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Land use-cover change processes in highly biodiverse areas: the case of Oaxaca, Mexico

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Abstract

Land use-cover changes (LUCC) such as deforestation, have resulted as global warming and a reduction of environmental services, with large negative consequences for mankind. Effects based on statistics alone have not been sufficient enough to detect, stop and eventually revert negative LUCC processes that are strongly related to biodiversity loss. It is, therefore, of prime concern to assess and depict cartographically, major LUCC processes simultaneously. Mexico harbors a large pool of biodiversity, mostly restricted to a few locations among which, The State of Oaxaca plays a major role. In this state, nevertheless, drastic negative LUCC processes are taking place. Land cover types, mapped in previous surveys, overlaid on recent Landsat imagery and 300 ground truth sites, were used to detect current LUCC. Rates of conversion of the most important LUCC processes were computed and mapped simultaneously. Oaxaca has lost over half a million hectares of forested areas during the last 20 years. The core results may contribute to the understanding of how LUCC and GIS methods can provide better and more targeted information that may help to improve conservation policies and land use planning strategies.

Keywords: Vegetation mapping; GIS; Deforestation; Re-vegetation; Oaxaca; Mexico

1. Introduction

Biological and cultural diversities are vanishing at an amazing rate (Myers, 2000; Boege, 2001). Negative land use-cover change (LUCC) processes, understood as the change from any primary dominated land cover into any man-made dominated one, have largely resulted as desertification, deforestation, habitat fragmentation, biodiversity loss, and eventually into global warming (Fearnside, 2001) and reduction of environmental services (Lambin et al., 2001; Peterson et al., 2001). Environmental impoverishment has often been documented by means of statistics depicting rates of forest loss (Walhberg et al., 1996; Groombridge and Jenkins, 2000; see also FAO's web page). Statistics alone, however, have not been sufficient to detect, stop and eventually revert negative land use-cover change processes. Detailed distribution patterns of where these processes take place ought to be considered as a fundamental yardstick in order to fill in the gap between problem detection and conservation action. Given these needs, it has become challenging to look for emerging, rapid and precise methods to assess the extent and effect of negative LUCC processes. This is specially crucial in inter-tropical developing countries, where negative LUCC processes result in the disappearance of one of their most valuable income (Daily et al., 1996; Constanza et al., 1997; Velázquez et al., 2001). In these countries, scientific guidance is urgent in order to achieve sound land use planning programs.

Mexico harbors an extraordinarily diverse biological richness (Mittermeier, 1988; Ramamoorthy et al., 1998). It also experiences drastic negative conversion processes (Klooster and Masera, 2000; Velázquez et al., 2002). During the last century, Mexico probably diminished its forest cover to half of its original surface. Nowadays, annual deforestation rates estimate a loss greater than 500,000 ha per year (Velázquez et al., 2002). Data have suggested that these LUCC processes take place in

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highly biodiverse areas. The states of Oaxaca, Chiapas, Michoacán and Guerrero are, by far, the regions where most Mexican biocultural heritage is harbored (Lorence and García et al., 1989). It is, therefore, of prime concern to assess and depict cartographically, major LUCC processes simultaneously.

The objective of this document is to depict current LUCC processes occurring in the state of Oaxaca, namely, deforestation, secondary succession and revegetation, with the aid of a geographic information system (GIS). The results are aimed at understanding how GIS methods can provide rapid and precise outputs that may help to improve conservation policies and land use planning strategies, simultaneously. The discussion focuses on conservation implications and methodological outreach for other highly biodiverse inter-tropical areas.

2. Method

2.1. Study area

The State of Oaxaca is located in the Southern Pacific coast of Mexico (Fig. 1). It encompasses over 9 million hectares (an area larger than Costa Rica). The topography is extremely irregular as a result of constant tectonic movements, so that at least eleven physiographic regions have been recognized. Soils and climate are conspicuously diverse and their variations depend heavily on elevation which ranges from sea level up to over 3000 m. Oaxaca's biogeographical location and its physical features makes it one of the most biodiverse regions world-wide (Gerez and Flores, 1994).

2.2. Current Oaxaca's land cover map

Before 2000, no consensus had been reached among researchers, government agencies and managers about a common Mexican vegetation classificatory system. For the last 30 years INEGI (National Institute for Statistics, Geography and Informatics, the official Mexican mapping agency) based upon the work of Miranda and Hernández (1963), conducted a mapping at the national level using field-verified aerial photography. This data proved to be the most suitable to allow updating and eventually to perform LUCC assessments. To this end, a detailed revision and discussion on land cover mapping and strategies was carried out in five workshops during the year 2000 (Palacio et al., 2000). The most important Mexican vegetation mapping experts gathered to formulate a classification scheme for vegetation and land-use

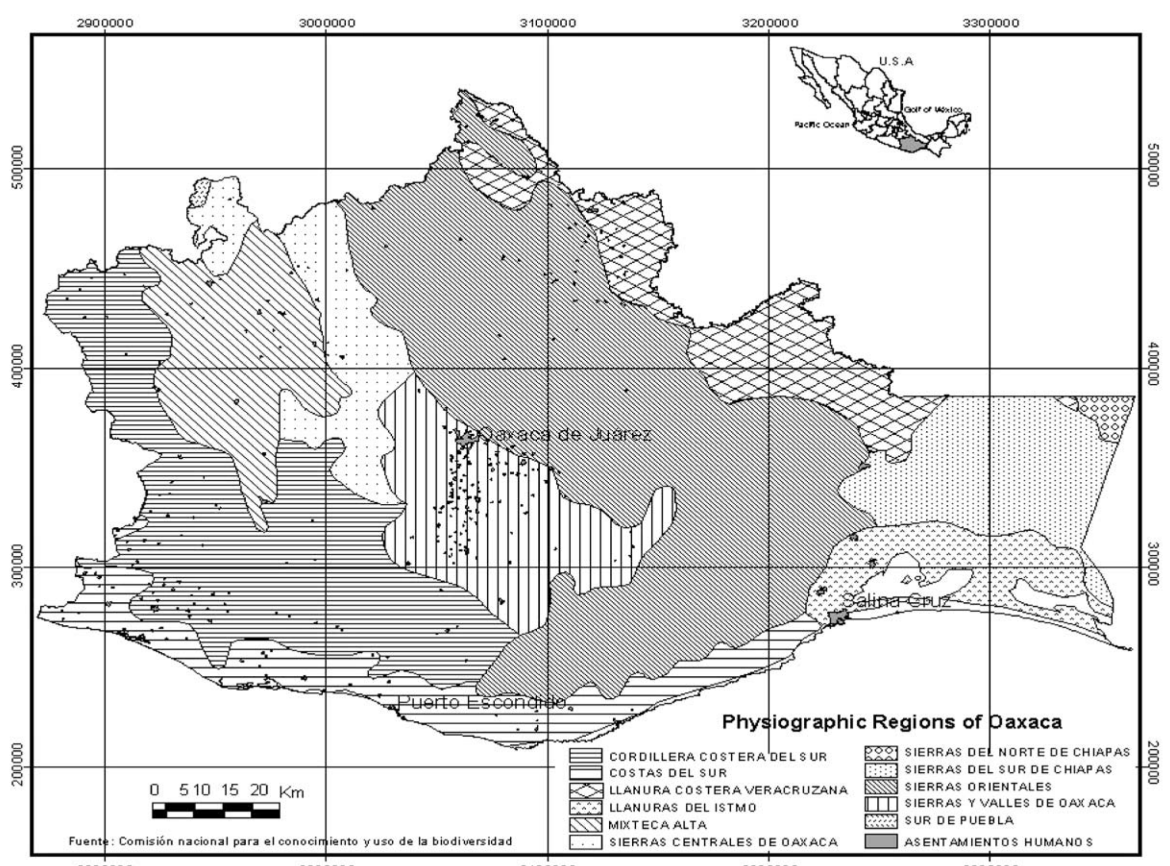

Fig. 1. The State of Oaxaca and its physiographic regions (source: www.conabio.gob.mx).

(Mas et al., 2002). The outcome brought a nested multi-level legend for mapping purposes comprising four levels: vegetation formations (suitable for national assessments), vegetation types (suitable for regional or state assessments), communities (suitable for local or municipality assessments) and subcommunities as suitable to depict forest trends; Table 1). The classificatory system obtained from the workshops was confronted with Landsat ETM+ images (previously corrected geometrically), taken between November 1999 and April 2000, and printed on a scale of 1:125,000. An inter-dependent interpretation procedure (FAO, 1996) was performed by overlaying the vectors depicting the land cover types mapped by INEGI in its previous surveys and by reorganizing, accordingly the adopted vegetation classificatory system (Fig. 2). This procedure allowed the updating of the land use/cover map for the entire country and the assessment of vegetation formation trends (Velázquez et al., 2002). Database quality assessment demonstrated that statistics derived from the national level study were 95% accurate at formation level (Mas et al., 2003). Prior to this study, no regional or state analysis had been done at the vegetation type level. To accomplish that, Oaxaca was chosen for three reasons: it harbors large vegetation complexity, it comprises high potential as an environmental service provider and it has experienced rapid land use conversion.

As previously described the same procedure for vegetation formations was performed in Oaxaca, but at vegetation type level. As a result, a preliminary land cover map in digital format was made on a scale of 1:250,000 (Fig. 2). A second step included the identification of map vegetation types most likely to be confused during Landsat interpretation. One example of this confusion is the so-called montane cloud forest, which is usually distributed together with the so-called medium height sub-perennipholious tropical forest. These two vegetation types are depicted similarly on the Landsat imagery. Thus, the vegetation types most prone to confusion were selected to conduct a field verification procedure to evenly sample possible errors throughout Oaxaca's territory. Simultaneously, a complete bibliographic database of most vegetation studies in the state was compiled, including geographic coordinates for each bibliographic reference and its corresponding vegetation type. This database was further complemented with 300 field verification points carried out from May to August 2001. At this stage, special attention was given to verify and distinguish the primary from the secondary vegetation types. During fieldwork, over 7% of the total surface of Oaxaca's state was cross-checked and all categories verified. A final land cover map of Oaxaca for the year 2001 and its correspondent statistics for all vegetation types were constructed with the aid of Arc/Info (8.1 version) geographical information system (GIS).

Table 1
Oaxaca's land cover categories hierarchically organized

Vegetation formation	Vegetation type	Vegetation community
Temperate forests	Conifers (*)	Cedar forest Fir forest Pine forest
	Broad-leaved and conifers (*)	Open pine-oak woodland Pine-oak forest
	Broad-leaved (*)	Oak forest
	Montane cloud forest (*)	Montane cloud forest
Tropical forests	Evergreen and sub-evergreen (*)	Tall evergreen tropical forest Short evergreen tropical forest Tall sub-evergreen tropical forest
	Deciduous and sub-deciduous (*)	Medium height (sub)deciduous tropical forest Short tropical (sub)deciduous tropical forest Short tropical thorny deciduous tropical forest
Scrubland	Xerophytic scrubland (*)	Mezquital Cactus scrubland Rosette-like desert scrubland Thorny tamaulipan scrubland Chaparral
Hygrophylous vegetation	Hygrophylous vegetation	Mangroves Coastal vegetation Riparian vegetation
Other vegetations	Other vegetations	Palm vegetation Halophylous and gipsophylous vegetation Costal dunes
Grassland	Grassland	Alpine grassland Natural grassland Savanna Improved grassland Cultivated grassland
Crops	Agriculture (irrigated)	Irrigated agriculture Humidity agriculture
	Rain-fed agriculture	Rain-fed agriculture
	Forest plantation	Forest plantation
Other land covers	Bare ground Water reservoir Human settlements	Bare ground Water reservoir Human settlements

Overall 29 vegetation communities, eleven vegetation types and eight vegetation formations were mapped. The legend was the result of five workshops with experts and the categories recognizable on Landsat images.

*Indicates vegetation types comprising secondary conditions detected from Landsat imagery.

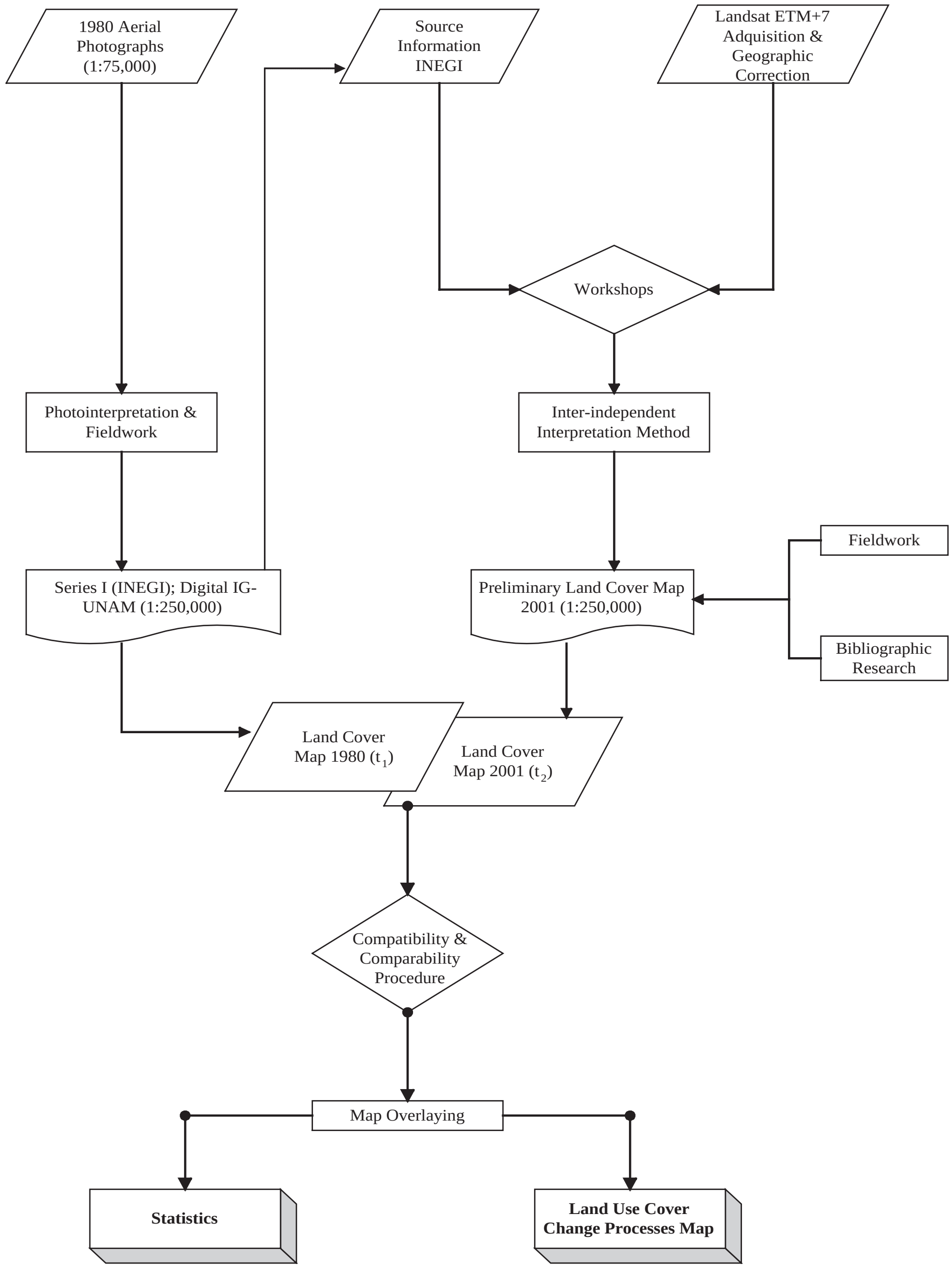

Fig. 2. Flowchart depicting the databases required and the methodological steps followed to construct the land use cover change processes map.

2.3. Land use/cover change analysis

INEGI elaborated the first land use and cover map for Oaxaca during 1979–1981. This database (hereafter referred to as t_1) and the one prepared for this study during 2001 (hereafter called t_2) were integrated into the same GIS database. To avoid errors while map overlapping, full cartographic compatibility was reached. This was obtained by using identical scales (1:250,000), a unique state border and the same cartographic projection. Furthermore, of original t_1 land cover categories were reclassified to ensure full comparability among vegetation types between t_1 and t_2. Hence, a map overlaid was performed via a GIS. The statistics were transferred into a transition matrix describing the performance of all vegetation types. A (Markovian) probability transition matrix was computed for all vegetation types to estimate the likely scenario within a similar time loop.

All vegetation types were grouped into three major land cover clusters. (A) The first (referred to as primary land cover) harbored all vegetation types predominantly dominated by primary land cover types such as temperate forests, tropical forests, xerophytic scrublands and hygrophilous tree-dominated vegetation types. Also pristine grasslands and pristine coastal vegetation types (e.g., dunes) were included in this cluster although these only represent a minor proportion of the cluster (about 4%). (B) The second cluster (denominated as secondary land cover) included secondary vegetation types of temperate forests, tropical forests and xerophytic scrublands. (C) The third cluster ("so-called" man-made land cover) was comprised of all man-made land cover categories such as crops, exotic forest plantations, improved grasslands for livestock production and human settlements (cities, towns and water dams).

Three major LUCC processes were identified on the basis of conversion among land cover clusters. Deforestation was regarded as the change from primary and/or secondary land cover clusters to man-made land cover cluster. Secondary succession is considered a two-way process comprising two steps: the first considers any transformation from a primary land cover cluster into a secondary land cover cluster, whereas the second includes changes from a secondary land cover cluster into a primary land cover cluster. Revegetation comprises changes from a man-made land cover cluster into a secondary or primary land cover cluster.

2.4. Conversion rates

Statistics were obtained and used to determine the actual conversion rates for each major process observed. The equation quoted below was used to calculate conversion rates (FAO, 1996):

$$x = \left[1 - \frac{S_1 - S_2}{S_1}\right]^{1/n} - 1,$$

where x is the rate of conversion processes, S_1 the surface of the cluster x at the date t_1, S_2 the surface of the cluster x at the date t_2, n the difference of years between the two dates ($\approx$21 years).

The areas where these processes take place were spatially displayed with the aid of the GIS in order to depict frontiers of negative LUCC processes.

3. Results

3.1. Vegetation complexity

Oaxaca comprises all vegetation types recorded in Mexico. Furthermore, 70% of the vegetation communities present in Mexico are harbored in less than 5% of the national territory. At local scales (1:50,000) other vegetation communities such as thorny scrubland (*sensu* Tenorio, 1997) were distinguished, but were not cartographically depicted here due to scale limitations. Nowadays, nearly 40% of Oaxaca is covered by temperate forest vegetation types (mainly conifer and montane cloud forest). Tropical forest vegetation types are also widely distributed (ca. 30% of the surface). Temperate and tropical vegetation types occur as mosaics in many mountainous areas in Mexico, although one always clearly dominates. Conversely, these vegetation types in Oaxaca intermix in similar proportions making complex vegetation mosaics difficult to distinguish from only Landsat imagery.

Table 2
Matrix of land use cover change processes between t_1 (1980) and t_2 (2001) in Oaxaca State

1980 (t_1)	2001 (t_2)			
	Primary	Secondary	Man-made	Total (%)
Primary	3,865,319	1,007,281	386,807	5,259,407 (56.6)
Secondary	255,573	1,139,445	367,721	1,762,739 (19.0)
Man-made	133,724	118,421	2,023,194	2,275,338 (24.5)
Total (%)	4,254,616 (45.8)	2,265,147 (24.4)	2,777,721 (29.9)	9,297,484 (100)

The figures represent the surface converted among clusters. The last column indicates the total amount of hectares covered by each cluster in 1980 (and its percentage), whereas at the bottom line the hectare for each cluster in 2001 (and its percentage) is given.

3.2. Land use cover change processes

The matrix shown in Table 2 provides the conversion figures among clusters as the result of crossing t_1 (1980) and t_2 (2001). The last column indicates the surface of each cluster in 1980, whereas the bottom line indicates the surface of each cluster in 2001. In total 9.3 million hectares were evaluated for land use/cover conversion. On the whole, over 40% of the primary vegetation types and 12% of the secondary vegetation types remained unchanged, whereas over 21% persisted as man-made land cover types.

Concerning conversions, primary temperate forest and primary tropical forest vegetation types were converted into secondary vegetation types in 21% and 17% of the surface area, respectively. About 40% of the primary forest vegetation types existing in the 1980s converted to secondary types. Seventeen percent of temperate secondary forest vegetation types changed to man-made and improved grassland and the same percentage was transformed into temperate primary types (Fig. 3). In addition, 24% of tropical secondary forest vegetation types were converted to man-made land cover and grassland, and only 9% reverted to tropical primary conditions. Xerophytic scrubland also experienced a tremendous depletion since over 40% was converted into man-made and grassland land cover types, although most changes derived from the secondary condition of scrubland. Within the study period none of the primary forest vegetation types changed into

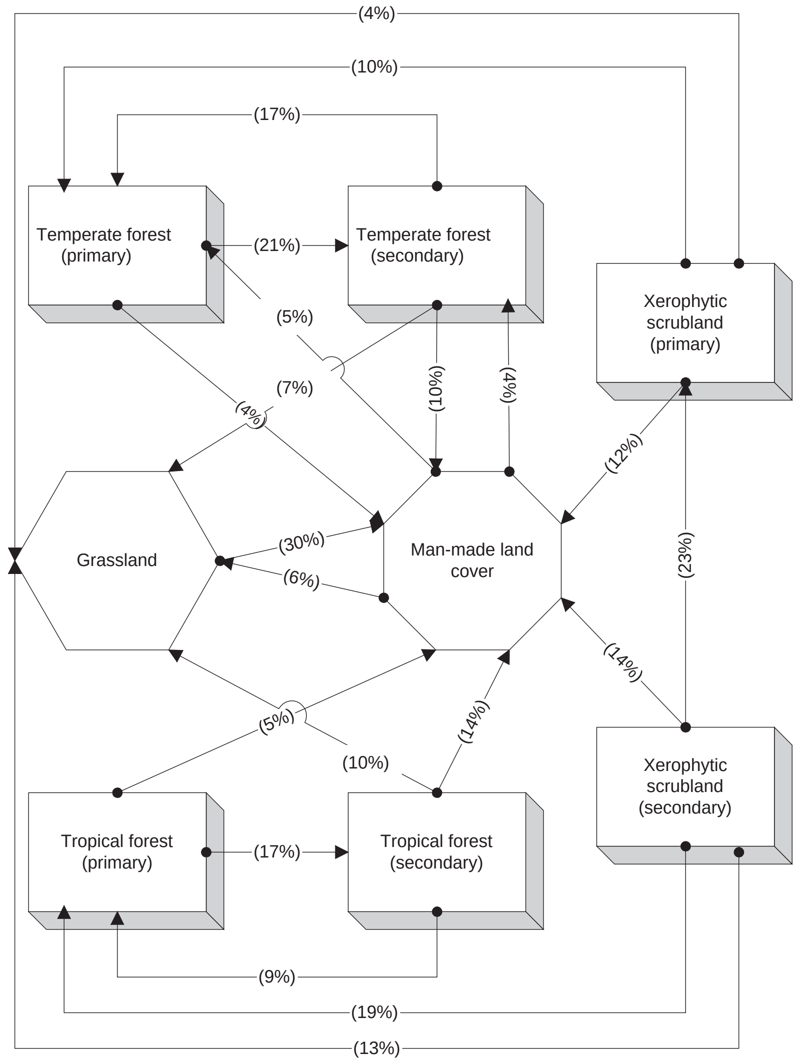

Fig. 3. Flowchart showing the probabilistic transition values derived from the period 1980–2001. Only values ⩾4% are presented. Additionally, other vegetation communities (such as mangroves, dunes and palms) changed 6% of their surface to grassland (comprised by alpine, natural, savanna, improved and cultivated communities) and to man-made land cover (9%). The remaining percentage of each class implied no change within the period.

grassland. In contrast, over 150,000 ha (about 2% of the total state's surface) were converted from secondary forest vegetation types (temperate and tropical) into man-made grassland. An evident result shows that secondary vegetation types serve as a first step to eventually convert an area originally covered with primary vegetation types into a man-made land cover.

3.3. Conversion rates

The rates of conversion computed between 1980 and 2001 are given in Fig. 4. The bars above zero represent the vegetation types that lost surface area, whereas the bars below zero indicate the vegetation types that expanded their surface area. Conifer and montane cloud primary forest vegetation types are losing surface area in a similar proportion (over 1% yearly), whereas primary (sub) evergreen tropical forest vegetation type is depleted faster (almost 2% on a yearly basis). Secondary xerophytic scrubland is vanishing at substantially faster speed (over 3% a year). Areas converted to improved grassland in the eighties are also diminishing at a fast rate (*circa* 2.5% on a yearly basis).

Most secondary forest vegetation types have experienced a substantial increase (above 1%) on a yearly basis (Fig. 4). These include, up to a large extent, highly fragmented forest vegetation types. At these places slash-and-burn agriculture is conducted on small surfaces (about 1 ha). Fallow lands (so-called "acahuales") were not mapped individually due to cartographic resolution. Dominant vegetation types were used to label each polygon. For example, temperate pine-oak forest fragments prevail at high elevations in the "Sierras Centrales de Oaxaca" although many rather

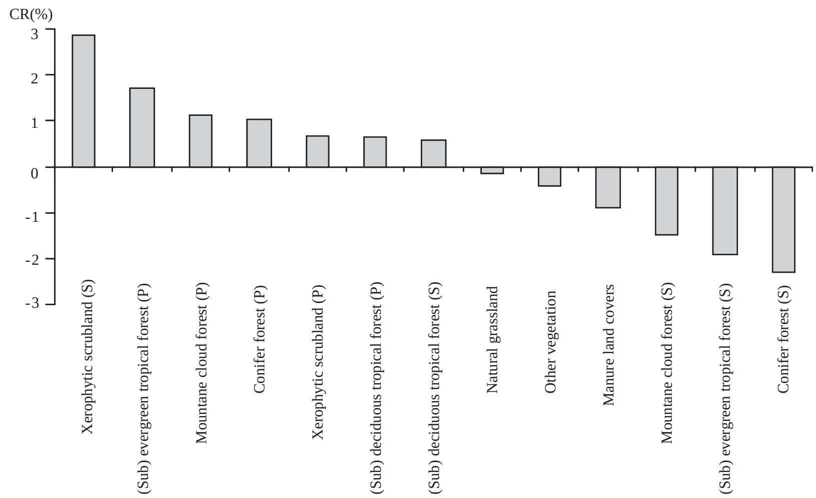

Fig. 4. Conversion rates (CR) among major vegetation types expressed in percentages. Most primary vegetation types (P) lost surfaces (given in positive values) and served as sources, for secondary vegetation types (S) and man-made land covers (sinks).

small rain-fed corn crops occur. In contrast, in the "Sierras y Valles de Oaxaca" the opposite pattern occurred.

3.4. Mapping LUCC processes

Fig. 5 shows the weight of the LUCC processes detected, expressed as a percentage of conversion. Gross deforestation, either from primary or secondary vegetation types, includes over 8% of the total state's surface (over 750,000 ha). Revegetation, in contrast, only took place in 2.6% of the state's surface. Net deforestation during the study period is, therefore, 511,361 ha (over 24,000 ha a year). Additionally, about 11% of the state's surface (1,022,723 ha) has experienced a conversion from primary to secondary vegetation types. The opposite process (secondary into primary) comprised 251,032 ha. Again, secondary vegetation types have served as the main sink of primary vegetation types, and as the core source for deforestation.

These processes are displayed cartographically in Fig. 6. Most deforestation in this period was observed in the "Cordillera Costera del Sur", the "Llanura Costera Veracruzana" and the eastern and southern localities of the "Sierra del Sur de Chiapas" (Fig. 1). Deforestation took place in less proportion in "Mixteca Alta" (between the towns of Coixtlahuaca and Huajuapan), portions of the "Llanuras del Itsmo" and patches within the "Sierras y Valles de Oaxaca". In addition to deforestation, transformation from primary to secondary vegetation types occurred throughout the state, mainly concentrated in the "Costas del Sur", "Cordillera Costera del Sur", the "Sierras del norte de Chiapas" and the "Sierras del Sur de Chiapas". The opposite processes (revegetation and recovery from secondary to primary vegetation types) occurred in a spread out

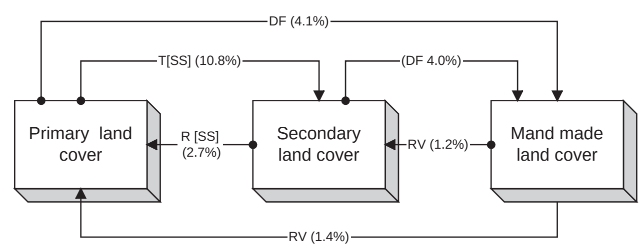

Fig. 5. Conversion processes depicted in Oaxaca State between 1980 and 2001. The figure represents the surface of the state converted (as a percentage). DF = deforestation; SS = secondary succession (transitional stages from primary to secondary [transformation] and vice versa [Recovery]); RV = revegetation (chiefly crops and water dams).

fashion throughout the state. Nevertheless, revegetation largely prevails in the "Sierras Orientales" the "Mixteca Alta", the "Sierras y Valles de Oaxaca" and the "Sierras Centrales de Oaxaca". Summing it up briefly, these processes depicted in Fig. 6 show the critical areas where environmental loss prevails.

4. Discussion

4.1. Conversion trends in Oaxaca

If conversion trends remain as the ones documented in this study, primary vegetation types and secondary vegetation types will be reduced to 1,159,596 and 900,161 ha, respectively. In other words, by the year 2022 only about 22% of the total state's surface will remain covered by autochthonous vegetation. A better scenario can be foreseen if local social initiatives devoted to the sustainable use of natural resources are enforced (Velázquez et al., 2001).

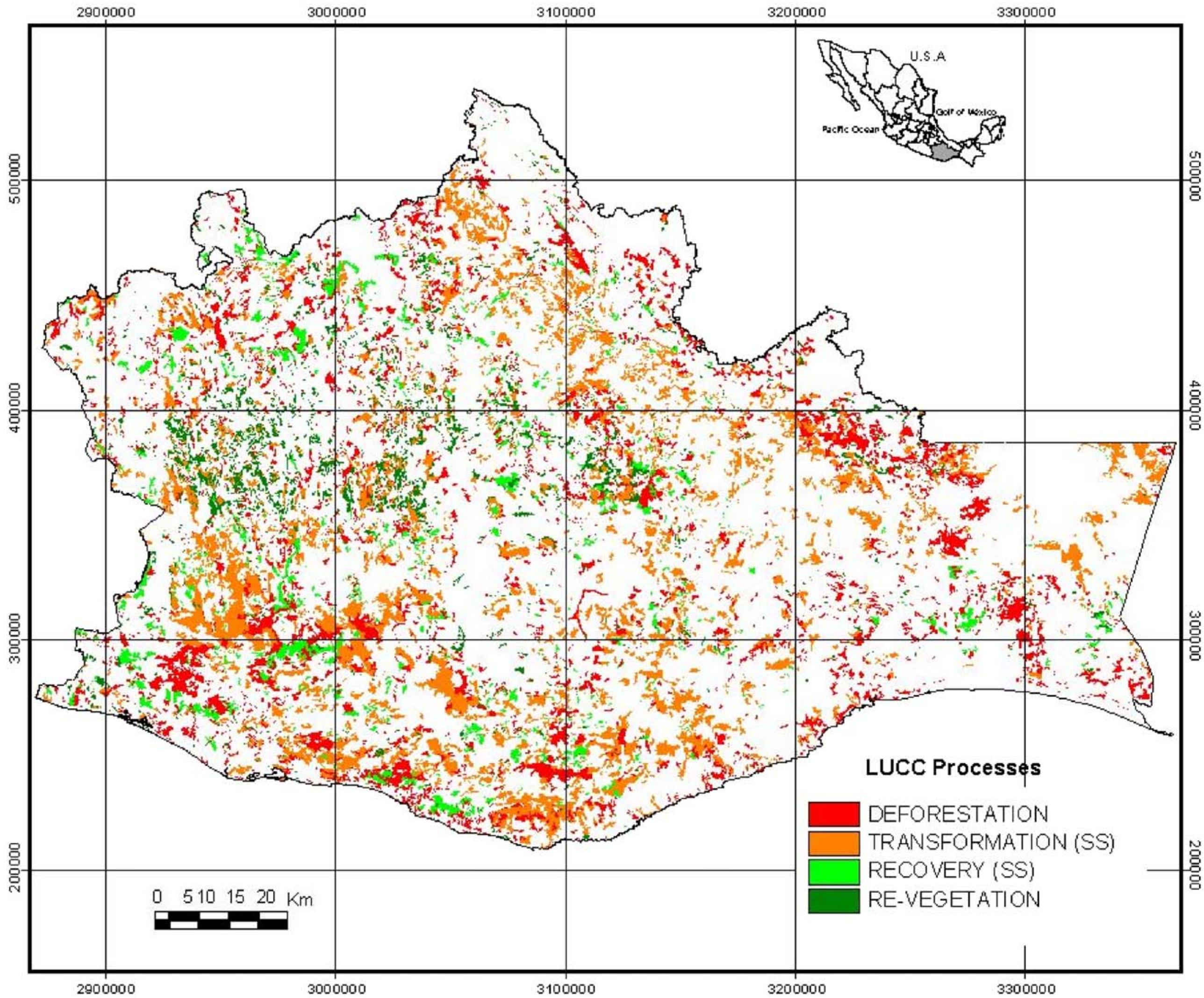

Fig. 6. Land use cover change processes map: deforestation, transformation, revegetation and recovery. Net deforestation in Oaxaca during the study period was of 507,717 ha.

4.2. Methodological outreach

According to FAO (1996), about half of the current human population (over 3 billion people) depends strongly on natural resources obtained from inter-tropical developing countries. Nonetheless, these countries experience the most drastic negative land use conversion (Lambin et al., 2001; FAO, 2001). Under this critical scenario, rapid, precise, and spatially explicit scientific methods to assess environmental trends ought to be developed (Pace and Groffman, 1998; Bocco et al., 2000). This is especially crucial for regions where scientific guidance is urgently needed to achieve sound land use planning, as in the case of Oaxaca. This study, for instance, was requested by the State Commission on Land Use Planning with the purpose to identify priorities to allocate limited funds for forest recovery purposes. Three core methodological aspects were essential in achieving the results presented in this paper. First, the sound use of pre-existing information (such as that provided by INEGI); second, the use of database management through remote sensing and GIS technologies (such as Landsat ETM + 7); and third, problem-oriented field-work strategy. All three were fundamentally in obtaining reasonable outcomes within a relatively short period (one and a half years). The execution of the project included a large number of experts from different disciplines working together in order to compile the conceptual methodological framework used in this research. The outreach of such a methodological framework may be applied to assess LUCC at places facing environmental complexity alike, similar land use planning needs and the same time-budget restrictions. Scale restrictions need to be considered since more precise interpretations ought to be made in order to depict conversion trends of vegetation communities at a local level.

4.3. Implications for social stakeholders

Local decision makers have increased their concern about two major processes detected in this study: deforestation and revegetation. The first process is relevant because of its enormous impact on biodiversity loss and disappearance of environmental services directly linked to a large number of economical activities (e.g., irrigated agriculture, tourism, among others). The second process (revegetation) shocked the policy makers because it, rather than an effective policy in conservation, represents the effect of migration. At the cost of abandoning their rain-fed cornfields, peasants have moved to urban areas and to the United States seeking employment for reasonable pay. This revegetation process, as a consequence of migration, has been documented in Oaxaca (Ramírez, 2002) and other regions in Mexico (Velázquez and Romero, 1999; Ramírez, 2001; García et al., 2002; Lopez et al., 2003).

The negative LUCC processes might be the result of an inadequate policy, which have encouraged conversion from natural vegetation into grassland for cropping and livestock production (Toledo, 1992; Velázquez et al., 2002). For example, large areas of tropical forest were deforested before 1980 for livestock production in the "Llanura Costera Veracruzana" (Toledo, 1989). These areas have been proven unsuitable for livestock production in the long term and currently a mosaic of annual crops (mainly sugar cane) and low productivity rangeland prevail.

Relevant international and national political changes on rural development took place in Mexico during the study period (e.g., green revolution and the NAFTA agreement). It is, therefore, crucial to analyze the sociopolitical-LUCC processes relationship in order to learn from past experiences. The present research (the statistics and map derived from this study) provides useful information to evaluate the relationship between LUCC and policies conducted during the last two decades on natural resource management and likely social or economical causes. In Chiapas, Guerrero and Michoacán (the other most diverse states in Mexico) similar environmental impoverishment has been documented (see Velázquez et al., 2002). Up to now, however, no quantitative, spatially explicit data has been given to assess and to eventually revert negative LUCC processes. Sound long term land use planning ought to include on an equal basis, LUCC processes as well as social and economic policies in order to be durable.

In Oaxaca, a large number of indigenous forestry organizations have proven to be effective in achieving forest use and conservation simultaneously. Over 10 municipalities in the "Sierras Centrales de Oaxaca" and many other similar organizations such as coffee growers in the "Cordillera Costera del Sur" are good examples of such promising initiatives (Moguel and Toledo, 1999; Boege , 2001; Bray et al., 2003). In addition, migration may also play a positive role in forest encroachment. In Yavesia municipality, for example, local stakeholders have decided to live off economic resources derived from migrants and devote about 90% of their almost pristine forest to conservation and ecotourism activities (Ramirez, 2002). In brief, local stakeholders are regarded as the driving force to effectively reorient forest trends. State and federal policy makers are aware of these initiatives and emerging programs are being launched to support and multiply them (see www.conafor.gob.mx). Scientific support upon which sound decisions can be based (at local and state levels) is crucial and the data presented here may play a key role in defining priorities for long term land use planning.

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