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Assessing implications of land-use and land-cover change dynamics for conservation of a highly diverse tropical rain forest

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A B S T R A C T

The Selva El Ocote Biosphere Reserve is located within the Mesoamerican biodiversity hotspot for global conservation. The area, poorly known relative to other humid tropical areas within Mexico, shows a mosaic of several types of forests, contains over 2000 species of vascular plants and 97 species of mammals, and plays a key role within Mexican tropical forests. We analyze the process of land-use/land-cover change (LUCC) within a 5755 km^2 area which includes the reserve. Viability of conservation of the area was assessed by an integrated multi-temporal analysis of the LUCC process. Three cartographical data bases – from 1986, 1995 and 2000 – were used to assess rates and trends in LUCC for seven land cover types: agriculture/pasture (A/P); four types of second-growth forest (SGF); and two types of mature forest (tropical and temperate). Even when taking into account pathways of regeneration, results show a fast net loss of primary and secondary forests, primarily due to the establishment of A/P.

For the entire area of study, the annual deforestation rate of tropical mature forests was 1.2% during the period 1986–1995, increasing to 6.8% for the period 1995–2000. For both periods, the annual deforestation rate was appreciably lower within the reserve (0.21% and 2.54%) than outside it (2.15% and 12.4%). The annual rate of conversion of tropical SGF to A/P was 1% during the first period and increased sixfold for the second period. Three future scenarios on forest cover were constructed using a Markovian model and annualizing LUCC transition matrices. Results show that between 29% and 86% of remaining forest may be lost within the next 23 years. Urgent action is necessary to reduce loss of biodiversity within this region. Particular attention must be paid to tropical SGF, which are rapidly being deforested.

1. Introduction

An accelerated loss of primary ecosystems and associated biodiversity worldwide, mainly due to human activity, has led to an urgent need to identify areas of high biodiversity ("hotspots") in order to promote their priority for conservation (Kati et al., 2004; García, 2006). Myers and Collaborators (2000) identified 25 hotspots throughout the five continents.

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However, identification of hotspots is not enough; it is also essential to assess the possibilities for their conservation, taking into account that these hotspots are subject to rapidly growing human population and activity (Cincotta et al., 2000). Thus, analysis of land-use/land-cover change (LUCC, *sensu* Turner et al., 1994) dynamics becomes a fundamental tool for adoption of conservation strategies within these hotspots.

Among the hotspots defined by Myers et al. (2000) worldwide, the Mesoamerica hotspot is second in number of endemic vertebrate species and tenth in number of endemic plant species. The Selva El Ocote Biosphere Reserve, located in the northwestern portion of the state of Chiapas, Mexico, is part of the Mesoamerica hotspot. The region contains four types of lowland tropical forests, with an estimated 2000 vascular plant species (Ochoa-Gaona, 1996), at least 30 species of amphibians, 53 reptile species (Diario Oficial de la Federación, 2000), 97 mammal species (22% of the total number present in Mexico) (Navarrete Gutiérrez et al., 1996), and 334 bird species (Domínguez Barradas et al., 1996). Due to increased human activity, the Selva El Ocote is becoming increasingly isolated from two neighboring areas of similar relevance for their high species and ecosystems biodiversity: the Chimalapas, in the state of Oaxaca, and Uxpanapa, in the state of Veracruz (Wendt, 1989). Together with the Lacandonia Forest, these three regions are the most important tropical rainforest refuges in the Northern Hemisphere of the Americas (WWF-SEMARNAT, 2001).While extensive studies have been carried out in the first two regions, the Selva El Ocote is poorly known, particularly regarding its biodiversity and the deforestation process affecting it.

Because of the national and global relevance of conserving the Selva El Ocote, it is essential to study the LUCC dynamics and assess the future persistence of the reserve's primary ecosystems. Such an analysis can contribute to the design of appropriate biodiversity conservation policies.

LUCC analysis has become a fundamental tool in assessing the environmental consequences of human activity (e.g., Hunt and Ditzer, 2001; Veldkamp and Lambin, 2001; Brown, 2003; Dunn, 2004). LUCC have consequences for level of biodiversity (Tallmon et al., 2003), geochemical cycles (Powers, 2004), and water quality (Shippers et al., 2004). LUCC dynamics are influenced by types of land cover involved, ecological mechanisms of succession and regeneration, physical components of the environment, socioeconomic activities together with their cultural context, and meteorological phenomena or other natural disasters (e.g., Dale et al., 1994; Kareiva and Wennergren, 1995; Lindenmayer and Franklin, 1997).

In this study, we consider land cover to be the biophysical state of the earth's land surface and immediate subsurface, including biota, soil, topography and groundwater; we analyze land cover using a set of categories (Lambin et al., 2003). Changes in land cover include changes in biotic diversity, actual and potential primary productivity, soil quality, and other aspects. Land use involves the manner in which biophysical attributes of the land are manipulated, as well as the intent underlying that manipulation (Turner et al., 1995). Based on these definitions, we know that land use affects land cover with various implications. Land use change may involve a shift to a different use or an intensification of the existing one. This study focused on land-cover changes which imply conversion from one land-cover class to another (Turner and Mayer, 1994).

Deforestation may be defined as the process of transformation or alteration of a primary or secondary forest area which leads to replacement of the original land-cover type to another one, either immediately or progressively (FAO-UNEP, 1990; Dale et al., 1993; Lambin, 1994, 1997; Phillips, 1997; Kaimowitz and Angelsen, 1998; Watson et al., 2000; Velázquez et al., 2002a). A common approach to studying deforestation is to consider it as a binary process in which the possible states of land cover are forest and non-forest (Mendoza and Dirzo, 1999; Chipika and Kowero, 2000; Mertens and Lambin, 2000). However, LUCC dynamics include processes of regeneration as well as cover loss; the net balance is the result of subtraction and addition derived from both trends. An increasing number of studies of LUCC dynamics are considering this balance between loss and regeneration, particularly in areas of high environmental and socioeconomic heterogeneity (De Jong et al., 1999; Cairns et al., 2000; Veldkamp and Lambin, 2001; Velázquez et al., 2002b, 2003).

This paper analyzes the dynamics of deforestation and LUCC in the Selva El Ocote Biosphere Reserve and its surrounding area. The paper integrates remote sensing methods with a geographic information system and standard tools for the analysis of LUCC. The analysis included data for two periods between 1986 and 2000, as well as these two periods considered together, and included land within and outside of the Selva El Ocote Reserve. To assess the possibilities for conserving these tropical forests, plausible future scenarios were explored using Markovian transition models, considering trends observed in land-cover changes in primary and secondary growth forests within this region.

2. Methods

2.1. Study area

The Selva El Ocote region is characterized by high environmental heterogeneity, largely due to its uneven topography, humidity gradient, and karstic geological substrate. Landscapes are complex and diverse, with varying elevations, climates, and vegetation types.

The study area includes slightly over 682,000 ha and is located within the coordinates: 17°23′N, 94°09′W to the northwest and 16°30′N, 93°06′ W to the southeast. The Selva el Ocote Biosphere Reserve is located in the center of this quadrangle, and the artificial lake formed by the Nezahualcoyotl dam to the north of the reserve (Fig. 1).

The study area extends over two different physiographic regions, and contains more than 20 of the land-cover categories used by the National Forest Inventory (Palacio et al., 2000), 13 climatic types (García, 1973), over 100 soil associations, and an elevation gradient ranging from 60 to 2080 m. The area's population of over 254,000 lives in nearly 2000 settlements of one to 30,000 inhabitants.

The socioeconomic context is also heterogeneous. Approximately 13% of these inhabitants belong to several native ethnic groups, mainly *Zoque*, *Tzotzil* and *Tzeltal*, but others have

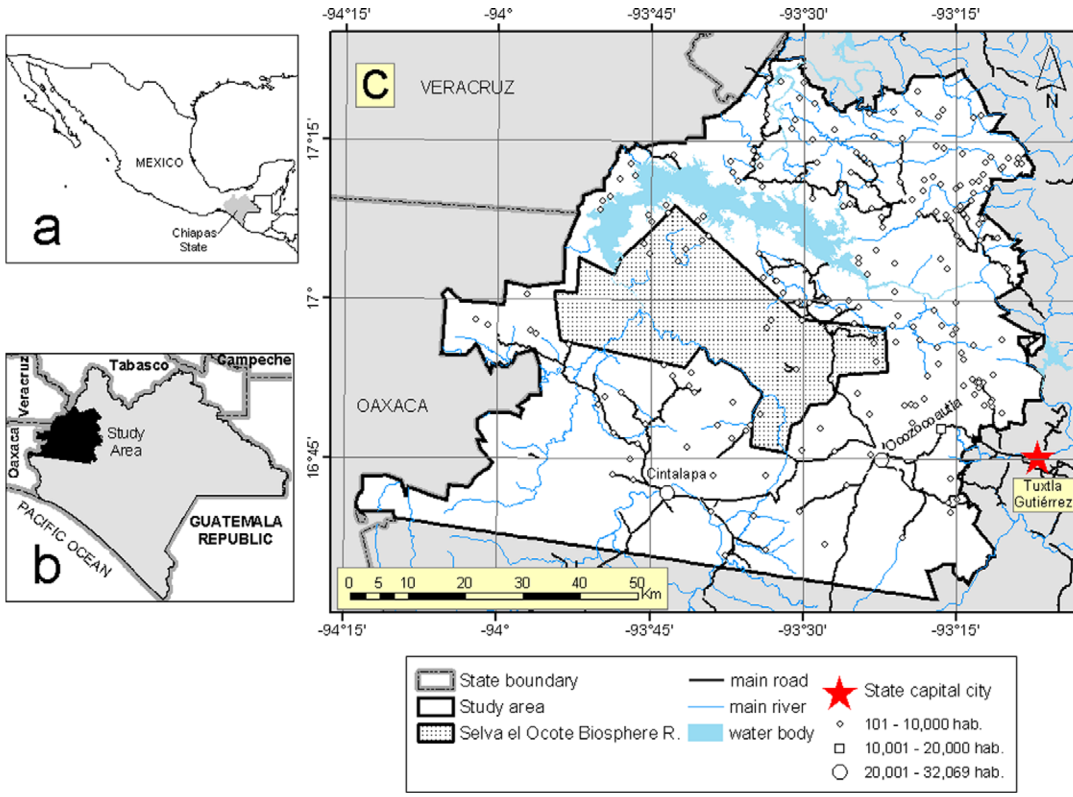

Fig. 1 – Location of the study area. The area is located in the northwestern part of the state of Chiapas, Mexico (a and b). The study area includes the artificial lake of the Nezahualcoyotl dam and the Biosphere Reserve (c).

arrived to the area from other regions of Chiapas or from other states (INEGI, 2000). The region under study has been populated by the *Zoques*, a culture adapted to living in lowland tropical forest, before Spanish colonization (Ekholm, 1998). Toward the end of the 19th century and beginning of the twentieth, selective logging of precious woods was a very important activity in the region. Construction of the Nezahualcoyotl dam was initiated in 1957, employing thousands of workers from different areas, strongly impacting the area surrounding the dam (Vásquez-Sánchez, 1996). *Tzotzils* and *Tzeltals* from the temperate Chiapas Highlands formed a new wave of colonization in the 1970s. In 1982, the volcano Chichonal, located to the northeast of the study region, erupted, provoking another wave of colonization from *Zoques*.

As in other tropical regions, the study zone has been subjected to strong pressures that resulted in large scale deforestation during the past forty years (Ewell and Poleman, 1980; Tudela, 1990). There is intense dynamism in LUCC, largely in relation to agriculture and grazing activities influenced by environmental conditions, economic activities in surrounding areas, market pressures, and governmental subsidies (Castillo Santiago et al., 1998).

2.2. *Land cover maps*

Three sub-scenes from satellite imagery, taken in 1986, 1995 and 2000, were interpreted. The first two are part of the Landsat Thematic Mapper (TM) series; the third belongs to the Enhanced Thematic Mapper Plus (ETM+) series. All three images were captured in February and March, during the dry season. Their spatial reference is path 022 row 048 in the Landsat World Reference System 2. On-screen visual interpretation was carried out by a method similar to that proposed for Tropical Ecosystem Environment Observations by Satellites Project (TREES) phase II (Achard et al., 2002). The three land-cover maps were digitized in El Colegio de la Frontera Sur geographical analysis laboratory. Different types of land cover were delineated by digitizing them with program ArcInfo 7.1. A color composition RGB 4, 7, 5 was used to display them on the screen. Bands 4 (0.750–0.900 μm), 7 (2.090–2.350 μm) and 5 (1.550–1.750 μm) were used to enhance differences among stages of succession of forested areas as well as features of agricultural and grazing areas. A scale of display of 1:80,000 was used, and a minimum map unit of 5 ha was applied. The interpretation was aided by three additional sources of information: INEGI vegetation and land-use maps with a scale of 1:250,000, edited from 1984 to 1988; the 2000 National Forest Inventory; (Palacio et al., 2000) and field verification.

The polygons of different land-cover classes in the subscene acquired in 1986 were labeled according to their cover class. Once the first digital map of the coverage was made, the polygons were copied and the segments that needing modification were changed based on the 1995 subscene. Segments were updated by adding, deleting, or modifying lines in order to reflect changes in land coverage occurring from 1986 to 1995. The same process was used to update changes occurring from 1995 to 2000, resulting in a third map. This process was used to avoid generation of false changes due to differences in delimitations of the same elements in two different scenes (Mas et al., 2004).

The three land-cover maps were the basis for LUCC analysis. Forty three categories used for designation of the polygons were adjusted as much as possible to those adopted by INEGI and the National Forest Inventory. However, overall accuracy of the interpretation was 47.4%. For this reason, these categories were regrouped to form ten more general classes. The resulting classes were: temperate forest, tropical forest, second-growth temperate forest, second-growth tropical forest, second-growth forest with slash and burn agriculture, shrub and savanna, agriculture and pasture, area of distortion, burned area, and area without vegetation.

Areas of distortion were those in which one or more of the scenes were covered by clouds or cloud shadows, by rivers with ever-changing margins, or by the dam's reservoir which fluctuates in water level. Burned areas were those that suffered effects of fire in any of the dates observed. Areas without vegetation are those in which no vegetation could be seen in satellite images; in general they correspond to water bodies, cliffs, exposed rocks and infrastructure. Areas of distortion and burned areas were excluded from the ten classes in order to avoid bias in analysis. In addition, areas without vegetation were excluded because they remained unchanged throughout the analysis period. In the results, we describe the seven classes of land cover used for the analysis.

In order to represent classification accuracy, an error matrix was employed (Congalton, 1991). A total of 306 reference points where used for the assessment (36–55 per class). These points were distributed across the study area using a stratified sampling scheme (Achard et al., 2002). The error matrix was normalized using an iterative proportional fitting procedure (using the program MARGFIT, Congalton, 1991) which forces each row and column to sum one. The overall accuracy value was 79.8%. Table 1 shows the error matrix. The major diagonal figures represent accuracy for each individual category. Finally, a Kappa analysis was performed with the Kappa program (Congalton and Green, 1999). The KHAT statistic obtained for the error matrix was 0.78. This accuracy is considered acceptable for interpretation of land-cover classes (Palacio Prieto and Luna González, 1994). Classes recorded with higher accuracy were shrub and savanna (89.2%), agriculture and pasture (80.3%) and tropical forest (80.3%), while the second-growth temperate forest was less precise (76.6%). The 2000 subscene was assessed for accuracy, assuming that a similar pattern holds for classification of the other two scenes, due to the fact that just one interpreter updated only changes which occurred from one date to the other.

2.3. Analysis of change in land cover and land use

Maps were incorporated into a multi-date geographic information system (GIS) using ArcView GIS 3.2a software. An overlaying analysis was performed in order to assess pathways of change observed among the three periods analyzed, and locate sites where these changes occurred. A mask was generated to eliminate areas that in a given scene corresponded to the categories of area of distortion, burned area, and area without vegetation, thus allowing for comparative analyses between dates based on the same area (Hall et al., 1995). The resulting area after applying the mask was 575,459 ha.

Categories of change were grouped in three stages: cover loss, regeneration, and unchanged. Cover loss occurs when land cover suffers a change with a concomitant loss of species diversity (for example, from primary forest to second-growth forest or from second-growth forest to agriculture or pasture) or when vegetation structure changes from trees to shrubs or from shrubs to weeds. Pathways of change which flow in the opposite direction indicate regeneration. Three maps of LUCC were generated: from 1986 to 1995, from 1995 to 2000 and from 1986 to 2000. Also, changed and unchanged areas were quantified for the three periods and for each land-cover category.

2.4. LUCC transition probabilities

With the information of land-cover classes from the three periods observed, transition probability matrices were elaborated for the periods 1986–1995, 1995–2000 and 1986–2000. Each matrix represents either the probability of persistence of each category of land cover from the first to the last year of the period, or the probabilities of transition to another land-cover category during the same period. Matrix values were standardized to obtain annualized change values.

The procedure for standardization of matrices to assess land-cover change was proposed by Rovainen (1996) in order to make comparisons based on annual values when the information derives from several different time intervals, as in the present study. Matrices analyzed are of 9 and 5 year periods

Table 1 – Normalized error matrix for the classification accuracy assessment

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
A/P	0.8031	0.0103	0.0126	0.0478	0.011	0.0542	0.0607
TemF	0.0132	0.7783	0.033	0.0107	0.1089	0.0157	0.0407
TroF	0.0154	0.0225	0.8011	0.0149	0.0336	0.071	0.0416
S/S	0.0647	0.0088	0.0108	0.8929	0.0094	0.0051	0.0074
TemSGF	0.0145	0.1483	0.0073	0.0118	0.7662	0.0173	0.0349
TroSGF	0.0192	0.0235	0.1249	0.0052	0.0083	0.773	0.0461
SGF + SBA	0.0699	0.0084	0.0103	0.0167	0.0626	0.0637	0.7686

Note: A/P = agriculture and pasture; TemF = temperate forest; TroF = tropical forest; S/S = shrub and savanna; 2GTemF = second-growth temperate forest; 2GTtroF = second-growth tropical forest; 2GF + SBA. = second-growth forest with slash and burn agriculture.

respectively. In order to annualize them, each probability matrix was separated by computing the matrix's eigenvectors and eigenvalues using the diagonalization method (Çinlar, 1975).

The latter method assumes that the probability of one cell belonging to class m during the initial year of the study period to class n during the final year (r_{mn}) is

$$r_{mn} = \frac{a_{mn}}{a_m} \tag{1}$$

where a_{mn} is the area covered by class m during the initial year and covered by class n during the final year and a_m the area covered by class m during the initial year.

When there are t years between the initial and final year, the probability transition matrix ($R^{(t)}$) is denoted by

$$R^{(t)} = [r_{mn}] \tag{2}$$

which is known from the land-cover maps. To obtain the annual probability matrix ($P = [p_{mn}]$), where p_{mn} denotes probability of changing from class m to class n during one year, we used the following procedure. Probability transitions may be regarded as stochastic processes. It is also assumed here that transition probabilities are time homogeneous, thereby fulfilling the Markov property. This means that, given the class during the final year, the probability to transition to class k (for all k) is independent of the classes at earlier points. This implies that

$$P \cdot P \cdot \dots \cdot P = P^t = R^{(t)} \tag{3}$$

Annual probabilities p_{mn} can be calculated using diagonalization (Çinlar, 1975), splitting P as follows:

$$P = B \cdot D \cdot B^{-1} \tag{4}$$

where D is a diagonal matrix. Matrix D has the eigenvalues of P in the diagonal. The columns in B consist of the corresponding eigenvectors. It can be shown that the D^t matrix has the P^t values in the major diagonal, then

$$P^t = B \cdot D^t \cdot B^{-1}, \quad t = 1, 2, \dots. \tag{5}$$

Thus from the known $R^{(t)}$ the annual probability matrix P can be obtained as

$$P = B \cdot \begin{bmatrix} \sqrt[t]{\lambda_1} & 0 & \cdots & 0 \\ 0 & \sqrt[t]{\lambda_2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \sqrt[t]{\lambda_7} \end{bmatrix} \cdot B^{-1} \tag{6}$$

Using a Markov chain model, the annualized matrices were used to generate a simulation of the proportion of cover that could be reached in a stable state if conditions were stationary. Markov chains are stochastic processes, and can be parameterized by empirically estimating transition probabilities between discrete states in the observed system (Balzter, 2000). The annualized matrices for each period (1986–1995 and 1995–2000) were analyzed by a log linear statistical test to discern whether they were significantly different (Caswell, 2000). The statistical analysis applied is described in detail in Appendix A.

2.5. Deforestation rates

Deforestation rates for the three periods were assessed based on forest cover data, using the formula proposed by FAO (1996):

$$DR = 1 - \left(1 - \left(\frac{A_1 - A_2}{A_1}\right)\right)^{\frac{1}{t}} \times 100 \tag{7}$$

where DR is the deforestation rate (% lost area/year); A_1 and A_2 are, respectively, initial and final forest areas; and t is the interval in years during which change in land cover is being assessed.

In addition, the deforestation rate within the reserve was computed and the result compared with deforestation outside the reserve.

2.6. Future scenarios

In order to explore the possible future evolution of tropical forest and second-growth tropical forest in the study area, an analysis was conducted based on the annualized transition matrices, assuming that the LUCC follow a Markovian dynamic. Three different scenarios were assumed for the period 2000–2030. In the first scenario, it is assumed that the probabilities of change recorded for the period of 1986–1995 will prevail. The second scenario assumes that the probabilities of change observed for 1995–2000 will be sustained. Finally, the third assumes that the long term probabilities of change will be those recorded for the total period 1986–2000.

3. Results

3.1. Analysis of LUCC

Based on the three land-cover maps analysis (Fig. 2), the area of each land-cover class for the three time periods analyzed was assessed (Table 2). The agriculture and pasture class (A/P) recorded the largest increase relative to total area, from 27% in 1986 to 37% in 2000.

Shrub and savanna (S/S) is a class of more or less dispersed shrubs and trees. Shrubs are areas resulting from human activities where shrubs of some species of *Acacia* or other legume family plants predominate. Savannas are, in general, secondary associations in which grasses predominate, but with an important number of shrubs and short trees which grow in poorly drained soils (Breedlove, 1981). Shrub and savannas were grouped together because in both types of land cover the most complex structural elements are short trees and shrubs. Also, these vegetation types do not lead to forest associations. It is probable that in S/S, soil conditions may limit establishment of more diverse types of land cover, but these conditions also make S/S inadequate for the sustained practice of either agriculture or grazing. Despite a slight increase in the extension of S/S, their percentage of land cover did not change significantly.

Second-growth forests with slash and burn agriculture (SGF + SBA) are forest areas in which patches cleared for agriculture are surrounded by a matrix of forest or second-growth vegetation. In general, agricultural patches span areas of 1-5

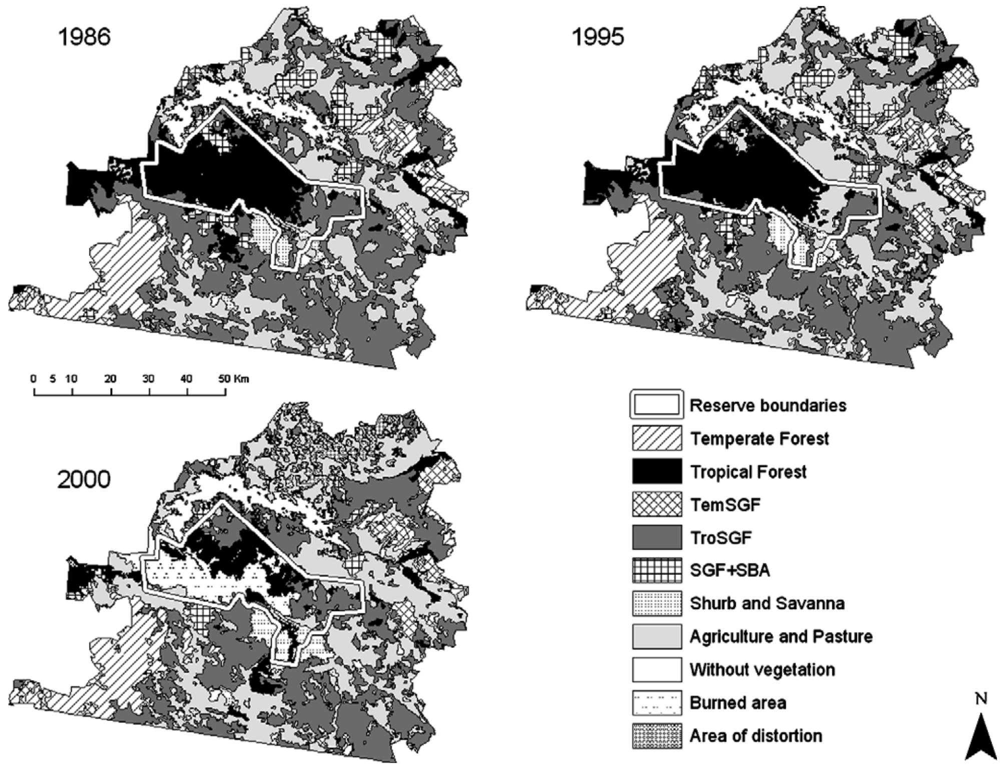

Fig. 2 – Land cover maps of the study area for 1986, 1995 and 2000. Land classes corresponding to "burned", "distortion" and "without vegetation" areas were not included in the land-cover/use change analysis so that the three maps would be comparable. *Abbreviations*: TemSGF = second-growth temperate forest; TroSGF = second-growth tropical forest; SGF + SBA = second-growth forest with slash and burn agriculture.

Table 2 – Land-use/land-cover classes used in the change analysis (area in ha)

Land cover class	1986		1995		2000	
Agriculture and pasture	156,429	(27%)	163,434	(28%)	212,507	(37%)
Second-growth forest with slash and burn agriculture	34,488	(6%)	33,426	(6%)	13,576	(2%)
Shrub and savanna	14,404	(3%)	13,817	(2%)	18,335	(3%)
Second growth temperate forest	22,916	(4%)	24,071	(4%)	28,536	(5%)
Second growth tropical forest	217,601	(38%)	219,266	(38%)	205,231	(36%)
Temperate forest	66,024	(11%)	64,337	(11%)	57,023	(10%)
Tropical forest	63,597	(11%)	57,108	(10%)	40,251	(7%)
Total	575,459	(100%)	575,459	(100%)	575,459	(100%)

ha, and are spread throughout the forest. SGF + SBA decreased from 6% to 2% during the period observed. This observation concords with observations made in other regions where intensification of agriculture is leading to shortening of the fallow period, causing a predominance of agricultural land (Metzger, 2003).

Temperate and tropical second-growth forests (TemSGF and TroSGF) are formerly deforested areas now undergoing a process of regeneration. This class includes forests in early stages of regeneration (up to 20 years since the last forest clearing). TemSGF showed a slight increase of 1% throughout the total period analyzed (1986–2000) while TroSGF decreased by 2% during the same period. Together, TemSGF and TroSGF had the largest area in the region of study, equivalent to nearly 40% in 2000.

Temperate forests (TemF) are highland forest areas, usually dominated by species of *Pinus* or *Quercus* (Breedlove, 1981), including mountain cloud forests (MCF) characterized by high plant and animal species diversity (Rzedowski, 1981; Alcántara et al., 2002). MCF play an important role in terms of biological species diversity, however, they are not present in the reserve. TemF also showed a slight decrease, from 11% to 10% (from 66,024 to 57,023 ha).

Tropical forest (TroF) areas are close lowland forest associations which include deciduous but mainly perennial forests (Calzada and Valdivia, 1979; Breedlove, 1981; Meave, 1990). The TroF class includes mature secondary forests (more than 20 years old) as these last were not possible to discriminate from mature forests. TroF contain the largest number of species within the region and showed a significant decrease for the 14 year period observed, diminishing from 11% to 7% (from 63,597 to 40,250 ha).

Fig. 3 shows pathways of change observed among the different types of LUCC. Lines indicate pathways; arrowheads the direction of change. Negative signs indicate cover loss, i.e., a loss of species biodiversity or structural complexity relative to the former land cover. Positive signs indicate a regeneration pathway, i.e., an increase in number, variety and variability of living organisms relative to the preexisting land cover. Thickness of the line indicates intensity of change in relation to original land cover. It is noticeable that in Fig. 3 the Temperate/Tropical Forest category appears only as a source but not as a destination of any other pathway. Also, cover loss pathways are more intense than recovery pathways.

Table 3 illustrates the transition matrix for the periods analyzed. Numbers represent estimated areas (in hectares) persisting within a given category or areas undergoing transformation to another category from the first to the second observation date. The most important changes occurred along pathways going from the forest classes (TemF and TroF) to SGF, from these to A/P, and from SGF + SBA to TroSGF. Pathways leading to cover loss predominate over those leading to regeneration in all cases, with the exception of the conversion of SGF + SBA to TroSGF, as can readily be seen in Fig. 3.

During the observation period, forest-class areas were in part converted to the A/P class. Most of the transformed A/P areas changed to SGF and, to a lesser extent, to S/S, while SGF + SBA were transformed to TroSGF, to A/P, and in a minor proportion to TemSGF. The most intense pathways were the conversions of TroF to SGF, from SGF to A/P and from SGF + SBA to SGF (Table 3; Fig. 3). A/P is the destination with the most arriving pathways, not all which are equally intense (Fig. 3). A/P transformed primarily to SGF and, to a small extent, to S/S. In fact, the ratio of area converted to A/P relative to that recovered from such classes is strongly asymmetric.

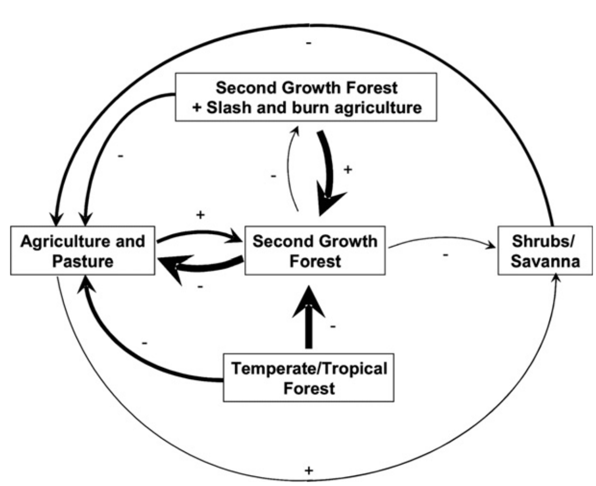

Fig. 3 – Land use change pathways. Positive signs indicate land-cover regeneration. Negative signs indicate cover loss. To simplify the diagram, the classes "temperate forest" and "tropical forest" were grouped into one category. Also both temperate and tropical second-growth forests have been grouped into one category.

A/P acts, therefore, as an attractor of other transformed land-cover classes.

Fig. 4 shows the LUCC maps, indicating, for each period, which areas suffered cover loss or regeneration. During the period 1986–1995, 7% of the study area underwent some degree of cover loss (Table 4). During the second period, 1995–2000, the extension of land in the same category increased more than twofold, to 17% of the total area. When examining the overall period (1986–2000), land undergoing cover loss is estimated at 19%. Otherwise, regeneration increased noticeably: 2% during the first period, 12% during the second and, 9% over the entire period. The areas of both cover loss and regeneration for the total period do not correspond to the sum of the individual periods because some areas in regeneration in 1995 were converted to A/P in 2000. Likewise, some areas open to agriculture in 1995 were in regeneration by 2000.

3.2. LUCC transition matrices

The probabilities of change were obtained from the transition matrices corresponding to the periods 1986–1995, 1995–2000 and 1986–2000 (Appendix B). During the first period, most probabilities indicate persistence within the same class or minimal changes to other classes. TemF showed great persistence (97%), and was only surpassed by TemSGF, with a persistence of 100%. On the contrary, the class with the least persistence was TroF, with 90%. Most of the transformed TroF converted to TroSGF (7%). Only 1% converted to A/P. Finally, 4% of A/P land converted to TroSGF, compensating in part the 5% of TroSGF converted to A/P.

During the period 1995–2000, LUCC dynamics were intensified along several pathways. Only 70% of TroF persisted; the rest mostly transformed into TroSGF (16%) and into A/P (9%). Persistence of TroSGF also decreased to 74%. Nearly one-fourth of TroSGF was converted to A/P, while, during the same period, 16% of TemSGF was also converted to A/P.

To find out whether significant differences existed among the periods analyzed, the transition matrices for each period were annualized (Appendix B). Using the log linear test, a value of G^2 was computed for the likelihood ratio test of 11,769.85. An important interaction existed among initial and final states of land cover and the period of observation, due to a significant dissimilarity in dynamics shown in the matrices of both periods.

3.3. Deforestation rates

Table 5 shows deforestation trends in the study area. First, the classes corresponding to TemF and TroF were grouped in order to obtain a general view of transformation due to deforestation. Afterwards, the deforestation rate was computed for each land-cover class. Finally, deforestation rates were calculated for all periods, inside and outside the reserve. Within the reserve, data are only shown for TroF because TemF are not present in this area. In all cases, deforestation rates dramatically increased between 1995 and 2000. During all periods, the largest deforestation rate was that of TroF, of which 6490 ha were lost during the first period and 16,857 ha during the second – the equivalent of approximately 721 ha/year

Table 3 – Land-use/land-cover transition matrix for the three time periods observed (area in ha)

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA	
1986–1995								*Total 1995*
A/P	149,409	524	771	751	36	11,685	259	163,435
TemF	–	64,337	–	–	–	–	–	64,337
TroF	–	–	57,105	–	–	–	–	57,105
S/S	166	–	–	13,651	–	–	–	13,817
TemSGF	–	1163	–	–	22,880	–	29	24,072
TroSGF	6854	–	4719	–	–	205,916	1776	219,265
SGF + SBA	–	–	1002	–	–	–	32,424	33,426
Total 1986	156,429	66,024	63,597	14,402	22,916	217,601	34,488	575,457
1995–2000								*Total 2000*
A/P	130,602	3223	5848	492	3594	60,248	8500	212,507
TemF	–	57,022	–	–	–	–	–	57,022
TroF	–	–	40,250	–	–	–	–	40,250
S/S	2490	–	–	13,910	–	1934	–	18,334
TemSGF	549	5746	–	–	19,322	–	2921	28,538
TroSGF	22,788	–	14,381	–	–	155,419	12,642	205,230
SGF + SBA	–	33	3118	–	–	–	10,425	13,576
Total 1995	156,429	66,024	63,597	14402	22,916	217,601	34,488	575,457
1986–2000								*Total 2000*
A/P	138,413	2712	4873	624	3905	53,690	8,290	212,507
TemF	–	57,022	–	–	–	–	–	57,022
TroF	–	–	40,250	–	–	–	–	40,250
S/S	3082	–	–	13,193	–	2059	–	18,334
TemSGF	909	4570	–	–	20,166	–	2892	28,537
TroSGF	21,029	–	9363	–	–	163,020	11,819	205,231
SGF + SBA	–	33	2621	–	–	497	10,425	13,576
Total 1986	163,433	64,337	57,107	13,817	24,071	219,266	33,426	575,457

Note: A/P = agriculture and pasture; TemF = temperate forest; TroF = tropical forest; S/S = shrub and savanna; 2GTemF = second-growth temperate forest; 2GTtroF = second-growth tropical forest; 2GF + SBA. = second-growth forest with slash and burn agriculture.

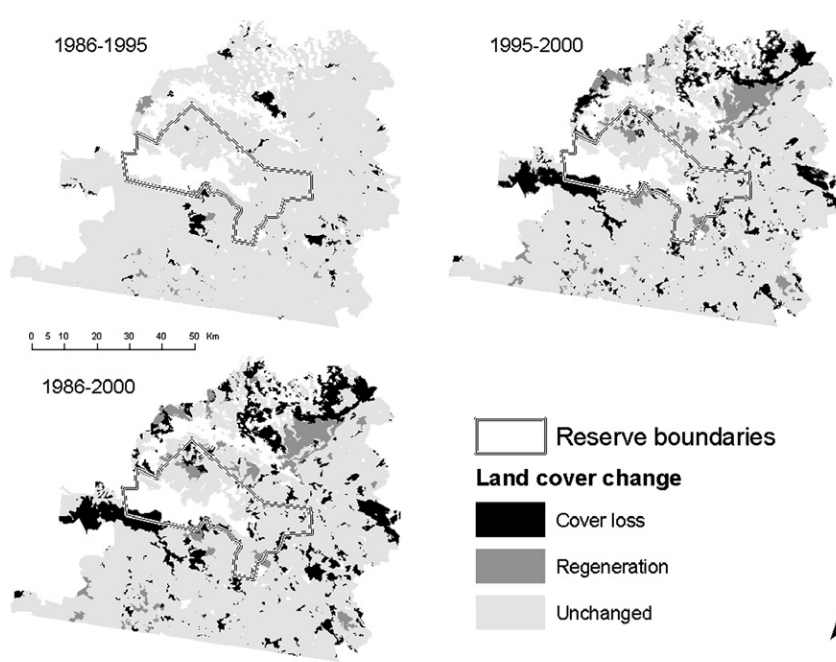

Fig. 4 – Land cover change maps for the periods 1986–1995, 1995–2000 and 1986–2000.

Table 4 – Forest cover loss and regeneration by time period[a]

	1986–1995		1995–2000		1986–2000	
	ha	%	ha	%	ha	%
Cover loss	42,264	0.07	99,406	0.17	111,996	0.19
Regeneration	10,123	0.02	67,391	0.12	49,894	0.09
Unchanged	523,073	0.91	408,663	0.71	413,569	0.72

a *Note*: Cover loss is the change from land-cover classes with high-biodiversity or structural complexity to those of low-biodiversity or structural complexity. Regeneration is the inverse of cover loss: the change from land-cover classes with low-biodiversity or structural complexity to those of high-biodiversity or structural complexity.

Table 5 – Annual deforestation rates (%) by forest cover class

	1986–1995	1995–2000	1986–2000
All forests	0.72	4.34	2.03
Temperate forest	0.29	2.38	1.04
Tropical forest	1.19	6.76	3.21
Tropical forest within the reserve	0.21	2.54	1.05
Tropical forest outside the reserve	2.15	12.40	5.94

(1.19% per year) during the first period and more than 3370 ha/year (6.76% per year) during the second.

Deforestation rates recorded inside the reserve are lower than those registered outside its boundaries. Within the entire area of study, in 1986 there were nearly 63,600 ha of TroF, but by 1995 only 57,100 ha remained. In 2000, the extension covered with TroF was 40,250 ha. During 1986, 52% of TroF in the study area were outside the reserve, while by 2000 this fraction decreased to 35%. The deforestation rate outside the reserve, already high during the first period (2.15%), dramatically increased nearly six times reaching a 12.4% annual value in the second period.

3.4. *Future scenarios*

The future landscape mosaic would change dramatically depending on which of the dynamics (1986–1995; 1995–2000; or 1986–2000) holds in the future. Fig. 5 shows the historic (1986–2000) and estimated (2000–2030) future evolution of each LUCC class. Assuming a persistence of the LUCC dynamics recorded for the first period (1986–1995), land covered by TroF would lose 29% of its present area (11,478 ha) by 2030. However, if the dynamics recorded between 1995 and 2000 were to hold, up to 89% of existing TroF would disappears – equivalent to an accumulated loss of 34,496 ha (Fig. 6). TroSGF would increase slightly under the first scenario and would lose up to 54,000 ha within the second scenario.

4. Discussion

Landscapes may be interpreted as a mosaic of LUCC forms in continuous change (Skole, 1994; Bennett et al., 2006), a transformation that in many instances results in processes of cover loss or regeneration. Deforestation is the most drastic process of degradation among possible changes of land cover. As in other regions of the world, most deforestation in Mexico – including the study area – involves TroF (Masera et al., 1997; Lambin and Geist, 2003; Fernside and Laurence, 2004). Deforestation in the study area is triggered by agricultural and grazing activities, but is not a one-stage process; it follows complex pathways and passes through a number of transient stages. Usually, the first step is removal of forest cover due to A/P activities. From there, the process follows one of several pathways. A portion of A/P land is abandoned after a number of years of use, and either second-growth vegetation begins to develop or S/S is established. The remaining land converted to A/P is kept under intensive use on a permanent basis.

In our study area there is also an increasing loss of second-growth forest, resulting in A/P land rarely being recovered sufficiently to lead to re-establishment of mature forests (for example, during the second period 24% of TroSGF was converted to A/P, Table 3). In fact, we observe that the region undergoes an arrest of the succession process. The loss of second-growth forest loss has negative implications on biodiversity and also entails large emissions of carbon dioxide to the atmosphere. Also, fallow lands (SGF + SBA) are being lost, probably as a combination of a shortening of the fallow period in slash and burn agriculture systems and because of the increase in grazing lands. This phenomenon has been observed in other regions of Mexico and Latin America (Metzger, 2003; Chowdhury et al., 2004).

Significant differences in LUCC process found between the periods assessed (1986–1995 and 1995–2000) show that selection of the base period for modeling future dynamics is critical. The projected fate of the region's tropical forests would differ dramatically depending on whether the recent history or the average trend observed during the past 14 years (i.e., the type of LUCC dynamics) prevails in the long term, (Figs. 5 and 6). Adding intermediate time periods to the analysis may provide more precise information of change dynamics. Such information may enable the establishment of contrasting scenarios, rather than pointing toward a single trend.

Deforestation rates registered for both land-cover types (TemF and TroF) are above national estimates, particularly in the case of TroF. Velázquez et al. (2002b) estimated, for a similar period of observation (1993–2000), a national annual rate of loss of TemF of 1.02%, and 2.06% for TroF. For the period 1995–2000, this study estimated corresponding annual rates of 2.38% and 6.76%, and up to 12.6% for tropical forest outside the reserve. These rates also greatly exceed the annual deforestation rate for México as a whole – 2% for

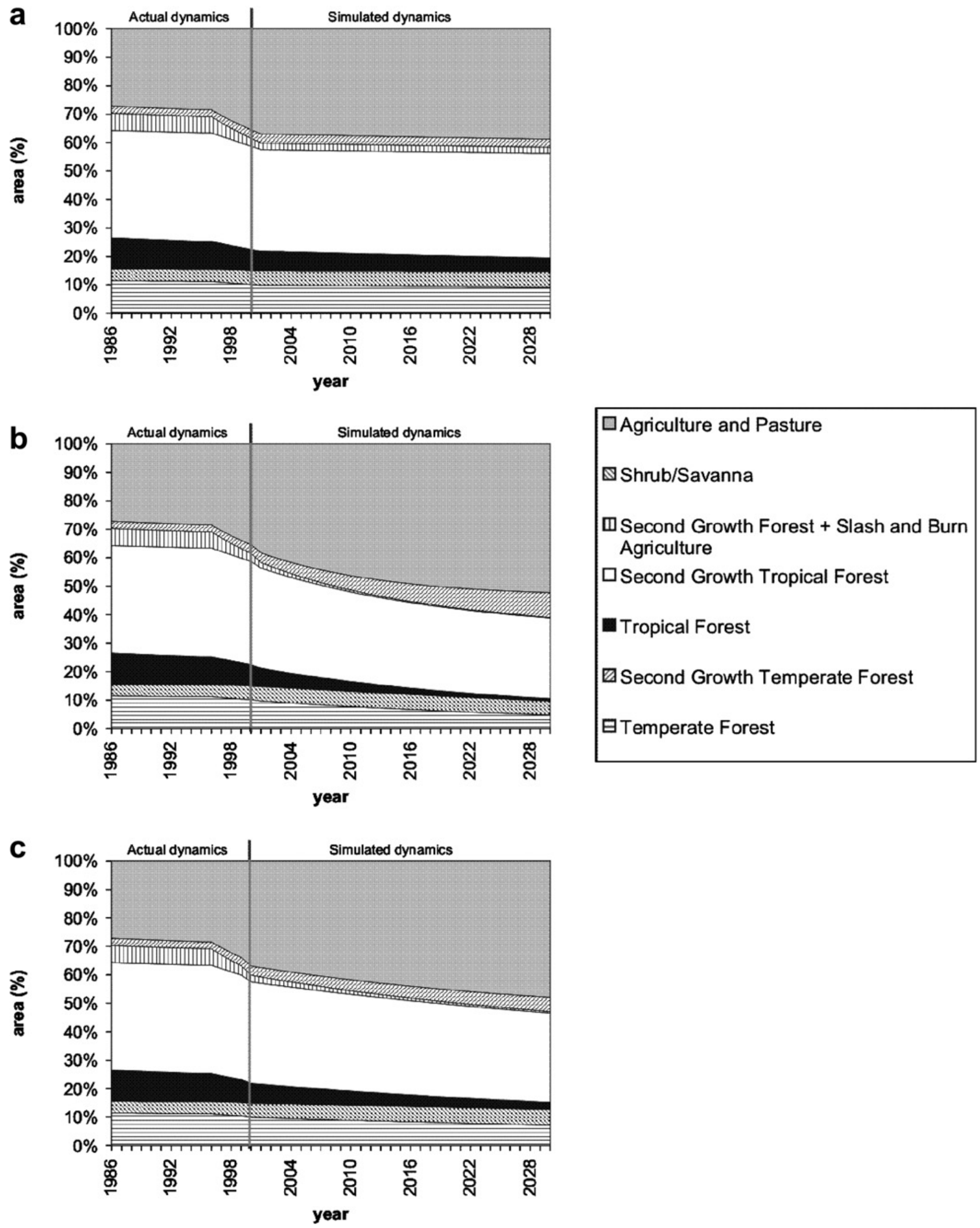

Fig. 5 – Simulation of the evolution of the analyzed land-cover classes within the study area under three future scenarios. The graph shows historical (1986–2000) and predicted (2000–2030) evolution of land-cover classes within the region. The scenarios are based on a Markovian model of land-use dynamics and consider that: (a) LUCC dynamics (transition probabilities) observed from 1986 to 1995 holds in the 2000–2030 period; (b) LUCC dynamics observed from 1995 to 2000 holds in the 2000–2030 period, and (c) LUCC dynamics observed from 1986 to 2000 holds in the 2000–2030 period.

evergreen tropical forests during the 1990s (Masera et al., 1997) and 0.5% for all close forests during last 25 years (Mas et al., 2004) – and for studies in adjacent regions, which range from 0.4% in northern Peten Guatemala (Sader et al., 1994) to 0.61% in the Yucatan Peninsula (Chowdhury et al., 2004).

The lower annual deforestation rate observed inside the reserve compared with the areas outside it (0.21% and 2.54%, respectively), is consistent with results from other authors. Mendoza and Dirzo (1999) found a sixfold difference between inner an outside annual deforestation rate in the Montes Azules Reserve for the 1984–1991 period. Mas (2005) found a difference of 0.3–0.6% in areas within and outside the Calakmul Biosphere Reserve, respectively. The Selva El Ocote obtained a Natural Protected Area (NPA) status in 1972, however, the Biosphere Reserve status was decreed only in 2000, increasing the area under protection from 48,000 to 101,000 ha. The recent implementation of the Biosphere Reserve and the smaller size of the former NPA suggest that, in our case, the lower deforestation rates observed inside the reserve may not be largely a result of the protection status

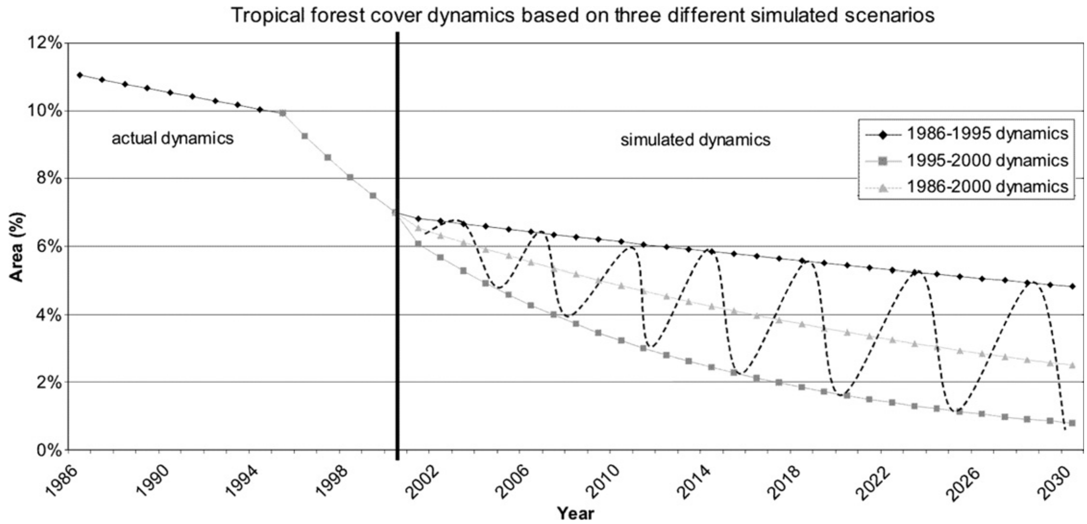

Fig. 6 – Simulation of the evolution of Tropical Forests within the study area under three future LUCC scenarios. The graph shows historical (1986–2000) and predicted (2000–2030) evolution of tropical forests within the region. The scenarios are based on a Markovian model of land-use dynamics and consider that: (a) dynamics (transition probabilities) observed from 1986 to1995 continue in the 2000–2030 period; (b) dynamics observed from 1995 to 2000 continue in the 2000–2030 period; (c) dynamics of the entire 1986–2000 period continue in the 2000–2030 period. The dotted line illustrates range of remaining forest area defined by the two most contrasting scenarios.

but, more likely, to the abrupt conditions of the land, which until now have limited the advance of the agricultural frontier.

In their study on a worldwide level, Achard and Collaborators (1998) did not include this region in "fast changing areas" or "deforestation hotspots", a term separate from "biodiversity hotspots" (Myers et al., 2000). Nevertheless, deforestation rates observed in the study zone are even higher than those recorded in the regions considered for Mexico in the TREES project.

On a methodological level, this study provides an integrated approach with a detailed multi-temporal analysis of the LUCC process, useful in evaluating the current forest dynamic in the region. We have also developed a first set of future scenarios using a Markovian model with annualized transition probability matrices, which allows comparing information from different time periods. These scenarios only take into account the history of LUCC. Information regarding other variables which drive changes may be incorporated in more sophisticated models in order to improve the forecast, enabling researchers to outline normative scenarios assessing varying dynamics according to specific conditions.

Markovian models are useful for exploratory analysis and for depicting contrasting scenarios. They have been used in many analyses of LUCC; for example, Geoghegan and Collaborators (2001) used a Markovian model to explore future LUCC change patterns in the Yucatan Penninsula. However, Markovian models are not spatial-explicit and assume that transition probabilities are time homogeneous. More detailed, spatial explicit LUCC models may be used in future analysis to get a better understanding of the causes, locations and pathways of LUCC dynamics (Veldkamp and Verburg, 2004; Verburg and Veldkamp, 2005). For example, multi-agents models linked to GIS (Brown et al., 2005) may improve understanding about household decisions and exogenous drivers linked to LUCC processes (Verburg and Veldkamp, 2005).

In tropical countries, mainly in Latin America, the socio-economic factors most related to deforestation are expansion of the agricultural frontier and population increase. However, the relative importance of each of these factors varies for different regions (Agrawal, 1995; Bawa and Dayanandan, 1997). It has also been established that building roads and other communications systems increases the rate of deforestation (Sader et al., 1994; Mas et al., 1996; Mertens and Lambin, 2000).

Methods used in this study have limitations which should be considered when implementing them in other areas. In recent years, automated classification methods of satellite images have been improved. Their purpose is to reduce interpreter bias. Nevertheless, hardware, software, and specialized personnel are necessary. Regardless of method used to elaborate the coverage maps, the process must be consistent when establishing a monitoring system. Considering the importance which the TroSGF could have, in the future it would be wise to use monitoring methods which allow for evaluating changes in this land-cover type. This study did not distinguish the varying states of TroSGF, but advances are continually made in methods for evaluating their evolution, whether it may be toward regeneration or cover loss (Kimes et al., 1998; Jin and Sader, 2005).

The data and tendencies which we have obtained are useful for understanding deforestation patterns in the study region. Important future steps for this analysis are to identify the proximal variables and driving forces of change which determine LUCC. We are currently developing a spatially explicit model on a regional level to examine future tendencies of change, taking into account the socio-environmental variables identified and their relative weight.

5. Conclusions

Deforestation is a complex process characterized by varying intensity during different periods, depending on the land cover class involved, geographical situation, local and regional environmental and socioeconomic conditions (Lambin et al., 2003). Through a detailed analysis of LUCC, deforestation rates and the most relevant transformation pathways of forested land in the study area have been identified.

Severe deterioration caused by deforestation has negative consequences on biodiversity conservation (Noss and Csuti, 1994; Forman, 1995; Tallmon et al., 2003; Den and Zheng, 2004; Ochoa-Gaona et al., 2004). The ever-vanishing connectivity of the study area with other regions of common biota and geological history reveals a rapid isolation of biological processes, which are impacted when both mature and second-growth forest cover is removed. Agriculture and grazing activities are concomitant with reduction in biodiversity (Sánchez-Azofeifa et al., 2003; Wright and Flecker, 2004; Sánchez-Cordero et al., 2005). These activities cause isolation barriers, which become the matrix with which biological organisms of this region of priority for conservation must contend, with obvious disadvantages (Castelleta et al., 2005).

While deforestation rates within the Reserve are still lower than the surroundings, our results reveal that pressure exerted over the forest area outside the reserve is very high, and that this is increasingly impacting the areas within the reserve's boundaries. The process of change is dominated by agricultural and grazing activities, and occurs equally in mature and in secondary growth forests, resulting in arrest of the succession process, and leading to suppression of mature forests.

Public policy regarding agricultural development should consider the relevance of this region for conservation of national heritage, supporting productive activities which promote development while maintaining natural ecosystems. More detailed studies of secondary vegetation communities and their process of regeneration in the region are necessary, especially regarding their role in the prevalence of rare or threatened native species. Protection strategies should favor TroSGF regeneration processes, proposing agricultural activities such as organic coffee growing, and favoring payment for environmental services which these plant communities provide.

Methodologically, this study demonstrates the importance of multi-temporal approaches and the relevance of discriminating the different pathways of LUCC changes triggered by deforestation. Also relevant is the need for making contrasting future scenarios based on annualized transition matrices. In order to improve the present analysis, spatially explicit models must be developed which render a more precise understanding of LUCC change dynamics, and which achieve a better diagnosis of areas more vulnerable to deforestation. Ideally, stochastic variables such as forest fires should also be included. Another challenge is to develop methods that incorporate historic land cover information covering longer time periods.

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Appendix A

Statistical analysis of annualized matrices

The model suggested by Caswell (2000) to determine the preponderance of a given factor (in this case time) is:

$$u + u_{F(i)} + u_{S(j)} + u_{T(k)} + u_{FS(ij)} + u_{ST(ik)} \quad \text{(A.1)}$$

where u is a constant, F is the final state of the cell, S is the initial state of the cell, and T is the time.

The model does not consider the *FST* interaction. Based on the high value of G2 (11769.8462) it is concluded that the *FST* interaction is relevant and, consequently, the difference between F and S depends on the date of observation. Such variation may be seen in the elements of matrix D.

Matrix D contains differences in change values between categories of the corresponding transition matrices. The values point to distinct dynamics in each period which may be observed by analyzing the values. While the value remains nearly constant in the remaining categories in the major diagonal, the last category (second growth with slash and burn agriculture) displays a low value relative to other categories. Otherwise, several cells have very high values, indicating that the proportions of change were different in each period.

Matrix *D*

T1\T2	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.97	–	–	33.10	–	6.15	–
TemF	9.15	0.98	–	–	7.84	–	–
TroF	11.83	–	0.94	–	–	4.23	8.65
S/S	1.64	–	–	1.00	–	–	–
TemSGF	215.87	–	–	–	0.96	–	–
TroSGF	9.53	–	–	–	–	0.94	–
SGF + SBA	85.55	–	–	–	325.68	19.82	0.80

This matrix is obtained by:

$$D = \frac{\left[\frac{\pi_{F=j/I=i}}{1-\pi_{F=j/I=i}}\right]_{T_1}}{\left[\frac{\pi_{F=j/I=i}}{1-\pi_{F=j/I=i}}\right]_{T_2}} \quad \text{(A.2)}$$

where $\pi_{F-j/I=i}$ is the probability that the cell acquires a j value in the final moment, given it had an i value in the initial time.

Appendix B

Transition matrices

The first three matrices represent probabilities of change among land-cover categories recorded for each period analyzed. The last three matrices are the corresponding annualized matrices.

Legend: A/P = agriculture and pasture; TemF = temperate forest; TroF = tropical forest; S/S = Shrub and Savanna; 2GTemF = second-growth temperate forest 2GTtroF = second-growth tropical forest; 2GF+SBA. = second-growth forest with slash and burn agriculture.

Transition matrix 1986–1995

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.96	0.01	0.01	0.05	0.00	0.05	0.01
TemF	–	0.97	–	–	–	–	–
TroF	–	–	0.90	–	–	0.00	–
S/S	0.00	–	–	0.95	–	–	–
TemSGF	–	0.02	–	–	1.00	–	0.00
TroSGF	0.04	–	0.07	–	0.00	0.95	0.05
SGF + SBA	–	–	0.02	–	–	–	0.94

Transition matrix 1995–2000

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.85	0.04	0.09	0.05	0.16	0.24	0.25
TemF	–	0.89	–	–	–	0.00	–
TroF	0.00	–	0.70	–	–	–	–
S/S	0.02	–	0.00	0.95	–	0.01	–
TemSGF	0.01	0.07	–	–	0.84	–	0.09
TroSGF	0.13	–	0.16	–	0.00	0.74	0.35
SGF + SBA	–	0.00	0.05	–	–	0.00	0.31

Transition matrix 1986–2000

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.83	0.05	0.09	0.03	0.16	0.28	0.25
TemF	–	0.86	–	–	–	0.00	–
TroF	0.00	–	0.63	–	–	–	–
S/S	0.02	–	0.00	0.97	–	0.01	–
TemSGF	0.00	0.09	–	–	0.84	–	0.08
TroSGF	0.15	–	0.23	–	0.00	0.71	0.37
SGF + SBA	–	0.00	0.05	–	–	–	0.30

Annual transition matrices

Annual transition matrix 1986–1995

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.99	0.00	0.00	0.01	0.00	0.01	0.00
TemF	0.00	1.00	0.00	0.00	0.00	0.00	0.00
TroF	0.00	0.00	0.99	0.00	0.00	0.00	0.00
S/S	0.00	0.00	0.00	0.99	0.00	0.00	0.00
TemSGF	0.00	0.00	0.00	0.00	1.00	0.00	0.00
TroSGF	0.01	0.00	0.01	0.00	0.00	0.99	0.01
SGF + SBA	0.00	0.00	0.00	0.00	0.00	0.00	0.99

Annual transition matrix 1995–2000

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.96	0.01	0.01	0.01	0.04	0.06	0.06
TemF	0	0.98	0	0	0	0	0
TroF	0	0	0.93	0	0	0	0
S/S	0	0	0	0.99	0	0	0
TemSGF	0	0.02	0	0	0.96	0	0.03
TroSGF	0.04	0	0.04	0	0	0.94	0.12
SGF + SBA	0	0	0.02	0	0	0	0.79

Annual transition matrix 1986–2000

	A/P	TemF	TroF	S/S	TemSGF	TroSGF	SGF + SBA
AP	0.98	0	0	0	0.01	0.03	0.02
TemF	0	0.99	0	0	0	0	0
TroF	0	0	0.97	0	0	0	0
S/S	0	0	0	1	0	0	0
TemSGF	0	0.01	0	0	0.99	0	0.01
TroSGF	0.02	0	0.02	0	0	0.97	0.05
SGF + SBA	0	0	0.01	0	0	0	0.92

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