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Regional analysis of indirect factors affecting the recovery, degradation and deforestation in the tropical dry forests of Oaxaca, Mexico

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This study evaluates the dynamics and identifies the indirect biophysical and socio-economic factors related to the recovery, degradation and deforestation of the tropical dry forest (TDF) cover in the municipality of Tehuantepec, Oaxaca, Mexico. Annual rates and transition matrices were determined to identify indirect factors; the cartographic information of 25 variables with shift points were overlaid and Generalized Linear Models (GLM) were applied. The change process with the greatest impact in TDF during the study period (1993–2011) was degradation, with 10468 ha degraded (12 per cent of the initial tropical cover); recovery of coverage was the second most important change process, with 4808 ha (5.5 per cent); and deforestation was the change process with the lowest impact, with a loss of 2800 ha (3.23 per cent). The net balance was negative, with a decrease (through land degradation and deforestation) of 8460 ha (9.75 per cent). The recovery of coverage was mainly associated with biophysical factors such as land suitability and accessibility to natural vegetation. On the other hand, deforestation and degradation of coverage were associated with both biophysical and socioeconomic factors such as land suitability, accessibility to natural vegetation, migration, marginalization, population pressure, economy, education and health. The findings of this study determined the spatial distribution of forest recovery, deforestation and degradation processes at a regional level, allowing for future researchers to focus their efforts at local and landscape levels. Also, the work allows for an approximation of the factors associated with the change processes studied, hence supporting the allocation of resources for the establishment of management, conservation, development and restoration strategies of tropical dry forests at the regional level.

Keywords: land-use cover change, regional level, IDW interpolation, ecological resilience, geo-statistical analysis

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Introduction

Anthropogenic disturbances of varying intensity, frequency, and duration have affected between 39 per cent and 50 per cent of terrestrial and aquatic ecosystems around the world (Kareiva *et al.*, 2007; Vitousek *et al.*, 1997). This situation is particularly serious in the case of the tropical dry forest(s) (TDF), which account for 42 per cent of tropical forests worldwide. In the past 100 years, this forest type has been cleared at an unprecedented rate and replaced by agriculture, plantations, pastures and secondary forests (Chazdon, 2014; García-Romero *et al.*, 2004). This loss of TDF cover demands an evaluation of the land-use cover change (LUCC) processes in which anthropogenic activities directly affect deforestation, recovery and degradation of forest cover.

Recovery consists of the re-growth of forests after a disturbance, and takes place following a sequence of ecological succession stages (Chazdon, 2014). Contrastingly, degradation is a process where human activities lead to the loss of structure, species composition and function or productivity of a primary forest (Secretariat of the Convention on Biological Diversity, 2002). Finally, deforestation is the loss of forest area to less than 10 per cent of the original cover (FAO, 2001).

Investigations on the direct and indirect factors relating to LUCC in TDF are scarce; in addition, most studies of LUCC in the tropics have focused on forest degradation and deforestation (Adedire, 2002; Chowdhury 2006; Díaz-Gallegos *et al.*, 2010; Ellis *et al.*, 2017; Makunga & Misana, 2017; Osorio *et al.*, 2015; Skole & Tucker 1993; Souza Jr *et al.*, 2013), which are processes that lead to the loss of biodiversity, habitat fragmentation, hydrologic alteration, soil degradation and loss, and climate change (Chazdon, 2014; Farley *et al.*, 2012; Geist & Lambin, 2002; Maass, 1995; Maass *et al.*, 2005). However, some previous studies have shown that the phenomenon of abandonment of agricultural land and pastures occurring in recent decades, has led to the recovery of the cover of secondary forests (Burgos & Maass, 2004; Crk *et al.*, 2009; Galicia *et al.* 2008; Hecht *et al.*, 2006; Osorio *et al.*, 2015). This abandonment has resulted mainly from the withdrawal of agricultural subsidies and credits that have caused the decrease in the price of maize and the abandonment of agricultural activity in Mexico (Galicia *et al.*, 2008).

Other studies have underlined the importance of investigating the biophysical, socio-economic, spatial and landscape factors associated with LUCC in TDF (Crk *et al.*, 2009; Galicia *et al.*, 2008; Osorio *et al.*, 2015). These can be grouped into direct and indirect factors (Geist & Lambin, 2002; Hosonuma *et al.*, 2012, Kissinger *et al.* 2002). The first involve variables that directly affect the loss of forest cover (*e.g.* gentle terrain slopes, proximity to roads and urban centers), since these factors facilitate activities such as agriculture, livestock ranching, fuelwood collection and vegetation clearing (Aide *et al.*, 2000; Chazdon, 2014; Hecht, 1993; Maass, 1995), hence favouring degradation and deforestation processes (Adedire, 2002; Aide *et al.*, 2000; Akinwumi *et al.*, 2001; Hecht, 1993; Karancsi, 2010; Kleemann *et al.*, 2017; Leroux *et al.*, 2017; Ramírez-Mejía *et al.*, 2017). The second set of factors—indirect factors (e.g. population density)—refer to social, economic, demographic and political factors that explain the direct factors affecting regional LUCC processes, albeit in a more critical way (Arroyo-Rodríguez *et al.*, 2017; Crk *et al.*, 2009; Geist & Lambin, 2002). The second set of factors have become even more important than direct factors (Crk *et al.*, 2009); therefore an understanding of both sets of factors as factors of change is imperative. Both direct and indirect factors are associated with various levels of analysis; direct factors can explain LUCC at the local level, while indirect factors account for landscape and regional levels (Arroyo-Rodríguez *et al.*, 2017). The evaluation of LUCC, as well as the direct and indirect factors associated with such changes, is normally analysed using a binary response variable to determine the presence or absence of recovery, degradation or deforestation of coverage. The analysis requires probability models of the occurrence of an event, such as logistic regression (included within the GLM), that work with dichotomous data (Crawley, 2007) and that allow for the determination of groups of variables (*e.g.* biophysical and socioeconomic) separately (Tabachnick & Fidell, 2007; Stevens, 2009).

Indirect factors need to be studied at different levels, such as the regional level, which corresponds to a medium-scale spatial representation (*i.e.* 1:1:250 000 to 100 000) involving diverse content (Da Costa-Gomes, 2000; Giménez, 2005; Van Young, 1992). Studies conducted on a regional level allow for an integral vision on the relationships between social, economic and political processes—both direct and indirect—that affect LUCC processes in large areas (Bürgi *et al*., 2005; Geist & Lambin, 2002; Rosas-Ávila *et al*., 2015).

The aim of this study is to analyse the dynamics of the recovery, degradation and deforestation processes, and determine the indirect biophysical and socio-economic factors derived from an analysis at the regional level, in a TDF located at the municipality of Tehuantepec, state of Oaxaca, Mexico. First, the LUCC dynamics was analysed for TDF, TDF secondary tree and shrub vegetation, urban areas, agriculture and pasture in relation to three processes—recovery, degradation and deforestation—for two periods (1993–2001 and 2001–2011). Second, we used a statistical model to investigate the importance of various biophysical and socio-economic variables aimed at identifying the key indirect factors that account for LUCC processes at the regional level. The findings of this study will contribute towards establishing adequate mitigation, restoration or conservation measures within the framework of the current global-change scenario (Lambin *et al*., 2001; Vitousek *et al*., 1997).

Material and methods

Study area

The study was conducted in the municipality of Santo Domingo Tehuantepec (120 188 ha; between 16°27′ N, 95°38′ W and 15°55′ N, 95°10′ W), located in the state of Oaxaca, one of the regions with the lowest socio-economic development in Mexico (Figure 1). The municipality is composed of 78 villages and a population of 61 872

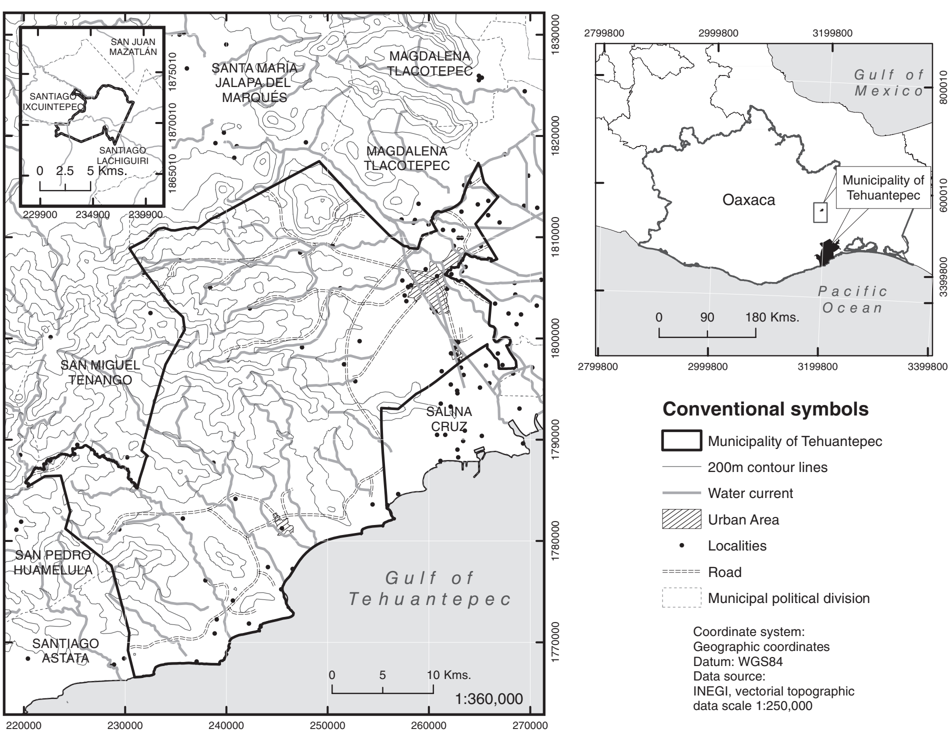

Figure 1. *Location of the municipality of Santo Domingo Tehuantepec, Oaxaca, Mexico.*
***Source*: Figure produced by authors using information from the INEGI (2013).**

inhabitants; it comprises an altitudinal gradient (0–1400 m asl) that includes high (16.83 per cent) and low complex sierras (51.57 per cent) modeled on Cretaceous metamorphic and sedimentary basements, as well as a coastal plain (18.93 per cent) and a coastal plain with hills (12.67 per cent), with outcrops of Quaternary alluvial sediments (INEGI, 2010). This region is characterized by a wet season that lasts between 4 and 7 months, where cumulative rainfall ranges between 500 and 2000 mm per year, contrasting with a dry season that lasts between 6 and 7 months (from November to May; Lebrija-Trejos *et al.*, 2010).

The municipality is largely comprised of tropical forest vegetation (mainly TDF; 74.88 per cent), followed by agriculture (18.95 per cent) as the main land use, forests (temperate and mesophyll; 2.86 per cent), urban areas (1.36 per cent), coastal dune vegetation (0.73 per cent), induced pasture (0.54 per cent), non-vegetated land (0.35 per cent), induced palm-tree forest (0.23 per cent), mangrove (0.08 per cent), and water bodies (0.02 per cent; INEGI, 2010).

Data collection

The cartographic information on vegetation for the municipality was obtained from land-use and vegetation maps Series II (1993; INEGI, 2001), Series III (2001; INEGI, 2005) and Series V (2011; INEGI, 2013) produced by the *Instituto Nacional de Estadística y Geografía* (National Institute of Statistics and Geography, INEGI) at a scale of 1: 250 000. The biophysical variables were obtained from the digital elevation model (DEM) and the thematic layers of INEGI, as well as from the *Comisión Nacional para el Conocimiento y Uso de la Biodiversidad* (National Commission for the Knowledge and Use of Biodiversity, CONABIO), while the socio-economic variables at the locality level were obtained from the INEGI 2000 and 2010 Population and Housing Censuses (INEGI, 2002, 2011) and the *Consejo Nacional de Evaluación de la Política de Desarrollo Social* (National Council for the Evaluation of Social Development Policy, CONEVAL; Table 1). The socioeconomic variables were processed by interpolating the values of the variables selected by locality using the Inverse Distance Weighting (IDW) technique, which defines the value of each cell by using the average of the data set weighted by the inverse of the distance (Burrough & McDonnell, 1998). The procedure allows for the heterogeneous representation of socioeconomic spatial data in cases where data for neighbouring localities have random values with no evident pattern (low spatial autocorrelation; for the case of the Tehuantepec population density, a Moran index = -0.05, $p < 0.05$; Farfán *et al.*, 2012).

Classification system and change processes

The land use and vegetation classification system of INEGI includes 24 categories that were grouped as follows: (1) dry tropical forest (TDF); (2) TDF secondary tree vegetation; (3) TDF secondary shrub vegetation; (4) rainfed agriculture; (5) irrigated agriculture; (6) induced pasture; (7) urban area; and (8) non-vegetated land. The TDF secondary shrub and tree vegetation differ from the mature forest due to changes in the structure of the communities. While the first is formed by shrub communities dominated by acacias that form a closed canopy of low size (~ 3 m), the second corresponds to a more advanced stage of recovery, which is characterized by dispersed individuals of arboreal species (*Bursera simaruba* (L.) Sarg., *Lysiloma divaricatum* (Jacq.) J.F.Macbr., *Pseudobombax ellipticum* (Kunth) Dugand, *Plumeria rubra* L. *f. acutifolia* (Poir.) Woodson, *Tabebuia ochracea* (Cham.) Standl., *Jacaratia mexicana* DC., *Cecropia obtusifolia* Bertol.) that protrude (> 3 m) from the shrub canopy. The LUCC processes considered in this

Table 1. Biophysical and socio-economic variables included in the analysis of the factors associated with recovery, degradation and deforestation processes in the tropical dry forest during the periods 1993–2001 and 2001–2011.

	Variable	Indicator	Source
Biophysical	Altitude	Land suitability	Digital Elevation Model, INEGI
	Orientation		
	Slope		
	Soil type		INEGI
	Soil degradation		
	Soil moisture		
	Rock types		
	Distance to rivers		CONABIO
	Type of climate		
	Mean annual precipitation		
	Mean annual temperature		
	Maximum temperature		
	Minimum temperature		
	Mean annual isohyets		
	Distance to villages	Accessibility to the vegetation	INEGI
	Distance to roads		
Socio-economic	Total population density	Population pressure	2000 and 2010 Population and Housing Censuses, INEGI
	Percentage of male population	Migration	
	Percentage of economically active population	Economy	
	Percentage of illiterate population above 15 years old	Education	
	Average education level		
	Percentage of population with no access to health care services	Health	
	Percentage of households with no water supply	Marginalization	
	Percentage of households with no services		
	Extent of marginalization		CONEVAL and INEGI

Source: Table produced by authors compiling information from official sources. INEGI: Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography); CONABIO: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (National Commission for the Knowledge and Use of Biodiversity); CONEVAL: Consejo Nacional de Evaluación de la Política de Desarrollo Social (National Council for the Evaluation of Social Development Policy).

study are TDF recovery, degradation and deforestation. The transitions included in each change process are summarized in Table 2 and Figure 2.

The land use and vegetation maps were overlaid cartographically to derive annual rates and transition matrices of the change processes for the periods 1993–2001 and 2001–2011. Transition matrices allow for the highlighting of areas that remain the same or are transformed in a given period of time (Pontius *et al.*, 2004). Annual rates of change were calculated using the following equation (FAO, 1995):

$$\delta = \left(\frac{S_2}{S_1}\right)^{1/n} - 1$$

Table 2. Transitions considered for each land-use cover change process.

Process	Date	Transition				
Recovery	Initial	TDF secondary tree vegetation	TDF secondary shrub vegetation	Rainfed agriculture	Irrigated agriculture	Induced pasture
	End	Tropical dry forest				
		--	TDF secondary tree vegetation			
		--	--	TDF secondary shrub vegetation		
Degradation	Initial	Tropical dry forest		TDF secondary tree vegetation	--	--
	End	TDF secondary tree vegetation	TDF secondary shrub vegetation		--	--
Deforestation	Initial	Tropical dry forest				
		TDF secondary tree vegetation				
	End	Rainfed agriculture	Irrigated agriculture	Induced pasture	Urban area	Non-vegetated area

Source: Table produced by authors using the spatial information of coverage and land use.

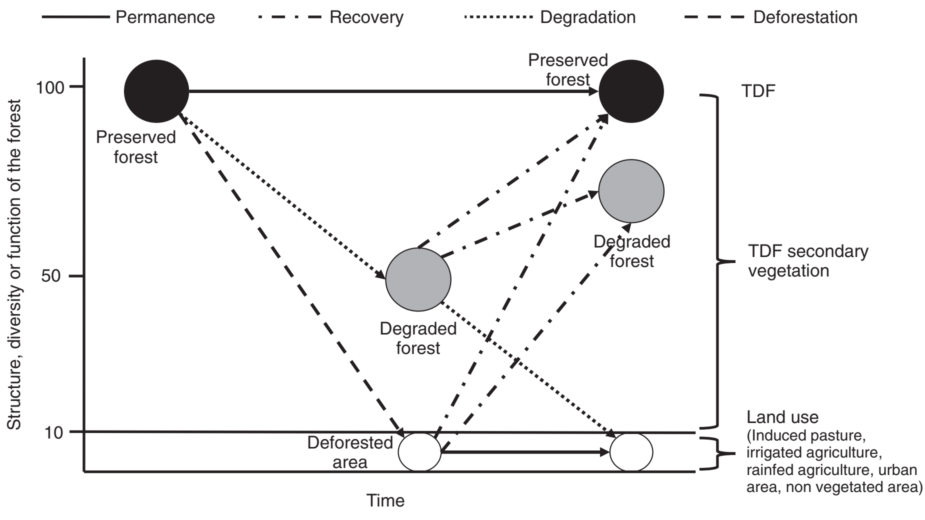

Figure 2. *Diagram of the transitions of land-use cover change processes studied.*
Source: **Figure adapted from Bradshaw (1984), Dobson et al. (1997), FAO (2001), Standish et al. (2014).**

Where δ is annual rate of change, S_1 is the area at Date 1, S_2 is the area at Date 2, and n is the difference between two dates, in years.

Validation of recovered, degraded and deforested areas

To support the results obtained from inputs at a scale of 1:250 000, a validation process of the areas of change was conducted. From these results, six work windows, each measuring 3 x 3 km were selected; each window was located in recovered, degraded and deforested areas for each period studied. Change points were visually identified in each window for each process from 1996 aerial photographs by INEGI and high-resolution (0.5 m) GeoEye imagery, in natural color, obtained from Google Earth™ for years 2004 and 2014. Validation points were established in two periods: 1996–2004 and 2004–2014. Due to the scarcity of high-resolution data, the images that supported the validation were the closest available for the study periods. Deforestation points were located considering plots with plant cover in the initial date of each period (1996/2004) and with no plant cover by the respective final date (2004/2014); recovery points were established considering the opposite process, i.e. plots with no plant cover in the initial period and that experienced recovery of plant cover by the final period. Degradation points were located considering the decrease in tree canopy cover within the windows studied as an indicator.

Identification of biophysical and socio-economic factors of LUCC

To identify the factors that promote TDF recovery, degradation and deforestation, a correlation analysis was performed in the first place to reduce dimensionality; as a result, one variable of the pair of variables with a correlation greater than or equal to 0.7 was eliminated. Afterwards, a cartographic overlay of the 25 biophysical and socio-economic variables selected and of the land-use and vegetation maps was applied

(Table 1). This process produced 30 000 random points; from each point, information was extracted from all the thematic layers. From this, binary information (change/no change) was inferred for each change process and period analyzed. The databases were refined by selecting only the change processes of interest for each study period. Each database contains the binary response variable (0, 1) and the value of each of the 25 variables analysed. Subsequently, the refined database was used to conduct binomial Generalized Linear Models (GLM) with a *logit* function, using the AIC criterion (Akaike Information Criterion) to select the best models (Crawley, 2007) and identify the contribution of one or more variables on the change processes studied. The logistic regression used as a statistical model allows for the introduction of continuous and categorical variables and determines their influence on the response variable. The biophysical and socioeconomic variables were analysed separately and without interactions. The analysis of variables in separate groups represents the advantage that logistic regression provides over other statistical models. (Tabachnick & Fidell, 2007; Stevens, 2009). In this case, the independent relationships between each change process (recovery, degradation and deforestation) were analysed for each period, first, against biophysical variables, and then later, against socioeconomic variables. The statistical analyses were executed using software R version 3.2.3 (R Core Team, 2015).

Results

The change process with the greatest impact on TDF during the study period (1993–2011) was degradation, with 10 468 ha of coverage degraded (12 per cent of the initial tropical cover); recovery of coverage was the second most important change process, impacting 4808 ha (5.5 per cent of the initial tropical cover); and deforestation was the change process with the lowest impact, recording a coverage loss of 2800 ha (3.23 per cent of the initial tropical cover). The net balance is negative for the municipality of Tehuantepec, with a decrease in vegetation cover (due to degradation and deforestation) of 8460 ha (9.75 per cent of the initial tropical cover). In the period of 1993–2001, the TDF decreased by 2630.81 ha (3.41 per cent), with an annual rate of change of -0.43 per cent; the TDF secondary tree vegetation recorded a decrease of

Table 3. Cover, annual change rates and global retreat/expansion of cover and land uses in the periods 1993–2001 and 2001–2011. Nomenclature: (TDF) tropical dry forest; (TDFST) TDF secondary tree vegetation; (TDFSS) TDF secondary shrub vegetation; (RA) rainfed agriculture; (IA) irrigated agriculture; (IP) induced pasture; (UA) urban area; and (NVL) non-vegetated land.

	Cover (ha)			Annual rates (%)		Retreat (-) or expansion (ha)	
LUCC / Periods	1993	2001	2011	1993-2001	2001-2011	1993-2001	2001-2011
TDF	76924.85	74294.03	70259.76	-0.43	-0.56	-2630.82	-4034.27
TDFST	5684.98	1744.03	5272.94	-13.73	11.70	-3940.95	3528.91
TDFSS	3964.02	11843.41	10090.91	14.66	-1.59	7879.39	-1752.50
RA	20149.03	19549.14	20433.88	-0.38	0.44	-599.89	884.73
IA	3656.32	3761.81	4967.60	0.36	2.82	105.49	1205.79
IP	1245.25	651.80	368.77	-7.77	-5.54	-593.46	-283.03
UZ	1078.55	1078.54	1078.81	0.00	0.00	-0.01	0.27
NVA	399.03	399.06	400.59	0.00	0.04	0.02	1.53

Source: Table produced by authors using annual change rates and transformed surface.

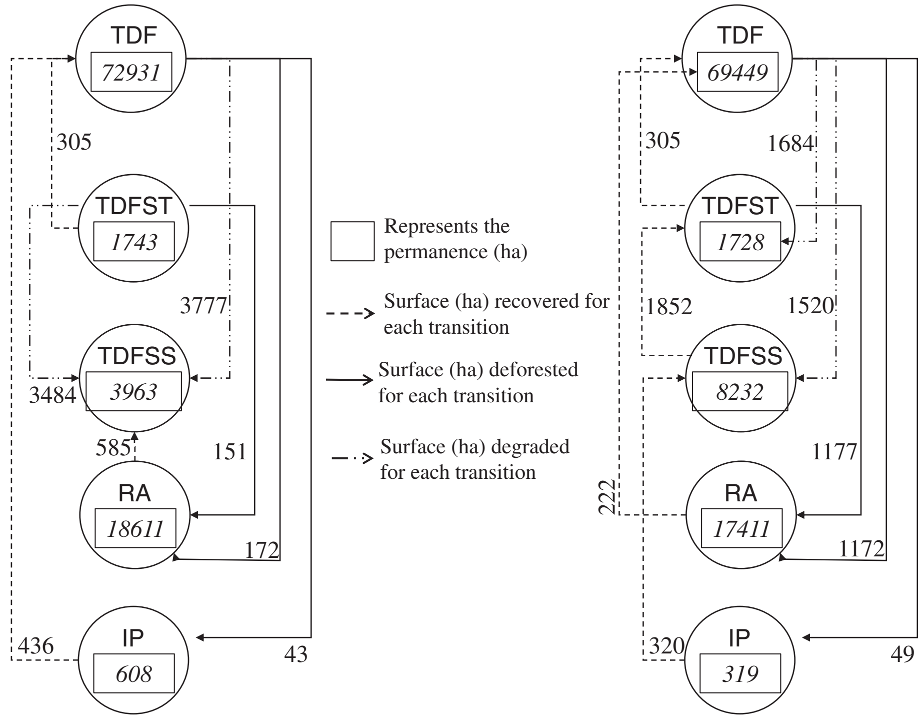

Figure 3. *Chart of the land-use cover change processes in the periods 1993–2001 (left) and 2001–2011 (right). Nomenclature: (TDF) tropical dry forest(s); (TDFST) TDF secondary tree vegetation; (TDFSS) TDF secondary shrub vegetation; (RA) rainfed agriculture; (IA) irrigated agriculture; and (IP) induced pasture.*
Source: **Figure produced by authors using the transition matrices obtained by spatial analysis.**

3940.94 ha (93.60 per cent) with an annual rate of change of -13.73 per cent; and the TDF secondary shrub vegetation underwent an increase of 7879.39 ha (198.77 per cent) vs. the initial cover, showing an annual rate of change of 14.66 per cent. In the period of 2001–2011, the TDF lost 4034.27 ha (2.01 per cent) at an annual rate of change of -0.56 per cent, while the TDF secondary tree vegetation recovered 3528.90 ha (271.66 per cent) at an annual rate of change of 11.69 per cent, and the TDF secondary shrub vegetation decreased by 1752.50 ha (213.57 per cent) at an annual rate of change of -1.58 per cent. Table 3 summarizes the changes in both study periods.

During the period of 1993–2001, the TDF underwent a recovery of 1.6 per cent, mainly due to the decline in rainfed agriculture—the type of land use with the greatest loss cover in this period. The TDF cover was degraded to TDF secondary shrub vegetation by 4.91 per cent, while 0.28 per cent of the original cover was lost, being replaced mainly by rainfed agriculture (Figure 3). In the period of 2001–2011, TDF cover showed a recovery of 1.07 per cent, mainly due to the decrease of TDF secondary shrub vegetation. The TDF cover was degraded to TDF secondary tree vegetation by 2.26 per cent, and to TDF secondary shrub vegetation by 2.04 per cent. Finally, 1.65 per cent of the initial TDF cover was lost due to the expansion of rainfed agriculture (Figure 3).

An indicator of the change processes can be summarized through the areas transformed (in ha) over the time of occurrence of each process. In this way, during the

Table 4. Surface areas transformed over time of occurrence of each process. Data in hectares.

	Change processes					
	Recovery		Degradation		Deforestation	
Covers/time	8 years (one year)	10 years (one year)	8 years (one year)	10 years (one year)	8 years (one year)	10 years (one year)
Tropical dry forest	1231.8 (154)	798 (80)	3777.42 (472)	3205.62 (320)	215.91 (27)	1229.83 (123)
TDF secondary tree vegetation	0.11 (0.01)	1858.64 (186)	3484.13 (435.51)	1.12 (0.11)	151.17 (19)	7.69 (0.77)
TDF secondary shrub vegetation	587.33 (73)	332.62 (33)	-	-	0.201 (0.02)	1195.69 (119)

Source: Table produced by authors using annual change rates and transformed surface.

period of 1993–2001 (8 years) the TDF recovered by 1231.8 ha, (~154 ha per year) while 3777.42 ha were degraded (~472 ha per year), and 215.91 ha were lost (~27 ha per year). For the period of 2001–2011 (10 years), the TDF recovered by 798 ha (~80 ha per year), while 3205.62 ha were degraded (~320 ha per year), and 1229.83 ha were lost (~123 ha per year; Table 4). According to the LUCC analysis, TDFs showed greater recovery potential in the first versus the second study period, while the rates of decrease in cover (degradation and deforestation) were higher in the second period.

TDF degradation, deforestation and recovery from 1993–2001 show irregular distribution patterns across the study area. The results show TDF degradation occurring close to urban areas with the highest population density in 2001–2011, a situation similar to deforestation and contrary to recovery, which was observed to have occurred primarily in areas far from urban areas and associated with rural areas (Figure 4).

The validation of recovery, degradation and deforestation areas showed that the change processes can be clearly visualized through the use of cartographic materials at a scale of 1: 250 000. In the first validation period, 38 degradation points, 19 recovery points and 36 deforestation points were identified in the areas of change shown; in the second period, 29 degradation points, 25 recovery points and 23 deforestation points were identified.

The statistical analyses indicate the following variables to be indirect factors of LUCC in the TDF: altitude, orientation (west, northeast, southwest, south, east), slope, soil degradation (overgrazing and farming activities), rock type, mean annual precipitation, maximum temperature, minimum temperature, mean annual isohyets (800—1000 mm and 1000–1200 mm), distance to villages, distance to roads, total population density, economically active population, illiterate population above 15 years old, population with no access to health care services, households with no water supply, households with no services, and extent of marginalization (Figures 5,6 and 7). The statistical relationships between factors and processes vary by period and are determined by the significance of the statistical model (Appendix 1). Indirect factors promoting the recovery, degradation and deforestation of vegetation cover can be grouped as follows: land suitability, access to vegetation, population pressure, economy, education, health and marginalization. The LUCC shows spatial and temporal variability with respect to the

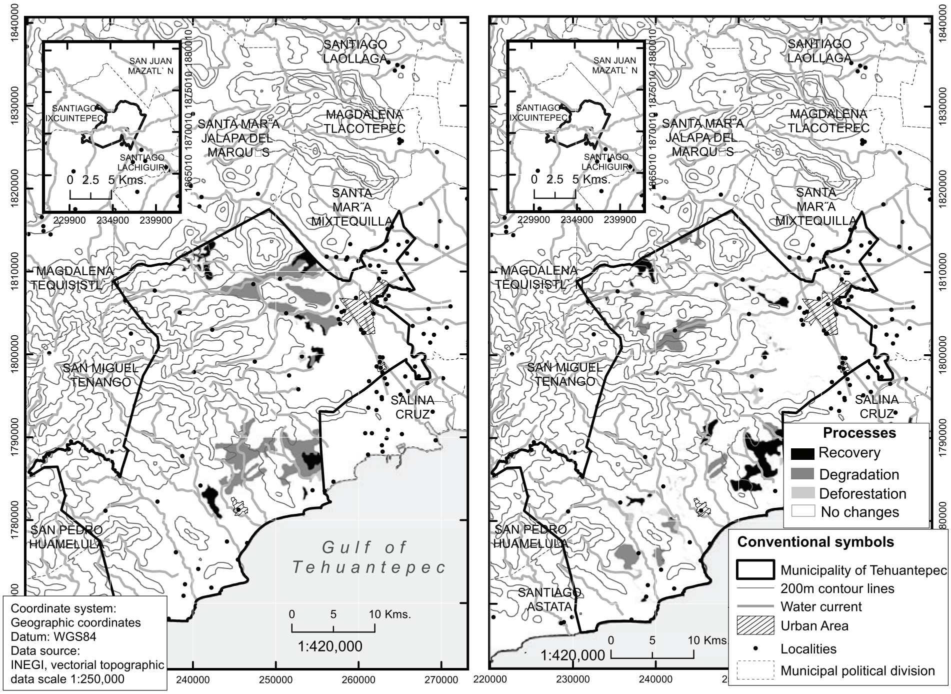

Figure 4. *Distribution of LUCC processes in the periods analysed (1993–2001: left; 2001–2011: right) in the municipality of Tehuantepec, Oaxaca, Mexico.*
Source: **Figure produced by authors using the results of spatial analysis.**

change processes. For instance, in the period of 1993–2001, the greater the percentage of households with no water supply, the greater the likelihood of degradation and deforestation. In 2001–2011, a similar relationship is established but with a higher probability of TDF recovery.

The intensity with which variables affect LUCC processes is observed in the logistic curves and is indicated by a higher probability of change with each variable for each process. The relationship between variable and process may be either positive or negative. For instance, higher values of a variable—which in turn increases the probability of change—are associated with a relationship that is considered positive; conversely, when a variable shows a low value, implying a higher probability of change, the relationship is negative. Positive responses for the recovery of the TDF were associated with the following variables: slope, distance to villages, distance to roads, economically active population, and households with no water supply. Negative responses involved variables such as altitude, total population density, male population, illiterate population above 15 years old, and population with no access to health care services. With respect to TDF degradation and deforestation, positive responses were obtained for total population density, economically active population, and households with no water supply, while negative responses were observed for variables such as altitude, slope, distance to villages, distance to roads, male population, illiterate population above 15 years old, and population with no access to health care services (Figure 8).

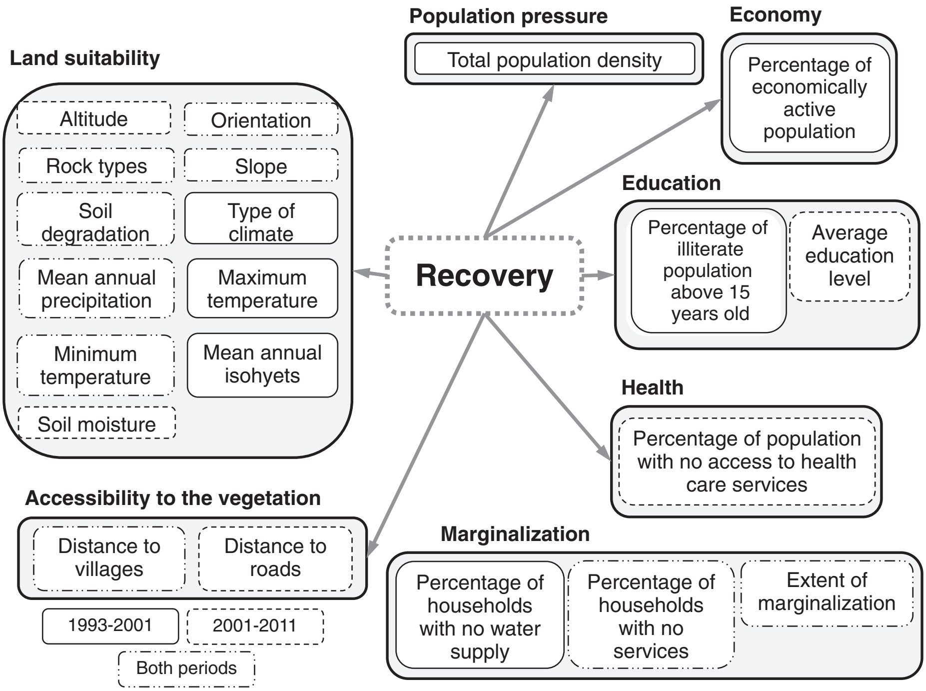

Figure 5. *Factors associated with the recovery of TDF cover, in both periods of study.*
Source: **Figure produced by authors through the statistical analysis of spatial data.**

Discussion

Due to the negative implications of deforestation on the provisioning of environmental services (Lambin *et al*., 2001), a large amount of information on loss of forests and annual rates of change have been produced over the past few decades. In Mexico, recent studies on LUCC have made it possible to obtain accurate information on the extent of the problem (Díaz-Gallegos *et al*., 2010; Durán *et al*., 2011; Galicia *et al*., 2008; García-Romero *et al*., 2004; Mas *et al*., 2009; Mas & Flamenco, 2011; Moreno-Sánchez *et al*., 2014;, Osorio *et al*., 2015; Rosete-Vergés *et al*., 2014), indicating annual deforestation rates (including all types of vegetation) of -0.5 per cent (FAO, 2010) for the period of 1990–2000, and -0.41 per cent for tropical forests in the period of 1976–2007 (Rosete-Vergés *et al*., 2014).

In the case of the TDF, the losses reported are far higher than those reported for other forest types. For example, in southern Mexico the annual deforestation rates of TDF in studies at the regional level were recorded at -2.89 per cent for the period of 1979–2000 (Durán *et al*., 2011), with annual rates of -3.71 per cent (1986–2000) and -4.53 per cent (2000–2011; Osorio *et al*., 2015). However, studies addressing other LUCC processes are still scarce, including those on degradation and recovery, and especially those focused on determining the biophysical and socioeconomic factors that cause these changes (Díaz-Gallegos *et al*., 2010; Durán *et al*., 2011; Figueroa *et al*., 2009; Kolb *et al*., 2013; Osorio *et al*., 2015).

In this study, the annual deforestation rates observed for TDF were considerably lower (-0.43 per cent and -0.56 per cent) than those reported in other studies, a finding supporting the fact that forests of Tehuantepec are in relative conservation status and

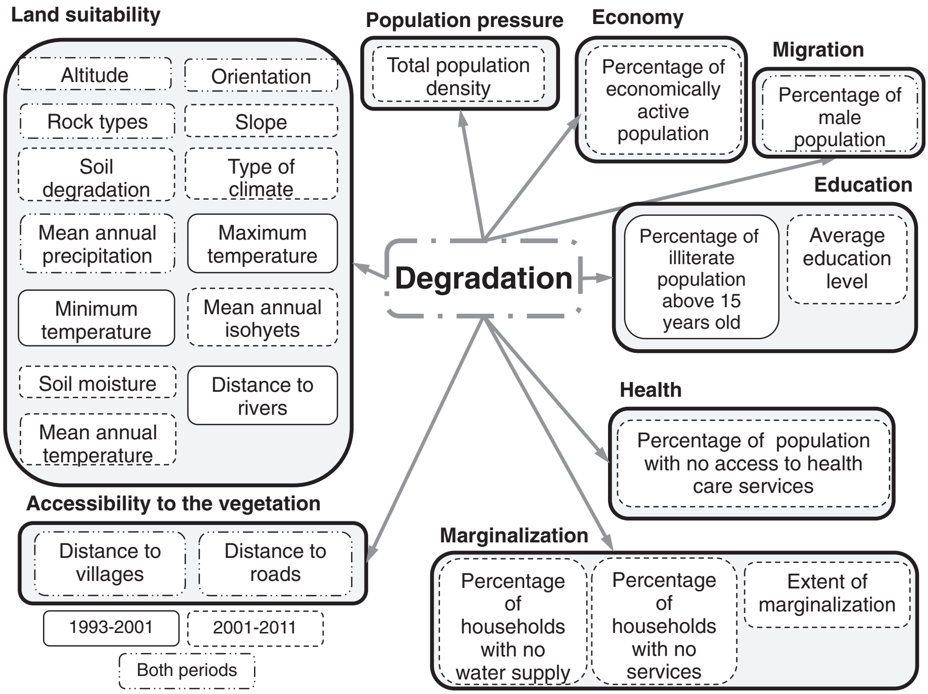

Figure 6. *Factors associated with the degradation of the TDF cover, in both periods of study.*
Source: **Figure produced by authors through the statistical analysis of spatial data.**

undergoing natural recovery processes (passive restoration). This situation is due to direct and indirect biophysical and socioeconomic factors. The leading direct factors of LUCC processes are altitude, slope, orientation, distance to roads, and distance to villages, i.e. biophysical variables that directly affect accessibility, the resource management system and the vulnerability of agricultural production (Crk *et al.*, 2009; Geist & Lambin, 2002). These results are partially consistent with those obtained in other tropical areas (*e.g.* Puerto Rico), where distance to the main roads, distance to natural reserves, slope and exposure are the key predictors of forest recovery (Crk *et al.*, 2009).

The socioeconomic variables include aspects such as population density, average educational level, economically active population, male population, population with no access to health care services, population with no water supply, and marginality index (Crk *et al.*, 2009). This type of causal factors affected the most important processes of the LUCC, illustrating the incidence of indirect variables on change processes.

As was similarly reported for other TDF areas, deforestation increased in low-altitude areas; in Tehuantepec, these areas coincide with the base of the sierra, hills and coastal plains, where water and soil are available and the topography is more stable (Burgos & Maass, 2004; Trejo & Dirzo, 2002). In these areas, the expansion of rainfed agriculture was probably intense in the mid-20th century (Challenger, 1998; Durán *et al.*, 2011; Osorio *et al.*, 2015), forcing the retreat of mature forests toward the interior of the sierras. Deforestation occurred mainly in areas close to villages, associated with forest clearing by increased fires, soil erosion, goat grazing, and extraction of forest resources, mainly firewood for self-consumption, all of which characterize rural communities of very low socioeconomic level (Aide *et al.*, 2000; Chazdon, 2014; Hecht,

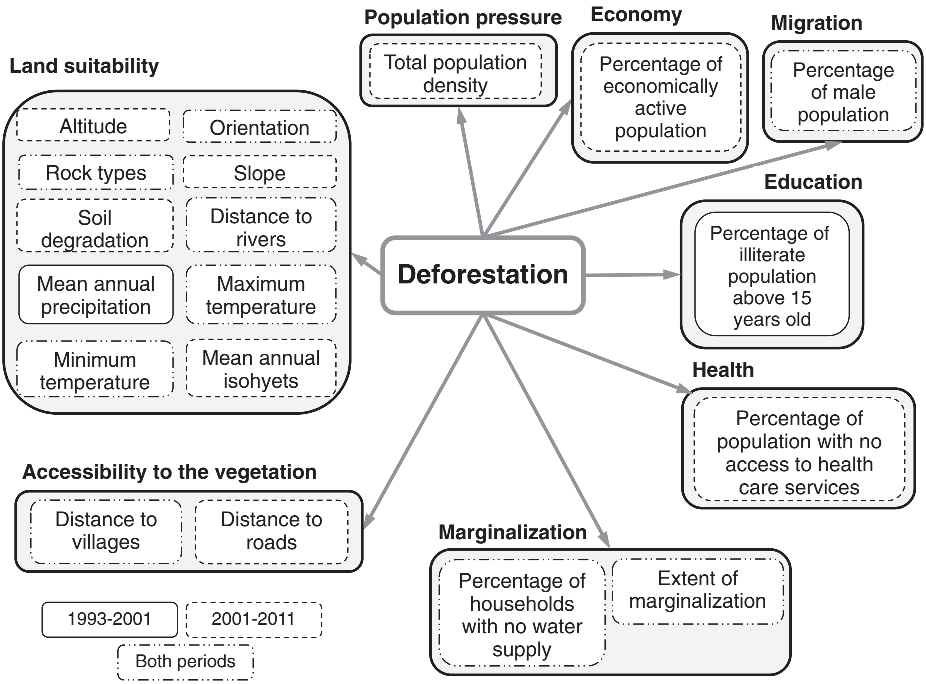

Figure 7. *Factors associated with deforestation of the TDF cover, in both periods of study.*
Source: **Figure produced by authors through the statistical analysis of spatial data.**

1993; Maass, 1995). Frequently, rainfed agriculture is practised together with extensive cattle-ranching, leading to heavier environmental degradation (Burgos & Maass, 2004; Geist & Lambin, 2002; Maass, 1995).

Since the 1970s there was a decline of rainfed agriculture as a result of indirect factors similar to those found in other regions of tropical America: a) withdrawal of government subsidies and external capital; b) inadequate size of agricultural parcels (2 ha on average) that restrain the use of machinery and yield; c) high investment in labour and lack of technological developments (*e.g.* fertilizers, improved seeds) and information on management and marketing (García-Romero *et al.*, 2004; Maass, 1995; Lambin *et al.*, 2001; Ortiz-Espejel & Toledo, 1998; Serrão *et al.*, 1996).

Notably, livestock activities increased as rainfed agriculture declined, leading to an expansion of livestock areas, specifically on coastal plains, where the availability of extensive plains and water were ideal for the development of this activity. The expansion of induced pasture in the municipality of Tehuantepec may be related to the livestock-ranching boom that led to the deforestation of extensive plains in southern Mexico and many other tropical countries, in response to a rise in global demand for meat production worldwide (García-Romero *et al.*, 2004; Serrão *et al.*, 1996).

Facing these changes in the patterns of land-use dynamics, the transition to the 21st century is characterized by erratic land use traits of areas dedicated to rainfed agriculture—recording expansions and retreats in both study periods that resulted in a net loss of natural vegetation cover. With regards to livestock ranching and its serious consequences to forest recovery (e.g simplification of landscape patterns and a lower probability of forest cover recovery; García-Romero et al., 2004; Lavorel, 1999); the

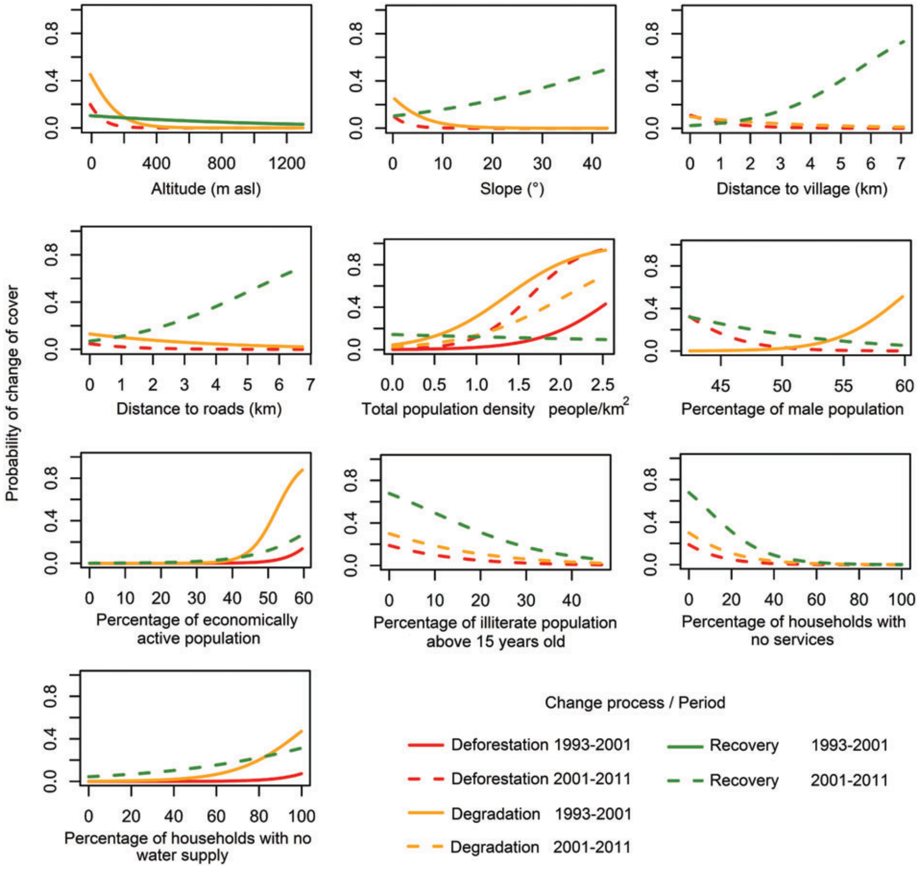

Figure 8. *Probability of change of the biophysical and socio-economic variables that govern the deforestation, degradation and recovery processes of the TDF in Tehuantepec, Oaxaca, Mexico.*
Source: **Figure produced by authors through statistical analysis of spatial information.**

transition to the 21st century is characterized by a heavy and steady loss of induced pastures, which has favoured recovery processes.

Currently, the areas most affected by disturbance processes are mainly areas that experience high rainfall (*e.g.* 800 to 1000 mm), have gentle slopes, and are located far from rivers but close to the main roads; *i.e.,* areas where high accessibility and geomorphological stability favour socio-economic development (Burgos & Maass, 2004; Trejo & Dirzo, 2002). Consequently, the main indirect socio-economic factors influencing the LUCC include the co-ocurrence of densely populated areas, with a high proportion of economically active population and few households with no services.

The results of the degradation analysis should be interpreted with caution, given the generality involved in the scale of the analysis, as some areas that are considered as degraded cannot be classified with certainty; *e.g.* areas with rocky outcrops and scarce soil development are confounding factors for classification. This suggests that the monitoring of degradation in the TDF implies a more detailed scale analysis (*e.g.* landscape and local). Although the study at the regional level faced accuracy issues in the identification of the degradation process, it was nonetheless successful in identifying and linking the indirect factors of LUCC to degradation within the TDF (Bürgi *et al.*, 2005; Da Costa-Gomes, 2000; Rosas-Ávila *et al.*, 2015; Van Young, 1992).

In many tropical regions of the world, recovery is related to detailed community patterns in different successional stages that facilitate the recovery of the forest (García-Romero *et al.*, 2004; Lavorel, 1999). However, the abandonment of agriculture and pasture land (Crk *et al.*, 2009; Galicia *et al.*, 2008; Hecht *et al.*, 2006; Osorio *et al.*, 2015) does not necessarily lead to recovery because parcels of land are repeatedly burned and cultivated, resulting in high fragility and low recovery indices (Lambin *et al.*, 2001; Uhl & Jordan, 1984). This may be a possible explanation for what happened in Tehuantepec, whereby the TDF experienced low recovery as evidenced by the unstable behaviour of secondary tree and shrub vegetation cover in the two study periods. Contrastingly, the TDF within the region showed signs of ecological resilience, evidenced by the recovery of natural vegetation cover with time. This supports the hypothesis that these forests have an intrinsic resilience potential in the absence of anthropic disturbances (Vieira & Scariot, 2006). The lower recovery rates of the TDF relative to degradation and deforestation in the region should lead to a re-examination of conservation and restoration strategies for such forests, given their intrinsic resilience potential, albeit at a slower rate, relative to other tropical forests like the tropical moist forests (Poorter *et al.*, 2016).

Finally, the usage of logistic regression as a statistical model, allowed us to analyze separately, the factors that influence each change process. This constitutes a unique advantage over other GLMs which can only assess the relationship between factors and processes studied simultaneously (Tabachnick & Fidell, 2007, Stevens, 2009). However, it should be noted that there are other GLMs (e.g structural equation models [SEM]) that provide a series of path diagrams which facilitate understanding of the relationships between explanatory variables and each response variable (Graham, 2008). The availability of such alternative models may inspire researchers to re-evaluate the usage of logistic regression in studies of this kind.

Conclusions

The change process with the greatest impact on TDF during the study period (1993–2011) was degradation (12 per cent). Recovery of the natural vegetation cover (5.5 per cent) was the second most important process. Deforestation was the change process with the lowest impact (3.23 per cent). The net balance was negative for the municipality of Tehuantepec, with a decrease in vegetation cover (due to degradation and deforestation) of 8460 ha (9.75 per cent of the initial tropical cover). Agriculture was the main activity that led to the loss of TDF cover. The biophysical and socio-economic factors associated with the highest recovery, degradation and deforestation in the TDF and the secondary vegetation types were indicators such as land suitability (altitude, slope), accessibility to the vegetation (distance to villages, distance to roads), population pressure (total population density, percentage of male population), education level (percentage of illiterate population above 15 years old), health (percentage of the population with no access to health care services), and marginalization (percentage of households with no water supply). Both tropical forests and associated secondary vegetation showed a recovery in their coverage. This indicates the occurrence of ecological resilience.

The findings of this study led to the spatial location of forest recovery, deforestation and degradation, making it possible for researchers to focus their research efforts at the local and landscape levels in further studies. Also, the work allows for an approximation of factors associated with the change processes studied, which, once identified, can influence the allocation of resources towards the establishment of management, conservation, development and restoration strategies for tropical dry forests at the regional level.

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Appendix 1

Relationship between biophysical and socio-economic variables and change processes in the TDF. The relationship between a given variable and each process can be either positive (+) or negative (-). For each process, the left and right cells refer to periods (1993–2001) and (2001–2011) respectively. The significance codes from the statistical analyses are as follows: 0 ≥ ** ≥ 0.001 ≥ *** ≥ 0.01 ≥ ** ≥ 0.05 ≥ * ≥ 0.1 ≥ _ ≥ 1.**

Variable	Recovery		Degradation		Deforestation	
Biophysical variables						
Altitude	-*	+****	-****	-***	-*	-***
Orientation	NO*; SO*; O**	NE**	SE***; S**	E*; SE**; S****; SO**	SO***	SO***
Slope	+****	+**	-****	-****	-*	-****
Soil type	Luvisol	Regosol	Vertisol	Feozem	Regosol	Feozem
Soil degradation	Overgrazing **** Agricultural activities****	Agricultural activities****	Agricultural activities	Overgrazing ** Agricultural activities****	Agricultural activities****	
Soil moisture	4 months 5 months	4 months** 5 months****	4 months	4 months**** 5 months****	4 months 5 months	
Rock types	Shale****; Limestone**** Limolite **; Acid intrusive igneous***, Conglomerate****; Metasedimentary*** Gneiss****/ Acid intrusive igneous**** Conglomerate****; Sedimentary breccia***; Metasedimentary**** Gneiss****		Shale****; Limestone**** Conglomerate****; Sedimentary breccia**** Metasedimentary****/ Shale**; Limestone****; Limolite **; Acid intrusive igneous**** Conglomerate***; Gneiss****		Limestone;** Limolite **; Acid intrusive igneous**** Conglomerate**** Metasedimentary***/ Conglomerate*; Metasedimentary***; Gneiss****	
Distance to rivers	+	+	-**	-	-**	-****
Type of climate	Warm subhumid (A)Cw_0****	Dry warm subhumid (Aw_0)	Dry warm subhumid (Aw_0)	Warm subhumid (Aw_0)****; (A)Cw_0****; Aw_1**	Dry warm subhumid (Aw_0)	
Mean annual precipitation	-**	-****	+****	+****	+****	-
Mean annual temperature	+	+	+	-***	+	+
Maximum temperature	+**	-	+****	-	+***	+**
Minimum temperature	+***	+****	+****	-	+****	+***

Appendix 1 Continued

Variable	Recovery		Degradation		Deforestation	
Mean annual isohyets	800 to 1000 mm***; 1000 to 1200 mm***	800 to 1000 mm****	800 to 1000 mm	800 to 1000 mm****; 1000 to 1200 mm****	800 to 1000 mm****; 1000 to 1200 mm**	800 to 1000 mm****
Distance to villages	+****	+****	+****	-****	-***	-****
Distance to roads	+	+****	-****	-****	-	-**
Socio-economic variables						
Total population density	-****	-	+	+****	+	+****
Percentage of male population	+	-	+**	-****	+**	-****
Percentage of economically active population	+**	+	+	+****	+	+****
Percentage of illiterate population above 15 years old	-***	-	+****	+*	+****	-
Average education level	+	+****	+	-****	-	+
Percentage of population with no access to health care services	-*	-****	+	-****	+	-****

Appendix 1 Continued

Variable	Recovery		Degradation		Deforestation	
Percentage of households with no water supply	+***	+	+	-****	+****	-****
Percentage of households with no services	+**	-***	-	-****	+	-
Extent of marginalization	+****	+****	+	-****	+****	-****

Source: Table produced by authors using the results of statistical analyses.