (Periódico Oficial, 2016).

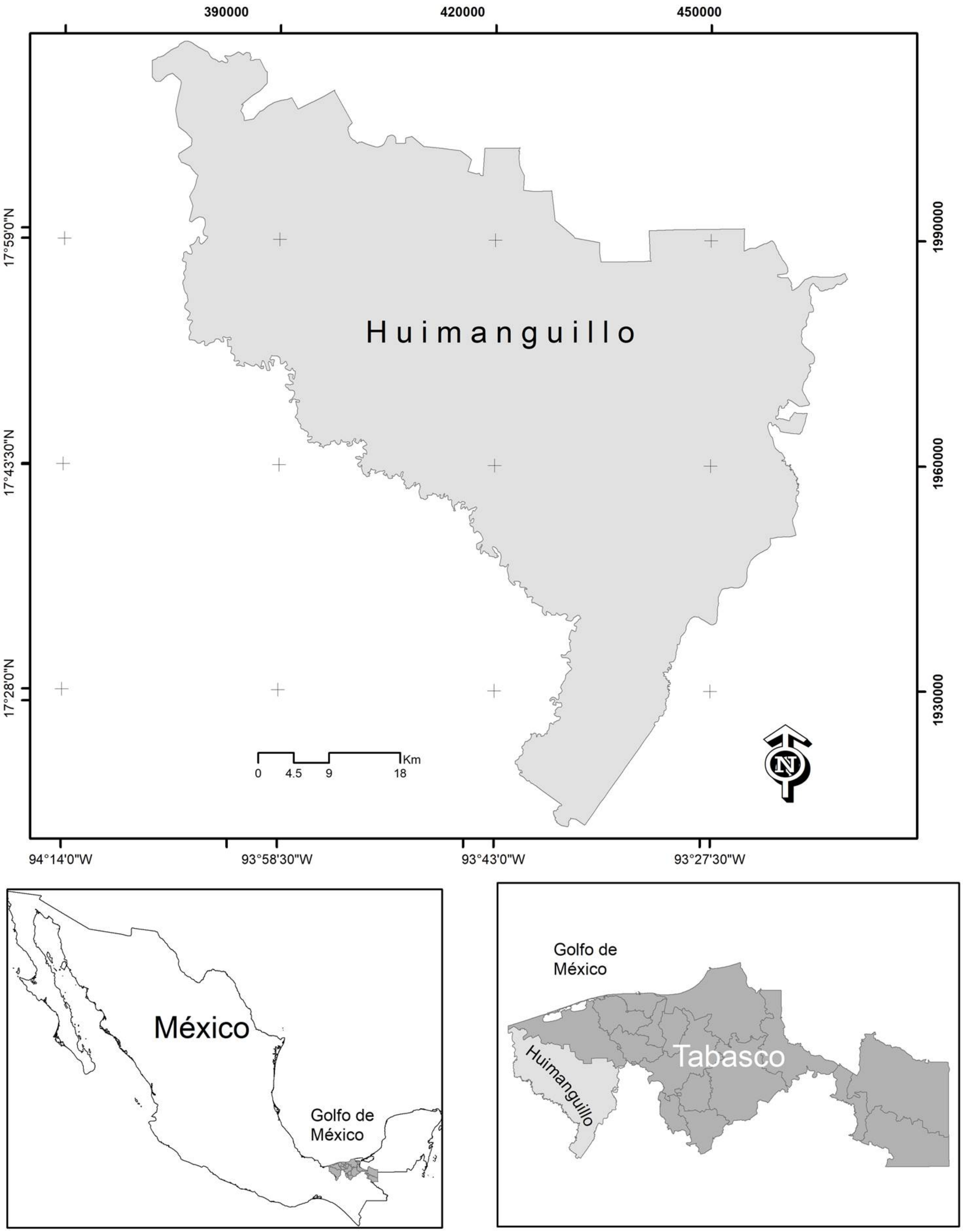

Figure 1. Geographical location of the study area.

Geographic Database

Two land-use shapefiles for 2000 and 2010 –*Datum* WGS84-UTM Projection, area 15N, developed through onscreen digitalization (Ordóñez and Martínez-Alegría, 2003), were utilized; the shapefile corresponding to the year 2000 was generated using the satellite image LANDSAT 5 TM (Thematic Mapper) for the same year, with a false color display (RGB 4,3,2); while that corresponding to the year 2010 was created with the SPOT image with a false color (RGB 1, 2, 3) (Ramos-Reyes *et al.,* 2016); the softwares Quantum GIS® and Arc GIS 10.5® were utilized; the in-field verification was carried out using GPS equipment. Later, the vectors were transformed to a raster format with a 50 m pixel size, using the software IDRISI Selva®. The theme categories were: 1) wetlands (continental and coastal lagoons, hydrophilic vegetation, and mangroves); 2) arboreal (high evergreen rain forest, secondary vegetation and forest plantations); 3) agricultural (grasslands utilized for stockbreeding and agricultural crops, and 4) urban lands (human settlements and highways).

Land-use change modeling (2000-2010)

The module utilized was the IDRISI Selva® Land Change Modeler (LCM), as it is oriented toward the constant problem of the accelerated conversion of the land and to the analytic needs of the preservation of biodiversity; it includes both the data analysis and the notion of land use changes and prediction of scenarios (Eastman, 2012). The IDRISI Selva® CrossTab module was also utilized to generate a matrix of change probabilities (2000-2010) which estimated a kappa statistic equal to 0.795. According to Eastman (2012), kappa values near 1 show an acceptable, reliable analysis of the spatial dynamics of the territory. The results of the Land Change Modeler (LCM) (2000-2010) include a summary that shows the surface are of each category in terms of persistences, gains, losses, and contributions between categories.

Change rates

The land use change rates were estimated using the formula developed by Palacio-Prieto *et al.* (2004):

$$Ar = [(S2 / S1) (1 / n) -1] * 100$$

Where:

Ar = Annual change rate (%)

S1 = Surface area covered at the beginning of the period (ha)

S2 = Surface area covered at the end of the period (ha)

n = Number of years of the period

Land use projection (2030)

The Markov chains simulate the prediction of the status of a system at a given time, based on two previous statuses (Eastman, 2012). It is a discrete procedure at a discrete time, in which the value at the time t1 depends on the values at the times t0 and t-1. The prediction materializes in a series of land use maps for a future time, in which the digital level of each pixel expresses the probability of belonging to the analyzed use (Eastman, 2012).

Cellular automata work like a set of identical elements known as cells, each of which occurs in a discrete space (Clarke and Gaydos, 1998). The same authors mention that these spatial units contain a history and an evolution of change through time, as well as such rules as the influence of the cells of adjoining a central cell.

The chains of Markov were utilized to calculate the probability of change from one pixel to another and to generate a matrix of probability of transition (Eastman, 2012). For this purpose, the 2000 and 2010 land use maps were utilized, and the Markov module of the IDRISI Selva® software was run; a 20-year interval was considered (2030). The results were: 1) a matrix of probabilities of transition, 2) a matrix of transition areas, and 3) a collection of images representing the probabilities of transition for each of the four land use categories considered (2030).

The land use map for the year 2010, the matrix of probabilities of transition (2030), and the collection of images of probabilities of transition (2030) generated were subsequently combined using the (CA-Markov) Cellular Automata module of the IDRISI Selva® software (Eastman, 2012), in order to obtain the map for the 2030 projection. The suitability of the model was assessed by comparing the similarity between the image for 2010 and the projected map for 2030, using the VALIDATE module (Eastman, 2012). The kappa statistic indicated that the values of the K standard (0.9574), Kno (0.9693), and Klocation (0.9837) were near 1; i.e., they are accurate for building scenarios (Eastman, 2012; Ahmed *et al.,* 2013).

Change of land use (2010-2030)

The image for 2010 was overlapped on the projection for 2030 (CA-Markov) by means of the Land Change Modeler and CrossTab modules in order to obtain the change matrices and the near 1 kappa statistic (0.9574); therefore, it is an acceptable, reliable image of the spatial dynamics of the territory (Eastman, 2012). Persistences, gains, losses and contributions between categories and change rates for the 2010-2030 period were thus estimated.

Results and Discussion

Change of land use 2000-2010

The Land Change Modeler proved that, during the 2000-2010 period, the land use with the greatest persistence was agricultural (83.0 %), followed by wetlands (11.5 %), arboreal vegetation (5.0 %), and the urban area (0.6 %) (Table 1; Figure 2).

The surface area gains in the wetlands (39 236 ha) and in the arboreal vegetation (24 773 ha) surpassed the losses and exhibited increase rates of 0.5 % and 4.0 %, respectively (Table 1). These gains, as a whole, are very favorable for maintaining the ecosystem services in the study area, including the water and food supply, the conservation of the biodiversity, the regulation of the climate and of the floods, and the protection of the coast (Kandus *et al.,* 2010; Balvanera, 2012).

Table 1. Quantification of the land use change, 2000-2010 (LCM).

Categories	2000 (ha)	%	2010 (ha)	%	Gains (ha)	%	Losses (ha)	%	Persistences (ha)	%	Tc (%)
Wetl	66 627	17.9	70 303	18.9	39 236	4.5	35 560	4.1	31 066	11.5	0.5
Arb	25 983	7.0	38 326	10.3	24 773	2.8	12 430	1.4	13 553	5.0	4.0
Agr	278 690	74.8	261 405	70.1	36 354	4.1	53 639	6.1	225 052	83.0	-0.6
Urb	1 492	0.4	2 758	0.7	1 266	0.2	0	0.0	1 492	0.6	6.3

Wetl = Wetlands; Arb =Arboreal; Agr = Agricultural; Urb = Urban.

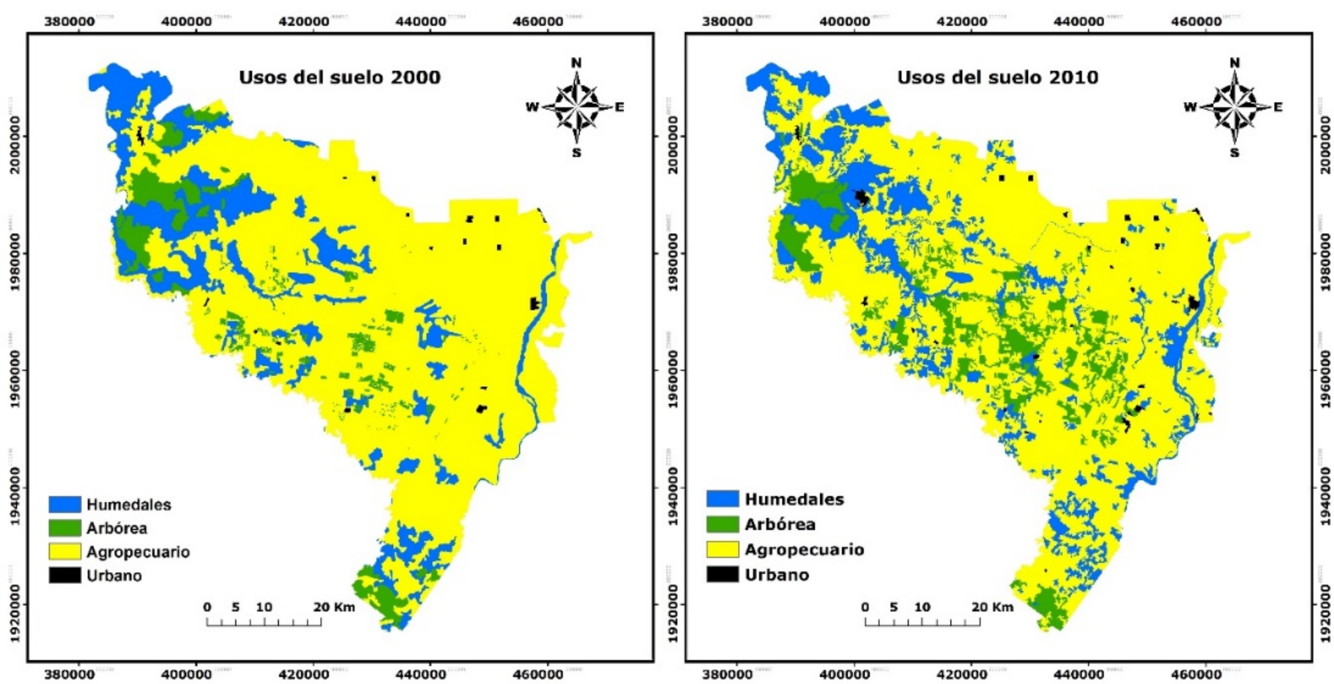

Figure 2. 2000 and 2010 land use maps.

Notably, the categories that contributed to the increase of the wetlands were, firstly, the agricultural area, with 3 744 ha, followed by the arboreal vegetation, with 191 ha; the growth of the latter is due to its regeneration, mainly on 12 609 ha that had previously been used for agriculture (Figure 3).

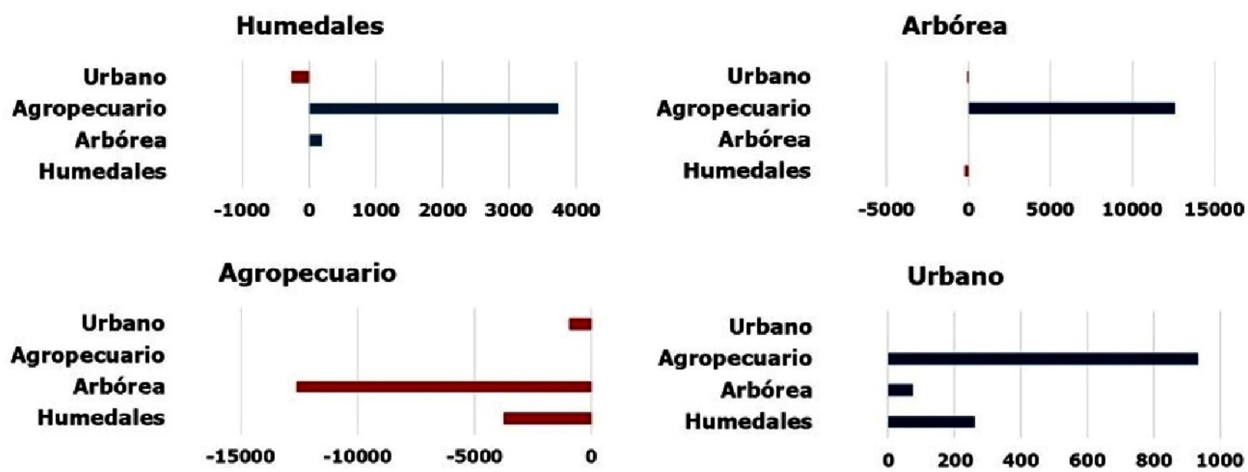

Figure 3. Contributions between categories, 2000-2010.

The increase of the wetlands is related to similar growths in the coast of *Tabasco*; e.g., at the *Centla* Marshes Biosphere Reserve, during 1990 and 2000, the mangrove registered a surface area of 808 ha (Guerra-Martínez and Ochoa-Gaona, 2006). The preservation of this type of vegetation in Mexican coasts is very important, due to the ecological and economic services they provide —the development of aquatic species, trade in timber for the construction of houses—, and because they are fuel sources (Yáñez-Arancibia *et al.,* 2014).

However, despite the gains in the wetlands (Table 1), Landgrave and Moreno-Casasola *et al.* (2012) found that around 912 942 ha of mangroves —equivalent to 60 % of the state's territory— had been lost in *Tabasco* between 1979 and 2008. At a national level, the land use change in the wetlands has caused the deterioration and loss of such ecosystem services as the prevention of the erosion of the soil and the beaches, and of the wildlife's habitat, as well as of the protection of the coastline against storms, which has allowed the waves to cause floods, with the resulting impact on the recreational activities (Hirales-Cota *et al.*, 2010).

The gains in arboreal vegetation (Table 1) imply the existence of a natural and induced regeneration process that includes the secondary vegetation and areas that have been reforested for purposes of forest exploitation. This is because one of the strategies for the conservation, restoration and promotion of the last spaces of the rain forest in *Huimanguillo* has been the payment of environmental services, which had beneficial effects on the regeneration of the rain forest and on the economy of the producers (Alejandro-Montiel *et al.*, 2010).

Programs like *Proárbol* stimulated the conservation of the forests in southeastern Mexico, and have been successful in rural areas of Huimanguillo. In *Tabasco*, particularly in the *Chontalpa* region, state and federal forest programs were implemented during the 2000-2006 period (Alejandro-Montiel *et al.,* 2010). After the six-year administration, the *Programa Estatal de Reforestación* (Proere) program reinforced the reforestation programs, achieving the recovery of 7 500 ha, similar to the maximum historical surface area of 8 000 ha that were reforested in 1994. This evidenced that the forestry activity has been stimulated in the state since the year 2000 (Alejandro-Montiel *et al.,* 2010). The forest plantations were also benefitted by these programs, as a surface area of 52 169 ha was planted from 1994 to 2005. However, despite the success registered during that reforestation period, today the regeneration rates are insufficient, as the losses of rain forest surface area in Huimanguillo surpass the annual reforestations (Alejandro-Montiel *et al*., 2010).

The agricultural surface area exhibited great losses (53 639 ha), with a negative change rate of 0.6 % (Table 1). Besides contributing to the growth of the wetlands and of large surface areas of tree vegetation, a third cause of the reduction of the agricultural land use was the growth of the urban area (932 ha) (Figure 3).

The urban area exhibited important gains (1 266 ha), with an annual growth rate of 6.3 % (Table 1). It grew considerably at the expense of the wetlands (260 ha) and of the tree vegetation (75 ha) (Figure 3); furthermore, this took place in the outskirts of previously established cities and close to the highways, where residential areas have been built (Periódico Oficial, 2016).

The analysis with LCM defined the land cover categories that contributed to the loss or gains of other categories (Figure 3). However, the existence of variables that influence the dynamics of each land use category must be taken into account. For example, the physical (slope, relief, orientations, etc.); socioeconomic (population density, distance to highways, distances to residential areas, shopping malls and factories), and environmental (protected natural areas, wetlands, soil type, etc.) variables (Pontius, 2000; Paegelow *et al.,* 2003; Palomeque-De la Cruz *et al.,* 2017).

The development of the municipalities in Mexico must consider an environmental planning that includes the legal declaration of protected natural areas, work lands for the population and homes built in non-vulnerable areas (Benítez *et al.,* 2012). In *Tabasco*, one of the goals of the Program on Ecological Zoning (Poet) (Galindo *et al.,* 2006) is: "To orient and assess the establishment and development of the productive activities, human settlements and the conservation of natural resources, regulating and reducing environmental impacts."

In response to this program, in the *Huimanguillo* municipality, the decree on natural protected areas in the northeast and southwest must be implemented in the short term, in order to regulate land use in the high evergreen rain forest, the mangroves, the hydrophilic vegetation, and the secondary vegetation (Figure 4), given that the present study registered significant persistences and gains for these covers. However, the application of the laws and programs for the management and urbanization in the country have been insufficient, and therefore, the growth and development of Mexican municipalities entail threats to the conservation of the biodiversity and human welfare (Bazant, 2010; MacGregor-Forsy and Ortega-Álvarez, 2013).

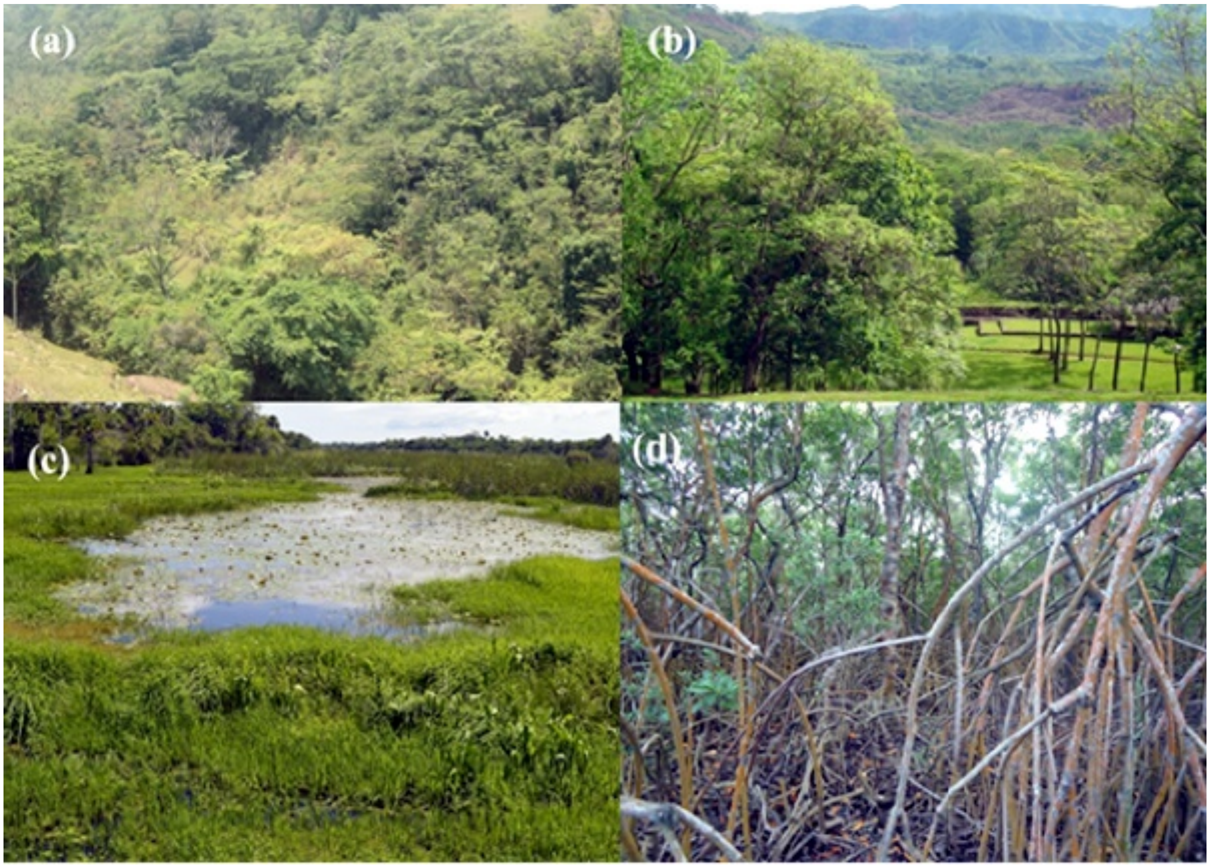

Figure 4. Vegetation of *Huimanguillo*, *Tabasco*, of importance for the conservation of a) Rain forest, b) Secondary vegetation, c) Hydrophilic vegetation, and d) Mangroves.

In this regard, the problem of irregular settlements in areas with a high of floods and other natural phenomena needs to be solved. Likewise, the anarchic growth of residential developments and condominiums, which has generated the accelerated change in the registered land use, must be stopped (Periódico Oficial, 2016).

The city of *Villa la Venta*, the seat of the municipal government of *Villa Chontalpa*, stands out among the priority areas that require a planned urban development (Periódico Oficial, 2016). The creation of a municipal zoning plan (PMOT) that will contribute to a sustainable development is crucial; likewise, it is indispensable to develop in the short run the Municipal Program of Urban Development (PMDU); this must indicate the orientations of urban development, determining the land uses, identifying the natural and agricultural spaces to be preserved, and defining the strategic urban projects for the municipality (Periódico Oficial, 2016).

Land use spatial projection (2030)

Modeling with Markov chains generated a matrix of probabilities of transition (2030) that showed the four categories of land use with probabilities of exhibiting significant transitions of surface area in 2030 with respect to 2010 (Table 2). This is due to the fact that modeling with Markov chains is linear and does not take into account the influence of external factors on the land use change (Pontius, 2000; Reynoso-Santos *et al.,* 2016), but is based exclusively on the internal dynamics of the system (Paegelow *et al.,* 2003; Reynoso-Santos *et al.,* 2016). This matrix, combined with the (CA-Markov) cellular automata model was the basis for the creation of the 2030 spatial projection (Figure 5).

Table 2. 2030 Matrix of probabilities of changes (*Markov*).

	Wetl	**Arb**	**Agr**	**Urb**
Wetl	0.2899	0.1145	0.5873	0.0084
Arb	0.2527	0.3084	0.4321	0.0068
Agr	0.1679	0.1012	0.7232	0.0077
Urb	0.0976	0.0375	0.0644	0.5006

Wetlands = Wetlands; Arb = Arboreal; Agr = Agricultural; Urb = Urban.

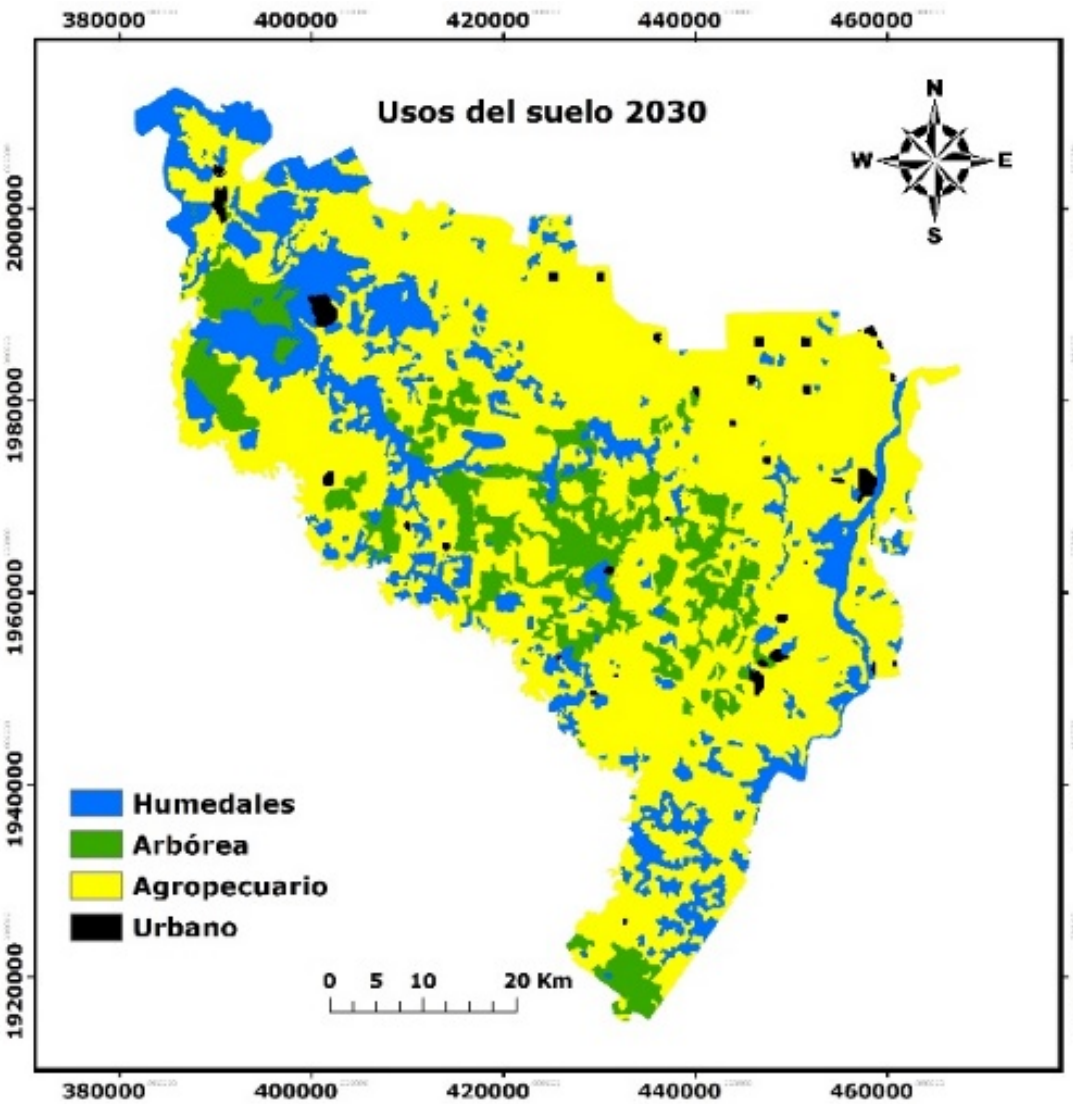

Figure 5. 2030 land use projection (Ca-*Markov*).

Change in land use, 2010-2030

Based on the LCM analyses (for the 2010-2030 period), gains in the wetland covers (7 197 ha), tree vegetation (9 937 ha) and urban zone (1 498 ha) (Table 3) were detected; these were also evidenced in their change rates (Table 3).

Table 3. 2010-2030 Quantification of the land use change (*LCM*).

Categories	2010 (ha)	%	2030 (ha)	%	Gains (ha)	%	Losses (ha)	%	Persistences (ha)	%	Tc (%)
Hum	70 303	18.9	74 213	19.9	7 197	0.8	3 286	0.4	67 016	7.8	0.3
Arb	38 326	10.3	46 428	12.5	9 937	1.1	1 835	0.2	542 478	63.3	1.0
Agr	261 405	70.1	247 895	66.5	2 922	0.3	16 433	1.9	244 973	28.6	-0.3
Urb	2 758	0.7	4 256	1.1	1 498	0.2	0	0.0	2 758	0.3	2.2

Wetl = Wetlands; Arb = Arboreal; Agr = Agricultural, Urb = Urban.

The categories that contributed to the increase of the wetlands were initially, the agricultural lands, with 2 625 ha, followed by the tree vegetation, with 1 618 ha (Figure 6), whose high growth took place at the expense of 9 857 ha of agricultural land (Figure 6). The agricultural use as a whole lost large surface areas (13 510 ha), due to the growth of the urban area, the wetlands and the tree vegetation (Figure 6). The urban area grew, basically, on large agricultural surface areas (1 028 ha), on 333 ha of wetlands, and on 137 ha of tree vegetation (Figure 6).

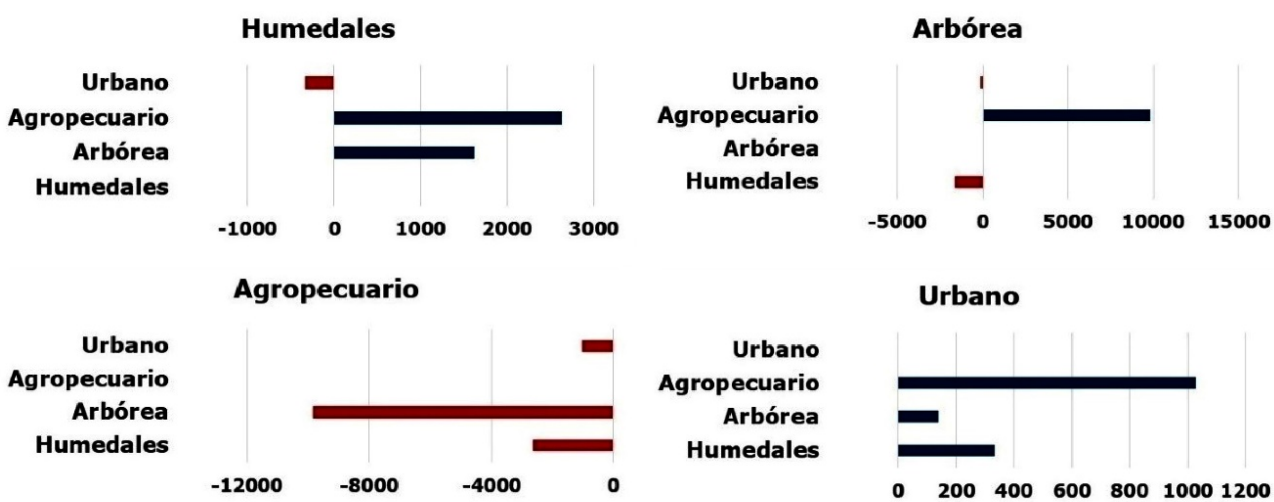

Figure 6. Contributions between categories, 2010-2030.

The distribution of the natural covers and the artificial uses, as well as the probabilities and the spatial projection of the change in land use for the year 2030, were detected based on the Markov chains and the cellular automata.

The cartographic information thus generated is essential for the creation of future environmental planning projects in regard to the potential land-use change scenarios, in order to avoid poorly planned development policies for the *Huimanguillo* municipality.

It is necessary to use the spatial models of the land-use change in order for the authorities and land-use planners to understand the scope of the changes and the risks that these imply. Furthermore, the registered modifications make it possible to identify the factors that are causing them, and therefore they are useful for following up the ecological zoning of the territory (Jiménez-Moreno *et al.,* 2011).

Conclusions

The Land Change Modeler (LCM), Markov chains and cellular automata detect the land use changes for the 2000-2010 period, the probabilities and the spatial projection for the year 2030 in the municipality of *Huimanguillo*, *Tabasco*, with great accuracy. There are records of important gains of the natural covers as a whole (64 009 ha), which are quite favorable for the maintenance of the ecosystem services. Also notably, the growth of the ecosystems, between increases of the urban area and the losses of agricultural areas will continue in the year 2030. This study highlights the importance of developing a municipal zoning plan (PMOT) that will seek to contribute to a sustainable development; likewise, a Municipal Urban Development Program (*PMDU*) must be developed in the short run, orienting it through the establishment of land uses; at the same time, protected natural areas must be decreed in the northeast and southwest of the municipality, in order to regulate the land use and contribute to the conservation of the high evergreen rain forest, the mangroves, the hydrophilic vegetation, and the secondary vegetation that still persist.

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Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Rodimiro Ramos Reyes, Juan Carlos Núñez and Rufo Sánchez Hernández: vector digitization with *Quantum GIS*™ and *Arc GIS* 10.5™, field work, photographs and writing of the manuscript; Miguel Ángel Palomeque de la Cruz: preparing of the gemoatic models on land use change with *Idrisi* Selva and writing of the manuscript.

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