Forest cover change in the Los Tuxtlas Biosphere Reserve and its future: The contribution of the 1998 protected natural area decree

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Abstract

The Los Tuxtlas mountain range harbors one of the last remnants of tropical rain forest on the coastal plain of the Gulf of Mexico. This volcanic range has a high degree of heterogeneity in its geology, climate and ecology, in addition to a very long history of human occupation. The original area covered by tropical forest has been drastically reduced by agricultural activities, and during the last four decades in particular, deforestation has been very intense. In order to protect the remaining forest, in 1998 the Mexican government created the Los Tuxtlas Biosphere Reserve (LTBR). While previous studies estimated deforestation rates and the amount of forest cover remaining in some areas of the LTBR, this is the first study to do so for the entire protected area. A retrospective analysis from 1986 to 2011 was conducted to assess the effect of the 1998 decree of the LTBR on deforestation rates, and to predict future changes in forest cover up to the year 2025 using Markov chains and cellular automata based on current deforestation patterns. The results show that shortly after the 1998 decree, deforestation rates in the LTBR not only decreased but reversed, however this trend did not continue. In recent years deforestation has again increased. Our projection shows that if current trends continue unchanged then by the year 2025 we might have lost close to 14% (ca. 9000 ha) of the forest cover that was present in 2011. The decree of the LTBR was part of the federal policy to protect biodiversity in Mexico and our results show that the strategy of establishing this protected area did work to protect tropical forest, at least temporarily in Los Tuxtlas. Also, our results show that it is not only possible to reverse forest loss within the ample buffer zone of the LTBR, it is also still relatively easy to achieve by promoting passive restoration.

1. Introduction

Protected natural areas (PNAs) are established for the long term conservation of biodiversity and associated ecosystem services in a given area (CONANP, 2006). With the goal of protecting biodiversity and promoting sustainable development, biosphere reserves in Mexico have legal status as a type of PNA (CONANP, 2006). To date, 42 Biosphere Reserves have been officially decreed in Mexico, all of which are under pressure from deforestation, habitat fragmentation, pollution, species invasion, forest fires and illegal hunting (CONANP 2006; Ervin 2003; Figueroa et al., 2011; Figueroa and Sánchez-Cordero 2008; Mendoza et al., 2005). It is necessary to quantitatively assess these pressures and their temporal trends (both recent and previous) in order to fulfil the PNAs’ objectives.

In 1998 the federal government published the decree that established the Los Tuxtlas Biosphere Reserve (LTBR) in southern Veracruz. As a result of the decree several actions and environmental projects designed to stop and if possible reverse deforestation within the reserve were initiated. The most noteworthy legal mandates of this decree include: forest cover may not be changed to any other type of land use within the reserve, flora and fauna may not be interfered with or extracted, and new towns and villages may not be established within the reserve (D.O.F., 1998). The reserve includes the largest and last remnants of tropical rain forest on the Gulf of Mexico coast (Guevara et al., 2004). The LTBR covers 155,122 ha (D.O.F., 1998), including three nucleus zones on the top of the highest volcanoes of the mountain range (9805 ha on the San Martin Tuxtla Volcano, 18,032 ha on the Santa Marta Range and 1883 ha on the San Martin Pajapan), all three surrounded by a single buffer zone (125,402 ha) that extends eastward to the Gulf of Mexico coast. In spite of the vast loss of forest cover in the region over the last 5 decades (Dirzo and García 1992; Guevara et al., 2004; Mendoza et al., 2005), the LTBR still harbors a very high diversity of the native fauna and flora. Tropical rainforest on the lowlands and cloud forest on the highest parts of the volcanoes were among the most widespread types of original forest of this region, the largest areas of which occur in the reserve (Castillo-Campos and Laborde, 2004).
Studies of the distribution of vegetation and plant species in the Los Tuxtlas mountain range have been done in different parts of the range, but typically have been restricted to a given part of the LTBR (Flores, 1971; Dirzo and García 1992; Ramírez 1999; see also Soriano et al., 1997), though some have encompassed the whole protected area (Andrle 1967; Guevara et al., 2004; Velazco Tapia 2007; PSSM-CONANP, 2011). These studies differ widely in the types of vegetation and land use cover reported and their respective areas, in part due to differences in the delimitation of the study site, but also as a result of the methods used to classify and estimate vegetation and land use cover types. Few of these studies indicate whether ground truthing was done, and when done, the methodology is rarely described in enough detail to replicate. None of these studies provides a quantitative assessment of the accuracy and degree of confidence in their vegetation and land use classification. This complicates the implementation and monitoring of sustainable management and conservation plans in the reserve. Until now we have not had any consistent or reliable maps of the forest cover in the whole area of the LTBR in which the methodology used to produce them and a quantitative assessment of their classification confidence are clearly stated.

Given the current threats facing all of the protected areas in Mexico and those threatening the LTBR in particular, it is crucial to develop a monitoring protocol that combines different spatial and temporal scales, in order to detect past and current trends in cover change that can be used as basis for estimating future trends and to identify those areas most at risk. In this study, we have made detailed maps of the forest cover for the entire LTBR over three decades in order to determine past changes and the current extent of forest cover, and to use the trends detected to predict changes in forest cover. Our main goal is to provide current, reliable, quantitative information for researchers, the authorities, and the inhabitants of the region of Los Tuxtlas and also for the decision-makers responsible for managing the LTBR. Information on the intensity, rate and trends of change in forest cover, as well as the magnitude and location of the affected areas is indispensable for making sound decisions on the sustainable use of resources and improving people’s welfare, in addition to preserving biodiversity and the environmental services provided by the LTBR and the Los Tuxtlas region in general.

2. Methods

2.1. Study area

The Los Tuxtlas Biosphere Reserve is located on the coastal plain of the Gulf of Mexico, in southeastern Veracruz, between 18°30′–18°40′ N latitude and 95°03′–95°10′ W longitude and covers a total area of 155,122 ha (Fig. 1). The reserve includes large parts of the municipalities of San Andrés Tuxtla, Catarine, Soteapan, Mecayapan, Tatabuican and Pajapan, as well as small portions of the municipalities of Santiago Tuxtla and Angel R. Cabada. The LTBR spans a very steep elevation gradient (0–1383 m a.s.l.) with a tropical wet climate in the lowlands and temperate very wet climate in the highlands. Mean temperatures are 18–22 °C with a maximum of 36 °C (Soto, 2004). Mean annual precipitation is 4700 mm/year with a relatively dry season from March to May (CONANP, 2006). The highly heterogeneous landscape of the reserve and its location on the southern coast of the Gulf of Mexico has promoted a high diversity of flora and fauna (3356 and 1702 species, respectively; Guevara et al., 2004).

2.2. Forest cover maps

The maps of forest cover were based on the hard classification of LANDSAT satellite images, obtained from the USGS Science for a Changing World project (http://glovis.usgs.gov/) for the years 1986, 1993, 1998, 2003 and 2011. All images were obtained with geometric corrections and we performed an atmospheric correction for all of them. The images were classified with a Maximum Likelihood algorithm run in Idrisi SELVA (Clark Labs, 2012) using 6 of the 7 bands (numbers 1–5, and 7).

Traditionally, training fields or pixels sets are defined by on-screen digitalization of polygons representing a given type of land cover that, ideally, has been verified in the field (i.e. ground truthed). However, this methodology usually produces classification errors by assigning different spectral characteristics or signatures to a given polygon. This explains why different GIS users often produce different classifications of the same image. To minimize this bias, our study included a segmentation routine, which generates polygons of pixels with similar spectral signatures that are contiguous (Liu et al., 2008, Blaschke 2010). In other words, in addition to the spectral attributes of the pixels, their spatial relationships are taken into account when the image is being classified. Our study defined only two land cover categories: forest and non-forest cover. Segments with a continuous tree cover were classified as forest cover and areas devoid of trees or with discontinuous tree pixels (i.e. isolated trees) were classified as non-forest cover, including manmade pastures, crop fields, human settlements, roads and water bodies (i.e. rivers and small lakes).

2.3. Analysis of forest cover change

The magnitude and tendencies of forest cover change were assessed by cartographic overlap and by estimating differences in forest cover between dates, to generate maps of change and their respective transition matrices for the following periods: 1986–1993, 1993–1998, 1998–2003 and 2003–2011. Deforestation rates (r) were estimated using the equation proposed by the FAO (1996):

\[ r = 1 - \left(1 - \frac{A_2 - A_1}{A_1} \right)^{1/t} \]

Where \( A_1 \) = forest area at t1 (initial area), \( A_2 \) = forest area at t2 (final area), t = time difference between t2 and t1 in years.

To estimate the degree of accuracy in our satellite classification maps we compared the classification values obtained from our most recent image (i.e. 2011) with the actual cover type recorded in the field. First, to assess the number of validation points needed for a high degree of accuracy (> 85% concordance), we pre-sampled 50 randomly selected sites within our study area, visiting them between February and March of 2014. This allowed us to estimate the proportion of concordances (p) and number of discrepancies (q) between the value indicated in the classified image of 2011 and the real cover type verified on the ground in 2014, by applying the following formula (Chuvieco, 1991):

\[ n = \frac{z^2pq}{E^2} \]

Where n = number of sampling points, z = abscissa of the normal distribution curve for a given probability value, p = proportion of concordances, q = proportion of discrepancies (q = 1 − p), E = allowed error level (± 5%).

Based on this pre-sampling of 50 points (which indicated an accuracy of 0.88) it was determined that 162 validation points were needed to attain a high level of accuracy in our classification. The 162 randomly selected points spread throughout the study area were used to estimate the Cohen-Kappa index of concordance, where values approaching 100 are very accurate. For earlier images (i.e. those older than 2011) we used the same 162 points to estimate their accuracy following the procedure of Campbell et al. (2015). Data were arranged in a confusion matrix, with observed land cover classes (verified forest and non-forest cover) from the ground as columns and satellite classes (classified as forest or non-forest) as rows. The Kappa (k) index formula is (Cohen, 1960):
To identify possible drivers of forest change in our study area we used a logistic regression model (Ludeke et al., 1990). Our maps derived from Landsat imagery were used to identify areas with loss (deforestation) or gain (reforestation) of forest cover versus areas of no change (sensi Echeverría et al., 2008), for the periods 1993–1998, 1998–2003 and 2003–2011, producing a transition map of deforestation and another of reforestation for each period. We were unable to include the period 1986–1993 in this analysis because we did not have enough information at the required spatial resolution prior to 1990. In each of the transition maps a total of 200 points were randomly selected with a minimum separation of 1.5 km in order to minimize spatial autocorrelation (assessing their spatial independence with Moran’s I). A total of 15 biophysical and socioeconomic variables were explored as possible drivers of change (deforestation or reforestation); including elevation (m a.s.l.), slope (0–90°), aspect (0–360°), average annual precipitation (mm), population density (# inhabitants/km²) at the initial and final time of each transition, population growth rate, marginalization index, land tenure (communal ejido vs. other types), distance to nearest: nucleus zone, locality with more/less than 300 inhabitants (i.e. average size of towns within the LBTR), road (paved and unpaved), forest edge and permanent river. To avoid multicollinearity we used a Spearman’s correlation analysis between all pairs of explanatory variables to ensure that they were not correlated. Since none of the 15 selected variables were autocorrelated we used all of them in a multiple stepwise regression for deforestation and another for reforestation, including in the final model only those that had a minimum value of $P < 0.10$. The models were evaluated using the area under the ROC curve (AUC) of forest change, following Gorsevski et al. (2006).

Elevation, slope and aspect were calculated using a digital elevation model (DEM) with a 15 m/pixel resolution (National Institute of Statistics, Geography and Informatics; INEGI). Average annual precipitation was calculated using an interpolated map (IDW method with 28 nearest neighbors and a power of 2) with data from meteorological stations with > 32 years of data (CONAGUA, 2017). Population density was interpolated from localities registered in the INEGI censuses of 1990, 1995, 2000, 2005 and 2010, and population growth was based on the same INEGI censuses. Marginalization index per locality was interpolated (IDW method) with data from the National Population Council (CONAPO) for 1995, 2000, 2005 and 2010. Land ownership was reported as a binary value for ejidos (1) or other (0) using data from the National Agency for Agrarian Reform (RAN). Distances in m to different map attributes were calculated as Euclidian distances from our forest cover maps from 1993, 1998, 2003 and 2003. Distance to roads (paved and not paved) was calculated from topographic maps (1:50,000) from INEGI and distance to the nearest nucleus zone was calculated from the reserve delimitation by CONANP (D.O.F., 1998). The distance to settlements with more than or less than 300 people was calculated using INEGI’s census data for each locality.

### 2.5. Forest cover change predicted for the year 2025

The area and distribution of forest cover in the LTBR for the year 2025 was predicted using cellular automata (CA) and Markov chains in Idriisi SELVA (Clark Labs, 2009). A “CA–Markov” model is a robust approach in the spatial and temporal modeling of land use changes (Kamusoko et al., 2009; Sang et al., 2011) whose accuracy for future predictions of change has been demonstrated in different studies (Araya and Cabral 2010, Guan et al., 2011; Behera et al., 2012). The analysis assumes that the future state of a given object (i.e. a pixel on a map) can be predicted based on its behavior between two past events (Irwin and Geoghegan, 2001). Our approach had two parts: a) Markov chains; a stochastic statistical procedure that simulates the probability of change in a given time period on the basis of the preceding state; in our case, a matrix of observed transition probabilities between maps for 1998 and 2011 was used to project future changes from current patterns (López et al., 2001; Sang et al., 2011). Thus, the stochastic Markov model alone lacks knowledge of spatial dependency and can predict a pixel into a
class different from surrounding pixels (salt and pepper effect) where this is not likely to occur. This effect was reduced with the second part of our approach: b) Cellular Automata (Rosin, 2006; Clark Labs, 2009; Selvapeter and Hordijk, 2009; Behera et al., 2012), which we employed to predict the future state of cells (i.e. pixels) based on the state and trends of their neighbors. The cellular automata use the transition areas and the conditional probability to predict land cover change over the period specified in the Markov chain analysis. Then a 5 x 5 Gaussian contiguity filter (Clark Labs, 2009) was used to develop a spatially explicit contiguity-weighting factor to decide the state of cells (change or no-change) based on their neighbors.

3. Results

3.1. Forest cover change

The satellite image classification of forest cover for all of the dates studied had an overall accuracy (i.e. concordance index) of more than 90% between the points verified in the field and the image classification. For the 25 year period covered by this study (1986–2011) the net area of forest lost was 20,732 ha, with a total annual deforestation rate of 1.1%. For the twelve years prior to the LBTR decree (1986–1998), the annual deforestation rate was 2.3% within the area that later became the reserve. During the five years that followed the federal decree (1998–2003), the annual rate of deforestation was negative: –1.8%; i.e., there was an increase in the forest cover area due to forest regeneration within the reserve. However, from 2003 to 2011 forest loss increased again, rather than recovering, with an annual rate of deforestation of 1.0%.

The most forest was lost from 1986 to 1993 (Table 1), with 13,064 ha of forest cut (1866 ha per year). In 1993 the total area covered by forest was almost 73,000 ha (46.9% of the LTBR area), and by 1998, when the reserve was created, had decreased to approximately 65,000 ha (41.6%) of the LTBR. Overall, from the date that the LTBR was established in 1998 to the last year of this study in 2011, the area covered by forest was greater than 65,000 ha with some oscillations, and the losses and gains of forest within the reserve resulted in a total net gain of 597 ha (46 ha gained per year) in the 13 years that followed the decree.

The probability of transition from forest cover to non-forest was highest for the earliest two transition periods (1986–1993 and 1993–1998) in our study, with both higher than 0.2 (Fig. 2). The spatial distribution of deforestation clearly differed during these two periods, as it was more intense on the Atlantic slope or watershed to the N and NW of the two highest volcanoes in the region (San Martín Tuxtla and Santa Marta) from 1986 to 1993 (Fig. 2a). From 1993–1998 deforestation was more intense in the eastern and southeastern parts of the reserve, between the Santa Marta and the San Martín Pajapan volcanoes (Fig. 2b), occurring on both watersheds (i.e. the Atlantic and continental slopes). The probability of transition from forest to non-forest was lowest during the first 5 years after the decree (1998–2003), and at the same time the transition from non-forest to forest (reforestation) was the highest (Fig. 2c). Although some of the reforestation transitions during this period occurred in the nucleus zones, most took place within the buffer zone, widely spread around the three nucleus zones. A noticeably different trend occurred during the same period and is clearly visible within the compact area of the buffer zone that is closest to the three main cities of the region, south of the San Martín Tuxtla volcano, where there was almost no change in forest cover (i.e. imperceptible deforestation or reforestation). For the last of the transition periods included in our study (2003–2011) the probability of change from forest to non-forest increased again, with a value approaching 0.2. Most of the deforested areas were located within the buffer zone of the reserve (Fig. 2d).

For 2011, the most recent year included in our study, 45% of the total area that still had forest cover within the reserve was located inside the three nucleus zones, which together represent only 19% of the LTBR area. Before the federal decree (1986–1998), the areas that were designated in 1998 as nucleus zones lost 2662 ha of forest over 12 years due to deforestation, and in the 13 years after the decree (1998–2011) 1167 ha was deforested inside the same areas. In other words, deforestation in the nucleus zones was almost halved after the 1998 decree. Within the nucleus zones a particularly sharp contrast was detected in the 5 years prior to the decree: between 1993 and 1998 a total of 1833 ha of forest was lost by deforestation in what was to become the nucleus zones. After the decree, between 1998 and 2003, a total of 1132 ha was reforested inside the three nucleus zones over 5 years. During that same 5 years slightly more than 5000 ha were also reconverted to forest (i.e. forest regeneration) within the buffer zone that surrounds the three nucleus zones (see some examples in detail in Figure A.1).

3.2. Drivers of forest change

The logistic regression showed that before the LTBR decree (i.e. the transition from 1993 to 1998), there were some social as well as biophysical variables that had a significant relationship with reforestation or deforestation (Table A.1); however, for the periods following the decree (1998–2003 and 2003–2011) only biophysical variables were significantly related with forest loss (deforestation) or gain (reforestation). Social variables related to forest cover change before the decree were marginalization, which had a positive relationship with deforestation, and land tenure, which was positive for both deforestation and reforestation (i.e. both were higher within ejidos than in other types of land tenure). During the five years that followed the decree (1998–2003) the distance to the nearest forest edge and to the nearest nucleus zone were significant in both the deforestation and the reforestation models, along with elevation for the deforestation model and precipitation in the reforestation model, respectively. For the period 2003–2011 both of the distance variables mentioned, together with slope, were significant in the deforestation model, whereas for this period only elevation and slope were significant in the reforestation model.

3.3. Future prediction of forest cover change for 2025

Our prediction for 2025 suggests that if the post-decree trends in land use and cover change continue as documented between 1998 and 2011, then by 2025 only 56,250 ha (36.4% of the LTBR area) will still be covered by forest within the reserve. That is, if post-decree trends continue unchanged then we could lose ca. 9000 ha of forest by 2025 within the LTBR. If current trends continue we estimate that the areas with forest cover in 2011 have an 81.7% probability of permanency or no change in forest cover projected to 2025, while the probability of future deforestation is 18.3% (Fig. 2e). The greatest loss of forest cover is predicted to occur within the buffer zone, which is also predicted to have the greatest area of forest recovery (i.e. reforestation), though the area recovered would be much smaller than the area cut. Our prediction
also shows that in 2025 the largest areas of continuous forest cover will be located inside the three nucleus zones.

4. Discussion

Our results show that the 1998 federal decree of the Los Tuxtlas Biosphere Reserve (LTBR) had a positive effect in that it slowed down and even reversed deforestation within the reserve. During the 12 years that preceded the decree (1986–1998) a total of 21,330 ha of forest were cut (1777 ha deforested per year) within the area that became the LTBR, while during the 13 years that followed the decree (1998–2011), deforestation not only decreased but there was a total net gain of nearly 600 ha of regenerated forest (46 ha reforested per year), though deforestation did not stop completely. The positive effects of the reserve were most clearly evident in the first 5 years after the decree, when 8060 ha of non-forest were re-converted to forest (i.e. young secondary forest), and less than 2000 ha of forest was cleared. This brief period (1998–2003) was the only time when reforestation exceeded deforestation within the reserve.

The annual national deforestation rate in Mexico between 1976 and 2000 was 0.51%, and rose to 1.3% between 1993 and 2000 (Mas et al., 2004). In our study area we estimated a deforestation rate of 2.3% between 1986 and 1993 and between 1993 and 1998; almost four times higher than the lowest national rate. Previously, in the northern region of the Los Tuxtlas volcanic range around the San Martín Tuxtla Volcano, Dirzo and García (1992) estimated a deforestation rate of 4.2% between 1967 and 1986. This much higher rate in the 20 years that preceded the first date of our study coincided with the creation of new roads in the lowlands of the Atlantic slope, N and W from the S.M. Tuxtla volcano and was also marked by notable immigration into the region (Dirzo and García 1992). Additionally, this is the period when cattle ranching began to displace slash and burn agriculture as the main economic activity in the area (Guevara et al., 2004). The National Commission for Protected Natural Areas (Comisión Nacional de Areas Naturales Protegidas, CONANP) also estimated deforestation rates between 1980 and 1996 to be approximately 2% within the reserve, and the rate slowed to less than 1% after the decree (Velazco Tapia 2007; PSSM-CONANP, 2011). In the years following 2000 these authors report a net gain of 1000 to 1500 ha of forest (regeneration) within the reserve, but for 2007–2011 they reported a net loss of close to 1000 ha of forest (PSSM-CONANP, 2011). The reliability of the maps from these studies is unknown as the description of their methods of ground verification were incomplete. Velazco Tapia (2007) used only 19 verification points for the whole reserve, while the PSSM-CONANP report (2011) does not include any ground-truthing method at all. Our study is the first to report forest change for the entire area of the LTBR with intense ground-truthing, and very high map accuracy (confidence > 90%).

4.1. Causes of forest cover changes

The results of the logistic regression analysis show that distance to forest edge was an important explanatory variable for both reforestation and deforestation during most of the transition periods studied. Forest felling proceeds from the open areas into the edge of forested areas and this explains the significant and negative relationship between deforestation and distance to the forest edge over all periods. Previous studies also found that deforestation increases in areas near the edge of the forest (Skole and Tucker, 1993; Ranta et al., 1998; Cochrane, 2001).

In the case of reforestation we also found that open areas near the forest edge were more likely to regenerate a secondary forest in a short time span, and most tropical studies have found that forest succession rate declines with increasing distance from the forest edge (Nepstad et al., 1996; Kolb 1993; Scot and Duncan 2000). For the first five years following the LTBR decree (i.e. 1998–2003), all over the buffer zone we
detected a relatively high rate of reforestation in areas that were very close to the edge of forest fragments or forested riparian belts (Fig. 2c and Fig. A.1). Reforestation within the LTBR was more likely to occur in areas near a forest edge with high precipitation but that were also far away from the nucleus zones (Table A.1). It is well known that establishment success and growth of woody plants is higher in more humid areas and this was particularly favored close to forest edges after the decree. However, the relationship of reforestation and deforestation with distance to the nearest nucleus zone is not easy to understand; our results indicate that areas near the nucleus zones or within them were more stable and less likely to change than areas far away from the nucleus zones, but we are not clear about the reasons for this. The notable reforestation during this period is strong evidence that it is not only possible to reverse forest loss within the ample buffer zone of the LTBR, our results also suggest that it is also still relatively easy to achieve by promoting passive restoration.

The temporal variation in the annual rate of deforestation in Los Tuxtlas could be related to variations in the number of inhabitants living in the region and its surroundings resulting from socio-economic factors that cause immigration and emigration from the area. Deforestation is expected to increase with population growth as more inhabitants convert forest for agricultural use (Cropper et al., 1997; Jha and Bawa, 2006; DeFries et al., 2010); however, our results show that changes in forest cover within the LTBR after the decree of 1998 were not related to any of the socio-economic variables that we used, not even population density or growth (Table A.1). Even when taking into account data for cities and towns outside of but near to the limits of the LTBR from the official census data for all of the municipalities in the region, there was no positive relationship between population growth and deforestation in the area over the course of the period we studied (Von Thaden, 2014). In fact, the INEGI (1995, 2000, 2005, 2010) census data shows the opposite: between 1995 and 2000 the population of the municipalities that form part of the LTBR increased by 4.9% while deforestation was slowing down; then, during 2005 and 2010 the population decreased by 8.9% but deforestation was again increasing between 2003 and 2011.

The main economic activity in Los Tuxtlas from the 1970s to the present has been cattle ranching, so man-made pastures are the most common type of land use in the region (Guevara et al., 2004; Guevara and Laborde 2014; Von Thaden, 2014). Cattle production in the state of Veracruz has increased considerably since the 1980s. Close to 36,000 tons of beef was produced in 1986 and this increased to almost 80,000 tons in 2003, an increase that was achieved by the extensive conversion of tropical forest into pastures across the entire state. Meat production peaked in 2003 and since then has been decreasing steadily (e.g. 50,000 tons were produced in 2011; SIAP, 2013). The decrease and reversal of deforestation in the LTBR after the 1998 decree (Fig. 2c) occurred when meat production in Veracruz was still increasing and therefore cannot be explained by lower beef production. Moreover, after 2003 when meat production was decreasing in Veracruz, deforestation within the LTBR increased again, though not as much as before the decree.

One possible explanation for the decrease in deforestation within the reserve is the topography and inaccessibility of the sites covered by forest. These sites are associated with the peaks of the volcanoes, have steep slopes and are far away from main roads (Dirzo and García 1992; Mendoza et al., 2005; Guevara et al., 2004). This does not, however, explain the reversal in deforestation (i.e. reforestation) that occurred after 1998. We would also like to mention that within the LTBR there are plenty of pastures and crop-fields on steep slopes and in remote locations, so topography and site accessibility do not fully explain the trends in forest cover after 1998. Since 2003 however, the slope and the elevation of the terrain has been having a more important effect on forest change dynamics (Table A.1), with more level or flatter areas having a highly dynamic nature between deforestation and reforestation, while the relatively few open areas that were reforested between 2003 and 2011 were mainly located at low elevations.

### 4.2. Conservation policies in the LTBR related to forest change trends

The slowing down and brief reversal of deforestation after 1998 were very likely the result of decisive and effective conservation efforts that had started before the federal decree, and that became more viable because of the decree and were enhanced by it. Particularly between 1996 and 1998 several towns, mainly in ejidos, started to implement different means of resource use and production that did not include forest felling, some of these included communal agreements to respect forested areas as reserves (Fuentes, 2011), such as in the following communities: cerro del Marinerio (100 ha, 1997), Mecayapan (100 ha, 1998), Benito Juárez (25 ha), Tatalucaipan (52 ha, 1996), La Perla de San Martín (512 ha, 1998), Venustiano Carranza (50 ha, 1996) and Ruíz Cortínez (288 ha, 1996). Some of these areas were recognized as reserves even by the regularization program carried out by the state and federal government (Programa de Certificación de Derechos Ejidales y Titulación de Solares; PROCEDE). Additionally, different government agencies such as SEDESOL (Secretaría de Desarrollo Social), SEDAP (Secretaría de Desarrollo Agropecuario y Pesquero) and PROAFT (Programa de Acción Forestal), together with local NGOs such as PSSM (Proyecto Sierra Santa Marta, A.C.), carried out focal projects that promoted the recovery of forest cover in some deforested areas. These actions that preceded the decree also contributed to the trends detected shortly after the decree.

Federal (mostly CONANP) and state authorities, working in conjunction with academics and local NGOs, were instrumental in convincing the local inhabitants and those living in neighboring towns and cities about the importance of stopping deforestation and of preserving the tropical forest of Los Tuxtlas. In 1998, CONANP opened a local office for the LTBR in the city of Catemaco, hired full-time personnel and acquired computers as well as five vehicles dedicated to implementing conservation and sustainable development plans in the reserve. A secure federal budget for the LTBR office in Catemaco, together with international funding from GEF and UNDP, was crucial for the implementation of management plans and conservation projects within the reserve (CONANP, 2006).

Another crucial aspect of the success of the LTBR decree was the prolific, high quality research on the biodiversity of Los Tuxtlas and its conservation, mainly done by public research centers in Mexico. The establishment of a biological research station by the UNAM national university (640 ha) in 1967 NE of the San Martín Tuxtla volcano and of another station by the Universidad Veracruzana state university (UV; 220 ha) in 1985 N of Lake Catemaco, greatly stimulated research in the region. Three books compiling the scientific knowledge of Los Tuxtlas biodiversity and ecology, deserve special mention for successfully spreading this knowledge not only among academics and students, but also among decision makers, members of NGOs and local inhabitants: Gómez Pompa and del Amo (1985); González-Soriano et al. (1997) and Guevara et al. (2004). They include studies by many of the researchers who have worked in Los Tuxtlas and made this information accessible to the Mexican public because they were published in Spanish.

The now extinct public research center, INIREB (Instituto Nacional de Investigación sobre Recursos Bióticos) participated actively in the protection of the forest on the peak of the San Martín Tuxtla volcano (1979) and that of the Santa Marta volcano (1980). Both of these loosely defined areas were properly delimited and incorporated into the current federal decree of 1998, which granted this area the highest possible level of protection under Mexican law, i.e. the category of biosphere reserve (Reserva de la Biosfera). From 1992 onward, several researchers from the INECOL, the UV and the PSSM NGO worked on the land use planning project for the Los Tuxtlas volcanic range, systematizing the cartographic, ecological and socio-economic information of the region, and providing the federal authorities with crucial information for the 1998 decree (Guevara et al., 2004; CONANP, 2006). Also, researchers at the INECOL working with federal and state authorities succeeded in getting the LTBR officially recognized and incorporated
into the international MAB-UNESCO Programme in 2006 (CONANP, 2006; UNESCO, 2006). Several local inhabitants and NGOs started projects and small protected patches within the buffer zone of the LTBR in order to further sustainable eco-tourism, restoration and conservation efforts (CONANP, 2006). These efforts along with funding from national (e.g. CONANP, SEMARNAT, state of Veracruz government) and international agencies (e.g. PNUD and GEF) were crucial to slowing down the deforestation and briefly reversing it after 1998. Unfortunately, during the last period of this study (2003–2011) deforestation in the LTBR increased again, occurring mainly within the buffer zone. Most of the areas deforested over this period were relatively young secondary forests or were part of narrow forested belts associated with permanent rivers.

4.3. Future forest change

If the trends in forest cover change that were prevalent before 2011 are allowed to continue into the future then we predict a substantial loss of forest cover by 2025; a loss of almost 9 thousand ha (8850 ha), or 14% of the forest cover present in 2011 (Fig. 2e). Our projection also shows that the three nucleus zones are not expected to be affected by deforestation or, if affected, the damage they sustain is expected to be minimal up to 2025 (4% of forest cover loss). This, however, only holds true if the current ban on cutting trees within the nucleus zones is enforced effectively into the future. The long term preservation of forest cover within the buffer zone, together with long term reforestation projects within this zone must be top priorities in the LTBR management plan. Their implementation and support are urgently needed. It is imperative to preserve the current patches of forest within the buffer zone and locate any areas that can be successfully reforested. These likely include pastures and crop fields with low productivity and that are located on steep slopes close to the seed sources of native tree species, and river banks which can be reforested and their forested belts widened. Additionally, economically sound alternative silvo-pastoral practices that use native tree species in active pastures, as part of riparian belts, living fences and as isolated shade trees should be favored within the buffer zone, in order to increase landscape connectivity and forest resilience.

5. Conclusions

The 1998 federal decree of the Los Tuxtlas Biosphere Reserve decelerated deforestation within the reserve’s buffer zone and almost completely halted forest loss inside its three nucleus zones. Shortly after the decree, a considerable area of open spaces located throughout the LTBR, including its buffer zone, were reconverted to forest, but regrettably this trend did not continue. Frequent monitoring and strict law enforcement have been successful in the preservation of forest cover within the nucleus zones. However, within the buffer zone forest felling increased again recently and this trend must be not only stopped but reversed as occurred in the early years after the decree. Our results show that stopping and even reversing deforestation within the buffer zone of the LTBR is still highly feasible but we must act soon, otherwise large open areas that are completely devoid of trees will increase in size around the forested nucleus zones and this will decrease landscape connectivity and forest resilience within the reserve. These detrimental effects within the buffer zone of the LTBR will not only erode the potential for the long term conservation of the native forest flora and fauna of Los Tuxtlas, but will also compromise the potential for adaptation and mitigation of future climate change within this still highly biodiverse volcanic range.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2017.12.040.

References


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