Applied Geography 31 (2011) 237–250

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Analysing land cover and land use change processes at watershed level: A multitemporal study in the Lake Cuitzeo Watershed, Mexico (1975–2003)

Manuel E. Mendoza [a,*], Erna López Granados [b], Davide Geneletti [c], Diego R. Pérez-Salicrup [d], Vicente Salinas [e]

[a] Centro Investigaciones en Geografía Ambiental, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de la Huerta CP 58190, Morelia, Michoacán, Mexico
[b] Departamento de Geología y Mineralogía, Instituto de Investigaciones Metalúrgicas, Universidad Michoacana de San Nicolás de Hidalgo, Ciudad Universitaria Edificio: U, Morelia, Michoacán, Mexico
[c] Department of Civil and Environmental Engineering, University of Trento, Via Mesiano, 77 38100 Trento, Italy
[d] Centro de Investigaciones en Ecosistemas, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de la Huerta CP 58190, Morelia, Michoacán, Mexico
[e] Instituto Tecnológico del Valle de Morelia. km 6.5 Carretera Morelia-Salamanca, Col. Los Ángeles, C.P. 38100, Morelia, Michoacán, Mexico

Keywords:
Land cover change
Remote sensing
GIS
Statistical analysis
Watershed management
Mexico

A B S T R A C T

We analysed land cover change processes over a 28-year time period in Central Mexico, by means of integration of existing databases of land cover and land use (1975 and 2000), and updating through visual interpretation of Landsat MSS and ETM + satellite images and orthophotos (1986, 1996 and 2003). Multitemporal analyses included mapping, evaluation of transition matrices, computation of rates of land use change for the main change processes during each period, and cluster analysis. We used watersheds, subdivided both as sub-watersheds and functional zones, as units of analyses. The processes of land use change in the area were not constant, as most of the land use changes took place over a period of less than ten years. This specific period coincided with both the Immigration Reform and Control Act of 1986, and a major catastrophic earthquake in central Mexico in 1985. Similarly, processes of land use change differed during the periods of analyses in the watershed functional zones. The methodological approach applied in this analysis integrates standard procedures to evaluate land cover and land use change in watersheds. Due to the practical value of the results, the data and information generated during the analysis have been made available to local authorities.

Introduction

Land cover (LC) and land use (LU) are two key elements describing the terrestrial environment in relation to both natural processes and human activities. Land cover refers to objects located on the planet surface which are of either natural or anthropogenic origin (Jansen & di Gregorio, 2002). In contrast, LU refers to objects that represent human activities that result in the production of goods and services for society.

During recent decades, the study of LC and LU change has become a prominent research topic, as change in LCLU has been recognized as one of the most important factors of environmental modification worldwide (Xiao et al., 2006). Changes in LC and LU, integrated as LCLU changes, have been directly linked to food security, human health, urbanization, biodiversity loss, trans-border migration, environmental refuge, water and soil quality, and runoff and sedimentation rates, among other processes (Dunjó, Pardini, & Gispert, 2003; Heistermann, Müller, & Ronneberger, 2006; Milesi, Hashimoto, Running, & Nemani, 2005). The balance between natural habitats and human-modified landscapes could decide the future of biodiversity conservation over large areas of the planet. Consequently, it is important to map and quantify the degree of human-driven conversion of natural habitat into disturbed or human-dominated environments (Lee, Carr, & Lankerani, 1995; Verbug, Van de Steeg, Veldkamp, & Villemen, 2009). In general terms, it is estimated that between 30 and 50% of the Earth's surface has been transformed or degraded by anthropic activities (Vitousek, Mooney, Lubchenco, & Melillo, 1997). Nevertheless, in recent years, several studies have demonstrated a recovery of forest areas, effected through a process known as forest transition (Satake & Rudel, 2007), in countries such as

* Corresponding author. Antigua Carretera a Pátzcuaro, No. 8701, Col. Ex-Hacienda de San José de La Huerta C.P. 58190, Morelia, Michoacán, México. Tel.: +52 443 3 22 38 39; fax: +52 443 3 22 38 80.
E-mail address: mmendoza@ciga.unam.mx (M.E. Mendoza).

0143-6228/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apgeog.2010.05.010

Vietnam (Clement, Orange, Williams, Mulley, & Epprecht, 2009; Meyfroidt & Lambin, 2008), Honduras (Redo, Joby Bass, & Millington, 2009) and Spain (Marey-Pérez & Rodríguez-Vicente, 2009) among others. Therefore, for a given study area, it is important to understand the relation and interaction of processes that result in the conversion of natural habitats into human-dominated environments, and vice versa (forest transition).

There is considerable current interest in both retrospective and real time mapping and monitoring of the spatial distribution of changes in the landscape at local, regional and global scales, using satellite imagery (medium resolution, MSS/ETM), or conventional aerial (low flight) or digital (high-resolution) photographs (see for example, Bayarsaikhan, Boldgiv, Kim, Park, & Lee, 2009; Brink & Eva, 2009; Pellikka, Lötjönen, Siljander, & Lens, 2009; Shultz, Cayuela, Echeverria, Salas, & Benayas, 2010). Scientists, politicians and environmental managers should be made more aware of the limitations associated with the measurement of landscape change, particularly with changes of landscapes which occur during two or more different time periods (Fuller, Smith, & Devereux, 2003). This is particularly true when landscape change is evaluated over long time periods, because sudden changes in response to natural or social causes can be mistaken as gradual over large periods. Similarly, the causes associated with sudden changes might be lost from analyses when large time periods are evaluated.

Despite the progress made in the characterization of LCLU change by satellite observation of the surface of the Earth (Loveland et al., 1999), global and regional land cover, and land use in particular, have been scantly described (Watson et al., 2000). Due to this deficiency, multitemporal analyses of LCLU change are required as an aid to understanding processes and patterns during given historical periods. It is important to understand how these prevail or change over time, and to recognize the dynamic nature of these rates of change. In particular, it is important to identify the factors that govern rates of change in LCLU in a given region, and how these rates might vary within subregions. This would allow the identification of relationships between patterns of LCLU processes, and socioeconomic variables such as migration (Fuller et al., 2003; López, Bocco, Mendoza, Velázquez, & Aguirre, 2006), human population growth (Ningal, Hartemink, & Bregt, 2008), concentration of industry (Currit & Easterling, 2009), presence of protected areas (Bayarsaikhan et al., 2009), and the response to natural catastrophic events.

In terms of watershed management, it is of particular relevance to understand how LCLU processes have changed over time, because they are linked and hence directly affect hydrological dynamics. Furthermore, while the principles, concepts and approaches related to watershed management have experienced important advances in recent years, no universal methodology for achieving effective watershed management is currently in place (Bhatta, Chalise, Myint, & Sharma, 1999; Gautam, Webb, Shivakotia, & Zoebisch, 2003; Naiman, Bisson, & Turner, 1997). We suggest that the incorporation of explicit watershed information into analyses of change in LC and LU can provide integrated analyses which could be invaluable for watershed management. In this sense, watersheds can be subdivided into sub-watersheds, or into functional zones. Therefore, it would be important to analyze how LCLU changes are affecting areas associated with a given sub-watershed or functional zone. We developed our study with data and information from the Cuitzeo Lake Watershed as a case study, and provide specific management recommendations for this site.

This paper analyses LCLU change processes over a 28-year time period within the Lake Cuitzeo Watershed, in Central Mexico. Specifically, the objectives of the paper are:

- To indentify LCLU at five time periods between 1975 and 2003 using remotely sensed data;
- To quantify LCLU change through transitional matrices;
- To identify the main LCLU change processes;
- To analyse LCLU change processes at watershed and sub-watershed level, focusing in particular on their environmental implications.

Study area

The closed watershed of Lake Cuitzeo is located in the Transmexican Volcanic Belt (TMVM), Central Mexico, and includes areas belonging to the Mexican states of Michoacán and Guanajuato. Its extreme coordinates are 19°30′ and 20°05′ Northern latitude and 100°35′ and 101°30′ Western longitude. Its surface area is approximately 4000 km^2 (Fig. 1). The watershed is representative of the environmental and socioeconomic conditions of central Mexico, especially of the TMVB, which covers around 131,584 km^2 (7% of the country), and includes the highest peaks in the country (Ferrusquía-Villafranca, 1993). The TMVM is an area of high biodiversity and endemism, in which 50% of the Mexican population live (INEGI, 2000). Therefore, it is of essence to understand the processes that govern human induced LCLU change because of the impacts that these processes can have on biodiversity conservation and human welfare (Villaseñor, Delgadillo, & Ortíz, 2006).

The watershed is formed by both low and high hills of Miocene-Pliocene volcanic origin, associated pyroclastic-fall deposits, and fluviolacustrine plains (Mendoza, Bocco, López, & Bravo, in press; Pasquarè, Ferrari, Garduño, Bibaldi, & Vezzoli, 1991). Andisols, luvisols, acrisols, and vertisols are the main soil types developed over these parent material units. The dominant land covers and land uses form a highly fragmented landscape of scrubland, forest and agricultural land, combined in a mosaic pattern (López et al., 2006). The climate is temperate, with summer rains accounting for about 80% of the annual precipitation, which is an average of 765 mm (Carlón Allende, Mendoza, López Granados, & Morales Manilla, 2009). Precipitation records show three relatively dry periods: a) 1940 to 1960, b) 1980 to 1990, and c) 1995 to 2000; these periods have been related to the reduction of the surface area of the lake (Mendoza, Bocco, Bravo, López-Granados & Osterkamp, 2006.). The lake itself is shallow with brackish waters, is located in the lowlands of the watershed and covers an area of about 300 km^2. It is the second largest lake in the country and has been proposed as a RAMSAR site.

The watershed comprises 28 municipalities which, in the year 1970, included 392 human settlements, a number which had increased to 687 by the year 2000 (INEGI, 2000). The population of the watershed in 1970 numbered 380,787 inhabitants (16.4% of the population of Michoacan state), and by 2000 it had grown to 837,773 (21.6% of the state's population). The principal economic activity undertaken in the study area in 1975 was mainly agriculture, centred on grain production and animal husbandry (on average, 88% of the economically active population worked on primary activities). By the year 2000, only 30% of the economically active population remained in the primary sector, while the majority were involved in secondary and tertiary activities (INEGI, 1970, 2000).

Materials and methods

Land cover mapping

LCLU was mapped at 5 different years, based on a set of available remotely sensed data and existing LCLU maps. We used a digital

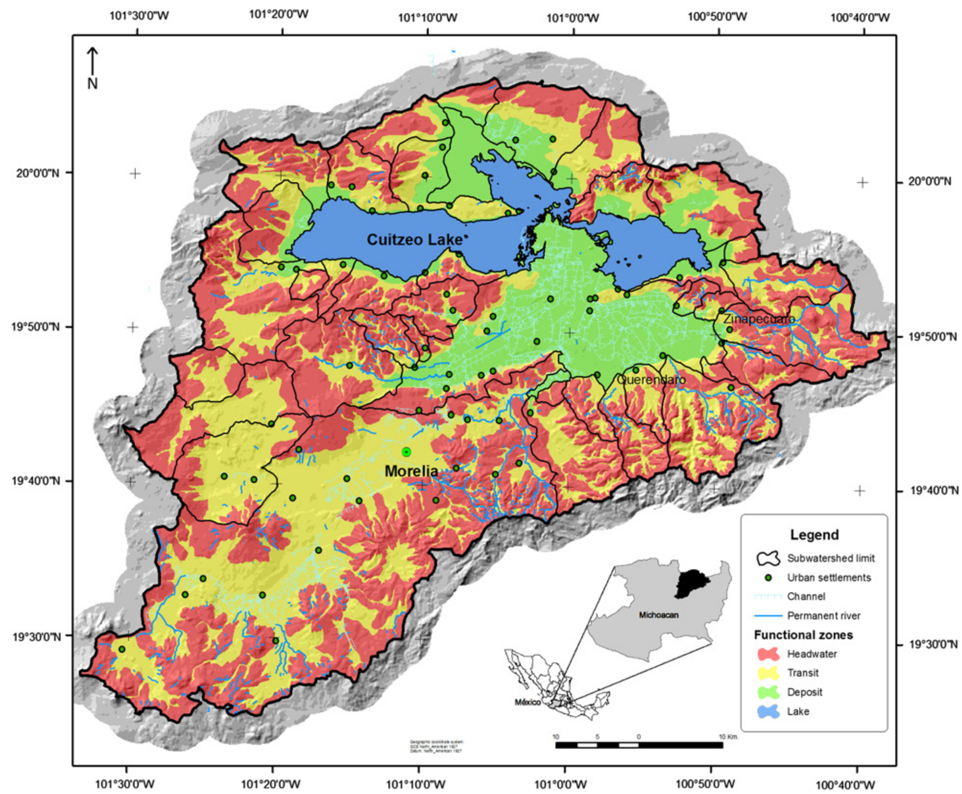

Fig. 1. Study area. Shadow map of Cuitzeo Lake watershed depicting main human settlements, functional zones and sub-watersheds.

map based on aerial photographs (scale 1:50,000) for 1975, for 1986 we used a Landsat MSS image (30 × 30 m), for 1996, we used digital Orthophotos (2 × 2 m), for 2000 we used a digital map based on aerial photographs (scale 1:37,000) and for 2003 we used a fused Landsat ETM image (10 × 10). These data have different spectral and spatial characteristics; hence a uniform legend and mapping scale were set prior to the analysis. In order to render all images comparable, they were rectified to Universal Transverse Mercator (UTM) projection and all mapped objects with areas of less than 3 ha (the minimum mapping area adequate for analysis at the scale used- 1:80,000) were aggregated to their neighbouring objects (Fig. 2).

The reference database for this analysis corresponds to the year 2000. This interpretation was validated during that year, with an accuracy value at the 95% confidence level (López et al., 2006). The 1975 interpretation was carried out on aerial photographs at scale 1:50,000. The use of aerial photographs at the above-mentioned scales ensure the appropriate detection of LC categories in a more cost-effective manner, compared to that of very high-resolution satellite imagery (not available for 1975; Zomeni, Tzanopoulos, & Pantis, 2008). In addition, conventional aerial photography allowed stereoscopic interpretation of relief–soil patterns. Available information sources were simultaneously consulted (reports, thematic maps, censuses, etc.). This allowed identification of the most relevant LC types and, as a consequence, the establishment of a legend for the study area (Anderson, Hardy, Roach, & Witmer, 1976; Jansen & di Gregorio, 2002; see Tables 1 and 2).

Database updating (1986, 1996 and 2003) was based on satellite images and orthophotos. Updating of maps was based on the criteria and rules of aerial photointerpretation (Van Zuidam & Van Zuidam-Cancelado, 1979, p. 309). Interpretation of units of LCLU was conducted on the computer monitor at a 1:80,000 scale, adjusting the interpretation of the year 1975 with updated data from 1986 to 1996, and that of the database of year 2000 to update data for the year 2003. Thus, five databases of LCLU were generated which together covered a period of 28 years. Ground truth data obtained in 2002 were used to validate the classification, and nine LCLU classes were generated for all the maps. This procedure was essential in order to decrease the uncertainty arising from both the simultaneous analysis of several conditions, and their homogenization at a regional scale (Tran, Knight, O'Neill, Riitters, & Wickham, 2002).

LCLU change detection

In order to make a detailed analysis of the dynamics of LCLU change, transition matrices were created. Transition matrices are tables with symmetric arrays, composed of the LCLU classes from the initial year in one axis and the same classes from the subsequent year in the other (time period 1 and time period 2). Each cell of the main diagonal of the matrix contains the surface area (in km^2) of each class of LCLU that remained unchanged during the time period analysed, while the remaining cells contain the estimated surface of a given LCLU class that changed to a different class during the same time period (Luenberger, 1979), thus representing the dynamics of LCLU change at local or regional scales. In a transition matrix, the conditional probability of LCLU at any given time depends mostly on the recent LCLU, and not on previous changes (Bell & Hinojosa, 1977). The causal variables (environmental and socioeconomic) are masked by the stochastic nature of the matrices and therefore the resulting models lack explanatory capability. Since the LCLU are described in an aggregated manner, the resulting model cannot be truly spatial (Lambin, 1997), but can still provide information of value for decision making.

In this study, transition matrices were created using the area covered by the different classes derived from the LCLU maps for the

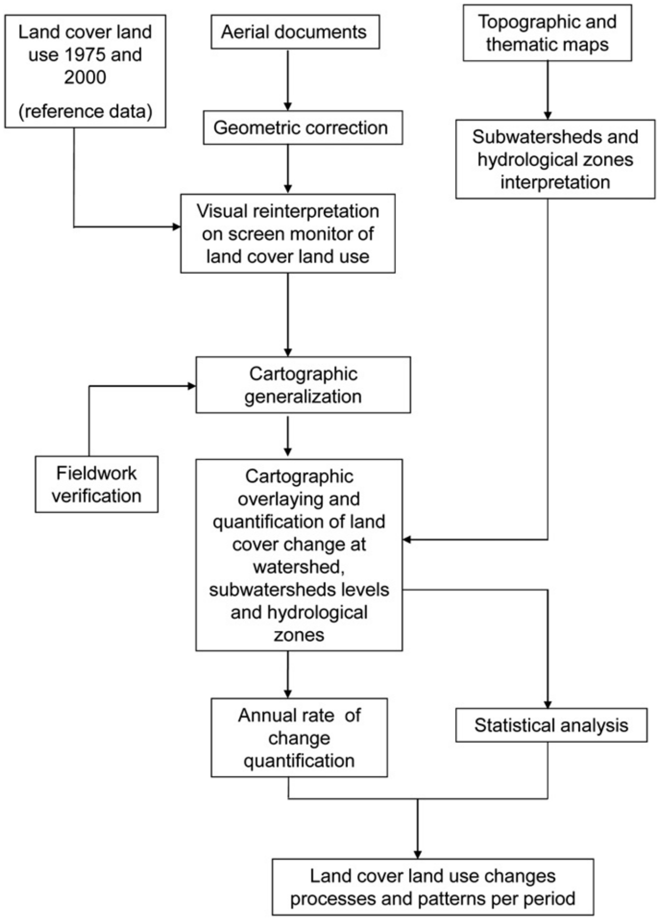

Fig. 2. Methodological flow diagram.

time periods of 1975–1986, 1986–1996, 1996–2000, 2000–2003 and 1975–2003. It was assumed that the probability of transition (P_{ij}) for each class in the matrix was proportional to the surface area of the corresponding class that remained unchanged throughout the analysed time periods. In mathematical terms:

$$P_{ij} = S_{ij}(t_1)/S_j(t_2) \tag{1}$$

where S_{ij} is the surface area of the "ij" element of the LCLU transition matrix during each initial year, and "Sj" is the surface area of the "j" LCLU class during the following year. Thus, for any "j" class: $SP_{ij} = 100$.

Quantifying and mapping LCLU change processes

The main LCLU change processes were detected through a two dimensional table, which consists in a multiconditional array for a coincidence analysis (Table 3) in ILWIS V.3.3 (ITC, 2005). The main processes in the study area identified were: forest degradation, deforestation, forest transition, scrubland increase, and urbanization. Forest degradation refers to a transition to a less dense forest cover (i.e., from closed to semiclosed or open forest, and from semiclosed to open forest). Deforestation refers to a loss of forest cover caused by an increase in scrubland or agricultural land. Forest transition refers to an increase in surface area or densification of forest cover. Scrubland increase refers to the encroachment of scrub into areas previously characterised as agriculture land. Finally, urbanization refers to the expansion of urban settlement at the expense of other LC types. It should be noted that, according to

Table 1
Description of LCLU classes in the Lake Cuitzeo Watershed, Mexico.

Code	Land cover and land use classes	Description
1.1	Closed forest	Arboreal associations. Pine, oak and mixed forest; > 90% canopy density
1.2	Semiclosed forest	Arboreal associations. Pine, oak and mixed forest; 70–90% canopy density
1.3	Open Forest	Arboreal associations. Pine, oak and mixed forest; 60–70% canopy density
2.1	Closed scrubland	Scrubby, anthropic vegetation, with scrub branching from the base of the stem. Generally, height is less than 4 m. In the study area, mainly represented by subtropical deciduous scrubland. 70–90% canopy density
2.2	Scrubland-grassland	Woody vegetation with scrub branching from the base of the stem, combined with herbaceous vegetation.
3.1	Grassland	Herbaceous vegetation dominant in terms of percentage cover (>to 75%).
4.1	Agriculture	Fruit tree plantations, rainfed and irrigated crops
5.1	Human settlement	Urban areas, including vacant land
6.1	Other covers	Small patches of forest plantation, aquatic vegetation, water bodies, flooded areas.

these definitions, loss of forest cover caused by its conversion to urban area is defined as urbanization rather than as deforestation. Five maps of the predominant LCLU change processes, identified during the different time periods, were subsequently generated for the whole watershed. Table 3 contains the definitions of the mapped LCLU change processes.

Rates of LCLU change in the watershed were calculated using the approach proposed by FAO (1995) described in Equation (2)

$$q = \left(\left(A_2/A_1\right)^{1/(t_2-t_1)}\right) - 1 \times 100 \tag{2}$$

where A_1 is the surface area of the LCLU category for the time period 1, A_2 is the LCLU category for the time period 2, t_1 is the initial year (time 1) and t_2 is the final year (time 2).

Spatial disaggregation of LCLU change processes

LCLU change was analysed at three spatial levels: the Lake Cuitzeo Watershed as a whole, its functional zones and finally, each separate sub-watershed. The sub-watersheds were delineated based on visual interpretation of a digital contour map and the boundaries drawn by means of standard interpretation keys of the drainage pattern and elevation contour arrangement. The sub-watersheds included those that arrive directly to the lake, or to the lacustrine plain surrounding the lake, and those that are closed. Functional zones were delineated according to an approach, based on hydrographical and topographical criteria (stream order and slope), that defined three zones from a fluvial system based on geomorphological aspects of a watershed according to the concepts proposed by Schumm (1977, pp. 338).

Headwater zone were defined as the area occupied by first order streams (scale 1:50,000), according to the Strahler classification system, up to the water divide. The deposition zone began at the altitude where the last stream reached the main stream, and ended at the shore of the lake. The remaining area between headwater and deposition is called the transit zone (Robertson, 1992). The headwater zone is distributed over 1764 km^2 and comprises approximately 40% of the total area of the basin, while the transit zone comprises 1352 km^2 and the deposition zone covers 575 km^2,

Table 2
Two-dimensional table used for modelling LCLU change processes in the Lake Cuitzeo Watershed, Mexico. Codes for columns and rows are described in Table 1.

	Land cover in time period 2									
Land cover in time period 1	Classes	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
	1.1	Unchanged	Degradation	Degradation	Deforestation	Deforestation	Deforestation	Deforestation	Urbanization	Deforestation
	1.2	Afforestation	Unchanged	Degradation	Deforestation	Deforestation	Deforestation	Deforestation	Urbanization	Deforestation
	1.3	Afforestation	Afforestation	Unchanged	Deforestation	Deforestation	Deforestation	Deforestation	Urbanization	Deforestation
	2.1	Afforestation	Afforestation	Afforestation	Unchanged	Other changes	Other changes	Other changes	Urbanization	Other changes
	2.2	Afforestation	Afforestation	Afforestation	Scrubland increase	Unchanged	Other changes	Other changes	Urbanization	Other changes
	3.1	Afforestation	Afforestation	Afforestation	Scrubland increase	Other changes	Unchanged	Other changes	Urbanization	Other changes
	4.1	Afforestation	Afforestation	Afforestation	Scrubland increase	Scrubland increase	Other changes	Unchanged	Urbanization	Other changes
	5.1	Afforestation	Afforestation	Afforestation	Scrubland increase	Scrubland increase	Other changes	Other changes	Unchanged	Other changes
	6.1	Afforestation	Afforestation	Afforestation	Scrubland increase	Scrubland increase	Other changes	Other changes	Urbanization	Unchanged

representing 33 and 14% of the study area, respectively. The remaining percentage is occupied by the lake itself. The main function of the headwater zone is the capture and delivery of water and sediments, levels of which are determined by conditions of land cover, soil properties and climate. In general terms, this zone is the most fragile and is therefore the usual target of protection or restoration efforts. The transit zone receives and transports the main quantity of water within the system. The deposition zone, at the bottom of the watershed, receives water, sediments (and pollutants) from the other upstream zones. In this study, LCLU change process maps were overlaid with the spatial distribution of the sub-watersheds and hydrological functional zones of the watershed to perform a coincidence analysis in a GIS.

Statistical analyses (pattern recognition)

We conducted a cluster analysis (Sokal & Sneath, 1963), to classify sub-watersheds according to two main criteria, surface and time, and their degree of similarity in terms of the processes of change in each time period. Because the sub-watersheds are of different size, a normalisation procedure was applied to obtain the proportional area occupied by each LCLU change class (Table 2) in each sub-watershed. This analysis was conducted for each time period. Median Euclidean distances were calculated with the mean distance linkage method. An 80% similarity was chosen as the threshold to generate groups (Johnson, 1998). GIS procedures (coincidence analysis) were carried out in ILWIS v 3.3 (ITC, 2005) and statistical analyses in PC-ORD (PCORD, 1999).

We also evaluated whether the proportion of unchanged territory in a given LCLU category differed between the three functional zones into which the watershed was subdivided, and between the four periods analysed, with a two way ANOVA without replication (Sokal & Rohlf, 1995, p. 887). Proportions of territory were arcsine transformed in order to fulfil the normality requirements of ANOVA in this analysis. By identifying differences in the proportion of unchanged territory, it was possible to test whether the proportion of territory that experienced LCLU change differed across functional zones and time periods, while avoiding the masking effect that large proportions of change could have on this analysis. We also evaluated whether the total area that experienced LCLU change differed in terms of the six processes of land cover. This was assessed for the three functional zones into which the watershed was subdivided, and between the four studied time periods, by means of a repeated measures ANOVA (Von Ende, 2001). Statistical analyses were conducted with SYSTAT V. 11 (Wilkinson, 1984).

Results

Land cover change at watershed level

Over the whole study period in the Lake Cuitzeo watershed, the largest surface area is occupied by agricultural land, although this

Table 3
Transition matrices of percent change for different LCLU classes during the periods 1975–1986, 1986–1996 and 2000–2003 in Lake Cuitzeo Watershed, Mexico. Codes for columns and rows are described in Table 1.

Cover/Percentage	1986								
1975	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
1.1	97.7	1.2	0.0	0.1	0.1	0.1	0.8	0.0	0.0
1.2	6.2	89.7	0.1	0.1	0.7	0.6	2.7	0.0	0.0
1.3	7.0	0.8	85.0	0.1	1.3	0.9	5.0	0.0	0.0
2.1	1.0	0.1	5.0	89.6	1.3	0.5	2.3	0.0	0.1
2.2	0.5	0.2	0.0	0.5	95.0	0.6	2.8	0.1	0.3
3.1	1.0	0.5	0.2	0.5	0.8	94.7	1.6	0.4	0.2
4.1	0.4	0.2	0.0	0.2	0.5	0.2	97.7	0.5	0.3
5.1	0.1	0.0	0.0	0.1	0.2	0.2	0.2	99.3	0.3
6.1	0.0	0.0	0.0	0.0	0.1	0.2	2.6	0.1	97.0
Cover/Percentage	1996								
1986	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
1.1	64.2	14.4	5.9	4.2	4.9	1.1	4.2	0.1	1.0
1.2	35.9	24.7	8.1	9.1	9.7	3.7	5.5	0.1	3.2
1.3	23.0	19.2	13.1	9.5	17.8	4.5	9.6	0.6	2.8
2.1	8.4	7.6	6.4	38.7	26.5	2.8	6.3	0.9	2.4
2.2	6.4	6.2	5.4	19.1	39.4	6.6	12.7	1.9	2.2
3.1	3.4	3.4	3.0	4.9	27.7	28.8	20.0	3.8	4.9
4.1	2.8	1.3	1.0	5.0	14.0	5.2	64.7	4.7	1.4
5.1	0.0	0.1	0.1	0.1	0.2	0.2	0.2	99.1	1.1
6.1	0.1	0.1	0.0	0.2	1.2	0.6	4.7	0.7	92.5
Cover/Percentage	2000								
1996	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
1.1	90.2	2.1	1.5	0.8	1.5	0.9	2.8	0.0	0.2
1.2	2.5	90.4	1.5	0.6	1.8	1.0	2.0	0.0	0.1
1.3	2.5	1.7	90.7	0.5	1.8	1.0	1.4	0.0	0.3
2.1	0.4	0.5	0.5	93.2	2.5	0.6	2.1	0.1	0.2
2.2	0.7	0.9	0.5	1.7	92.3	1.2	1.9	0.2	0.6
3.1	0.7	0.7	0.8	0.7	2.8	90.9	1.4	0.8	1.3
4.1	1.1	0.5	0.2	0.6	1.4	0.4	94.2	1.0	0.7
5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
6.1	0.0	0.0	0.0	0.2	0.5	0.3	1.5	1.3	96.1
Cover/Percentage	2003								
2000	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
1.1	98.0	0.3	0.3	0.1	0.5	0.2	0.7	0.0	0.0
1.2	3.0	91.9	0.5	0.5	1.8	0.5	1.8	0.0	0.0
1.3	4.3	1.8	88.5	0.5	1.9	1.1	1.7	0.1	0.1
2.1	0.8	0.2	0.1	94.8	1.9	0.4	1.6	0.0	0.3
2.2	0.7	0.3	0.2	0.7	95.0	0.8	2.0	0.0	0.3
3.1	1.5	0.7	0.6	0.7	2.1	92.7	1.3	0.0	0.5
4.1	0.5	0.1	0.0	0.4	0.6	0.1	97.9	0.2	0.1
5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
6.1	0.1	0.0	0.0	0.1	0.4	0.4	0.9	0.6	97.4
Cover/Percentage	2003								
1975	1.1	1.2	1.3	2.1	2.2	3.1	4.1	5.1	6.1
1.1	62.9	14.8	5.9	4.4	5.1	1.2	4.5	0.1	1.1
1.2	37.6	24.5	7.9	9.3	8.7	2.8	5.8	0.2	3.2
1.3	23.3	20.4	14.6	6.1	14.7	4.7	12.2	0.7	3.3
2.1	10.3	7.4	5.2	38.5	26.5	2.4	6.0	1.5	2.2
2.2	6.6	6.1	5.2	19.2	38.8	6.6	12.7	2.5	2.3
3.1	4.1	3.5	3.0	5.1	27.1	28.0	19.5	4.7	4.9
4.1	3.1	1.4	0.9	5.1	13.8	5.2	63.3	5.9	1.3
5.1	0.0	0.1	0.1	0.1	0.2	0.2	0.1	99.2	0.8
6.1	0.1	0.1	0.0	0.1	1.2	0.5	6.6	1.6	89.9

LU shows a decreasing trend over time (from 43% to 33%). Agricultural land is mainly located on the plains and undulating hillsides. Scrubland-grassland has consistently been the second more extensive LC in the watershed, with a tendency to expand its coverage (13%–16%), and is mainly located on undulating to gently sloping areas. Closed forest cover has remained constant (12%), and is located on undulating to gently sloping areas. Scrubland is the third more extensive LC in the watershed, displaying an increasing trend in surface area (5%–8%). Similarly, closed scrubland is mainly located on undulating to gently sloping areas. The area covered by human settlement is mostly associated with the urban areas of Morelia and Zinapecuaro. This last surface increased within the watershed from 2% to 4% of coverage. Although in absolute terms the increase represents only two per cent units, this expansion implies a doubling of the original surface area of urban settlements over the study period (Fig. 3).

As shown by the transition matrices (Table 3), during the periods 1975–1986, 1996–2000 and 2000–2003, the probability of forest vegetation types remaining in the same LC class is high (above 85%); but the opposite was true during the periods 1986–1996 and 1975–2003, where only up to 13% of the area under this LC remained unaltered. The lowest probabilities of permanence (i.e. higher transition probabilities) in these time periods correspond to the categories of open and semiclosed forests, while highest probabilities of change (i.e. lower permanence probabilities) were associated with denser forests. In addition, probabilities of conversion from other categories to forest cover are relatively high (up to 10% during the period 1975–2003). The probabilities of total change of the forest cover (deforestation) estimated for 1986–1996 and for the whole study (1975–2003) period, are relatively high, reaching values of up to 12%. Probabilities of permanence of scrubland, during the periods 1986–1996 and 1975–2003, are comparatively low, due in both cases to the elevated dynamism displayed by these LC categories (change from closed scrubland to scrubland-grassland and *vice versa*), and a trend of conversion from agricultural land (in particular rainfed agriculture) to scrubland. Human settlements display practically 100% probabilities of permanence, as would be expected given that it is almost inconceivable that a human settlement would convert to any other LCLU class within a time frame such as the one analysed in this study.

It is important to state that the values presented in Table 3 could contain an error of around 1%, caused by position, related to the difficulty to find proper control points on highlands (mountain and highills), or interpretation related to the spectral similarities of different types of covers; nevertheless the higher values have sufficient confidence at this level because of the quality of the data and the updating procedure employed in this research.

The results of the analysis of LCLU change processes are depicted in Fig. 4. In general, changes occurred in small areas, and most took place between 1986 and 1996. This was a period in which deforestation occurred in about 4% of the watershed area, and forest transition in almost 8%. Forest degradation occurred in less than 3% of the study area, and scrubland increase was identified over 11% of the watershed. Other changes were mostly due to agropastoral dynamics: conversions between closed scrubland, scrubland-grassland and grassland.

Table 4 shows the rates of change of the main LCLU change processes detected in the Lake Cuitzeo Watershed during the study period. It can be seen that the highest deforestation rate occurred during the period from 1986 to 1996, with an annual forest loss rate of 1.5%. The lowest deforestation rate is observed in the period 2000–2003, with an annual forest loss rate of 0.15%. An increase in forest cover had occurred during the period 1996–2000, with an annual rate of 0.2%. Forest degradation took place throughout the whole period at variable annual rates (from 0.2% to 3.5%). Once again, the highest rate of forest degradation corresponds to the period 1986-1996. With the exception of the first time period, annual urbanization rates are high throughout the study interval, ranging from 0.4% in the period 1975–1986 to 7.9% between 1986 and 1996; following the latter time period, a gradual reduction in annual urbanization rate is observed. Reduction in scrubland cover is observed to have occurred during the initial and final periods (1975–1986 and 2000–2003, respectively), while expansion of this LC is observed during the intermediate periods of 1986–1996 and 1996–2000.

Land cover change at sub-watershed levels

The spatial overlaying of sub-watersheds with the identified LCLU change processes allowed for the characterization and analysis of changes which occurred at the sub-watershed level. The observed change in the patterns of LCLU change over the study period is presented in Table 5 and Fig. 5. Cluster analysis by period indicated that at no time interval did the clustered units and number of clusters remain constant. During the period 1975–1986 five clusters were formed, seven during 1986–1996, and four during both of the intervals 1996–2000 and 2000–2003. The greatest complexity of LCLU change processes was observed when analyzing the total time period between 1975 and 2003, in which eight clusters were grouped.

The predominant LCLU change process during the initial period (1975–1986) was forest degradation, followed by forest transition, and to a lesser degree, scrubland increase. Two sub-watersheds could not be clustered for this initial period. Forest transition was

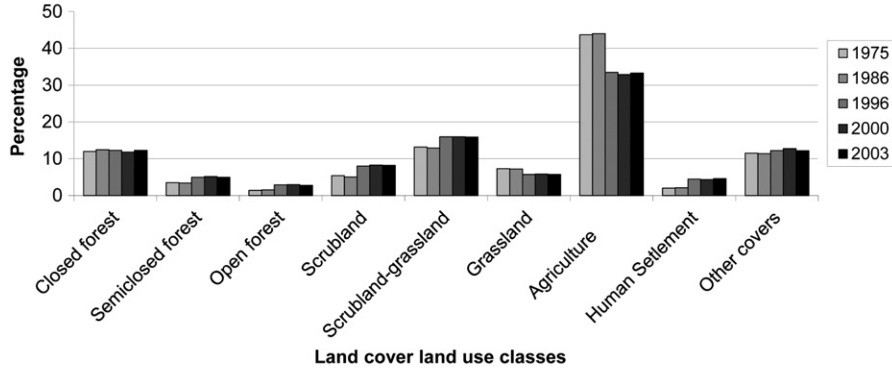

Fig. 3. Land cover and land use classes per year.

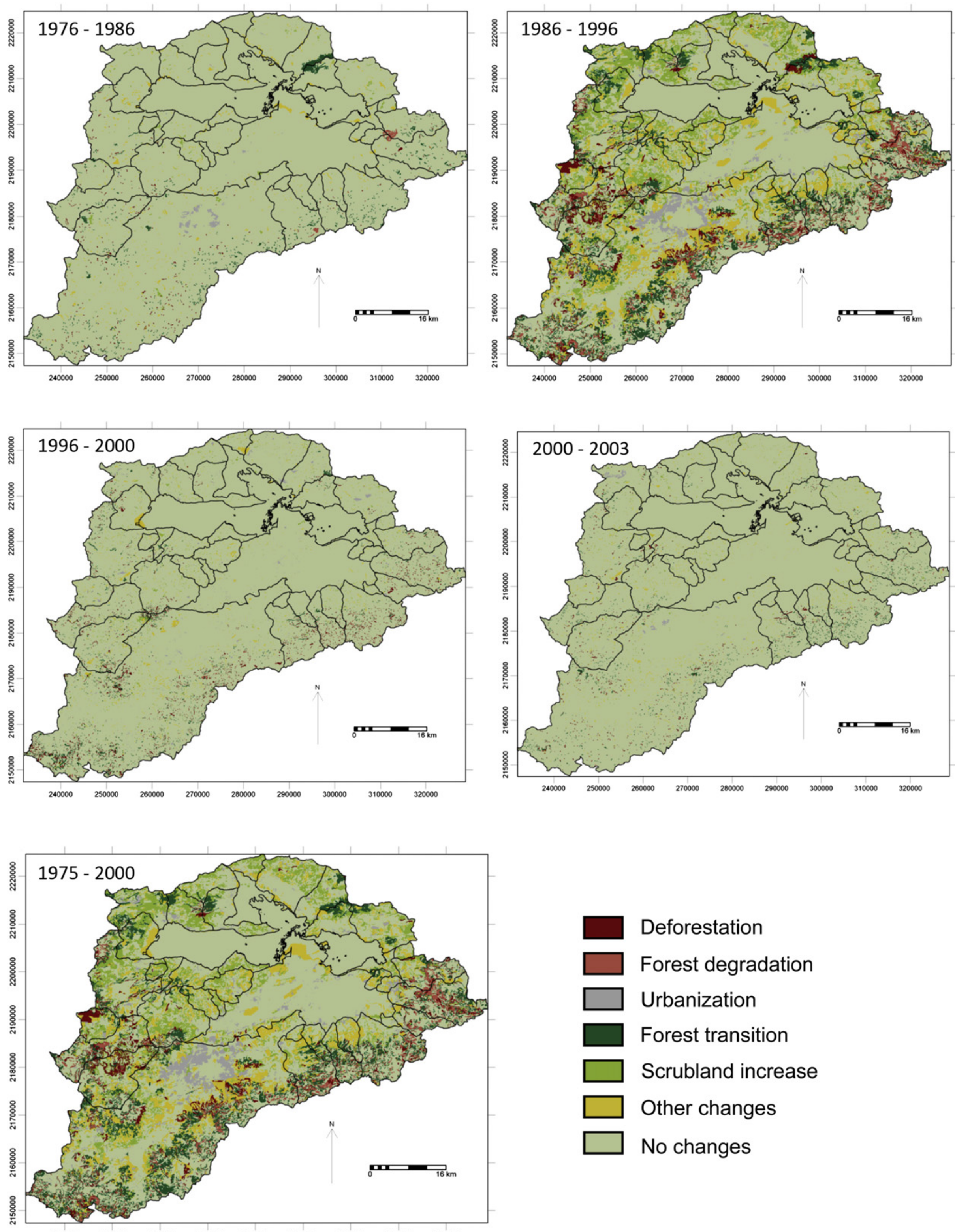

Fig. 4. Maps of land cover and land use change processes per period.

observed to be dominant in two contiguous sub-watersheds in the northeast portion of Lake Cuitzeo Watershed. Forest degradation was concentrated in the eastern portion of the watershed. Scrubland increase predominated in two sub-watersheds in the central-western sector of the study area, while forest transition and forest degradation were dominant in two separate sub-watersheds located in the eastern and western sectors of the watershed. Most of the sub-watersheds did not show LCLU changes during this

Table 4
Rates of LCLU change processes in the Lake Cuitzeo watershed, Mexico, between years 1975 and 2003 according to FAO model.

Years	Δt	% (FAO, 1995)
Annual deforestation/afforestation rate		
1975–1986	11	0.2448
1986–1996	10	1.4799
1996–2000	4	−0.2116
2000–2003	3	0.1496
Annual forest degradation rate		
1975–1986	11	−0.1673
1986–1996	10	−3.4685
1996–2000	4	−0.9860
2000–2003	3	−2.1873
Annual urbanization rate		
1975–1986	11	0.3839
1986–1996	10	7.8837
1996–2000	4	3.2143
2000–2003	3	1.0508
Annual scrubland increase/decrease rate		
1975–1986	11	−0.3104
1986–1996	10	2.9308
1996–2000	4	0.2914
200–2003	3	−0.1827

initial period. However, it is interesting to note from the available data that processes of deforestation and forest transition were already underway during the first time period of this study (1975–1986).

The first period to show significant LCLU change is that of 1986–1996, an interval that is characterized by complex processes ongoing within each sub-watershed. In this time period, urbanization is recognized in three of the seven clusters, while the most frequent process of LCLU change was scrubland increase. In the same period, three sub-watersheds experienced change processes that could not be clustered. Moreover, scrubland increase was detected in all the sub-watersheds in the northern sector of the study area, forest transition was located in the southern sector of the study area and the only area in which no change predominated was the Lake Cuitzeo plain.

Between the years 1996 and 2000 there was an observed decrease in the complexity of LCLU change patterns. Nevertheless, scrubland increase, forest transition and deforestation remain the main cluster discriminating processes. During this period, four sub-watersheds could not be clustered at the 80% similarity level. During the same interval, unchanged sub-watersheds and forest transition processes were distributed throughout the Lake Cuitzeo Watershed; other changes and forest transition predominated in two sub-watersheds in the western portion of the study area, while four sub-watersheds, dominated by the processes of scrubland increase and forest transition, were detected along the area of the lakeshore. The remaining sub-watersheds in the Lake Cuitzeo Watershed all registered forest transition processes during the above-mentioned time period.

During the time interval between 2000 and 2003, landscape stability was once more the main clustering criterion, followed by other LCLU change processes associated with the dynamics of the silvopastoral character of rural areas, which are not evaluated in the present study. In the same time period, forest transition was present in all the sub-watersheds of the study area, a pattern of forest transition-deforestation was present in two contiguous sub-watersheds in the southern sector of the watershed, the plain remained unchanged, and two sub-watersheds were not clustered.

Table 5
Clustering of sub-watersheds by LCLU change processes in Lake Cuitzeo Watershed, Mexico. A) Forest Transition, S) Scrubland increase, F) Forest degradation, D) Deforestation, U) Urbanization, N) No changes, NC) Unclustered.

1975–1986			1986–1996			1996–2000			2000–2003			1975–2003		
No. of sub-watersheds	Surface in km^2	Predominant processes (code)	No. of sub-watersheds	Surface in km^2	Predominant processes (code)	No. of sub-watersheds	Surface in km^2	Predominant processes (code)	No. of sub-watersheds	Surface in km^2	Predominant processes (code)	No. of sub-watersheds	Surface in km^2	Predominant processes (code)
28	3107	N	11	779	S A U	8	393	D S A	31	2718	N O	10	642	S A F
2	251	A D	2	19	N O S	20	2826	N A D	1	425	N	3	221	S A D
2	82	F	9	1814	An S D F U	2	171	O D	2	217	An N	2	30	S N
2	45	S	4	22	F A S	4	96	S O	2	181	A D	7	1640	An F U
2	115	A	2	56	S U	4	148	N C	2	93	N C	2	176	D F A
2	33	NC	5	238	S A N							2	45	An O
			2	432	N O							7	258	S A N
			3	69	U							2	432	N O
												3	189	N C

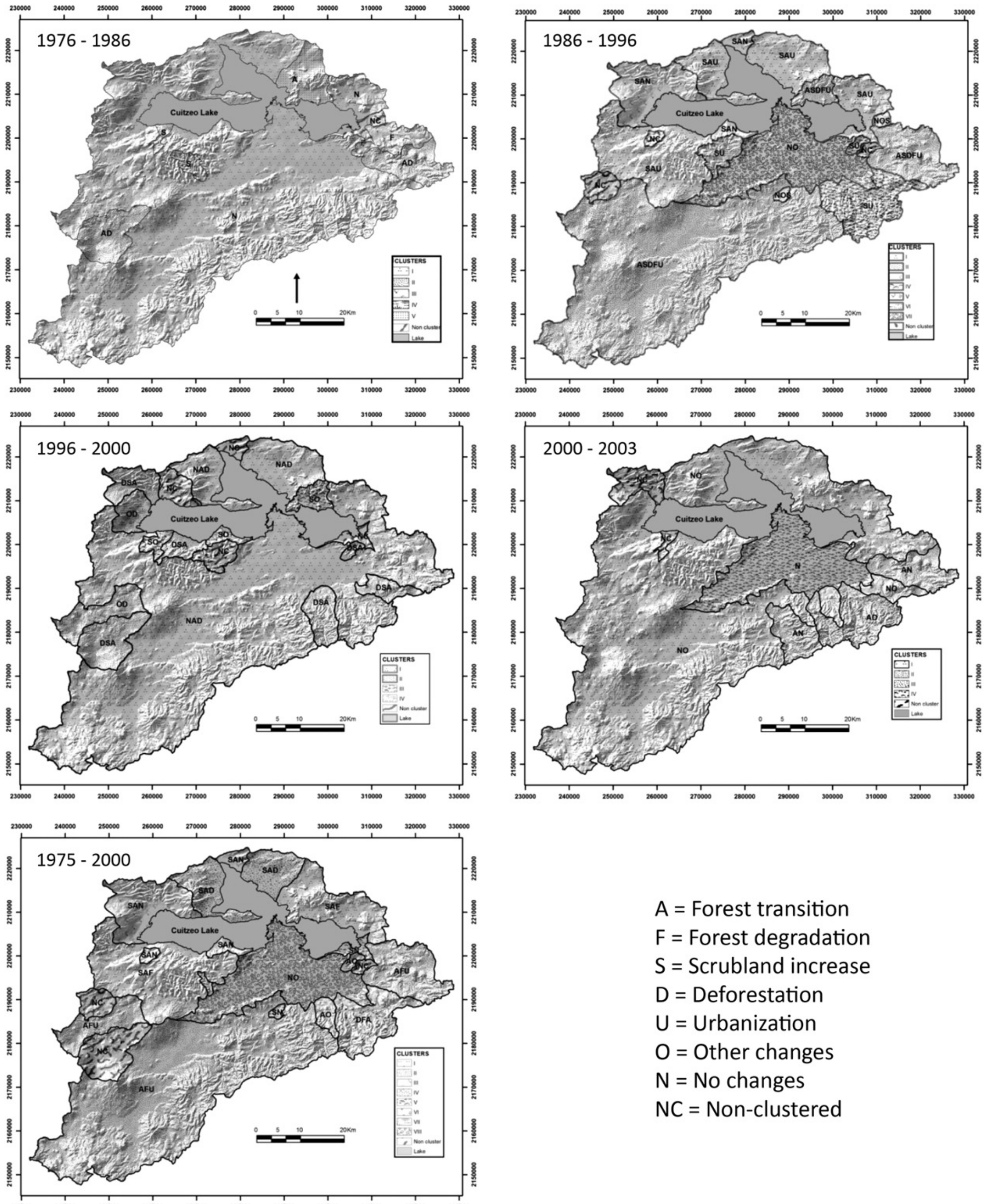

Fig. 5. Subwatersheds clustered by LCLUC processes. A) Forest Transition, S) Scrubland increase, F) Forest degradation, D) Deforestation, U) Urbanization, N) No changes, NC), No clustered.

The analysis of the complete study period (1975–2003) somewhat masks the urbanization process that took place mainly during the interval between years 1986 and 1996, however, the complexity of the LCLU change processes is once more made evident. Throughout the total study interval, three sub-watersheds could not be clustered..

Land cover change at functional zones

The initial step for the analysis of functional zones was to characterize the LCLU in each zone for each year. Fig. 6 shows that even in year 1975 the headwater zones were not completely covered by the original vegetation types: the geomorphological

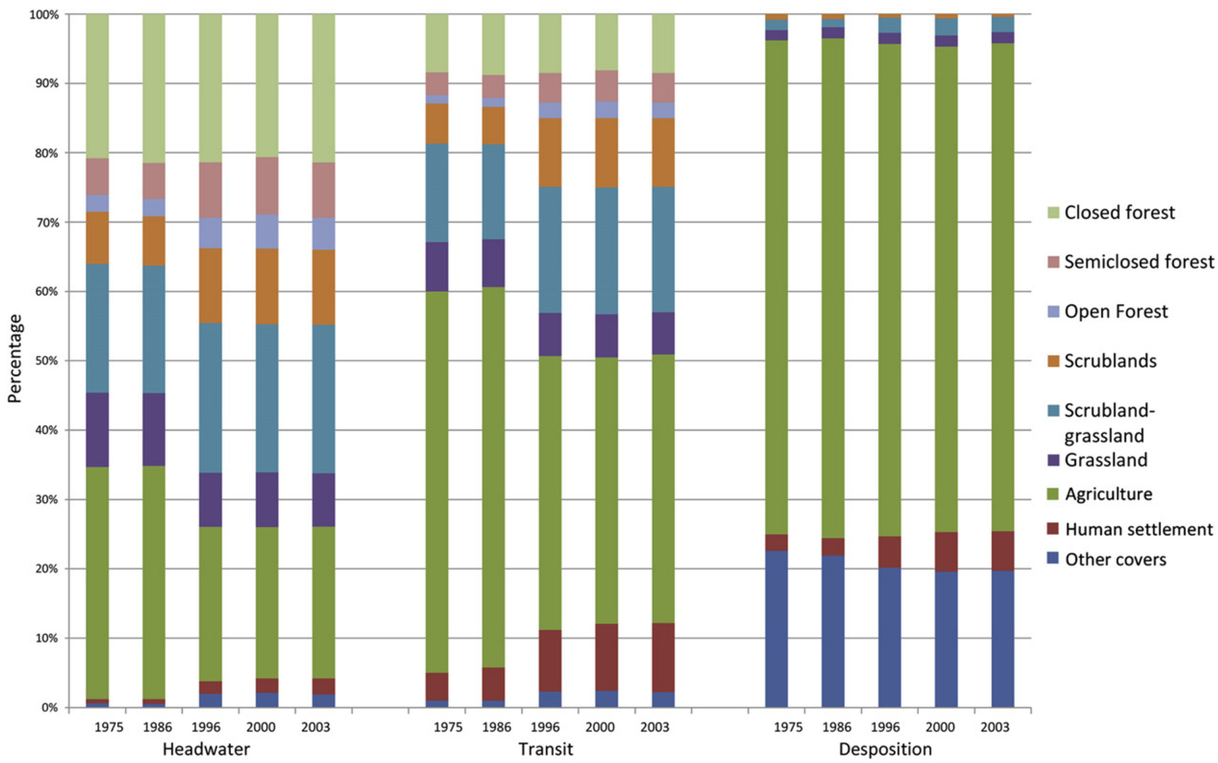

Fig. 6. Land cover land use per functional zone and year.

characteristics of the headwater zone had facilitated their use for agricultural activities since pre-colonial times (Macías Goytia, 1997). Throughout the study period, between 28% and 34% of the headwater zones were covered by one of the classes of forest, 25%–32% was covered by scrubland, 8%–11% by grassland, and 22%–34% was used for agriculture. During the same interval, the predominant LCLU in the transit zones were agriculture (33%–55%), followed by scrubland-grassland (19%–22%) and forests and grassland (8–11%). The dominant LCLU in the deposition zone throughout the time period analysed were, in descending order, irrigated agricultural land and other covers (lake and flooding areas).

The distribution of LCLU change processes in the functional zones of the watershed is shown in Fig. 7, in which it is clearly evident that negative processes in the headwater zone (deforestation and forest degradation) were present only during the period 1986 to 1996; an interval in which the arboreal cover of the headwater zone was reduced by a 6% and degraded, in terms of density, by 5%. In the same functional zone, urbanization processes occurred in an area of less than 2%; conversely, scrubland increase and forest transition, processes that have a positive effect in the headwater zone, took place in 14% and 13% of the zone, respectively. Within the same time interval, the transit zone was impacted by deforestation and forest degradation in 4% and 2% of its area, respectively, while urbanization was present in 5% of the zone. As compensation for the above-mentioned negative processes, scrubland increase and forest transition occurred in a surface area of 16% and 6%, respectively. Finally, 3% of the deposition zone was found to be affected by urbanization.

In the three functional zones, processes associated with agro-pastoral dynamics covered between 10% and 15% of the watershed surface area. Analysis of the LCLU change processes by functional zone, throughout the entire study period (1975–2003), revealed the same patterns as those described above.

ANOVA indicated that the proportion of area with no land cover change differed between the four periods of analysis, but not between the three functional zones within the watershed area ($F_{\mathrm{Period}} = 12.3$, $\mathrm{DF}_{\mathrm{Period}} = 3$, $P_{\mathrm{Period}} = 0.006$; $\mathrm{F}_{\mathrm{Functional\ zone}} = 2.63$, $\mathrm{DF}_{\mathrm{Functional\ zone}} = 2$, $\mathrm{P}_{\mathrm{Functional\ zone}} = 0.15$). During the second period, from 1986 to 1996, all three functional zones of the watershed experienced greater LCLU change; hence, this time interval presented the lowest proportion of unchanged area within the watershed (Fig. 8).

The total area under each one of the six categories of LCLU change varied depending on the functional zone of the watershed ($F = 12.1$, $P = 0.002$), the LCLU change process ($F = 3.6$, $P = 0.039$), and the period analysed ($F = 52.9$, $P < 0.001$). As mentioned above, the period 1986–1996 was clearly the most dynamic in terms of LCLU change processes. Deforestation, forest transition, and scrubland increase were always highest in the headwater and transit zones of the watershed, but forest transition covered more area than deforestation in all the four periods of study. Forest degradation was always highest in the headwater zone of the watershed. In three of the four study periods, urbanization took place mainly in the transit zone of the watershed, followed by the deposition zone. The category which incorporated all other changes occupied more area in the first two study periods than any other LCLU category. Interestingly, the specific functional zone of the watershed which featured the greatest number of changes varied drastically in the first three periods (Fig. 9), i.e., no particular portion of the watershed consistently experienced greater LCLU change throughout the whole study period.

Discussion

In this manuscript, we integrate standard procedures for understanding LCLU dynamics with watershed information detailed both in terms of sub-watersheds and functional zones. This

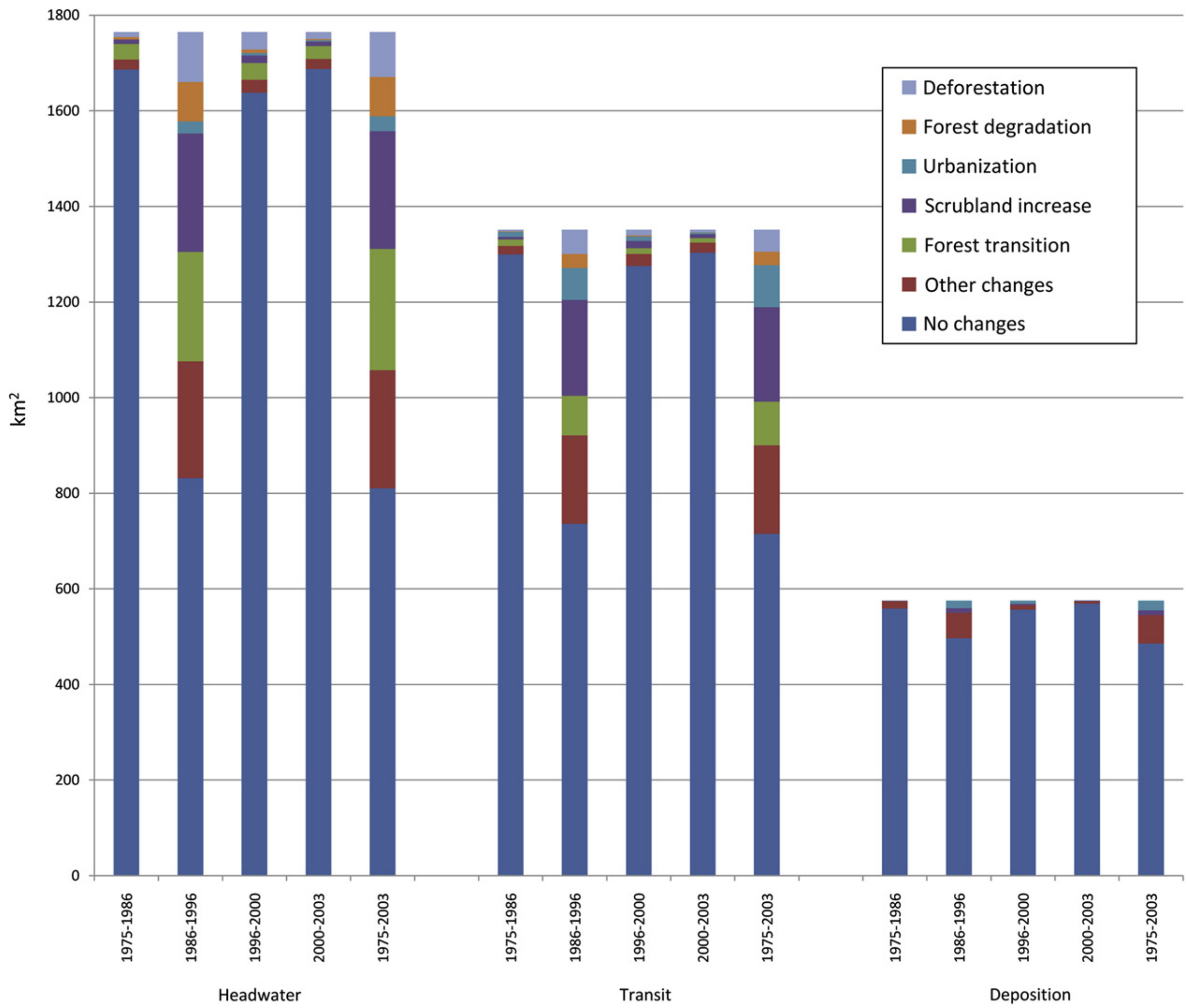

Fig. 7. Land cover land use change per functional zone and period.

integration allows for the accurate identification of potential causes that govern LCLU dynamics, and thus provides insights invaluable to the improvement of watershed management. Despite the fact that LCLU are recognized as key environmental indicators, their evolution has not been properly integrated into decision-making processes. The main assumptions made in this study, which were successfully tested, is that rates of change differ through time; that the total time period gives only an overall and general idea of LCLU change processes in the area; and that the final period of analysis can only impart information regarding the most recent environmental processes to affect the study region. As a consequence, decision making processes regarding natural resource management at a watershed level should give different relative importance to each period, and an effort should be made to identify the drivers of change during each period and how these changes must be integrated into land use planning.

The quantitative evidence of LCLU dynamics presented here is based on remote sensing and coupled with GIS and statistics analyses. The outputs corroborate and indeed go further than the findings of some earlier studies at both regional (Soto-Galera, Paulo-Maya, López-López, Serna-Hernández, & Lyons,1999; López, Bocco, Mendoza, & Duhau, 2001; López, Bocco, Mendoza, Velázquez, & Aguirre, 2006; Carlón Allende et al., 2009; Mendoza et al., in press) and national level (Mas et al., 2004; Velázquez,

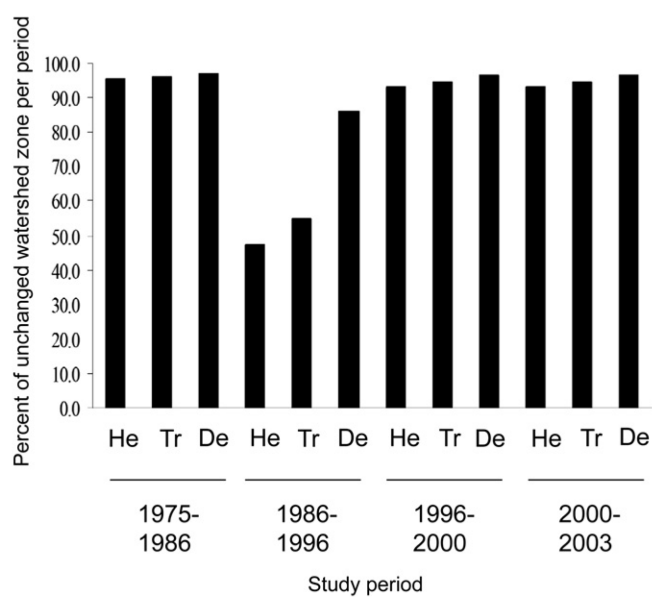

Fig. 8. Percentage of territory with no apparent change in land cover and land use during four study periods in the three watershed functional zones (He = Headwater, Tr = Transition, De = Deposition) in Lake Cuitzeo Watershed, Mexico.

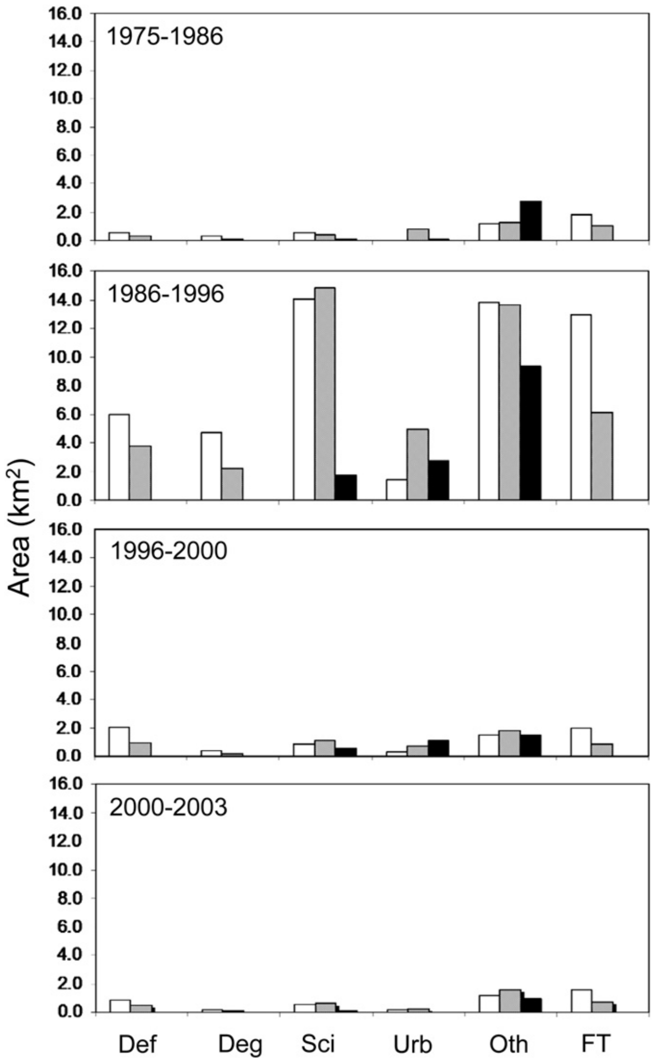

Fig. 9. Area covered by each land cover change category (Def = deforestation, Deg = Degradation, Sci = Scrubland increase, Urb = Urbanization, Oth = Other changes, and FT = Forest transition) during four study periods in the three hydrological functional zones (Headwater = white bars, Transition = dashed bars, and Deposition = black bars) in Lake Cuitzeo Watershed, Mexico.

Mas, Palacio-Prieto, & Bocco, 2002). In particular, the LCLU changes detected and quantified were not constant through time. Instead, we found that spatial changes occur in pulses, and that the complexity of patterns of LCLU change varies over time. This result was the consequence of applying the approach of quantifying LCLU information for 5 different periods for the first time (see Velázquez et al., 2003; Alcantara Ayala, Esteban Chávez, & Parrot, 2006; Gómez Mendoza, Vega Peña, Ramírez, Palacio Prieto, & Galicia, 2006; García Frapolli, Ayala Orozco, Bonilla Moheno, Espadas Manrique, & Ramos Fernandez, 2007; Martínez et al., 2009; Geissen et al., 2009).

The multitemporal LCLU change retrospective monitoring and evaluation at watershed, sub-watershed, and functional zone levels used in this study can be replicated in other sites. This is particularly true if, instead of using visual interpretation techniques on remote sensing images, the analysis is based on digital techniques, although it is recognized that these products have lower accuracy. The advantage of digital techniques for mapping is that, when based on conventional products (SPOT, ETM), they are less time consuming and costly. DTM analysis on GIS (c.f. hydrotols-ArcGis, Dem hydroprocesing-ILWIS) can be applied on watershed and sub-watersheds, and can also automatically classify streams by order.

One of the main features of the watershed evaluated as an example in this study is the presence of anthropogenic impact in certain zones. For example, the capital city of Morelia, with almost one million inhabitants (INEGI, 2000) and located in the central part of the watershed, constitutes the major urban core of the study area. Moreover, the city is undergoing a clear expansion process, experiencing a fast urban growth calculated to have been 600% over the period 1975–2000. Thus, urbanization is one of the major impacts on the natural assets of the region (López et al., 2001), as well in the state of Michoacán (Bocco, Mendoza, & Masera, 2001). Another important social feature of the region is the high emigration rate. Apart from migration to the capital city of Morelia, there are also high levels of migration to the USA. High emigration rates over the past years (1986–1996) are presumed to have had consequences for LU change within the watershed, due to the abandonment of agricultural land (Arredondo León, Muñoz Jiménez, & García Romero, 2008; López et al., 2006).

Forest degradation in the headwater and transit zones reduces the water recharge capacity of the system, and increases the transportation of sediments and nutrients to the downstream areas, affecting water quality in the artificial and natural water bodies located in the deposit zone, including Lake Cuitzeo itself. In addition, the degradation of the higher zones of the watershed reduces the lifetime of water reservoirs due to sediment accumulation. Thus, the transit and particularly the headwater zones are appropriate areas for the application of conservation programs, while deposition zones are more suitable for efforts of restoration and conservation (see González, 2008). As a result, the inclusion of different functional zones can strengthen the robustness of predictive models for assessing a range of human impacts.

Although in this study driving forces of change were not explicitly analysed, it is important to briefly mention them. The explanation for LCLU change is multifunctional, but one factor in particular may better explain one of the change processes. It is well documented that rapid population growth, poverty, and welfare condition are the main driving forces of land use change in developing countries (Lambin, Geist, & Lepers, 2003; Meertens, Fresco, & Stoop, 1996; Ramankutty & Foley, 1999). The rate and surface area of the LCLU change processes assessed in the present study, both at the level of watershed and of functional zone, reached their highest values during the period 1986–1996, when levels of emigration to the USA increased, as did the periods of permanence of emigrants in that country (Corona Vazquez, 1990), this statement was verified, based on some interviews carried out with local landowners in some sub-watershed, which are not analysed here. Despite the lack of precise quantification of undocumented migrants, indirect estimates and the results of several anthropological studies made in both the originating communities and the places of destination of migrants (Corona Vazquez, 1990), consistently register an increase in the number of migrants during the period 1986–1996, compared to previous decades.

The change in the migration pattern is related to the application of the Immigration Reform and Control Act (IRCA), or Simpson-Rodino Law which, according to Cornelius (1989), seems to have accelerated the change from temporal to permanent emigration and settlement in the USA of undocumented workers, by providing them with the opportunity to legalize their immigration status when they were able to prove they had worked for at least 90 days in farms during the twelve month period ending on the first day of 1986.

Another important variable related to the LCLU patterns and processes of change is associated to the Mexican economic crisis of the eighties which, together with other pressure factors in the labour market, caused a general deterioration of the standards of living of the Mexican population. One of the consequences of such deterioration was the search for alternative and complementary means of survival, among which were participation in marginal economic activities, and the new modalities of internal migration. During the same decade, demand for Mexican labour in the USA was sustained, in particular in the state of California, which showed a higher economic dynamism compared to the economy of the USA as a whole (Corona Vazquez, 1990).

Another noteworthy change was the expansion of urban areas experienced during the 1986–1996 period. This process also coincides with the aftermath of the earthquake of September 19th, 1985, that affected Mexico City. That disaster, which reached 8.1° on the Richter scale, caused the death of tens of thousands of people, and triggered the migration of thousands of families out of Mexico City. Many of these migrants subsequently settled in the city of Morelia. The earthquake also led to the launch of a federal decentralization policy, which promoted the rapid growth of medium sized cities, such as Morelia, by the arrival of federal government employees and their families. This growth consequently increased the demand for services, thereby increasing human pressure on natural resources and negatively impacting environmental goods and services.

In this sense, the current debate on the direction of land use change,provides a useful theoretical platform upon which landscape changes can be investigated, allowing the analysis of landscape transformation to provide hard evidence that contributes to the development of a theory of land use change in developing countries brought about by agricultural (Zomeni et al., 2008), silvopastoral and forestry activities. As a consequence, this information was submitted to the local environmental and urban agency at Michoacán State in order to improve the program of land use planning in Cuitzeo.

Conclusions

LCLU change processes in the Lake Cuitzeo Watershed did not have a constant rate: most of the changes took place over an interval of less than ten years (between 1986 and 1996) within the total 28 year period analysed. The output of this study was obtained by using LCLU information for five dates. This is the first time this type of analysis has been carried out at regional level. This analysis allow us to properly evaluate land cover change over long time periods, recognizing sudden changes in response to natural or social causes, that would otherwise have been impossible to document.

The critical period was associated with a profound economic crisis in Mexico, and is coupled also to the application of the IRCA in 1986, which limited the transit of Mexican undocumented workers to the USA. This finding implies that the more fundamental causes of LCLU change in the Lake Cuitzeo Watershed are derived from public policy decisions, some of which were not even taken within the country. In addition, a rapid increase in the population of the capital city of Morelia and neighbouring municipalities, partially as a consequence of a telluric event that affected Mexico city, hundreds of kilometres away, substantially amplified the pressures on natural resources in the Lake Cuitzeo Watershed and in the region in general. On the one hand, these LCLU change processes modify the spatial distribution of LCLU, and on the other they have both negative and positive impacts on the natural resources in the territory (e.g., forestation vs. forest transition), which vary in intensity through time and in spatial pattern.

This study has provided important insights into the dynamics that occurred between 1975 and 2003 in a rural area with a high urbanization rate, and provides a solid quantitative foundation for the design and implementation of environmental policies and for institutional analyses.

The results depicted three spatial units of analysis (watershed, sub-watersheds and functional zones), and were also useful for the provision of land use planning recommendations, such as identifying where, and over what quantity of land, LCLU changes are taking place in this area. As a consequence, we identified the spatial units in which restoration and conservation policies and associated implementation actions can best be conducted.

Building upon this, further location-specific and in-depth analyses of the relationship between governmental organization and land use conditions may be necessary in order to fully understand the roles played by community-based institutions, among other factors, in land use changes over time. Some other important concerns that should be addressed by future research are whether and how positive changes in forest and scrubland covers have benefited local users, the long term sustainability of the existing community-based rural institutions, and how changes improve or degrade the environmental services in the watershed.

Acknowledgments

The present research was funded by UNAM through a grant for the project: "*Evaluación espacial y multitemporal de los cambios de cobertura y uso del terreno en la cuenca del lago de Cuitzeo: implicaciones para la sucesión forestal y el mantenimiento de la diversidad vegetal*" (clave IN304408). This research was also partially supported by a project granted by CONACYT: "*Uso de técnicas de análisis multicriterio para la priorización de subcuencas para la conservación, restauración y el aprovechamiento de los recursos naturales en la Cuenca del Lago de Cuitzeo*" (clave 2005-C01-011). The authors thank M. Skutsch, S. Zárate and P.C. Alcántara for reading and commenting on a previous version of this paper, we also thank to two anonymous referees for their comments, and T. Carlón, G. Menapace and H. Felipe for helping with GIS analysis and A. Navarrete for production of the figures.

References

Alcantara Ayala, I., Esteban Chávez, O., & Parrot, J. F. (2006). Landsliding related to land-cover change: a diachronic analysis of hillslope instability distribution in the Sierra Norte, Puebla, Mexico. *CATENA, 65*, 152–165.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). A land use and land cover classification system for use with remote sensing data. *Geological Survey Professional Paper, 964*, 28.

Arredondo León, C., Muñoz Jiménez, J., & García Romero, A. (2008). Recent trends in landscape dynamics trends in tropical highlands, central Mexico. *Interciencia, 33*(88), 569–577.

Bayarsaikhan, U., Boldgiv, B., Kim, K. R., Park, K. A., & Lee, D. (2009). Change detection and classification of land cover at Hustai National Park in Mongolia. *International Journal of Applied Earth Observation and Geoinformation, 11*, 273–280.

Bell, E. J., & Hinojosa, R. C. (1977). Markov analysis of land use change: continuous time and stationary processes. *Socio-Economic Planning Science, 11*, 13–17.

Bhatta, B. R., Chalise, S. R., Myint, A. K., & Sharma, P. N. (1999). Recent concepts, knowledge, practices, and new skills. In *Participatory integrated watershed management: Trainers resource book*. Nepal: ICIMOD, PWMTA-FAO, and Department of Soil Conservation and Watershed Management.

Bocco, G., Mendoza, M. E., & Masera, O. (2001). La dinámica del cambio de uso de suelo en Michocán. Una propuesta metodológica para el estudio de los procesos de deforestación. *Investigaciones Geográficas, 44*, 18–38.

Brink, A. B., & Eva, H. D. (2009). Monitoring 25 years of land cover change dynamics in Africa: a sample based remote sensing approach. *Applied Geography, 29*, 501–512.

Carlón Allende, T., Mendoza, M. E., López Granados, E., & Morales Manilla, L. M. (2009). Hydrogeographical regionalisation: an approach for evaluating the effects of land cover change in watersheds. A case study in the Cuitzeo Lake Watershed, Central Mexico. *Water Resources Management, 23*(12), 2587–2803.

Clement, F., Orange, D., Williams, M., Mulley, C., & Epprecht, M. (2009). Drivers of afforestation in Northern Vietnam: assessing local variations using geographically weighted regression. *Applied Geography, 29*(4), 561–576.

Cornelius, W. A. (1989). Impacts of the 1986 US immigration Law on emigration from rural Mexican Sending communities. *Population and Development Review, 15*(4), 689–705.

Corona Vazquez, R. (1990). La migración de mexicanos a los Estados Unidos: cambios en la década de 1980–1990. *Revista Mexicana de Sociología, 55*(1), 213–233.

Currit, N., & Easterling, W. (2009). Globalization and population drivers of rural-urban land-use chage in Chihauhua, Mexico. *Land Use Policy, 26*, 535–544.

Dunjó, G., Pardini, G., & Gispert, M. (2003). Land use change effects on abandoned terraced soils in a Mediterranean catchment, NE Spain. *CATENA, 52*, 23–37.

FAO. (1995). *Forest resources assessment 1990. Global synthesis*. Roma: FAO.

Ferrusquía-Villafranca, I. (1993). Geology of Mexico: a synopsis. In T. P. Ramamoorthy, R. Bye, A. Lot, & J. Fa (Eds.), *Biological diversity of Mexico: Origins and distribution* (pp. 3–107). New York: Oxford University Press.

Fuller, R. M., Smith, G. M., & Devereux, B. J. (2003). The characterization and measurement of land cover change through remote sensing: problems in operational applications? *International Journal of Applied Earth Observation and Geoinformation, 4*, 243–253.

García Frapolli, E., Ayala Orozco, B., Bonilla Moheno, M., Espadas Manrique, C., & Ramos Fernandez, G. (2007). Biodiversity conservation, traditional agriculture and ecotourism: land cover/land use change projections for a natural protected area in the northeastern Yucatan Peninsula, Mexico. *Landscape and Urban Planning, 83*, 137–153.

Gautam, A. P., Webb, E., Shivakotia, G. P., & Zoebisch, M. A. (2003). Land use dynamics and landscape change pattern in a mountain watershed in Nepal. *Agriculture, Ecosystems and Environment, 99*, 83–96.

Geissen, V., Sánchez-Hernández, R., Kampichler, C., Ramos-Reyes, R., Sepulveda-Lozada, A., Ochoa-Goana, S., de Jong, B. H. J., Huerta-Lwanga, E., & Hernández-Daumas, S. (2009). Effects of land-use change on some properties of tropical soils-an example from Southeast Mexico. *Geoderma, 152*(3–4), 87–97.

Gómez Mendoza, L., Vega Peña, E., Ramírez, M. I., Palacio Prieto, J. L., & Galicia, L. (2006). Projecting land use change processes in Sierra Norte de Oaxaca, Mexico. *Applied Geography, 26*, 276–290.

González, D. I. (2008) Análisis multicriterio para la priorización de subcuencas y municipios para la aplicación de las políticas de conservación y aprovechamiento de los recursos naturales en la cuenca del lago de Cuitzeo. MSc Thesis, Centro de Investigaciones en Geografía Ambiental, Universidad Nacional Autónoma de México.

Heistermann, M., Müller, C., & Ronneberger, K. (2006). Land in sight? Achievements, deficits and potentials of continental to global scale land-use modeling. *Agriculture, Ecosystems and Environment, 114*, 141–158.

INEGI (Instituto Nacional de Estadística, Geografía e Informática) (1970). IX Censo General de Población y Vivienda, México. Ciudad de México, México. pp. 923.

INEGI (Instituto Nacional de Estadística, Geografía e Informática) (2000) XII Censo General de Población y Vivienda, México. Ciudad de Aguascalientes, México. pp. 987.

ITC. (2005). *ILWIS 3.3 integrated land and water information system, GIS software*. International Institute for Geo-Information Science and Earth Observation. The Netherlands: Enschede.

Jansen, L. J. M., & di Gregorio, A. (2002). Parametric land cover and land-use classification as tools for environmental change detection. *Agriculture, Ecosystems and Environment, 91*, 89–100.

Johnson, E. D. (1998). *Applied multivariate methods for data analysis*. California: Thomson Learning.

Lambin, E. F. (1997). Modeling and monitoring land-cover change processes in tropical regions. *Progress in Physical Geography, 21*(3), 375–393.

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources, 28*, 205–241.

Lee, H., Carr, J. L., & Lankerani, A. (1995). Human disturbance and natural habitat: a biome level analysis of a global data set. *Biodiversity and Conservation, 4*, 128–155.

López, E., Bocco, G., Mendoza, M. E., & Duhau, E. (2001). Predicting land cover and land use change in the urban fringe. A case in Morelia City, Mexico. *Landscape and Urban Planning, 55*, 271–286.

López, E., Bocco, G., Mendoza, M. E., Velázquez, A., & Aguirre, R. (2006). Peasant emigration and land-use change at the watershed level. A GIS-based approach in Central Mexico. *Agricultural Systems, 90*(1–3), 62–78.

Loveland, T. R., Zhu, Z., Ohlen, D. O., Brown, J. F., Reed, B. C., & Yang, L. (1999). An analysis of the IGBP global land-cover characterization process. *Photogrammetric Engineering and Remote Sensing, 65*, 1021–1032.

Luenberger, D. G. (1979). *Introduction to dynamic systems: Theory, models, and applications*. New York: John Wiley & Sons.

Macías Goytia, A. (1997). Tres Cerritos en el desarrollo social prehispánico de Cuitzeo. Tesis de Doctorado en Antropología Física. Facultad de Filosofía y Letras. UNAM, México, 609 pp.

Marey-Pérez, M. F., & Rodríguez-Vicente, V. (2009). Forest transition in Northern Spain: local responses on large-scale programmes of field-afforestation. *Land Use Policy, 26*(1), 139–156.

Martínez, M. L., Pérez Maqueo, O., Vázquez, G., Castillo Campos, G., García Franco, J., Mehltreter, K., et al. (2009). Effects of land use change on biodiversity and ecosystem services in tropical montane cloud forests of Mexico. *Forest Ecology and Management, 258*, 1856–1863.

Mas, J. F., Velázquez, A., Díaz-Gallegos, J. R., Mayorga-Saucedo, R., Alcántara, C., Bocco, G., et al. (2004). Assessing land use/cover changes: a Nationwide multidate spatial database for Mexico. *International Journal of Applied Earth Observation and Geoinformation, 5*(4), 249–261.

Meertens, H. C. C., Fresco, L. O., & Stoop, W. A. (1996). Farming systems dynamics: impact of increasing population density and the availability of land resources on changes in agricultural systems. The case of Sukumuland, Tanzania. *Agriculture, Ecosystems and Environment, 56*, 203–215.

Mendoza, M. E., Bocco, G., Bravo, M., López-Granados, E., & Osterkamp, W. R. (2006). Predicting water surface fluctuation of continental lakes. A GIS and RS based approach in Central Mexico. *Water Resources Management, 20*(2), 291–311.

Mendoza, M. E., Bocco, G., López, E., & Bravo, M. Hydrological implications of land cover and land use change: Spatial analytical approach at regional scale in the closed watershed of the Cuitzeo Lake, Michoacan, Mexico. Singapore Tropical Geography, in press.

Meyfroidt, P., & Lambin, E. (2008). Forest transition on Vietman and its environmental impacts. *Global Change Biology, 14*, 1–18.

Milesi, C., Hashimoto, H., Running, S. W., & Nemani, R. R. (2005). Climate variability, vegetation productivity and people at risk. *Global and Planetary Change, 47*, 221–231.

Naiman, R. J., Bisson, P. A., Turner, M. G., Kohm, K. A., & Franklin, J. F. (1997). Approaches to management at the watershed scale. In *Creating a forestry for the 21st century: The science of ecosystem management*. Island Press.

Ningal, T., Hartemink, A. E., & Bregt, A. K (2008). Land use change and population growth in the Morobe Province of Papua New Guinea between 1975 and 2000. *Journal of Environmental Management, 87*(1), 117–124.

Pasquarè, G., Ferrari, L., Garduño, V. H., Bibaldi, A., & Vezzoli, L. (1991). *Geologic map of central sector of Mexican volcanic Belt, State of Guanajuato and Michoacán, México*. Map and Chart Series MCH072. Geological Society of America.

PC-ORD. (1999). Multivariate analysis and classification of ecological data. *ESA Bulletin*.

Pellikka, P. K. E., Lötjönen, M., Siljander, M., & Lens, L. (2009). Airborne remote sensing of spatiotemporal change (1955–2004) in indigenous and exotic forest cover in the Taita Hills, Kenya. *International Journal of Applied Earth Observation and Geoinformation, 11*, 221–232.

Ramankutty, N., & Foley, J. A. (1999). Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles, 13*, 997–1027.

Redo, D., Joby Bass, J. O., & Millington, A. C. (2009). Forest dynamics and the importance of place in western Honduras. *Applied Geography, 29*(1).

Robertson, K. (1992). *Guías de aAnálisis de Terreno. Geomorfología Aplicada*. Colombia: Instituto Geográfico Agustín Codazzi.

Satake, A., & Rudel, T. (2007). Modeling the forest transition: forest scarcity and ecosystem service hypotheses. *Ecological Applications, 17*(7), 2024–2036.

Schumm, S. A. (1977). *The fluvial system*. New York: Blackburn Press.

Shultz, J. J., Cayuela, L., Echeverria, C., Salas, J., & Rey Benayas, J. M. (2010). Monitoring land cover change of the dryland forest landscape of Central Chile (1975–2008). *Applied Geography*. on line.

Sokal, R. R., & Rohlf, F. J. (1995). *Biometry*. San Francisco: W.H. Freeman and Company.

Sokal, R. R., & Sneath, P. H. A. (1963). *Principles of numerical taxonomy*. San Francisco: W.H. Freeman Company. xvi + 359 pp.

Soto-Galera, E., Paulo-Maya, J., López-Lápez, E., Serna-Hernóndez, J. A., & Lyons, J. (1999). Environmental auditing change in fish fauna as indication of aquatic ecosystem condition in Río Grande de Morelia-Lago de Cuitzeo Basin Mexico. *Environmental Management, 24*(1), 133–140.

Tran, T. L., Knight, G. C., O'Neill, V. R., Riitters, H. K., & Wickham, J. (2002). Fuzzy decision analysis for integrated environmental vulnerability assessment of the mid-Atlantic region. *Environmental Management, 29*(6), 845–859.

Van Zuidam, R., & Van Zuidam-Cancelado, F. I. (1979). *Terrain analysis and classification using aerial photographs*. The Netherlands: ITC Books VII-6; Enschede.

Velázquez, A., Duran, E., Ramírez, I., Mas, J. F., Bocco, G., Ramírez, G., et al. (2003). Land use-cover change processes in highly biodiverse areas: the case of Oaxaca, Mexico. *Global Environmental Change, 13*, 175–184.

Velázquez, A., Mas, J. F., Palacio-Prieto, J. L., & Bocco, G. (2002). Land cover mapping to obtain a current profile of deforestation in Mexico. *Unasylva (FAO), 210*(53), 37–40.

Verbug, P. H., Van de Steeg, J., Veldkamp, A., & Villemen, L. (2009). From land cover change to land function dynamics: a major challenge to improve land characterization. *Journal of Environmental Management, 90*, 1327–1335.

Villaseñor, J. L., Delgadillo, C., & Ortíz, E. (2006). Biodiversity hotspot from a multigroup perspective: Moses and Senecios in the Trasmexican volcanic belt. *Biodiversity and Conservation, 15*, 4045–4058.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of earth's ecosystems. *Science, 277*, 494–499.

Von Ende, C. N. (2001). Repeated-measures Analysis: growth and other time-dependent measures. In S. M. Scheiner, & J. Gurevitch (Eds.), *Design and analysis of ecological experiments* (pp. 134–157). New York: Oxford University Press.

Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J., & Dokken, D. J. (2000). Land use, land-use change and forestry. *Intergovernmental Panel of Climate Change* 24.

Wilkinson, L. (1984). *SYSTAT: The system for statistics*. Evanston, IL, USA: Systat, Inc.

Xiao, J., Shen, Y., Ge, J., Tateishi, R., Tang, C., Liang, Y., et al. (2006). Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing. *Landscape and Urban Planning, 75*(1–2), 69–80.

Zomeni, M., Tzanopoulos, J., & Pantis, J. D. (2008). Historical analysis of landscape change using remote sensing techniques: an explanatory tool for agricultural transformation in Greek rural areas. *Landscape and Urban Planning, 86*(1), 38–46.