Forest Systems
31 (3), e018, 13 pages (2022)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2022313-18937
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Conflicts and future scenarios of land use in eastern Mexico

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Abstract

Aim of study: To develop an analytical framework for analyzing and assessing the land-use changes and conflicts, based on low requirements of information and useful in developing countries. Additionally, to generate future trend and alternative scenarios to estimate the likely impacts of each use.

Area of study: The analytical framework was tested in the Pixquiac sub-basin, Veracruz, Mexico.

Materials and methods: We used satellite imagery for the characterization of the study area, map algebra to determine changes in use over time and conflicts with potential uses, as well as Markov chains and cellular automata for the generation of trend scenarios.

Main results: Our framework tested to be reliable. We detected a loss of forest cover of 653.12 ha from 2002 to 2018, and 5,299 ha of land use conflict. If the trend continues, an additional 279 ha of forest cover will be lost by 2042.

Research highlights: We proposed a framework to analyze the dynamic of land use change in small watersheds where the urban use is the driving for changes to other land uses. Our method allowed capturing the transition between land uses and conflicts with the potentialities of the territory. In addition, given that most of developing countries lacks high-resolution spatial information our method would be useful for other regions of the world with similar conditions. Finally, various trend and alternative scenarios to evaluate the impact of the policies applied to the territory on land-use changes were obtained.

Additional key words: forest; land management; Markov; MOLUSCE; Pixquiac sub-basin.

Abbreviations used: CURBA (California Urban and Biodiversity Analysis); ES (Environmental Services); GIS (Geographic Information Systems); MOLUSCE (Methods of Land Use Change Evaluation); PES (Payment for Environmental Services).

Citation: Chablé-Rodríguez, G; González-Guillén, MJ; González-Martínez, TM; Gómez-Guerrero, A; Fernández-Reynoso, DS (2022). Conflicts and future scenarios of land use in eastern Mexico. Forest Systems, Volume 31, Issue 3, e018. https://doi.org/10.5424/fs/2022313-18937

Received: 30 Oct 2021. **Accepted:** 24 Oct 2022.

Funding agencies/institutions	Project / Grant
CONACYT	000104 grant program
Colegio de Postgraduados, Mexico	

Competing interests: The authors declare that they have no known competing economic interests or personal relationships that could have influenced the work presented in this paper.

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Introduction

Land-use change is the process that has had the greatest negative impact on ecosystems globally (IPBES, 2019), especially due to dispersed and disorderly population growth (Luján *et al*., 2021). This change directly affects ecosystems through the process of aggregation, where small, dispersed families or communities become larger contiguous towns and cities (Gonzalez, 2000). There are also changes due to the expansion of agricultural activities resulting from increased demand for resources (Ruiz *et al*., 2017). Direct impacts include habitat loss, soil erosion and forest fragmentation (Sulieman, 2018). Indirect impacts include decreased ground water recharge, microclimate alterations, fragmentation of biological corridors, and fauna migration, among others (Trisurat *et al*., 2016). For this

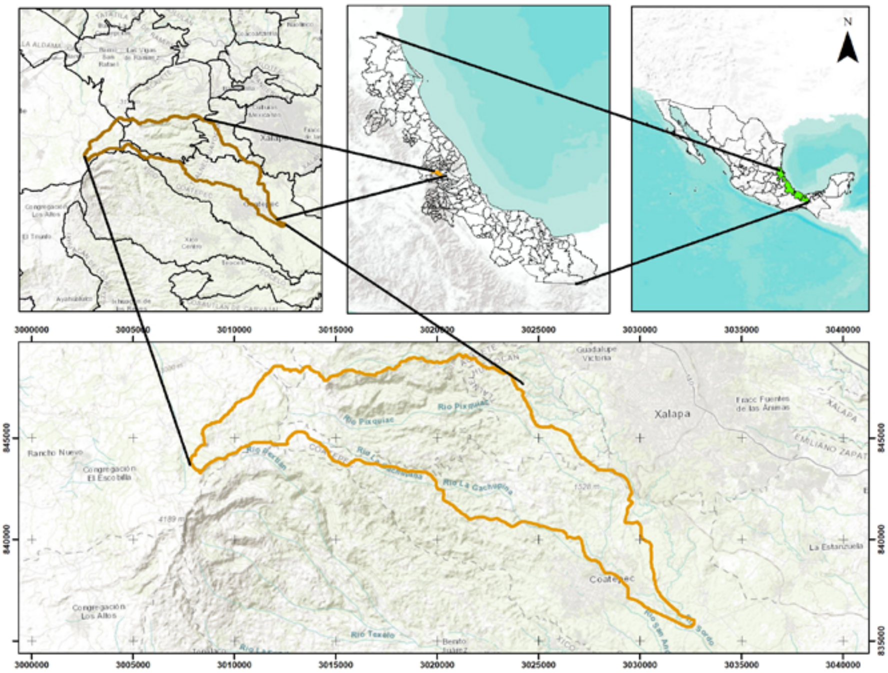

Figure 1. Location map of the study area of Pixquiac River sub-basin (brown line polygon), in the Veracruz state (green polygon), Mexico.

reason, the protection and integrated management of forest areas has become one of the greatest challenges facing society, especially in places where current land use is intensive and differs from its potential (Froese & Schilling, 2019; Castellanos & Agudelo, 2020).

Current land use should consider environmental conditions related to soil, topography, climate and water availability, which may be limiting for the development of agricultural, livestock or forest activities (Camargo *et al*., 2020). Failure to do so means generating conflicts between current and potential uses, which have led to various problems, including ecosystem degradation (Roodposhti *et al.,* 2019), dramatic landscape modification (Dislich *et al.*, 2018), loss of biodiversity, and changes in the services that forest ecosystems provide (Koo *et al*., 2020). Globally, in the last three decades, the area deforested averaged 5.9 million hectares per year (0.15% of the total forest area). In the Americas, for the same period, the area lost was 2.66 million ha (0.47% of the total) (FAO, 2020) and in Mexico, between 2001 and 2018, the annual loss was estimated at 212,000 ha (0.05% of the total forest area) (CONAFOR, 2020). The lower Mexican percentage was due to the reduction in deforestation and the increase in forest area in some zones (FAO, 2020). However, the problem of land-use change continues to be the trigger for the degradation of forest ecosystems.

The dynamics of land-use change vary greatly in spatial and temporal terms. Economic, demographic, technological, cultural, political and management aspects are the drivers of change operating at the local and regional level (Meyfroidt *et al*., 2018). Understanding the phenomenon of land-use change in terms of conflicts of use and its trend is fundamental in the planning of the territory and in the implementation of conservation strategies for forest ecosystems and their environmental services (ESs) (Galicia *et al.*, 2018).

Over time the development of land use change prediction models and their impact on the landscape has been restricted by the large amount of information it requires. However, over the last few decades, computer systems have begun to overcome this limitation. Modeling abilities have also been enhanced through the availability of remote sensing data and Geographic Information Systems (GIS) technology. Fortunately, in many parts of the world a solid base of regional ecological, economic, and social research allows researchers to examine the interaction between human communities and the landscape.

Simulation models exist to analyze land-use change over time and space (Wang *et al*., 2018). Dale *et al*. (1998) developed a strategy for assessing land use impacts on natural resources through integrating spatially explicit environmental data and computer models. These models simulate the susceptibility of species to ecosystem disturbances based on geology, soil, slope, land use/land cover conditions and human activities. The habitat risk map obtained can be used in land management planning.

On the other hand, the Patuxent Landscape Model simulates ecological processes on watershed scale in interaction with economic factors that influence land use patterns (Voinov *et al*., 2007). In addition, Imhoff *et al*. (2000) studied the ecological impacts of a major urban sprawl, while Maizel *et al*. (2000) examined considering various ecolog-

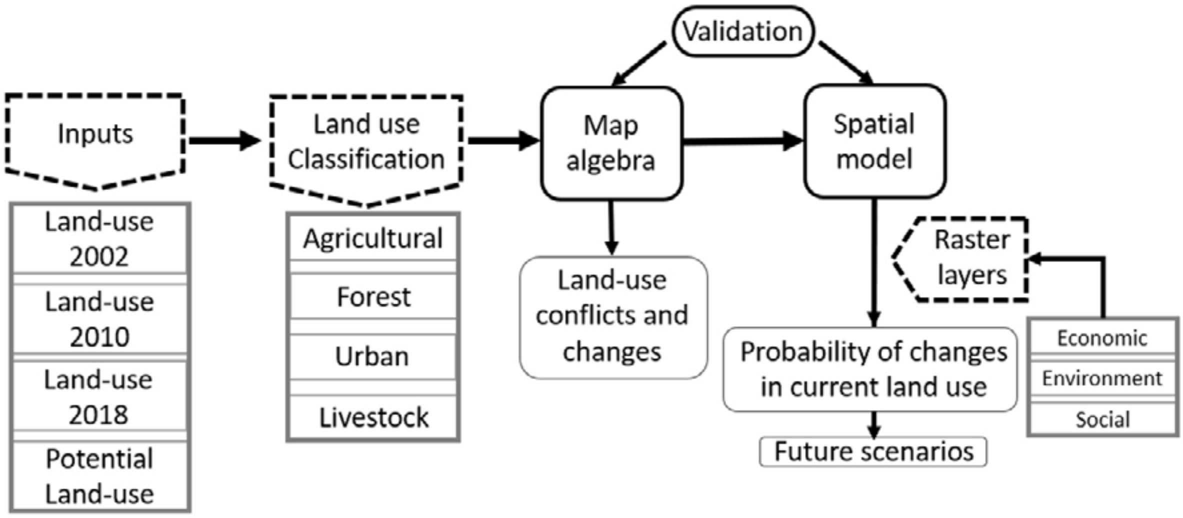

Figure 2. The analytical framework used in the Pixquiac sub-basin

ical factors, the settlement patterns of the United States in the last 230 years and their relationship to different land uses. In the Baltimore-Washington region, an urban growth study was conducted that analyzed the different links between social, physical and ecological processes that make up the ecosystem (Foresman, 2000). In the same way, Levia & Page (2000) did a study in the region of Sterling, MA, USA focused on the identification of agricultural areas suitable for urban use, through cluster analysis considering various variables such as distance to the city center and main roads, slope of the terrain and size of the farm. The Urban Simulation Model (UrbanSim) and the California Urban and Biodiversity Analysis (CURBA) model represent two perspectives on urban growth and its spatial relationship with land-use change (Waddell, 2002). In addition, Gonzalez (2000) developed an analytical framework based upon the CURBA model which simulates and assesses the influence of future human population growth on land use change based on biophysical, economic, and social variables at different scales and under several scenarios (Gomben *et al*., 2012). Finally, the comparative classification of changes detected in the field (Dislich *et al*., 2018) and the analysis of documentary information (Giri *et al*., 2019) are methodologies used to assess dynamically changes in land cover. However, they do not consider socioeconomic variables (Wu Z *et al*., 2019) meanwhile the multi-temporal analysis and the generation of future scenarios do take into account environmental and socioeconomic variables.

Modeling through cellular automata is one of the most used methods to generate alternative and trend scenarios (Gomes *et al*., 2021). This mathematical and computational model allows describing a dynamic system composed of a set of data that acquire different states or values (Wu H *et al*., 2019). Among its applications, it evaluates the dynamics of land-use change and its impacts through alternative scenarios that contrast different management policies. However, it is not enough to know the dynamics of changes in land use on a temporary scale, it is necessary to determine the conflicts between current and potential uses to have a comprehensive vision of land use in the region.

The mountainous area of the central region of Veracruz, Mexico, in addition to having diverse environmental values, is of great hydrological importance at the local level since it supplies drinking water to the city of Xalapa, Veracruz. However, land-use change on forested land has not been halted. As a result, there has been a decrease in the water supply, leading municipal authorities to ration the supply by distributing it by turns during the dry season. Consequently, it is fundamental to develop planning tools that permit local land managers, developers, stakeholders, and other parties to predict possible patterns of future land use to anticipate potential conflicts between various use and environmental factors within the sub-basin.

The main objective of this study was to develop an analytical approach that could be applied to evaluate forest areas and their use changes in areas that have conservation or development support but have limited geospatial information. An additional objective was to use the analytical framework to generate alternative future scenarios of land use change in a small pilot watershed, Pixquiac sub-basin, and estimate the likely impacts of such uses. The first step was to develop an analytical framework, through satellite imagery, a multi-temporal analysis of land-use conflicts during the period 2002-2018. With this information, we constructed a spatial model that simulates changes in use based on socioeconomic and environmental variables. The inclusion of environmental and socioeconomic variables in the spatial model permitted us to obtain a more realistic interpretation of the results. Our analytical approach also allowed us to consider future scenarios, namely, Tendential, Conservation and Development. The research hypothesizes that the proposed framework is sensitive enough to detect land use change dynamics over time so that it allows the building of future land-use scenarios.

Material and methods

Study area

The Pixquiac River sub-basin is in central region of Veracruz, Mexico, within the La Antigua River watershed, and includes part of the municipalities of Perote, Las Vigas, Acajete, Tlalnehuayocan and Coatepec in the state of Veracruz (Fig. 1). It covers 10,660.23 ha and is 30.27 km long. It is located on the windward slope of the Cofre de Perote, an inactive volcano whose altitudinal variation ranges between 1,040 and 3,760 m (García *et al.*, 2008). Average annual precipitation is 1,800 mm, which is distributed in the months of May to October. It is a mountain sub-basin with a dense drainage network (Maldonado *et al.*, 2017). The predominant vegetation includes cloud forests, pine-oak forests, shade coffee plantations and grasslands (García *et al.*, 2008). In the middle and upper part, there are isolated localities with a high degree of marginalization (López *et al.*, 2020).

Analytical framework

The analytical framework was developed in three phases (Fig. 2):

— *Land-use changes and conflicts through spatiotemporal analysis*

Land uses were determined for the years 2002 and 2018 through a supervised classification of satellite images from Landsat 5, 7 and 8 sensors, and Sentinel 2 images. Cartographic information on land use and vegetation at a scale of 1:250,000 from INEGI Series III and VI maps (INEGI, 2003, 2017a) was used as reference information. The cartographic analysis was carried out with ArcGIS® (ESRI, 2011).

The cartographic information generated was classified into four main uses: agricultural, forest, livestock, and urban. The minimum size area for a polygon was 0.25 km^2; land use polygons with a smaller area were incorporated into the neighboring category with the largest contact area. A 56-points field verification was performed with a random sampling of the resulting land-use classes.

The land-use layers were transformed into raster format and map algebra was used to analyze the spatiotemporal dynamics of land-use change between 2002 and 2018.

Current and potential land uses were compared to identify areas with correct current use and those that differ from their potential productive use, for example, an area of current agricultural use with suitability for forest use. Potential land use was determined based on the E14-3 thematic chart at a scale of 1:250,000 (INEGI, 2017b). Through the comparison of current (2018 land-use) and potential land uses and statistical analysis, the conflict matrices were developed.

— *Probability of changes in current land use*

The probabilities of change in current land use were estimated through a first-order Markov chain model, taking as a basis the change between 2002 and 2018. This first-order model provides various events in a system that initially is in state *i* and over time passes to state *j*, making it quite useful for analyzing future land-use change projections (López *et al.*, 2001).

Markov chain models have several assumptions, the first of which is to consider that land-use change is a stochastic process and that it is found in different categories of the states of a chain. In turn, a chain is defined as a stochastic process whose property includes the value of the process at time *t*, where X_t depends only on its value at time *t-1*, X_{t-1}, and not on the sequence of values $X_{t-2}, X_{t-3}, \ldots, X_{t-n}$, expressed in the equation [Eq. 1] (Mohamed & Worku, 2020):

$$P\{X_t=aj\ X_0=a_0, X_1=a_1, X_2=a_2, \ldots, X_{t-1}=a_1\} = P\{X_t=aj\ X_{t-1}=a_i\} \quad [1]$$

where: *P*= transition probability; *X*= system analyzed; *t*= time; $a_{i\,=}$ initial state; and $a_{j\,=}$ final state.

This model considers the transition states as a process that is only conditioned by the initial state, and is expressed in matrix form as [Eq. 2]:

$$n_{t+1} = Pn_t \quad [2]$$

where: n_t= vector of the fraction of the land area in each of the different land uses at time *t*; n_t*+1*= vector of the fraction of the land area for the same land uses at *t*+1; and *P*= matrix *m*m* in which the probability that a site that is in state *i,* over time *t*, can transition to state *t+1* is expressed. This matrix is standardized, so the sum of the transition probabilities of any state is always equal to one (López *et al.*, 2001).

— *Construction of the spatial model stimulating land-use changes*

We integrated spatial information from previous phases through the MOLUSCE (Methods of Land Use Change Evaluation) plugin in QGIS 2.18 software (QGIS.org, 2022; MOLUSCE, 2017). The application of the Markov chain was evaluated to determine the probability of change for each use. The model's seasonality, convergence and stability were obtained by performing 1,000 iterations at discrete time. Dynamic variables were integrated to interact with existing changes in land use such as Euclidean distance from roads and localities, elevation through a digital model, and terrain slope (Al-Juaidi *et al.*, 2018; Doelman *et al.*, 2018). The degree of dependence between dynamic variables was evaluated through the Pearson correlation.

For the validation of the spatial model, 2010 land uses were determined following the methodology applied in the first phase. This intermediate land use determination was combined with the information generated in 2002, to obtain the land use projection for 2018 through the

MOLUSCE module. A value of 1,000 iterations was set for the neural network learning curve within the module. Validation consisted of comparing the projection obtained from the model with that obtained in the supervised classification for the years 2002-2018. The degree of accuracy of the simulation was determined with the Kappa index.

Alternative future scenarios

Once the model was constructed and validated, three alternative future scenarios were generated with a projection period of 24 years, from 2018 to 2042. Future land-use change scenarios were constructed considering variables that have shown an effect on the dynamics of change within the study area. For example, conservation-oriented policies (Rodríguez & Merino, 2017) focused on maintaining forest cover, or policies aimed at increasing agricultural productivity (Lawrence *et al*., 2019) seeking to increase available food resources, livestock production (Vargas, 2018) whose driver is society's demand for meat and population growth in the region (Fiuza *et al*., 2022), among others.

Trend scenario. This scenario was obtained, through cellular automata, by taking the land-use changes detected from 2002 to 2018 and then projecting them to 2042, maintaining a constant trend.

Development scenario. The development scenario assumes a 50% increase in the area from forest to agricultural use. This increase was focused on the agricultural frontiers through buffer zones in the study area.

Currently, the Mexican government follows a policy to promote the agricultural sector through various programs such as *Sembrando vida* (Sowing life), *Producción para bienestar* (Production for well-being), *Programa de fomento a la agricultura, ganadería, pesca y acuicultura* (Program to promote agriculture, livestock farming, fishing and aquaculture) and *Precios de garantía* (Guaranteed prices). They consist of providing subsidies to small and medium-scale producers to implement agroforestry systems and increase grain and livestock productivity (SADER, 2021). These programs could stimulate and increase the conversion of conservation land use to agricultural uses.

Conservation scenario. This scenario included a 50% increase in the forest use area based on the conversion of agricultural and livestock uses, following the same logic as the Development scenario, but applied to forest use.

The foundation of this scenario was based on the implementation of programs, such as the payment for environmental services (PES) scheme, that promote the care, conservation and increase of forest use areas. One example is the *Fideicomiso Coatepecano para la Conservación del Bosque y el Agua* (FIDECOAGUA; Coatepecano Trust for Forest and Water Conservation) whose objective is focused on the conservation of forests through economic compensation by incorporating them into a PES program (Nava *et al*., 2018).

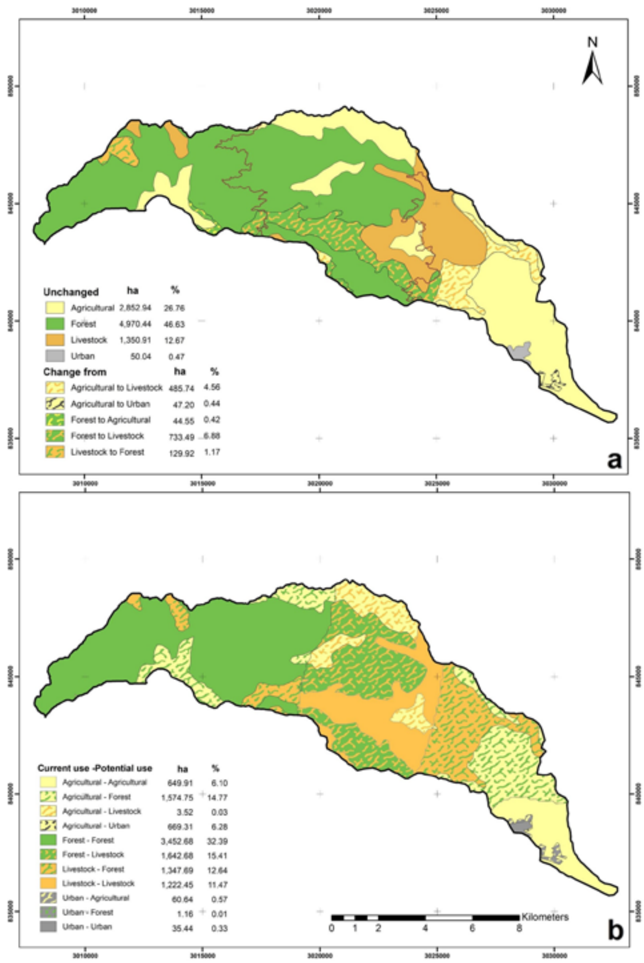

Figure 3. Maps of land-use changes during 2002-2018 (a), and land-use conflicts (b) in the Pixquiac sub-basin.

Finally, the alternative scenarios were submitted to the scrutiny of local stakeholders and decision makers who validated and determined the feasibility of their implementation and results. This validation was carried out through meetings with FIDECOAGUA, which is the integral water management agency of the Municipality of Coatepec and operates a PES mechanism in the region. As well as with Consejo Municipal de Agua y Saneamiento Xalapa, which oversees the water management that comes from the Pixquiac sub-basin and provides resources for the conservation of the areas. The information was also presented and approved by the ejidal authorities of the agrarian nuclei of San Andrés Tlalnehuayocan, San Pedro Buenavista and Agua de los Pescados.

Results

When applying the analytical framework to the study area, we find that during the 2002-2018 period, 86.53% (9,224.33 ha) of the Pixquiac sub-basin remained unchanged, while 13.47% (1,345.90 ha) of the area under-

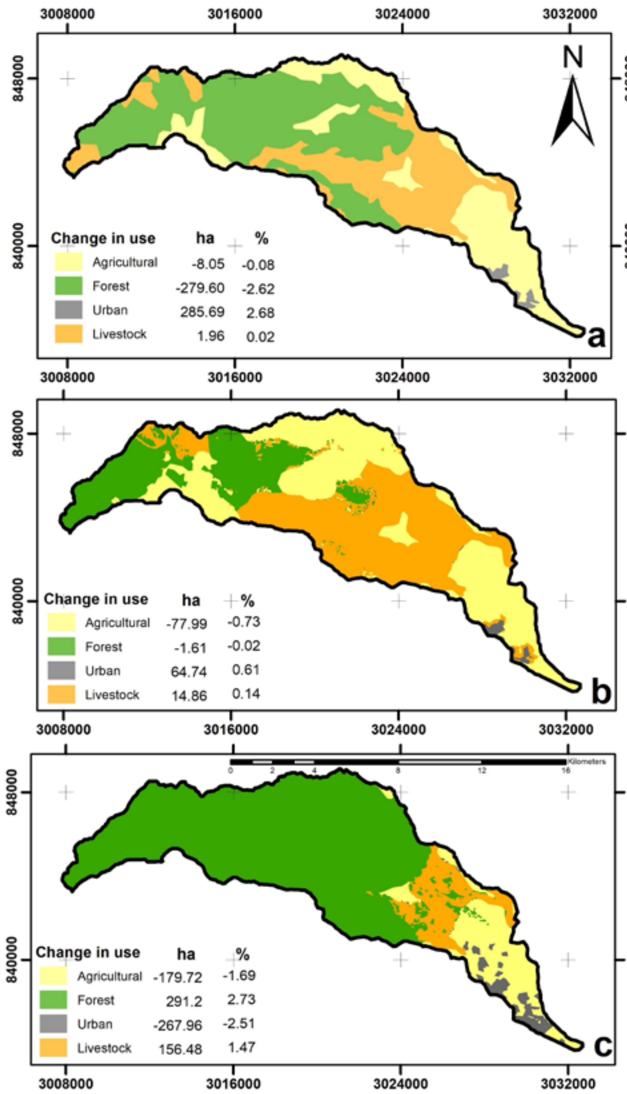

Figure 4. Scenario maps: trend (a), development (b) and conservation (c), projected for the year 2042 in the Pixquiac sub-basin.

went changes in land use. The main changes were located in the middle and lower part of the watershed (Fig. 3a).

Table 1 presents the land-use transition matrix. The main loss of forest (733 ha) and agricultural (485 ha) area occurred due to livestock use. However, some livestock use areas were converted to forest use (125 ha), especially in the upper part of the sub-basin.

In absolute terms, the forest use area was the class that had the greatest loss with 653.12 ha, 6.13% of the sub-basin area, followed by the agricultural area, which decreased by 488.39 ha (4.58%). The area corresponding to the livestock class had a significant increase of 1,094.31 ha (10.97%), making it the class with the greatest increase, followed by urbanization, which had an increase of 47.20 ha (0.44% of the total).

It is important to highlight that the forest class was the land use with the largest area in the two time periods analyzed, compared to the others. On the other hand, urban land use represented less than 1% of the total watershed area (Fig. 3a), but almost doubled its area, going from 50.04 ha to 97.24 ha.

Fig. 3b shows the conflict map of the Pixquiac sub-basin where 57.87% of the area presented a correct use, *i.e.*, current and potential land uses coincided. However, 42.13% of the area presented a conflict in the potential forest use whose current use was agricultural and urban. There are also areas with agricultural potential that were transformed into urban areas due to population growth. Land-use conflict interactions were mostly found in the middle and lower areas of the watershed.

The current, potential and conflicting area of each land use within the sub-basin is presented in Table 2. Of the total current land-use area in the sub-basin (10,660.23 ha), forest use accounted for 47.80%, followed by 27.18% for agricultural use, 24.11% for livestock use, and 0.91% for urban use.

The potential use of the land within the sub-basin was predominantly the forest use (59.81%), followed by the livestock (33.16%), agricultural (6.67%) and urban (0.37%) uses. The areas with use conflicts covered 4,490.44 ha, of which 2,186.94 ha corresponded to agricultural use, 1,280.92 ha to forest use, 964.30 ha to livestock use and 58.28 ha to urban use (Table 2).

For the generation of scenarios, the level of correlation between the variables included in the model (elevation, slope, Euclidean distance from roads and localities) was determined. None of the variables presented a significant correlation, that is more or less than 0.08 (Schober *et al.*, 2018) so they were considered valid. Most of the variables analyzed showed a positive correlation except for the relationship between slope and Euclidean distance to localities.

On the other hand, the stabilization of the neural network learning curve was reached around 250 iterations with an error rate of 2%, which indicates the optimization of the network in the generation of future scenarios. Regarding validation, the Kappa index had a value of 0.96, which indicates that the fit of the map projected through the MOLUSCE module, against the map generated through the supervised classification of satellite images, was satisfactory (Berg *et al.*, 2004).

Trend scenario

By 2042, in the Pixquiac sub-basin, the probability that one hectare of forest use will maintain its use was 76%, followed by 23% probability that it will change to livestock use, 1% that it will change to agricultural use and zero probability of a change to urban use. Livestock use had a high probability of maintaining its use (85%) and a 15% probability of changing to forest use (Table 3).

The Trend scenario suggests an increase in the change dynamics. For example, livestock use will increase by almost 300 ha (2.68%) in the upper and middle part of the

Table 1. Transition matrix covering the period 2002-2018 in the Pixquiac sub-basin (areas in ha).

	Use	2018				
		Agricultural	**Forest**	**Livestock**	**Urban**	**Total**
2002	**Agricultural**	2,852.94		485.74	47.20	3,385.88
	Forest	44.55	4,970.44	733.49		5,748.48
	Livestock		124.92	1,350.91		1,475.83
	Urban				50.04	50.04
	Total	2,897.49	5,095.36	2,570.14	97.24	10,660.23

watershed. The urban area will continue to grow in the lower part of the watershed, while the forest area will lose 280 ha (2.62%) due to changes to other uses. However, it did not show a change to urban use.

According to the area of change (Fig. 4a), forest areas and some agricultural areas will be mostly transformed into grazing or livestock use areas.

Development scenario

This scenario indicates that, throughout the sub-basin, the forest area will be segregated into small patches. There is a 45% probability that one hectare of forest use will be maintained, 29% that it will become agricultural use and 26% that it will be transformed into livestock use (Table 4). The forest use area has disappeared in the lower and middle parts of the watershed (Fig. 4b). The change between land uses, with respect to the current scenario, indicates an increase of 64.74 ha (0.61%) for livestock use and 14.86 ha (0.14%) for urban use. However, there is a decrease of 77.99 ha (0.73%) for agricultural use and 1.61 ha (0.02%) for forest use.

Conservation scenario

This scenario showed (Fig. 4c) that forest areas could present an increase in total area and the consolidation of a continuous cover in the study area. The Table 5 has a 100% probability that one hectare of forest will maintain its use. Livestock use showed an inverse trend to forest use due to the decrease and fragmentation of agricultural and livestock uses. The forest area had the greatest increase with 291.20 ha (2.73%), followed by urban use with 156.48 ha (1.47%), while livestock use presented a loss of 267.96 ha (2.51%) and agricultural use of 179.72 ha (1.69%).

In relative terms, there is a greater change dynamic in the Conservation scenario (8.40%) compared to the Trend scenario (5.40%) and the Development scenario (1.69%).

Discussion

Land-use conflicts and changes over time

According to the National Forestry Commission (CONAFOR, 2020), about 212,000 ha of forest are lost each year in Mexico, mainly due to the increase in agricultural frontiers and urban sprawl. In the central region of Veracruz, the anthropogenic factors driving land conversion are the atomization of land tenure, the growth of urban areas and the sale of land for the construction of housing developments (López *et al.*, 2020).

Public policy has increased support for agriculture, negatively impacting forest conservation. In the Pixquiac sub-basin, the different factors driving change such as the marginalization of localities in the upper part and the lack of employment or government support have adversely affected forest areas and increased other land uses.

Table 2. Area of current, potential and conflicting land uses in the Pixquiac sub-basin.

Class	Current use		Potential use		Conflicting[a]	
	ha	%	ha	%	ha	%
Agricultural	2,897.49	27.18	710.55	6.67	-2,186.94	-20.51
Forest	5,095.36	47.80	6,376.28	59.81	1,280.92	12.02
Livestock	2,570.14	24.11	3,534.44	33.16	964.30	9.05
Urban	97.24	0.91	38.96	0.37	-58.28	-0.55
Total	10,660.23	100.00	10,660.23	100.00	4,490.44	42.13

[a]Negative numbers indicate that the current use area exceeds the potential use area.

Table 3. Land-use change probability matrix for the Pixquiac sub-basin (Trend scenario).

		Change in use: Trend to the year 2042				
		Agricultural	**Forest**	**Livestock**	**Urban**	**Total**
Current uses in 2018	**Agricultural**	0.71	0.01	0.25	0.03	1.00
	Forest	0.01	0.76	0.23	0.00	1.00
	Livestock	0.00	0.15	0.85	0.00	1.00
	Urban	0.00	0.00	0.00	1.00	1.00

The livestock area had the greatest increase with 10.27%, followed by urban use with an increase of 0.47%. However, forest and agricultural use showed a decrease in area. At the local level, this can be explained by the current increase in government support for stockbreeding in the central region of Veracruz (Thiébaut & Velázquez, 2017), which causes a direct transition from either forest or agricultural use to livestock use. On the other hand, the expansion of the urban footprint where the city of Coatepec is located is causing a change in the uses present in the lower part of the sub-basin. This is due to the lack of economic-productive alternatives for the local population, such as the generation of employment or the development of sustainable projects in accordance with the use of the land (Benítez *et al*., 2012).

The identification of land-use conflicts provided relevant information to help understand the situation faced by forest areas in the Pixquiac sub-basin. The determination of conflicts is a land management tool that allows defining guidelines for land-use optimization in an effort to maximize the benefit to society both in terms of ES provision and in economic terms. Brown *et al*. (2017) and Kim *et al*. (2019) point out that land-use conflicts are conceived as a growing expression of human pressure on the environment.

In total, 27.42% of the sub-basin presents conflicts with the potential forest use, mainly due to agricultural use in the upper and middle zone of the sub-basin, which accounts for 14.77% of the area. These conflicts have direct repercussions on the provision of hydrological environmental services by the forests, as they are directly related to the water shortage problem faced by the city of Xalapa. On the other hand, areas that were formerly used for agricultural or livestock purposes have been recovering their original vegetation due to abandonment caused by emigration to nearby urban areas (Velázquez & López, 2021) or by orographic conditions (Griffith *et al*., 2017), especially in the upper and middle parts of the sub-basin.

Land-use potential should be taken into consideration in order to design strategies for optimal land-use management that seeks greater forest, agricultural and livestock productivity. Ayram *et al*. (2017), Mokondoko *et al*. (2018) and Rosa da Conceicão *et al*. (2018) agree that a region that takes into account the management of land-use conflicts in determining the application of support for conservation promotion is better focused on areas that can be considered priorities.

Land-use planning in the Pixquiac sub-basin, employing the potential use of the territory as a reference, is essential to promote measures that regulate agricultural activities and, in turn, encourage sustainable forest use. There are successful cases in other regions of the world, where this has allowed an integrated management of the territory, obtaining favorable results to balance productive and conservation activities (Jiang *et al*., 2020).

Future land-use change scenarios

The Pixquiac sub-basin supports diverse agricultural, forest and residential activities. However, the Trend scenario indicates a decrease in the future due to the dynamics of the observed changes. The probability that one hectare of forest use will remain in the same use is relatively high (76%). This result is consistent with those obtained in other studies where there is a constant transition to other uses (Biswas *et al*., 2019). The lack of economic support for the owners of conservation lands can cause these areas to gradually diminish and the negative consequences can be reflected in ES production (López *et al*., 2020).

This study makes it possible to observe and analyze what would happen in the event of an increase (conservation scenario) or reduction (development scenario) of 50% of areas of forest use over a period of 24 years. The projected period is considered long and therefore, there may be biases in the results. First, the model used to generate the baseline scenario is essentially static, while land use change is dynamic over time. For example, previously held patterns of growth, development, and infrastructure in the region may change. This can directly impact the growing trend of urban land use. Second, some explanatory variables could change during the study period. For example, as populations increase, new roads are constructed, while existing roads may be upgraded in status. These new and upgraded roads would likely influence future development in the region, yet their placement is not known at this time. Finally, the longer the projection time, the greater the possibility of bias in the constructed scenarios. However, this study explores what could happen in the medium term based on

Table 4. Land-use change probability matrix for the Pixquiac sub-basin (Development scenario).

		Change in use: Developed scenario to the year 2042				
		Agricultural	**Forest**	**Livestock**	**Urban**	**Total**
Current uses in 2018	**Agricultural**	0.97	0.00	0.01	0.02	1.00
	Forest	0.29	0.45	0.00	0.26	1.00
	Livestock	0.04	0.08	0.88	0.00	1.00
	Urban	0.00	0.00	0.00	1.00	1.00

the current trend. Future studies of land use change should include analysis at different time scales. However, the projected decrease in forest cover in the Pixquiac sub-basin is not as drastic as in other parts of the world. The percentage of loss of forest area reached a rate of 0.40% per year, above the global average, which is 0.15% per year for the total area of forests (Keenan *et al*., 2015).

The results obtained through the Development scenario show an increase in agricultural and livestock uses at the expense of the decrease in forest areas, so that, if this scenario were to come true, the environmental and territorial consequences will be negative.

The Conservation scenario allowed us to estimate the effect of integrated land management that strengthens economic activities in the forestry sector. This management would not only increase the forest area cover but would also bring benefits related to ES provision (Shahbazian *et al*., 2019). It should be considered that the productive income that landowners are obtaining under the current use (Rahman *et al*., 2016) could decrease in the medium and long term as soil productivity decreases (Lu *et al*., 2015).

The analysis of the detection of land-use conflicts and the generation of alternative future scenarios is an important planning tool to improve integrated land management in the Pixquiac sub-basin. Local management mechanisms can be implemented for the care of the forests, similar to the FIDECOAGUA program in the Coatepec region, which is a municipal project whose objective is to conserve forests with economic resources obtained through a payment for environmental services scheme that is channeled to forest landowners (Nava *et al*., 2018). It is necessary to focus the resources collected on forest areas with hydrological ability and that have a greater probability of change of use, or to reconvert those whose suitability has been changed due to land-use conflicts.

Assessment of the impacts of future land-use change scenarios

The future land-use change scenarios examined here provide only an idea of the wide range of possible futures for the study area. Each alternative scenario would result in different impacts on the landscape and ground water recharge. Therefore, the scenarios can be evaluated against various socioeconomic and environmental criteria (Cunha *et al*., 2021). For example, assumed land-use change levels are incorporated into each scenario. Political constraints could alter these parameters or restrict land-use changes to areas conducive to ground water recharge, where there is high water catchment suitability and ecological values are high (Pineda *et al*., 2016).

The analytical approach presented here can be used to generate a myriad of alternative future scenarios. Alternative scenarios could explore what would happen if land-use changes increased or decreased with respect to those in the Trend scenario, or if the changes occurred in a compact or disaggregated manner. Each of these scenarios could be evaluated based on a set of ecological and socioeconomic criteria to determine the possible impacts on water supply, biodiversity and habitat, taxes, water consumption, and so on.

Finally, another advantage of the analytical framework applied in the present study is that it considers the application of the parameterization of the methodology, which

Table 5. Land-use change probability matrix for the Pixquiac sub-basin (Conservation scenario).

		Change in use: Conservation scenario to the year 2042				
		Agricultural	**Forest**	**Livestock**	**Urban**	**Total**
Current uses in 2018	**Agricultural**	0.60	0.36	0.03	0.01	1.00
	Forest	0.00	1.00	0.00	0.00	1.00
	Livestock	0.01	0.60	0.39	0.00	1.00
	Urban	0.00	0.00	0.00	1.00	1.00

can be applied on any spatial and temporal scale with basic geospatial data. The model can be improved by considering weighted values for the measurement of variables, as well as the inclusion of more variables such as land value or access to services (Gonzalez, 2000). Thus, future studies of conflicts and land use change should include these considerations.

Conclusions

The analytical framework in this study lies in an analysis of the evolution of the study area over time and the analysis of the conflicts of use, however, it is also noteworthy the methodology used, which can be applied to similar regions. This study serves as a precedent to perform a multitemporal analysis in a particular area, especially in countries with limited spatial and temporal information.

The development of a model based on multi-temporal analysis, by means of GIS, can evaluate the present and future dynamics of land-use changes in a defined time interval, also generating information that serves as a basis for decision making in the implementation of public policies within the study area.

The modeling processes used are valid for the generation of multiple scenarios, whether trend or alternative ones; likewise, the use of neural networks together with transition matrices is a methodology that can be useful as a planning tool to develop future scenarios, based on biophysical variables that influence the development of human activities.

Conflicts in forest use caused by agricultural, livestock and urban activities occurred in about 50% of the sub-basin area. The fact that forest areas are close to rural communities led to a decrease in forest cover and a transition to livestock use, which in turn caused a decrease in the environmental services provided by forests, such as ground water recharge.

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