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Article

Cambios en la cobertura y uso del suelo en la región del Soconusco, Chiapas

Land cover and land use change in the *Soconusco* region, state of *Chiapas*

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Resumen

El Soconusco se caracteriza por ser una de las regiones agrícolas más productivas del estado de Chiapas, en la que aún se conservan zonas de alta biodiversidad amenazadas por el cambio de uso del suelo. El objetivo de este trabajo fue analizar las trayectorias del cambio en la cobertura y usos del suelo en tres cuencas de dicha región durante un período de 25 años. Se clasificaron imágenes de satélite de 1990, 2000 y 2015. Los resultados mostraron una significativa pérdida de la vegetación natural (bosques, manglares y vegetación secundaria), además de la expansión de los asentamientos humanos. Se identificaron procesos diferentes de cambio en cada uno de los paisajes evaluados: Costa, Planicie y Sierra. En la Planicie, el cambio de uso de suelo predominante fue la sustitución de cultivos básicos por plantaciones agrícolas. En los paisajes de Sierra y Costa, donde hay remanentes importantes de bosques, el cambio más evidente fue la deforestación. A pesar de que en la región se registraron fuertes incrementos en la densidad poblacional y en las áreas urbanas, las zonas dedicadas a la producción de cultivos básicos se han mantenido sin modificaciones. El patrón de cambios en la cobertura de suelo indica que la región de estudio está en un proceso de intensificación de la agricultura y de la urbanización.

Palabras clave: Deforestación, intensificación de la agricultura, palma de aceite, pérdida de sistemas agroforestales, urbanización, uso de suelo.

Abstract

The *Soconusco* region is described as one of the most productive agricultural regions in the state of *Chiapas*, where high biodiversity areas threatened by land use change are still preserved. The objective of this work was to analyze the trajectories of land cover and land use change in three watersheds in this region over a 25-year period. Satellite images from 1990, 2000, and 2015 were classified. Results show a significant loss of natural vegetation (forests, mangroves, and secondary vegetation) and the expansion of human settlements. Different processes of change were identified in each of the assessed landscapes: Coast, Plain and Highlands. In the Plain, the predominant land use change was the replacement of basic crops by agricultural plantations. In the Highland and Coast landscapes, where significant forest remnants are found, the most evident change was deforestation. Although the region experienced strong increases in population density and growth of urban areas, the areas dedicated to staple crop production have remained unaltered. The pattern of land cover change indicates that the study region is undergoing a process of agricultural intensification and urbanization.

Key words: Deforestation, agricultural intensification, oil palm, loss of agroforestry systems, urbanization, land use.

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Introduction

Changes in land cover, particularly due to deforestation, and changes in land use (CLU) are some of the processes that contribute to global climate change, local loss of biodiversity, and increased vulnerability to natural disasters (Cochard and Delzon, 2013; Newbold *et al.*, 2016).

From 1990 to 2000, Mexico exhibited deforestation rates close to 190 000 ha yr⁻¹. This figure has decreased slightly in recent times, so that, from 2010 to 2015, decreases in tree cover of nearly 149 000 ha yr⁻¹ were recorded (FAO, 2015). Agricultural uses have also changed; many rural landscapes in developing countries show evidence of the loss of traditional agriculture in favor of more intensive land uses, largely driven by the demand for raw materials (Vliet *et al.*, 2012).

In the specialized literature, the causes of land cover and land use change are classified into two main groups called direct factors or proximate causes, and root or indirect factors, or underlying causes (Challenger and Dirzo, 2009; Rautner *et al.*, 2013). Proximate causes refer to activities that have a direct effect on land cover and land use, *e.g.* expansion of livestock or of the agricultural frontier; whereas, underlying causes correspond to forces operating in a broader context, generally external to the study area, but affecting the decisions made by local actors (Klooster, 2003; Grau y Aide, 2008; Defries *et al.*, 2010).

In a meta-analysis of deforestation in the tropics, Geist and Lambin (2002) conclude that shifting agriculture and population growth are the most frequently cited proximate factors. However, it is very difficult to generalize about the processes that lead to the loss of tree cover, due to the socio-environmental particularities of each region (Corona *et al.*; 2016; Calzada *et al.*; 2018).

Land cover maps and analysis of production statistics can suggest hypotheses regarding the role of factors related to land cover change and the nature of the associated underlying causes (Park and Lee 2016; Ayandale and Howard 2017). However, for a good interpretation of these changes, it is advisable to have maps with a thematic and spatial resolution in order to capture the processes of interest. This is particularly desirable in regions with complex

landscapes, *i.e.* regions with a rugged relief, or where the intense land-use changes result in a diverse, dynamic landscape.

The object-based approach to satellite image classification has been relevant because it allows the integration of contextual information and expert knowledge into the analysis (Flanders *et al.*, 2003), avoids the presence of isolated pixels (salt and pepper effect) and establishes relationships between objects in the image and the features of the terrain. The first stage of object classification is segmentation, *i.e.* the delimitation of discrete regions with pixels that have relatively similar values (Gao, 2009). In a second stage, labels or classes are assigned to the segments by means of one of the available classifiers.

In the present work, the object-based classification approach was applied to obtain land cover maps for three years (1990, 2000, and 2015) of an area with intense land-use change dynamics. The objective was to identify trends and spatial patterns of land-use change over a 25-year period.

Materials and Methods

Study area

The *Soconusco* economic region is located in the south of the state of *Chiapas*, in the *Mazatán*, *Tapachula*, *Tuxtla Chico*, *Frontera Hidalgo*, *Suchiate*, *Metapa* and *Cacahoatán* municipalities; together, the seven municipalities have a total area of 2 032 km² and cover three river basins: those of the *Coatán*, *Cahoacán* and *Puerto Madero* rivers (Figure 1). The area is located in an altitudinal range of 0 to 4 100 m, including mountain ranges, hills and alluvial plains (INEGI, 2001). The predominant climates are warm sub-humid, and humid temperate. The combination of altitudinal and climatic elements gave rise to a wide variety of ecosystems, including mangrove swamps in the alluvial plains; medium sub-evergreen forests in the midlands and hills, and mesophilic mountain forests and pine forests in the highlands. It also favored an optimal development of agricultural and livestock activities; coffee, mango and banana crops occupy an important portion of this territory and are among the most commercialized crops both nationally and internationally (Flores, 2019).

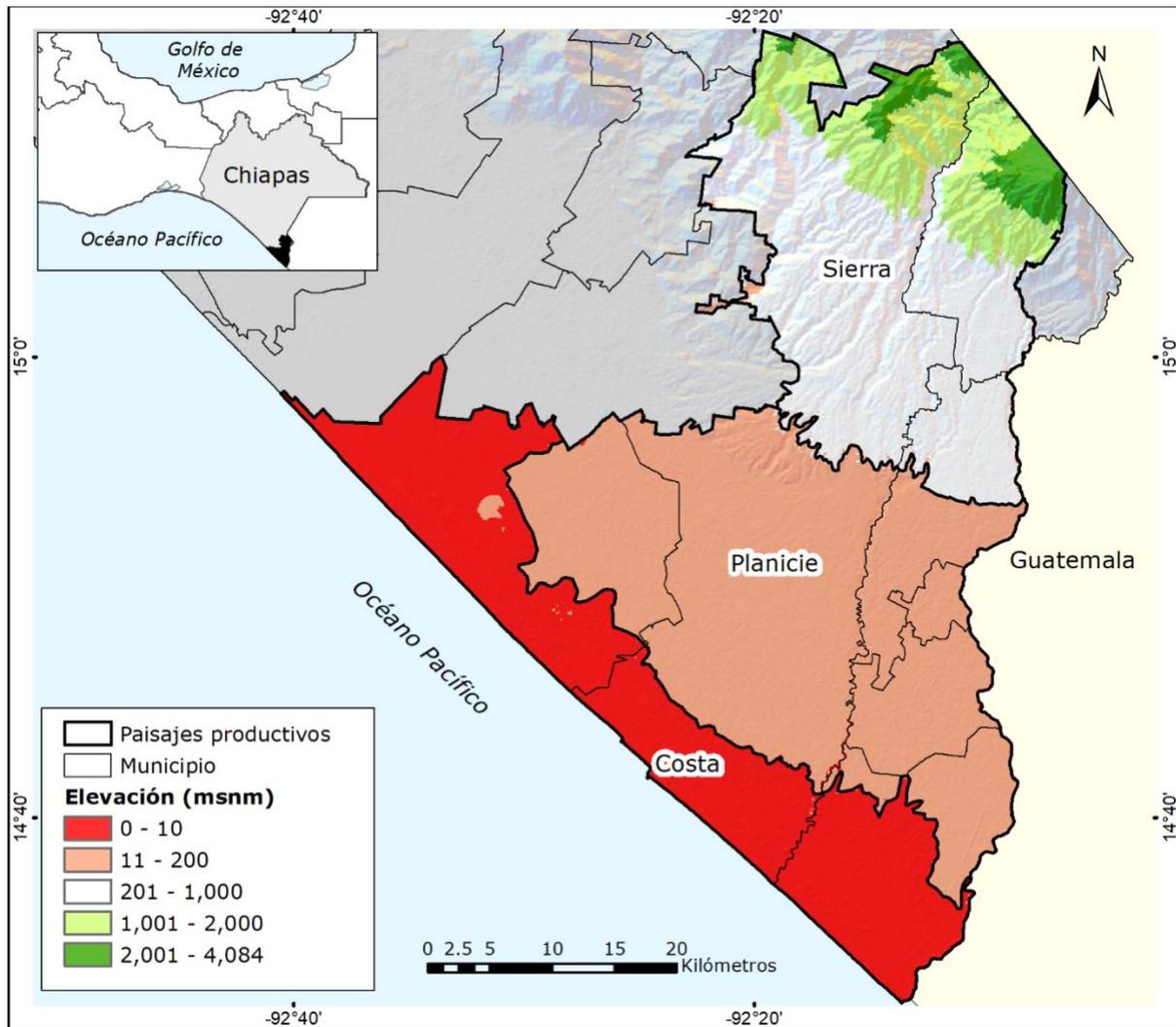


Figure 1. Location map of the study area.

Satellite image classification

Three land cover and land use maps corresponding to 1990, 2000 and 2015 were produced; in their construction process, first an automated classification and a photointerpretation classification were carried out.

Three Landsat images downloaded from www.glovis.usgs.gov, whose acquisition dates corresponded to the dry season (January to April), were used to obtain cloud-free scenes (Path 021, Row 051): Landsat 5 TM 10, January 1990; Landsat 7 ETM,

February 15, 2000, and Landsat 8 OLI 15, April 2015. Orthophotos from 1996, a digital altitude model with a pixel size of 30 m, and high-resolution images from the Google Earth platform were used as support material. Additionally, from March to May 2015, field trips were conducted at 100 control sites, selected according to fully targeted criteria, to obtain sufficient information to define the training samples with which the classification algorithms were calibrated. The information collected at each site was as follows: 1) geographic position in UTM coordinates (determined with a Garmin eTrex20x GPS navigator); 2) type of land cover and land use; 3) terrain exposure (determined with a compass, Naturehike, modelo NH15A003-E), and 4) photographs of the site (taken with a Canon Powershot Elph 18 camera). Field data were also utilized to determine the legend of the maps (Table 1).

Table 1. Description of the legend used for satellite image classification and interpretation.

General categories	Land cover and land use types	Description
Natural and semi-natural vegetation	Forests	Arboreal vegetation in a good state of conservation. It includes the Mesophilic Mountain Forest, Coniferous Forest and the Sub-evergreen Tropical Forest
	Mangrove	Arboreal vegetation resistant to saline conditions typical of land-sea transitions.
	Hydrophilic Vegetation	Non-woody vegetation associated with water bodies, including reed beds
	Disturbed forest	Includes areas of secondary arboreal vegetation (<i>acahuales</i>), disturbed forests and coffee agroforestry systems under shade.
Plantations	Coffee	Coffee plantations that do not use shade trees.
	Mango	Agricultural plantation
	Banana	
	Palm oil	
Crops	Crops	Agricultural land uses including rainfed crops, irrigated crops, cultivated pastures.
Human settlements	Human settlements	
Water bodies	Water bodies	
Others	Without apparent vegetation	Areas where there is no apparent vegetation cover on the ground surface. Mainly sand banks and roads.

An object-oriented approach was used for the supervised classification, which consists of two stages: in the first stage, the image was divided into a series of regions (segments or polygons), and in the second, identifiers were assigned according to the land-cover types described in the text at the foot. For the creation of the segments, the spectral and spatial characteristics of the image were considered together; the edge algorithm of ENVI 5.1 (ENVI, 2015) was used; this algorithm requires the calibration of two parameters: "Scale level" and "Merge level", which range between 0 and 100. The scale level controls the size of the segments, while the merge level allows merging similar adjacent segments.

Tests were performed with different values for the two parameters. The combination of Scale Level = 50 and Merge Level = 80 was the one that visually produced the segments of the most adequate size, i.e., segments that clearly delimited the stands by maintaining a minimum number of these.

A post-processing phase was applied to the maps resulting from the supervised classification of the images for the three years (1990, 2000, and 2015), in order to identify the types of agricultural plantations, such as oil palm, banana, and mango. In this phase, the 1996 orthophotos, Google Earth images, and data from field trips were used as support material.

In order to obtain an estimator of the level of thematic error in the maps, a stratified random sampling design was used; 100 sampling points or sites were spatially distributed over the entire study region; in each of these, the type of land cover and land use were photo-interpreted with high-resolution images from Google Earth™. This data set was different and independent from the one used in the calibration of the classifiers. The error was calculated by comparing the degree of coincidence between the sampling sites and the map generated from the supervised classification, according to the analysis methodology proposed by Olofsson *et al.* (2014). The thematic error estimation was applied only to the 2015 map, as the availability of high-resolution imagery for the years, 1990 and 2000, was limited.

Characterization of land-cover and land-use change

In order to obtain change matrixes, a map overlay analysis was carried out, using only two maps derived from the supervised classification, but grouped according to the general categories described in Table 1. The change matrixes obtained correspond to the complete 1990-2015 interval.

In order to have a clearer interpretation of the relevant changes and processes over the last 25 years, three landscapes were defined according to the characteristics of the relief and the productive aspects identified in the Basin (Figure 1).

The first landscape, the Coast, corresponds to the alluvial plains located at an altitude of 0 to 10 masl, characterized by the presence of wetlands. The predominant productive activity corresponds to livestock and, to a lesser extent, to agricultural plantations. The next landscape, the Plains, comprises mainly the areas located at 11 to 200 masl, with slight slopes; most of the agricultural activities —rainfed and irrigated agricultural crops, cultivated pastures and agricultural plantations of mango, banana and oil palm— are carried out here. Finally, the *Sierra* is located at altitudes between 201 and 4 100 m, where the terrain slopes are often steep; the prevailing physiography in this area favors the distribution of forest remnants, and conditions are favorable for coffee cultivation practiced as an agroforestry system or under shade.

Results

Classification of images

The overall accuracy of the 2015 map was 92 %, an acceptable level for land cover maps. Table 2 shows user and producer accuracy levels for each of the 2015 land cover classes. Most classes were identified as having a high reliability (accuracy ≥ 0.78), with the exception of Coffee Plantations, which often exhibited a spectral response similar to that of Disturbed Forest, resulting in low producer accuracy. Given the low level of estimated reliability, the coffee plantations may cover a surface area almost five times

larger than the one estimated by the classification; in spite of this, it was decided to keep these plantations as a separate class, given that their extension is minimal.

Table 2. Results of the accuracy assessment of the 2015 land-cover map.

Category	Cover	User accuracy	Producer accuracy	Original surface area (ha)	Adjusted surface area (ha)	Confidence interval
Natural and semi-natural vegetation	Forests	0.78	1	6 869	5 343	± 1 358
	Mangrove	0.83	1	7 464	6 220	± 2 438
	Aquatic vegetation	1	1	6 434	6 434	± 0
	Disburbed forest	0.83	0.9	60 490	56 186	± 20 644
Plantations	Coffee plantation	0.83	0.14	1 986	11 737	± 19 771
	Mango plantation	0.83	1	16 060	13 383	± 5 246
	Banana plantation	1	1	11 196	11 196	± 0
	Palm tree plantation	1	1	854	854	± 0
Crops	Crops	1	1	76 757	76 757	± 0
Human settlements	Human settlements	1	1	12 679	12 679	± 0
Others	Without vegetation	1	1	1 176	1 176	± 0
Water body	Water body	1	1	1 515	1 515	± 0

N = 100

It was not possible to assess the accuracy of the maps for the other two years (1990 and 2000) due to the scarcity of high-resolution images; moreover, the same training samples (or most of them) were used for all three images, and, therefore, a similar level of error was assumed for all three maps.

Table 3 summarizes the results of the satellite image classifications for 1990, 2000, and 2015. As may be observed, the Crops category (irrigated and annual rainfed crops and pastures) was the predominant one. This land cover had a consistent decrease in the 1990-2000 and 2000-2015 periods, but the largest decrease was recorded in the latter, reducing its occupation rate of 45 % of the area to 38 %. A similar behavior was observed in the category that includes natural and semi-natural land cover, although in this case the highest rate of loss occurred from 1990 to 2000.

Table 3. Surfaces of land cover types and land use in the study area in 1990, 2000 and 2015.

Categories of change	Land-cover types	1990		2000		2015		Rate of change in land use	
								1990-2000	2000-2015
		ha	%	ha	%	ha	%		
Natural and semi-natural vegetation	Forests	9 218	4.5	7 655	3.7	6 869	3.4	-1.8	-0.7
	Mangrove	9 071	4.4	7 654	3.7	7 464	3.7	-1.7	-0.2
	Hydrophilic Vegetation	6 741	3.3	6 116	3	6 434	3.2	-1	0.3
	Disturbed forest	66 099	32.4	62 047	30.5	60 490	29.7	-0.6	-0.2
Plantations	Coffee	246	0.1	778	0.4	1 986	0.9	12.2	6.4
	Mango	2 854	1.4	8 789	4.3	16 060	7.9	11.9	4.1
	Banana	8 694	4.3	9 766	4.8	11 196	5.5	1.2	0.9
	Oil palm	0	0	0	0	854	0.4		-100
Crops	Crops	93 637	45.9	91 780	45.1	76 757	37.7	-0.2	-1.2
Human settlements	Human settlements	4 011	1.9	6 377	3.1	12 679	6.2	4.7	4.7
	Without vegetation	1 814	0.9	1 230	0.6	1 176	0.6	-3.8	-0.3
Water body	Water body	1 289	0.6	1 473	0.7	1 515	0.7		

Agricultural plantations and other types of plantations exhibited a steady increase in the two periods under analysis. Regarding the last category, the accelerated growth of human settlements, which have doubled in size in the last 15 years, is noteworthy.

Processes of change by type of landscape

Figure 2 shows the spatial distribution of land cover changes for the three dates of analysis. The large growth of agricultural plantations, which includes not only an increase in the occupied area, but also a greater dispersion of the area, is noteworthy. The change in the size of the city of *Tapachula*, the largest human settlement in the area, is also noticeable.

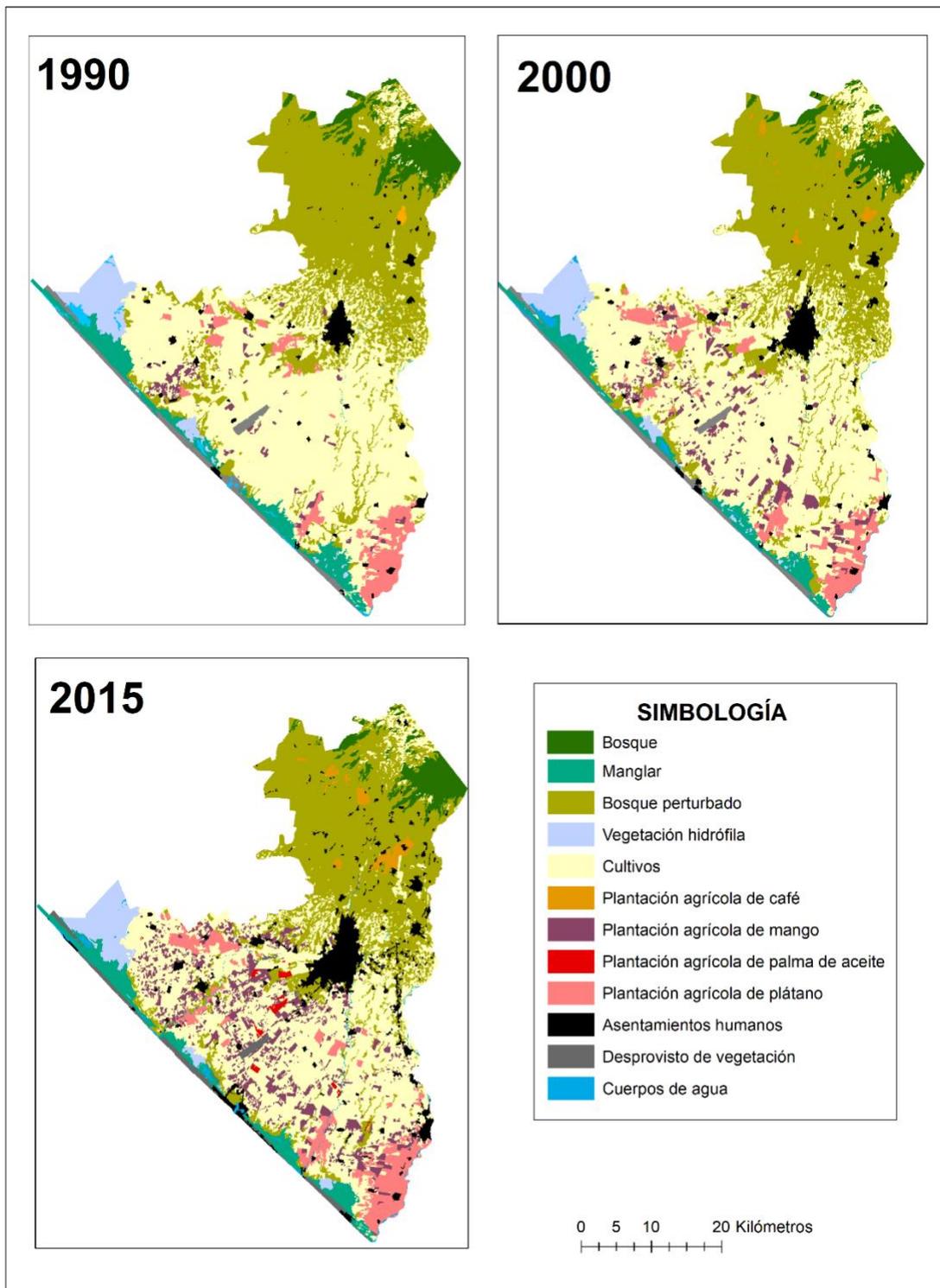


Figure 2. Spatial distribution of land cover and land-use 1990, 2000 and 2010.

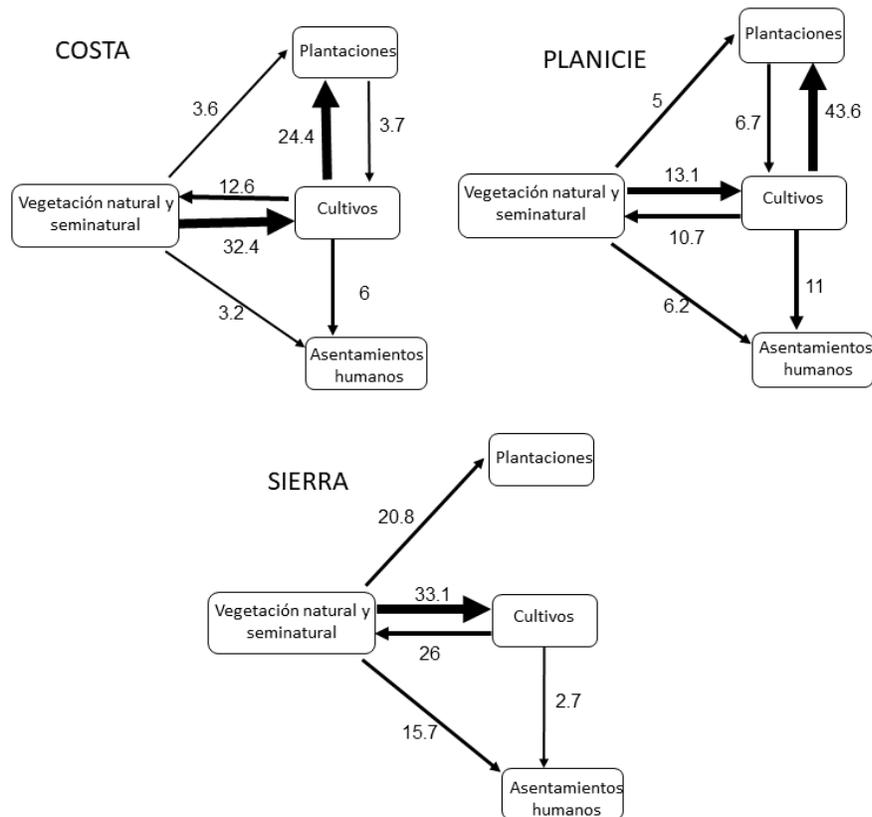
The change matrixes (Table 4) are the result of overlaying maps and provide information on losses and gains in land cover, but more importantly, they provide information on the transitions or types of land cover that replace the original one. Table 4 shows these matrixes for the three production landscapes; the figures represent hectares.

Table 4. 1990-2015 matrixes of change by type of productive landscape (ha).

		1990				
		Natural and semi-natural vegetation	Crops	Plantations	Settlements	Water bodies
Coast 2015	Natural and semi-natural vegetation	15 228	923	15	106	195
	Crops	2 371	6 953	274	196	9
	Plantations	262	1 789	2 041	14	2
	Settlements	231	439	22	1 049	39
	Water bodies	154	165	73	44	513
Plains 2015	Natural and semi-natural vegetation	6 791	3 925	330	19	0
	Crops	4 828	53 688	2 480	181	11
	Plantations	1 836	16 027	5 936	147	0
	Settlements	2 260	4 043	242	3 382	0
	Water bodies	100	201	105	2	67
Mountain range 2015	Natural and semi-natural vegetation	51 327	2 273	79	20	0
	Crops	2 896	2 809	0	1	0
	Plantations	1 818	1	159	5	0
	Settlements	1 374	234	6	556	0
	Water bodies	23	3	0	0	11

The columns show the categories at the beginning of the period, and the rows show the permanence (in bold) and the changes at the end.

Figure 3 is based on the data from the matrixes and schematically shows the dominant processes of change. On the Coast, the predominant changes were from Crops to Plantations (1 789 ha) and human settlements (371 ha). Natural vegetation exhibited losses and gains, but, in net terms, there was a decrease in these areas, which were occupied by Crops. According to Table 3 and Figure 2, the vegetation types affected were hydrophilic vegetation, mangroves and some remnants of disturbed forest.



Vegetación natural y seminatural = Natural and semi-natural vegetation; *Plantaciones* = Plantations; *Cultivos* = Crops; *Asentamientos humanos* = Human settlements.

The thickness of the arrow indicates the magnitude of change. Figures show the percentage contribution of each transition; the total (100 %) is the sum of all areas that underwent a change in coverage between 1990 and 2015. Only the main changes are shown.

Figure 3. Dominant processes of land cover change in the three productive landscapes, in the 1990-2015 period.

In the plains, the productive systems with the highest economic value for the *Soconusco* region are concentrated: mango, banana, and oil palm plantations, as well as the main population centers. The dominant process in this area was the

replacement of crops by plantations (16 026 ha).

In the *Sierra*, fragments with forest vegetation and coffee agroforestry systems predominate; the most reported changes were the substitution of natural and semi-natural vegetation by crops.

Discussion

Land cover and land use maps

The results of the maps show several aspects to be highlighted in the changes observed in the landscapes during the analysis period: deforestation, substitution of agricultural crop areas by plantations and the expansion of urban areas.

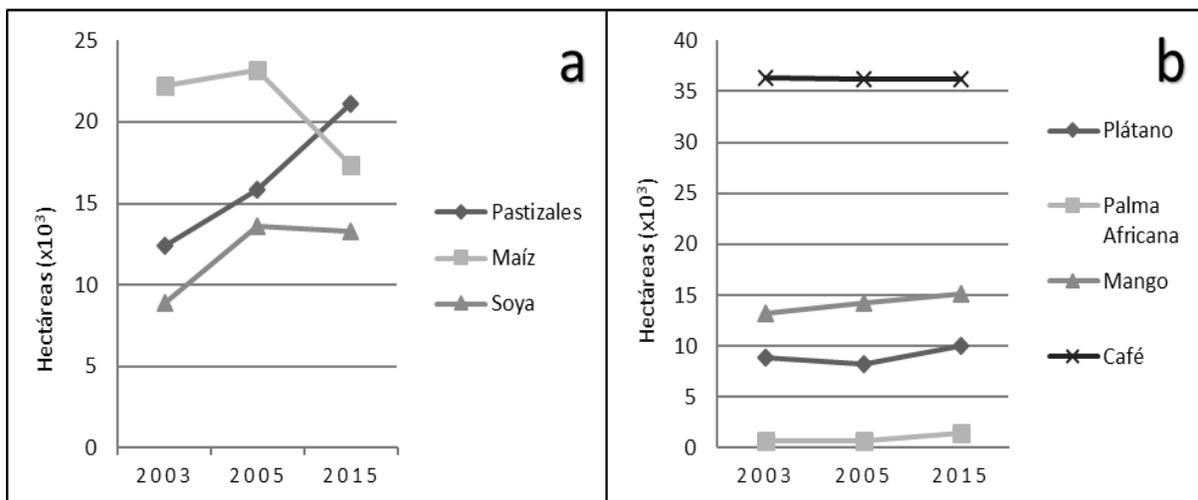
Deforestation is an important process in the study area, although not of the magnitude observed in other regions of the country (Ellis *et al.*, 2021). However, it did affect such vegetation types as mountain mesophilic forests and mangroves, which are crucial not only for their biological diversity, but also for their key role in mitigating climate change (Adame *et al.*, 2018).

Frequently, research carried out at the international (Bürgi *et al.*, 2004; Belay y Mengistu 2019; Tuffour-Mills *et al.*, 2020) and national levels (Rosete *et al.*, 2008; Mas and Flamenco, 2011; Calzada *et al.*, 2018;) agrees that the main processes of change are due to the conversion of forests and secondary vegetation to agricultural and livestock uses. In this region, due to its climatic characteristics, another process has also occurred: deforestation from the loss of shaded coffee agroforestry systems.

Given their moderate environmental impact, it has traditionally been considered that coffee agroforestry systems can coexist in high biodiversity regions, which contributes to their conservation. However, a fragile balance in which grain prices (Jurjonas *et al.*, 2016) and pests (Henderson, 2019) trigger the loss or degradation of forest cover underpins the permanence of these systems. The growth of coffee plantations without shade may be a response to the phenomenon observed by Henderson (2019) in other

regions of *Chiapas*, where, in order to fight rust, coffee varieties that are sensitive to this fungus have been replaced by others with greater resistance, but which do not require the shade of trees.

The replacement of agricultural crop areas with plantations was another one of the changes observed; in this sense, SIAP (2020) agricultural production statistics confirm the pattern of land use change observed in the maps. Agricultural production data show a decrease in corn area (Figure 4), which went from 22 223 ha in 2003 to 18 048 ha in 2014. A similar trend is observed in soybean production. While pastures grew strongly, from 12 378 ha to 18 149 ha, perennial crops in general showed a slight increase in their extensions, except for coffee and cocoa (SIAP, 2020).



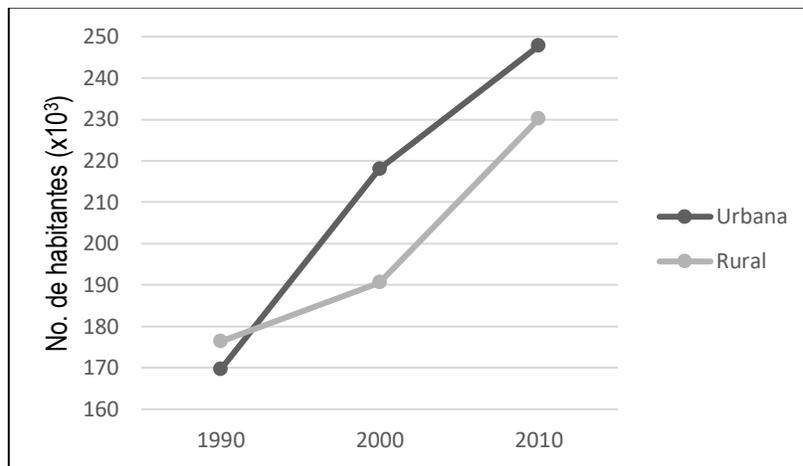
Source: SIAP (2020)

Figure 4. Surface area of annual (a) and perennial (b) crops.

This pattern of reduction of areas devoted to the production of staple crops seems to be related to the phenomenon, observed at the national level, of increasing dependence on the importation of basic grains as an effect of the Free Trade Agreement (Valencia *et al.*, 2019).

Finally, the expansion of urban areas observed in the maps also coincides with census data, since the region experienced moderate population growth from 1990 to 2010,

with a population growth rate of 1.63 %, which represented 346 000 inhabitants in 1990, and 477 800 in 2010 (INEGI, 1990; INEGI, 2010), concentrated in the urban areas of the country (Figure 5). At the cartographic level, which was reflected in an expansion of human settlements, the area of this category tripled from 4 000 to 12 000 ha, mainly because of the expansion of the city of *Tapachula*.



Source: Population and Housing Censuses (INEGO, 1990, 2000, and 2010).

Figure 5. Historical population growth in the municipalities of the study area.

Productive transformations by type of landscape

The dominant process on the coast was the loss of natural and semi-natural vegetation due to the expansion of agricultural crops and plantations. Agricultural production data obtained from SIAP (2020) confirmed a strong growth of cultivated pastures in the municipality of *Suchiate* (from 600 to 5 000 ha) and a strong deforestation in the period studied. The rapid expansion of these activities into hydrophilic vegetation areas is a cause of concern because it increases the risk of deterioration or deforestation of the mangroves (Barrasa, 2017).

In the Plains, the dominant process of change was the conversion of agricultural crops into agricultural plantations (banana, mango, oil palm). Oil palm is an attractive

product for farmers because of the growing demand in the food industry market, the increase in prices and the public programs that support its establishment (Fletes-Ocón and Bonnano, 2015; Castellanos, 2018).

At the national level, *Chiapas* is the state with the largest area cultivated with oil palm, with a little more than 45 000 ha (SIAP, 2020), located in the economic regions: Rain Forest, Coast, and *Soconusco*; also, there are 11 oil extraction plants, six of them located in *Soconusco* (Castellanos, 2018).

Apparently, the deforestation processes observed in the mountain range are due to the conversion of forest areas into annual agricultural crops (Cortina-Villar *et al.*, 2012) and to the transformation of shade coffee plantations (agroforestry system) into unshaded coffee plantations (Henderson, 2019). According to the maps generated in this study, in 1990 there was an area of 200 ha of unshaded coffee, which quadrupled in 2015, —a figure that may be even higher due to the high spectral confusion registered in this category (Table 2).

Evidence cited in other papers points in the same direction. Henderson (2019) and Jurjonas *et al.* (2016) find that coffee agroforestry systems are highly susceptible to price variations and diseases. In recent years, coffee rust mainly affects agroforestry systems (Henderson, 2019); therefore, one of the strategies promoted to deal with it, the use of coffee plant varieties resistant to the pathogen, but that do not require the shade provided by the forest canopy (Jha *et al.*, 2011). This has resulted in a loss of tree cover, which coincides with the decrease in disturbed forests observed in this study.

Conclusions

Maps with high spatial and thematic detail allow a better understanding of land use change processes; in addition to quantifying the trajectories of change, it is possible to generate hypotheses about the potential causes of landscape transformation.

The pattern of land cover change and the agricultural and demographic statistics indicate that the study region is undergoing a process of agricultural intensification and urbanization. The trend in the loss of natural and semi-natural vegetation, including mangroves and agroforestry systems, is also a cause for concern.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Rosa Elena Escobar Flores: field data recording, mapping and drafting of the manuscript; Miguel Ángel Castillo Santiago: definition of methodology, review, and correction of the manuscript.

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