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Predicting land-cover and land-use change in the urban fringe A case in Morelia city, Mexico

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Abstract

Land-cover and land-use (LCLU) change was quantified for the last 35 years within and in the vicinity of a fast growing city in Mexico, using rectified aerial photographs and geographic information systems (GIS). LCLU change was projected for the next 20 years using Markov chains and regression analyses. The study explored the relationships between urban growth and landscape change, and between urban growth and population growth. The analysis of Markov matrices suggests that the highest LCLU attractor is the city of Morelia, followed by plantations and croplands. Grasslands and shrublands are the least stable categories. The most powerful use of the Markov transition matrices seems to be at the descriptive rather than the predictive level. Linear regression between urban and population growth offered a more robust prediction of urban growth in Morelia. Hence, we suggest that linear regression should be used when projecting growth tendencies of cities in regions with similar characteristics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Land-cover and land-use change; Markov models; Landscape; Urban growth; Mexico

1. Introduction

Intensive use of natural resources calls for increasingly detailed inventories of its components and an investigation of the changes which took place in the past (Aaviksoo, 1995). This is particularly important in fast, usually unplanned, changing areas, such as urban settlements in developing countries (Ramachandran, 1992; Bocco and Sanchez, 1995; Rodríguez, 1995). Urban settlements in the developing countries are, at present, growing five times as fast as those in the developed countries. The concentration of urban

population is becoming particularly characteristic for developing countries. In 1990, for example, 36% of the urban population of the developing countries lived in cities above 1 million inhabitants, compared to 22% in 1950 (United Nations, 1996). Cities in the developing countries are already faced by enormous backlogs in shelter, infrastructure and services and confronted with increasingly overcrowded transportation systems, insufficient water supply, deteriorating sanitation and environmental pollution.

In Latin America and the Caribbean 73% of their population was living in urban areas in 1995; the level of urbanization is similar to that of Europe. This urbanization trend will continue in all countries and it is estimated that the urban population in the region will amount to 82% of the total population. Many

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countries where urbanization level is still below 60%, such as the two most populated — Brazil and Mexico — will have relatively high urban population growth rates (United Nations, 1996).

Land-cover and land-use (LCLU) change analyses and projection provide a tool to assess ecosystem change and its environmental implications at various temporal and spatial scales (Lambin, 1997). Despite their relevance, quantitative data describing where, when and how change occurs are incomplete or inexact (Turner et al., 1993). Thus, research on this subject is important in order to understand patterns of LCLU change as well as their social and environmental implications at different spatial and temporal scales.

Remote sensing techniques for measuring urban areas and estimating urban population have been used since the 1950s (De Bruijn, 1991; Bocco and Sanchez,

1995). One of the main basic theoretical approaches behind has been the allometric growth model that relates population data to the corresponding urban area. The procedure can be reverted to compute population from remotely-sensed urban areas (Henderson and Xia, 1997).

In this research, LCLU change was quantified for the last 35 years in the vicinity of Morelia, a fast growing city in Mexico (Fig. 1), using rectified aerial photographs and geographic information systems (GIS). In addition, LCLU change was projected for the next 30 years using Markov matrices and regression analyses. The research explored the relationships between urban growth and landscape change, and between urban and population growth. Given that the data required to feed the suggested models can be easily gathered, the approach can be extrapolated to

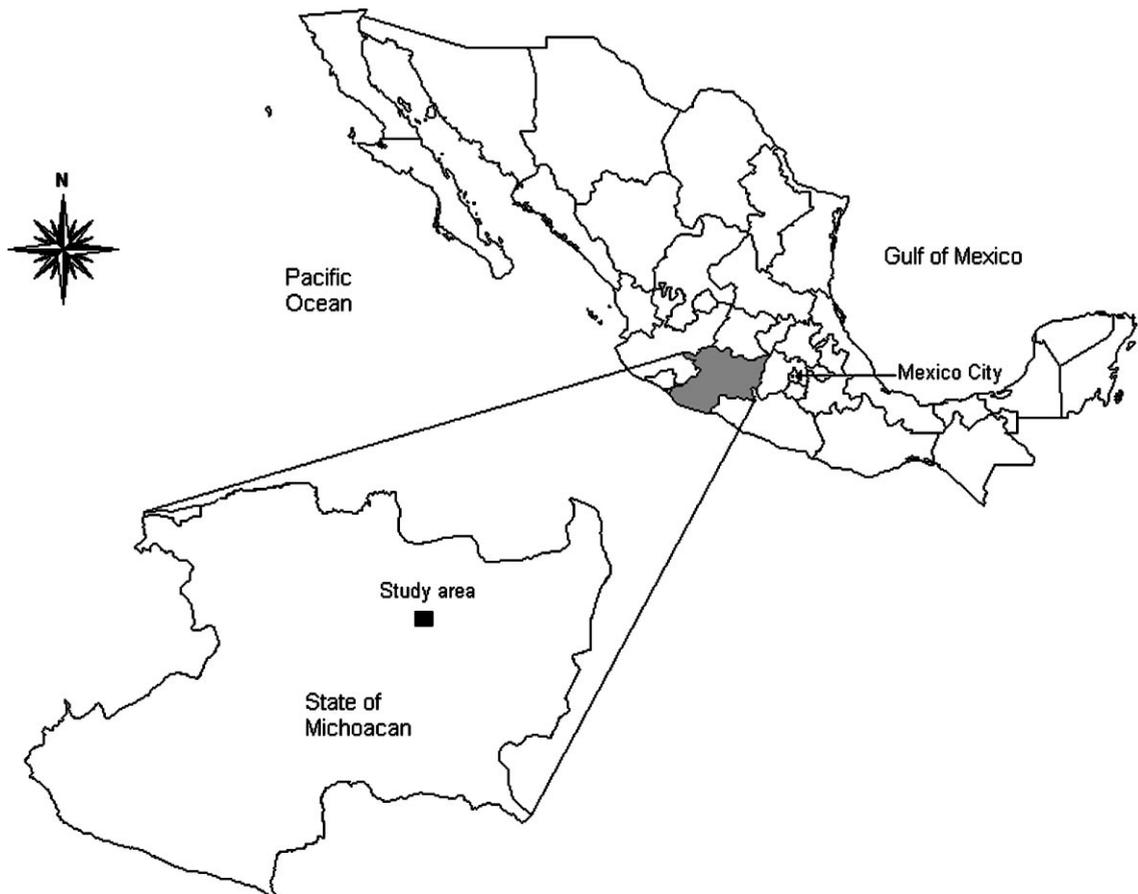


Fig. 1. Location of study area.

similar areas of fast growth and cover change, especially in other developing countries.

2. Method

2.1. Study area

Morelia is the capital city of Michoacán, one of the poorest states in Mexico. The city originated during colonial times (ca. 1500 AD), on a quaternary volcanic environment of lavas covered by pyroclastic materials. Climate is temperate and seasonal; original land-cover was temperate mixed forest of *Quercus* sp. and *Pinus* sp. Major land-uses in the area are rain-fed agriculture and cattle-grazing. In January 2000, Morelia’s population was 549,404 inhabitants (preliminary national census data; see INEGI, 2000). The city is one of the 75 Mexican cities ranked in 1995 within the category of “mid-cities” (between 100,000 and 1 million inhabitants). These group, including Morelia, has grown faster during the last decade than the four big Mexican metropolitan areas (Mexico City, Guadalajara, Monterrey and Puebla; see Aguilar, 1992; Graizbord, 1992). Morelia, however, is not highly dynamic

economically, as other “mid-cities”. Specifically, the industrial sector (for both the internal and external markets) is not well developed. Rather, Morelia plays a major role as a university town, a commercial center and a provider of public services for its surrounding region. In 1990 (last available data; see INEGI, 1990/1993), 10% of Morelia’s economically active population belonged to the primary sector, 25% to the secondary and 62% to the tertiary. Commerce and services employed 3.5 persons per every person employed by the manufacturing activity.

2.2. Approach

To quantify LCLU change (Fig. 2) land-cover patterns were interpreted on sequential black and white panchromatic aerial photographs (1960, 1975 and 1990), corresponding to the city of Morelia and the surrounding urban fringe (nearly 200 km²). Aerial photography approximate scales were, respectively, 1:25,000, 1:50,000 and 1:25,000. Final cartographic products were produced at the coarsest scale. To compare results of prediction with independent data, an enhanced and georeferenced Landsat TM color composite of 1997, with 30 m spatial resolution was used.

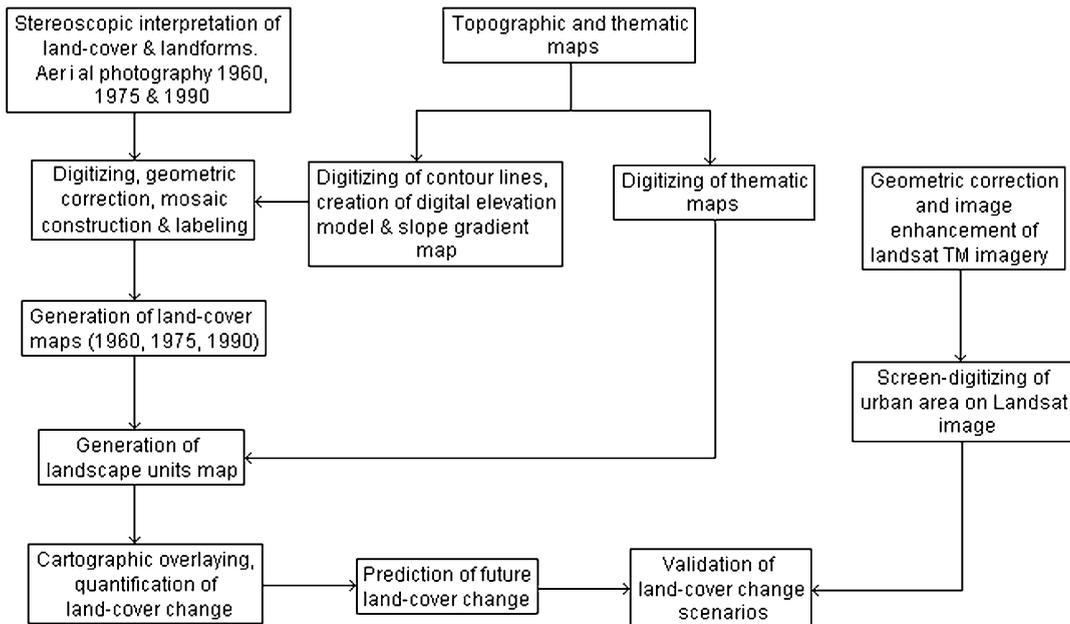


Fig. 2. Method flow diagram.

Supplementary cartographic data encompassed a topographic map (1:50,000 scale, 20 m contour interval), as well as thematic maps of rock type and soils. Sequential demographic data were obtained from the census of 1940, 1960, 1970, 1980 and 1990. All cartographic material as well as the aerial photographs and the census data were produced by the Mexican national mapping agency (INEGI, 1990/1993). All data sets were handled in digital format in GIS (ILWIS, 1990/1997).

Landscape was described using a terrain analysis approach where landforms and land-cover are combined (Verstappen and van Zuidam, 1991). Differentiating mapping criteria for landforms were lithology and rock structure, morphometry and soil type. Major landforms discriminated were summit surfaces, (volcanic) slopes, foot-slopes, alluvial plains, valleys and isolated hills. Land-cover categories were temperate mixed forest, *Eucaliptus* sp. plantations, grasslands, shrublands, croplands (primarily rain-fed maize), main urban area (Morelia), and other urban settlements (López Granados, 1999). Land-use was related to land-cover and function; it encompassed primary activities (forestry, agriculture and cattle-raising), and urban settlements (residential, commercial, services, industries and vacant lots).

Aerial photointerpretation was carried out using standard photographic keys (tone, texture, pattern, shape and size). The minimum mapping unit was set at 3 mm on the base map for both, radius of circular features, and side of rectangular features. This size corresponded to real features of 75 and 150 m, on aerial photographs of, respectively, 1:25,000 and 1:50,000.

2.3. Data base generation and accuracy

Field-verified, interpreted aerial photographs for both land-cover (1960s, 1970s and 1990s) and landforms were digitized in a standard digitizing tablet. Geometric correction was accomplished in the GIS through monoploting, a restitution approach for inner photo orientation that requires the metric coordinates of a set of at least nine control points from every photo and corresponding base map, and altitude form a digital elevation model (DEM) (McCullough and Moore, 1995). Thus, geometrically corrected mosaics of land-cover and relief were obtained and labeled. Accuracy for both position and labeling was checked thoroughly following Bocco and Riemann (1997).

The registration of interpreted aerial photographs to the digitizing tablet was done according to standards (one root mean square error or less in digitizing units) for every digitizing session. A total of 84 photos were geometrically corrected; the error accepted for every control point in every photo was 0.6 mm or less on the base map (1:50,000). Polygon labeling quality for eight categories of land-cover was set at 97%. Twenty-five percent of the total number of polygons (1496) of the three dates was evaluated.

2.4. Statistical analyses

Regression analysis was performed between change in urban area as interpreted for three dates and corresponding change in population (census data from INEGI, 1990/1993). In addition, change in population (census data) was correlated to time for 1940, 1955, 1960, 1970, 1980 and 1990.

Change in land-cover was assessed using first- and second-order Markov chains (Aaviksoo, 1995) for the periods 1960–1975 and 1975–1990. Markov chains represent a dynamic system of special classes involving transition probabilities, described as symmetric matrices (Luenberger, 1979; Logofet and Lesnaya, 2000). In the study case, transition matrices contained in both axes, respectively, land-cover categories for times 0 and 1. Every cell of the diagonal represented the probability for each category to undergo no change; in the rest of the cells the probability of transition from a given category to the other categories was given (Dirzo and Masera, 1996). The stochastic nature of the approach does not allow for a thorough explanation of change processes involved, and since land-cover change is described in aggregated terms, the model is not spatially-explicit (Lambin, 1997). On the other hand, urban growth was projected as a function of demographic growth and validated for the year 1997 against the urban area as depicted on the satellite image.

3. Results and discussion

3.1. Change detection and description

The most extensive landforms in the study site were the alluvial plains, occupying 27.5% of the area, and

the gently sloping units ($<10^\circ$ slope gradient), occupying 32.5% of the area. Sixteen percent of the area was mapped as steep (volcanic) slopes ($>10^\circ$ slope gradient). The remaining 25% corresponded to other minor landform units.

The quantification of LCLU change for the analyzed categories is given in Table 1. Croplands was the largest class throughout the study period; however, the area devoted to crops has decreased substantially during this period. Most of the crops were located in the alluvial plains and gently sloping units. Forests (basically temperate mixed forests of pines and oaks) increased from 1960 to 1990. In addition, *Eucaliptus* plantations have been apparent since 1975, especially on both gentle and steep slopes. These plantations were part of a not very successful soil and water conservation program sponsored by the local government in the 1970s.

The main urban area of Morelia underwent the greatest growth (from 709 ha in 1960 to 3368 in 1990), and fragmentation. One of the major reasons for this expansion was the migration from rural areas in Michoacán, following a drop in the prices of agricultural products. A second reason was the migration from other urban areas, such as Mexico City and other cities in central Mexico.

Other urban settlements were incorporated by Morelia (Figs. 3–5), a very common process in fast growing urban settlements lacking the adequate planning. Most of the urban area (46%) is now located on the alluvial plain, occupying former agricultural land

of prime quality. The urban expansion also occurred on different types of slopes, some of them affected by landsliding and rock-fall (mass-movements processes affecting entire slope portions, as typified in the literature; Garduño et al., 1998). This has increased the vulnerability of part of the city to geologic risk, a fact that is not easily accepted by local authorities.

Within the city, the most dynamic class was the residential–commercial one, which expanded from 790 ha in 1960 to 3185 ha in 1990 (Table 2; Figs. 6–8). The second highly dynamic class was vacant lots, that increased from 108 ha in 1960 to 1040 ha in 1990. The city became more complex and fragmented; in 1960 there were 25 polygons covering seven categories, whereas in 1990 there were 260 polygons distributed in 14 cover classes (Table 2).

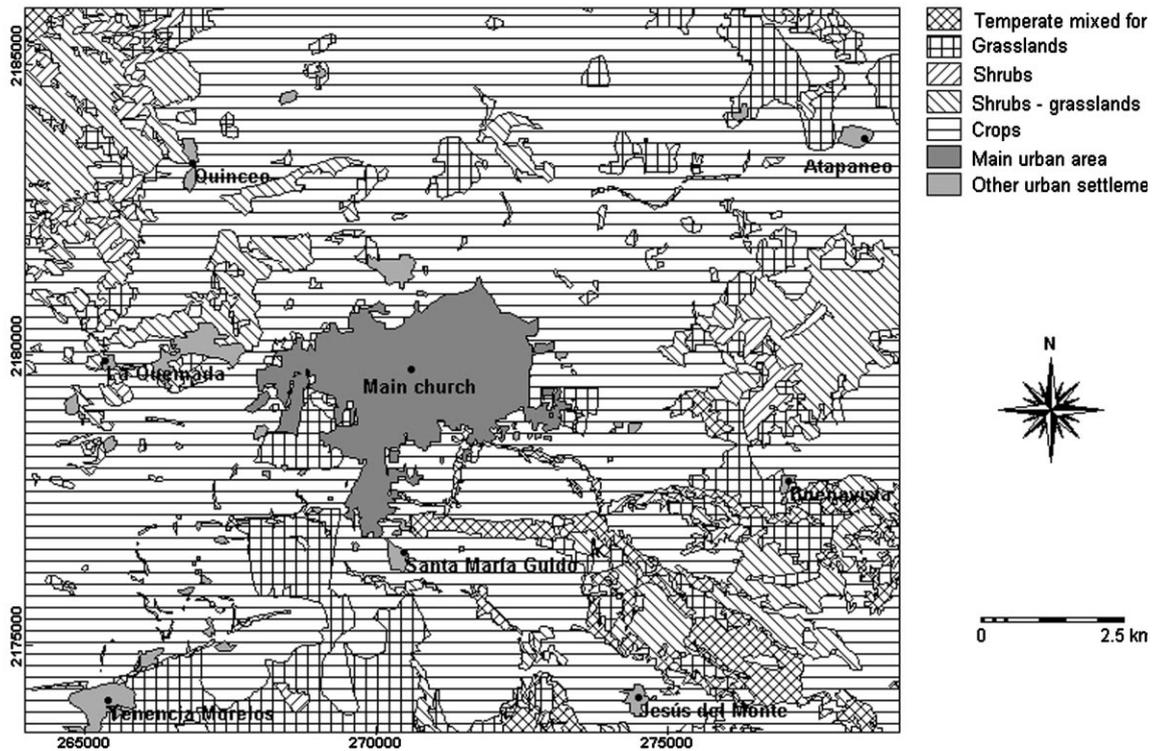
The first-order Markov matrix of 1960–1975 (Table 3, Fig. 9) indicated that the urban area of Morelia, other urban settlements and croplands were the most stable classes with 1.0, 0.86 and 0.81 probabilities, respectively. The most dynamic classes were grasslands and shrublands (actually a result of long-term fallow practices), with transition probabilities of less than 0.3; these categories attracted other classes, very especially croplands. The characteristics of the traditional farming system existing in the region, which includes extensive fallow periods, accounts for this fact.

The main urban area of Morelia and *Eucaliptus* plantations were the most stable classes as depicted by the Markov matrix of 1975–1990 (Table 4, Fig. 10),

Table 1
Number of polygons and area measurements of LCLU categories for 1960, 1975 and 1990^a

Categories	1960			1975			1990		
	No. of polygons	Area (ha)	Cover (%)	No. of polygons	Area (ha)	Cover (%)	No. of polygons	Area (ha)	Cover (%)
Temperate mixed forest	74	847	4.5	32	712	3.8	91	1788	9.5
<i>Eucaliptus</i> sp. plantations	0.0	0.0	0.0	2	77	0.4	4	353	1.9
Grasslands	112	2562	13.7	35	1451	7.7	58	729	3.9
Shrubs	46	412	2.2	19	788	4.2	34	823	4.4
Shrubs–grasslands	124	2230	11.9	45	2790	14.9	144	1603	8.5
Crops	14	11392	60.8	13	10627	56.7	29	7588	40.5
Main urban area	25	1004	5.3	70	1713	9.1	260	5081	27.1
Other urban settlements	84	303	1.6	88	592	3.2	93	787	4.2
Total	479	18750	100.0	304	18750	100.0	713	18750	100.0

^a Entire study area.



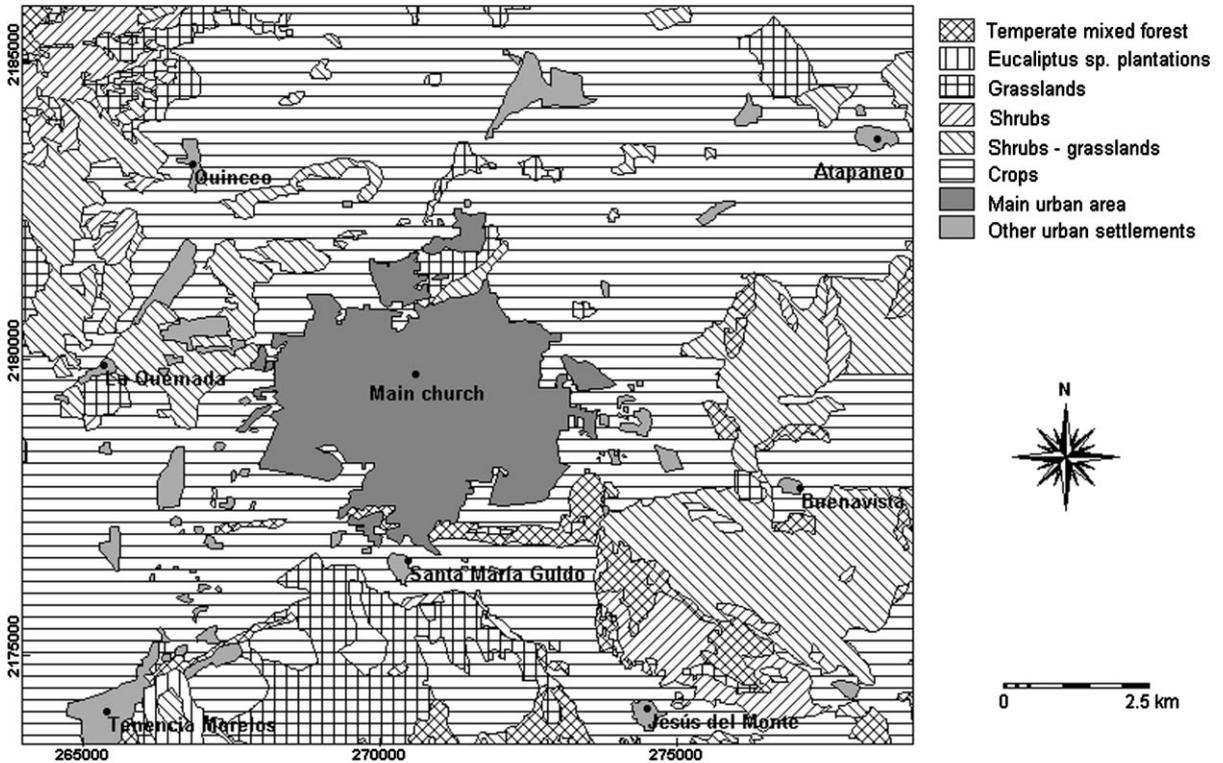
Source: photointerpretation of aerial photographs, scale 1:25,000

Fig. 3. Land-cover and land-use map of the region (1960).

Table 2

Area measurements of land-cover within Morelia for 1960, 1975, 1990

	1960		1975		1990	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Grasslands	1.2	0.1	0	0.0	42	0.8
Shrubs	0	0.0	0	0.0	5	0.1
Shrubs–grasslands	0	0.0	0	0.0	16	0.3
Crops	0	0.0	0	0.0	138	2.7
Residential–commercial	791	78.7	1115	65.1	3185	62.7
Industry	7	0.7	32	1.9	113	2.2
Cemeteries	10	1.0	19	1.1	19	0.4
Parks	85	8.5	68	4.0	163	3.2
Residential	2	0.2	3	0.2	195	3.8
Vacant lots	108	10.8	404	23.6	1040	20.5
Schools	0	0.0	70	4.1	83	1.6
Irregular settlements	0	0.0	0	0.0	62	1.2
Malls	0	0.0	0	0.0	18	0.4
Reservoirs	0	0.0	2	0.1	2	0.0



Source: photointerpretation of aerial photographs, scale 1:25,000

Fig. 4. Land-cover and land-use map of the region (1975).

with transition probabilities of 1.0 and 0.89, respectively. Croplands increased their transition probabilities, indicating an intense loss of agricultural land in favor of residential uses. Grasslands and shrublands still behaved as very dynamic classes.

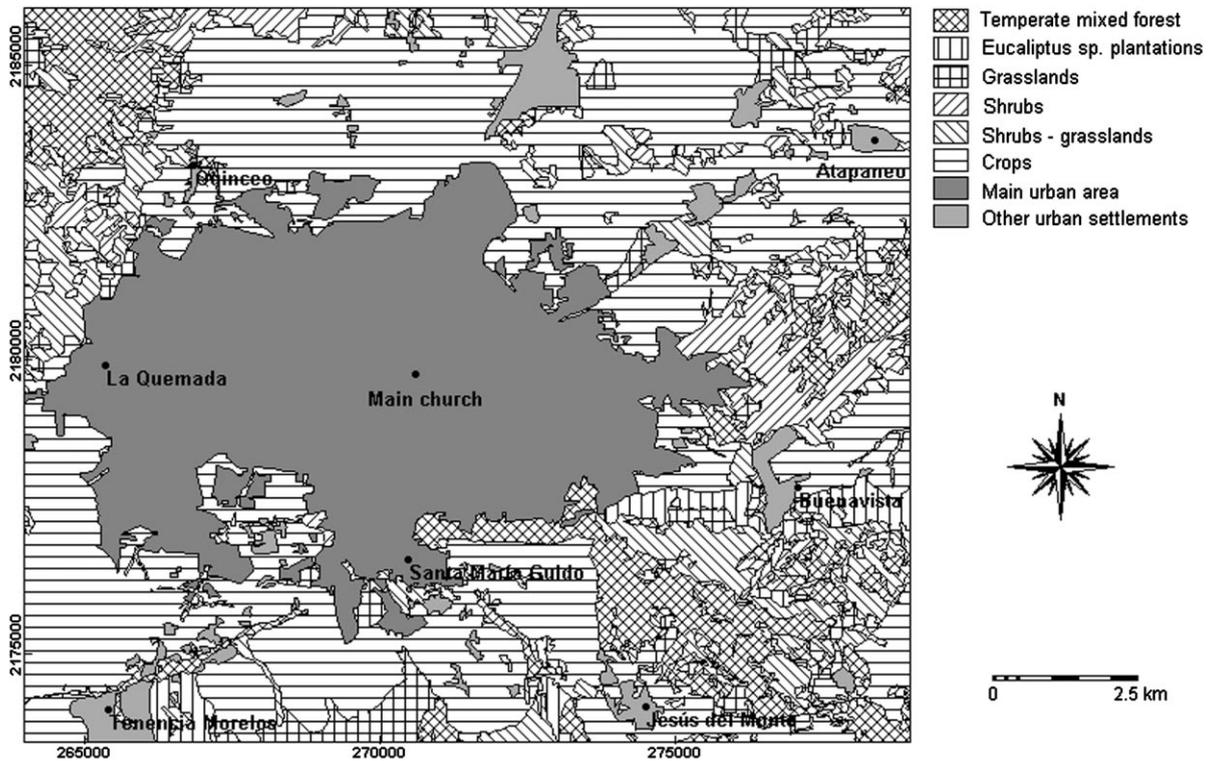
3.2. Change prediction using Markov matrices

Second-order Markov matrices were tested for goodness of prediction of LCLU transition. The model was calibrated by predicting the situation

Table 3
1960–1975 Markov matrix^a

Categories	Temperate mixed forest	<i>Eucaliptus</i> sp. plantations	Grasslands	Shrubs	Shrubs–grasslands	Crops	Main urban area	Other urban settlements
Temperate mixed forest	0.41	0.00	0.03	0.17	0.17	0.15	0.06	0.01
<i>Eucaliptus</i> sp. plantations	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Grasslands	0.05	0.03	0.28	0.03	0.23	0.31	0.06	0.02
Shrubs	0.05	0.00	0.16	0.25	0.45	0.09	0.00	0.01
Shrubs–grasslands	0.04	0.00	0.07	0.18	0.51	0.18	0.00	0.02
Crops	0.01	0.00	0.04	0.00	0.06	0.81	0.04	0.03
Main urban area	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Other urban settlements	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.86

^a Values are probabilities of transition.



Source: photointerpretation of aerial photographs, scale 1:25,000

Fig. 5. Land-cover and land-use map of the region (1990).

in 1990 using the 1960–1975 matrix. According to the model, forests, grasslands and croplands tended to decrease, while plantations, shrublands and urban classes tended to increase their surfaces (Table 5). Measured versus predicted values for 1990 are given in Table 6. Intuitively, best predictions were estab-

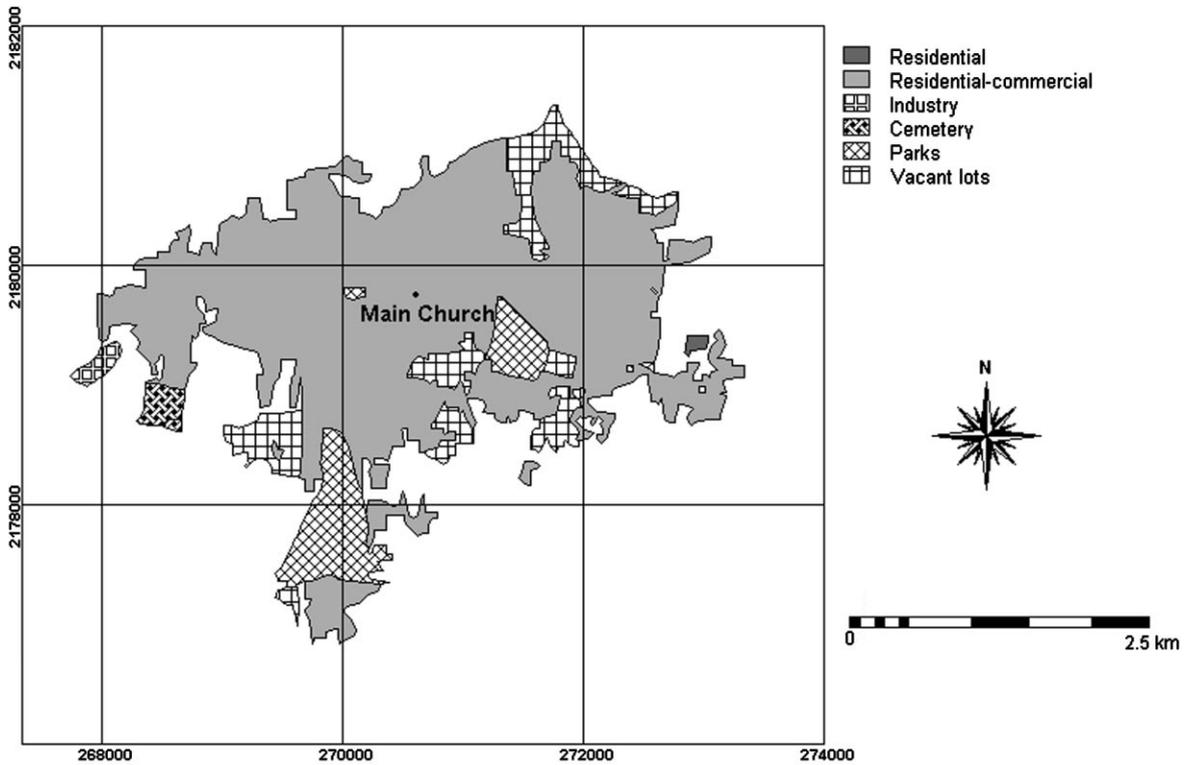
lished for the less represented classes in 1975 (plantations, shrublands and other urban settlements).

To quantitatively assess the overall performance of the prediction, a χ^2 test (Statistica for Windows[®], ver. 4.5) was used. Hypothesis tested were

Table 4
1975–1990 Markov matrix^a

	Temperate mixed forest	<i>Eucalyptus</i> sp. plantations	Grasslands	Shrubs	Shrubs–grasslands	Crops	Main urban settlements	Other urban settlements
Temperate mixed forest	0.67	0.00	0.04	0.04	0.10	0.05	0.06	0.03
<i>Eucalyptus</i> sp. plantations	0.00	0.89	0.00	0.00	0.03	0.00	0.00	0.09
Grasslands	0.10	0.02	0.19	0.05	0.09	0.38	0.15	0.02
Shrubs	0.60	0.00	0.07	0.10	0.17	0.04	0.01	0.01
Shrubs–grasslands	0.17	0.08	0.04	0.17	0.28	0.07	0.19	0.01
Crops	0.02	0.00	0.02	0.02	0.05	0.64	0.22	0.03
Main urban area	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Other urban settlements	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.59

^a Values are probabilities of transition.



Source: photointerpretation of aerial photographs, scale 1:25,000

Fig. 6. Urban-cover map (1960).

- H0: there are no significant differences between observed areas (by means of aerial photo interpretation) and predicted areas (from matrix exponentiation).
- H1: the above-mentioned differences are significant at $\alpha = 0.05$.

Results yielded a χ^2 value of 6677 (with 7 degrees-of-freedom), far above the accepted threshold value of 20.3; the null hypothesis was thus rejected in favor of the alternative one, suggesting that the second-degree Markov matrix was not a successful predictor of LCLU change patterns in Morelia.

Table 5
Area prediction (ha) of LCLU in 1990^a

	Temperate mixed forest	Plantations	Grasslands	Shrubs	Shrubs–grasslands	Crops	Main urban	Other urban settlements	Total
Temperate mixed forest	157	0	55	124	213	203	78	17	847
<i>Eucaliptus</i> plantations	0	0	0	0	0	0	0	0	0
Grasslands	124	86	287	177	569	981	248	90	2562
Shrubs	24	1.7	49	66	160	93	9	8	412
Shrubs–grasslands	122	4.3	203	336	834	615	43	73	2230
Crops	186	31	597	209	1047	7738	994	590	11392
Main urban area	0	0	0	0	0	0	1004	0	1004
Other urban settlements	0	80	0	0	0	0	79	223	303

^a Using 1960–1975 Markov matrix; Table 3.

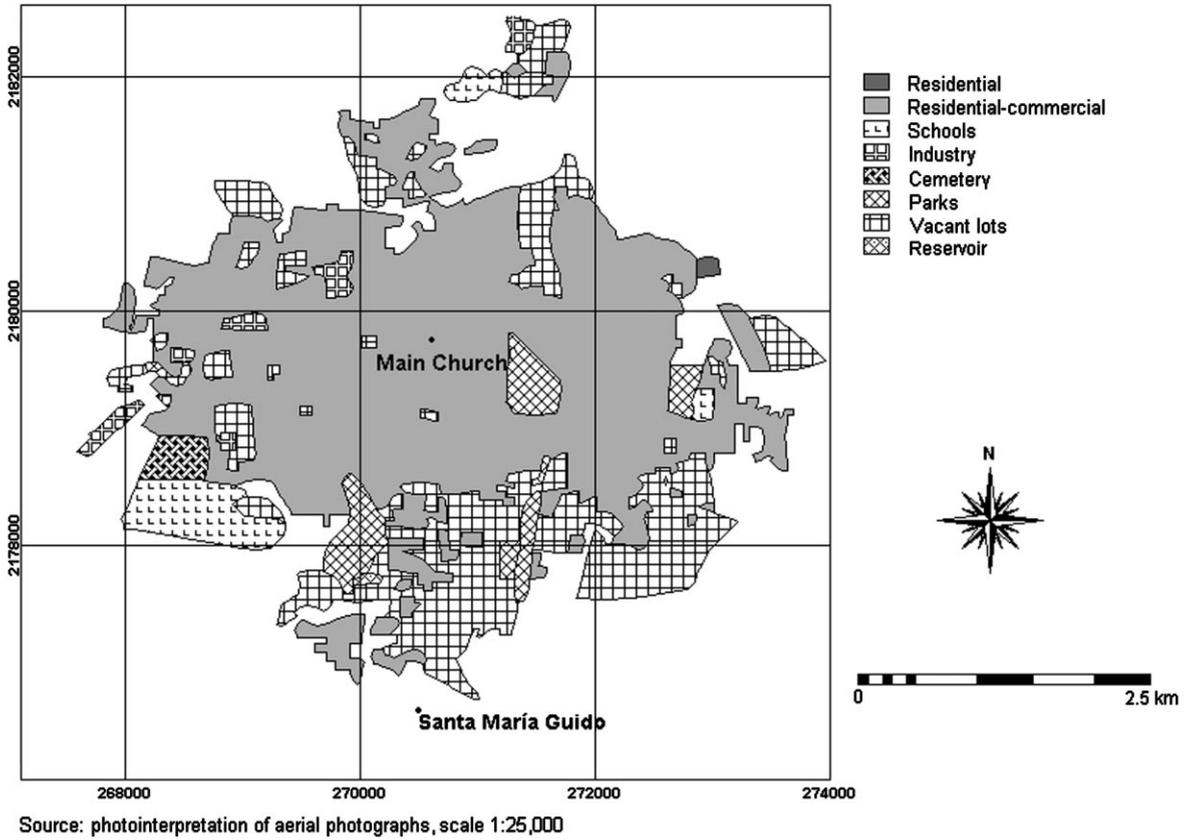


Fig. 7. Urban-cover map (1975).

3.3. Change prediction using regression analysis on population growth

Other approaches were thus searched for, namely the relationship with population growth, to predict LCLU change. To assess the relationship between, respectively, urban and population growth, population growth was first related to time by means of an exponential regression. The parameters obtained were: $r = 0.98$, $r^2 = 0.97$, $P = 0.99$, $\alpha = 0.05$.

The predictive model resulted (Fig. 11)

$$y = 8.977 \times 10^{-36(0.047x)} \tag{1}$$

where y stands for population and x for time.

Further, the growth of urban area was related to population growth (Table 7) using both, a linear and an exponential model. Parameters obtained for the linear model were: $r = 0.96$, $r^2 = 0.93$, $P = 0.62$, $\alpha = 0.05$.

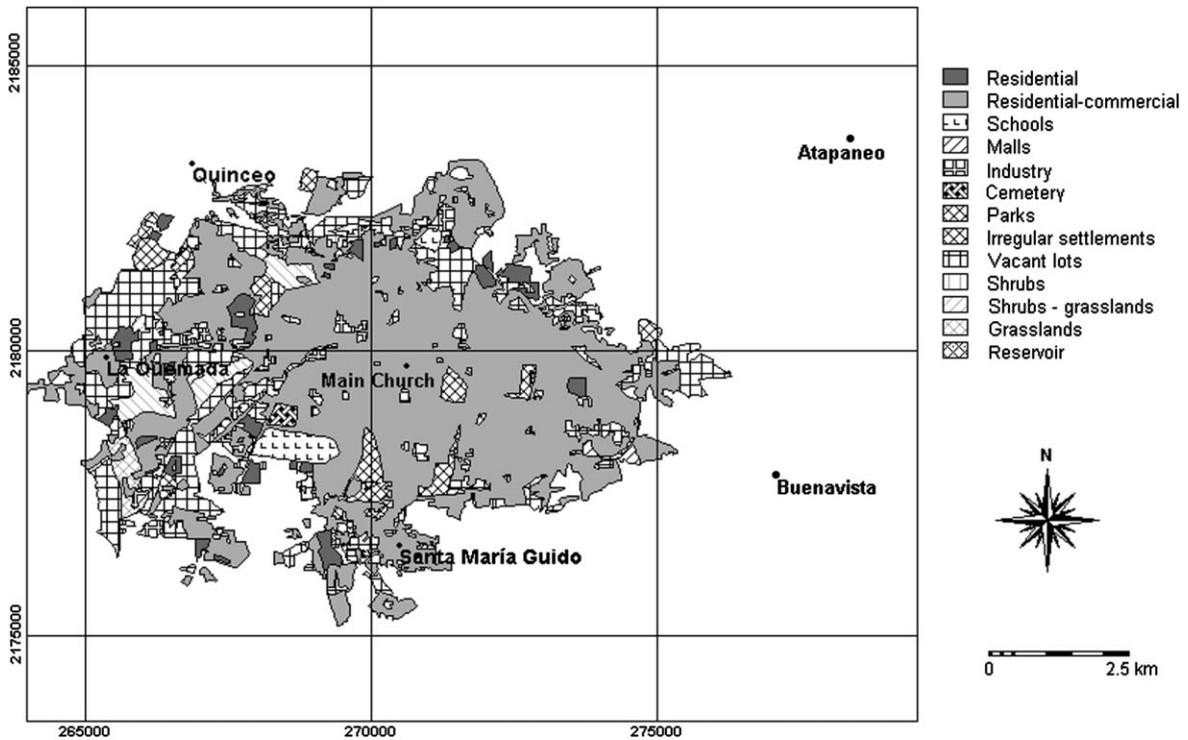
The predictive model resulted (Fig. 12)

$$y = -664.551 + 0.013x \tag{2}$$

Table 6
Observed and predicted area (ha) per category of LCLU^a

Class	1990 (measured)	1990 (predicted)
Temperate mixed forest	1788	613
<i>Eucalyptus</i> sp. plantations	353	124
Grasslands	729	1191
Shrubs	823	912
Shrubs–grasslands	1603	2823
Crops	7588	9630
Main urban area	5081	2455
Other urban settlements	787	1001

^a Observed value was obtained from a GIS area calculation on the geometrically corrected satellite image. Area was predicted using a linear regression model (see text).



Source: photointerpretation of aerial photographs, scale 1:25,000

Fig. 8. Urban-cover map (1990).

where y stands for urban area and x for population. Parameters obtained for the exponential model were: $r = 0.95$, $r^2 = 0.91$, $P = 0.39$, $\alpha = 0.05$.

The predictive model resulted (Fig. 12)

$$y = 574.893^{4.996 \times 10^{-6} \cdot x} \quad (3)$$

Eq. (2) was preferred for this exercise because the exponential model did not contribute with an increase in the explanation of variance. Therefore, the linear

Table 7
Population (inhabitants) and urban area (ha)^a

Year	Population	Area
1960	100,828	1004
1975 ^b	236,942	1713
1990	428,486	5081

^a Morelia, 1960–1990.

^b The value for 1975 was interpolated using Eq. (1) and data from INEGI, 1990/1993.

model was used to predict the urban area of Morelia for 1997; the results of the prediction were compared to the area measured on the satellite image. Predicted area was 6089 ha while observed area was 5970 ha; the difference was less than 2% of the studied area, a value within the geometric error of the database. The prediction can thus be considered as satisfactory.

However, a closer analysis of the data on which the model was based revealed a remarkable change between 1960–1975 and 1975–1990 periods (Table 7). For the first one, while urban population grew 136%, the growth in urban area was 71%; for 1975–1990, population grew 180% but the growth in area was 293%. Thus, from 1975 onwards, Morelia showed a decrease in its population density that might persist or even become more dramatic in the future.

Two main reasons may explain this fact. First, the average growth of urban housing development currently in Mexico is far superior than the corresponding increase in population. This is due to a decrease in the

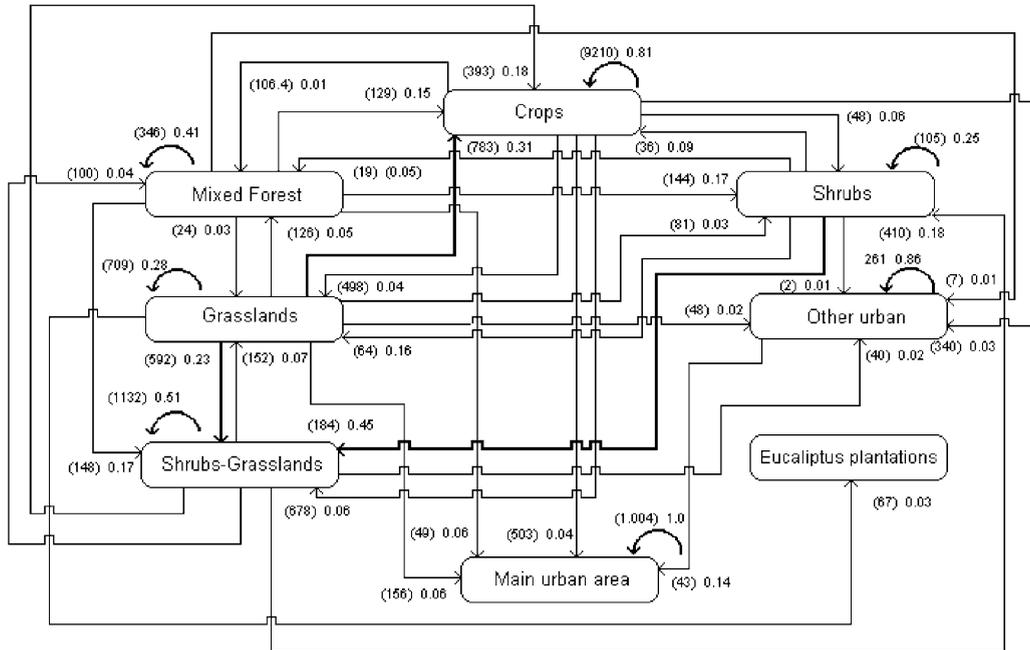


Fig. 9. 1960–1975 land-cover transitions (from the Markov matrix; Table 3). The value in the parenthesis represents change in ha; the value outside the parenthesis represents probabilities of change for that transition. Bold lines indicate high transition probabilities.

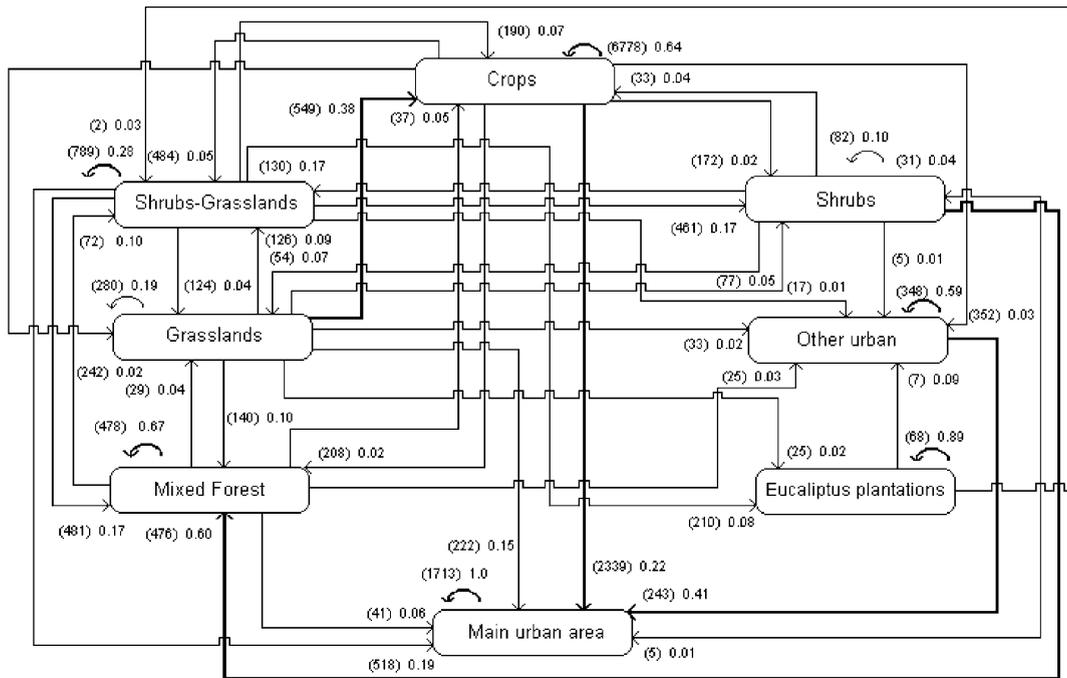


Fig. 10. 1975–1990 land-cover transitions (from the Markov matrix; Table 4). The value in the parenthesis represents change in ha; the value outside the parenthesis represents probabilities of change for that transition. Bold lines indicate high transition probabilities.

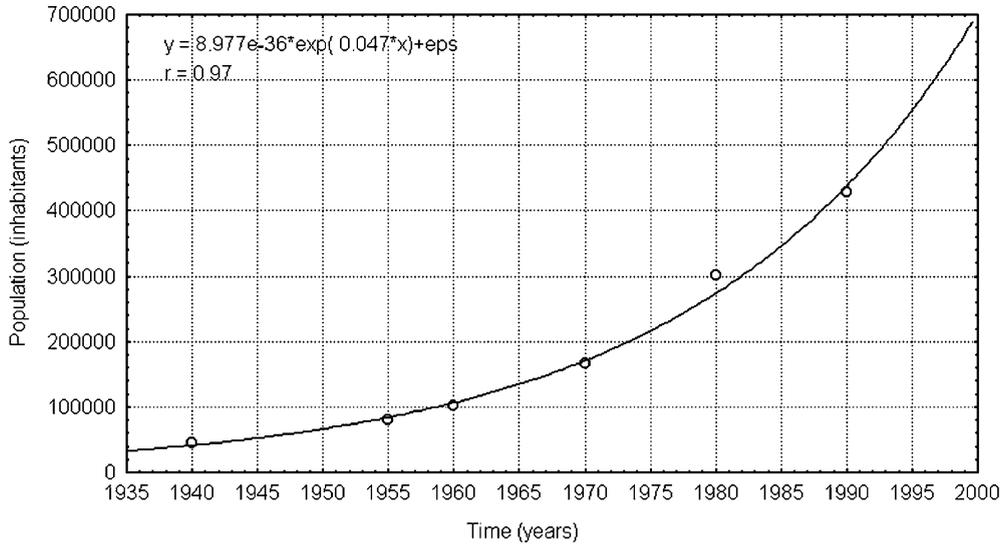


Fig. 11. Scatter-diagram of population (inhabitants) and time (years), exponential fitting.

average number of family members per dwelling and a faster rate of house creation (Duhau, 1998). For example, between 1970 and 1990, in the Metropolitan Area of Mexico City the average annual rate of housing growth was 3.5, while the corresponding rate for population growth was 2.6. Between 1990 and 1995, the former was 2.1 and the latter was 3.9 (Cruz, 1998). The second reason refers to change and diver-

sification of urban activities (development of commerce and industries) as well as the speculative transformation of formerly agricultural land to urban area (Duhau, 1998).

In Morelia these two factors are depicted by data describing the change in both the different types of categories and their areas in 1960, 1975 and 1990 (Tables 1–2; Figs. 6–8). While the urban area at large

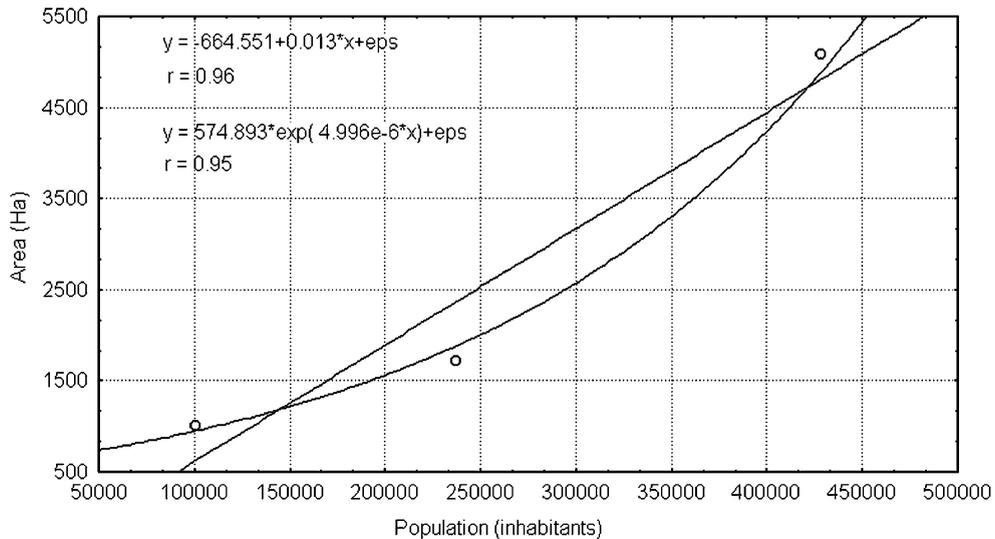


Fig. 12. Scatter-diagram of area (ha) and population (inhabitants), linear and exponential fittings.

(including irregular settlements) increased by a factor of 2.9 between 1975 and 1990, the class residential–commercial increased by a factor of 3.7. In addition, the category vacant lots has shown a remarkable increase since 1975; it covered 10.8% of the urban area in 1965, 23.6% in 1975 and 20.5% in 1990. Other new or almost new categories (such as industries and malls) appear for the first time, or exhibit a substantial growth. This is related to a slow but steady industrial development in the region.

4. Conclusions

Morelia is undergoing a fast, unplanned development. The city area grows without any consideration on the landscape types that are being transformed. Speculative processes seem to lack control from authorities, a process already described for other cities in Mexico and elsewhere in developing countries (Bocco and Sanchez, 1995; Rodríguez, 1995; United Nations, 1996). This explains the fragmentation of the urban area and the increase in vacant lots. In addition, no measures are being taken by the government concerning urban development on landscape units under geologic and seismic risk.

This research has shown that urban planning in this type of settlements can be based on models and data which can be easily gathered using widely available aerial photographs (conventional or digital) and increasingly popular GIS and automated databases with good quality levels.

The analysis of the Markov matrices suggests that the highest attraction is provided by the city of Morelia, the *Eucaliptus* plantations and the rain-fed crops; the grasslands and shrublands, on the contrary, are the less stable categories. Markov chains are a widely used model and did help describing the general tendencies of change in Morelia, as stated in Section 3.1. The transition matrices proved useful to describe quantitatively LCLU change patterns. However, prediction capabilities were not strong. Linear regression between urban and population growth offered a more robust approach to predict urban growth in this type of cities.

A more accurate prediction of urban growth ought to take into account the change in population as well as the average family size. In addition, the rate of house

creation and its links to urban soil requirements should be also considered for further research. To this end, Markov matrices stand as a valuable descriptive tool, whose application may be enhanced by developing a typology of urban land-uses aimed to record the change in inner urban patterns.

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