Six decades of urban green change in a neotropical city: a case study of Xalapa, Veracruz, Mexico

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Abstract

The process of expansion of human settlements commonly occurs without proper urban planning, which can directly affect green areas located within cities and adjacent areas. This study focuses on: (1) a spatiotemporal analysis to quantify the growth of the city of Xalapa (1950s to 2010s), (2) changes in woody vegetation cover within the boundaries of the city, and (3) land use and landscape changes and urban sprawl by decade from the 1980s to 2010s. To achieve this, we used digital images (i.e., ortho-photos, SPOT images), which were classified and integrated into a geographic information system. Based on the processed imagery, we delimited the urban polygon of the city, and quantified its woody vegetation cover changes and land use changes in areas surrounding the city for each decade of study. We found that over the past six decades, the city of Xalapa has grown in similar proportions per decade, mostly concentrated southward, fitting strongly and significantly to quadratic and linear growth patterns. Urban sprawl increased over the study period, Shannon's relative entropy increasing from 0.58 to 0.73. Woody cover within the city occupied a similar proportion (19–29%) of total city area throughout the study period because of the addition of patches of woody vegetation from formerly outlying areas, despite infill urbanization replacing preexisting urban green areas. Land use change in the area surrounding the city went from a transition through different uses (e.g., woody vegetation to cropland to urban; 1980s–2000s), to a direct change from woody vegetation to urban use (2000s–2010s), and exhibited landscape fragmentation over the period of study. Our results show that an integrated combination of remotely-sensed data and landscape metrics can be used to monitor urban patterns and processes, and that the results obtained can be incorporated into urban planning and management.

Keywords Urbanization · Urban expansion · Vegetation cover · Landscape change · Urban ecology

Introduction

In the last six decades, the world's urban population has increased nearly five-fold at an average rate of 2.6% per year, and the urban population has grown from less than one billion to 3.6 billion (UN 2012). Currently, the human population is predominantly urban, as more than half the total global population lives in cities (Grimm et al. 2008). Some of the drivers behind this rise of urban development include the increase in human life expectancy, globalization, and industrial dynamics (UNDP 1996).

Growth and land cover change in urban areas have several implications; on the one hand, they can stimulate higher economic production and generate employment opportunities, but on the other hand, they modify ecological and hydrological processes and contribute to increases in informal settlements and loss of agricultural land and woodlands. Urban sprawl is a type of urban development with a low-density, dispersed spatial pattern resulting from unplanned growth that leads to inefficient resource utilization and negative environmental and social impacts (Ewing 1997; Hasse and Lathrop 2003; Poelmans and Van Rompaey 2009). One of the main ecological effects of rapid urban sprawl is the modification and, in some cases, loss of ecological processes through changes in the structure and composition of former habitats (Grimm et al. 2008). This constitutes an important threat to biodiversity, and worrisome damage to the environmental services that green areas provide to the human population (Main et al. 1999; Czech et al. 2000; Melles 2005; Pisanty et al. 2009). Thus, the loss of green areas within cities is an important environmental and social concern (Sorensen et al.

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1998). Urban green areas (e.g., parks, gardens, greenways) not only provide recreational benefits and/or scenic embellishment, but also contribute to the quality of life of inhabitants of urban areas (e.g., water-related ecosystem services, oxygen production, climate regulation, control of soil erosion; Sorensen et al. 1998). In addition, urban green areas provide habitat for wildlife as they act as ecological islands because of their spatial arrangement and heterogeneity (McKinney 2008; MacGregor-Fors et al. 2011).

One decade ago, Latin America was already noted for its large cities that contained 13.7% of the world's total urban population. For instance, in 2000, São Paulo, Mexico City, and Buenos Aires were among the largest cities in the world (Rodriguez 2002). By 2005, there were four Latin American cities with total populations >10 million each: Mexico City (19 million), São Paulo (18.8 million), Buenos Aires (12.8 million), and Rio de Janeiro (11.7 million) (USAID 2010). At present, most Latin Americans are still living within urban areas (>78%), a higher percentage of urban population than that of Europe, Africa, or Asia (World Bank 2009). Although Mexico City is the most populated urban area in Mexico, other medium-sized cities should not be overlooked, as they are growing at rapid rates without proper urban planning (CONAPO 2004). A good example is the city of Xalapa, the state capital of Veracruz in central-eastern Mexico. This city has grown irregularly with limited urban planning strategies at the expense of surrounding agricultural and natural areas (Benítez 2011); however, little is known about the dynamics of the city's expansion. Xalapa is one of the greenest cities in Mexico (Williams-Linera et al. 2002), and is embedded in a cloud forest region of great biological diversity and ecological importance (Rzedowski 1996; Challenger 1998). The area occupied by cloud forest in the region has decreased rapidly due to the urbanization process, which has resulted in isolated fragments dominated by secondary vegetation (Castillo-Campos 1991).

To increase the understanding of urban dynamics, improve urban planning and reduce ecological impacts resulting from urban sprawl, the analysis of urban growth as a pattern and process (sensu Bhatta et al. 2010) is essential for city planners and administrators. Our study analyzes the urbanization rate of the city of Xalapa over the last six decades (1950s–2010s) and its impact on urban green areas using remotely sensed data (e.g., aerial photography and satellite imagery) and landscape metrics to account for heterogeneity, structure and pattern of the urban area. The study focused on: (1) changes in the coverage of urban green areas (i.e., woody vegetation) within the urban polygon; and (2) the type, rate, and spatial characteristics of land use change within inter-decade sprawl areas. Given the nature of current urbanization practices in the region, we expected the proportion of urban green areas to decrease over time, the most frequent change of land use to be from agriculture to urban, and to find evidence of fragmentation of formerly woody vegetation areas and high dispersion of urban areas in the sprawl areas of the most recent decades.

Methods

Study area

This study was undertaken in the urban area and surroundings (i.e., inter-decade sprawl areas) of the city of Xalapa. Currently, the city covers an area of 65.5 km^2 and is located between 19° 31′ and 19° 36' North and 96° 55′ and 96° 59' West (Fig. 1). The human population of Xalapa is about one half million and the city has an annual population growth rate of 0.5% (INEGI 2010). Due to the elevation range of Xalapa (600 masl: 1120–1720 masl), the city has two main climate types: (1) temperate humid, and (2) semi-warm humid. The long-term average annual rainfall is 1493 mm, and average annual mean temperature is 18 °C (Soto-Esparza and Gómez-Columna 1993).

Because the city is the state capital, most of the public and government agencies and educational centers of the state of Veracruz are located in Xalapa. Additionally, commercial activities are widely distributed throughout the city, which means that Xalapa receives a considerable regional immigration flow (Gobierno del Estado de Veracruz-Llave 2002). Additionally, several productive industries are found in the areas surrounding the city, such as coffee production (an important system that contributes to economic benefits of the region; Gordon et al. 2007), and other agricultural crops (e.g., corn, chili peppers, sugar cane, oranges; Gobierno del Estado de Veracruz-Llave 2002).

The original vegetation covering the region before the development of the city predominantly consisted of cloud forest (Rzedowski 1978), followed by oak forest, coniferous forest, tropical dry forest, and riparian vegetation (Castillo-Campos 1991). Current urban vegetation in Xalapa is mainly distributed in private gardens, public parks, ecological parks, median strips, and forest patches, including a significant number of exotic species (Capitanachi et al. 2004).

Spatial and temporal methods

To analyze the spatiotemporal changes in urban growth and urban green areas, and to describe the patterns occurring during the inter-decade sprawl areas in the city of Xalapa, the study was divided into four methodological steps: (1) digital processing of ortho-photographs and SPOT satellite imagery, (2) delineation of the city boundaries for each study decade; (3) mapping and quantification of the area covered by urban green areas within the city over the study period; and (4) analysis of land use change in inter-decade sprawl areas during the period 1980s–2010s, as no remotely-sensed data were available for the first two decades of the study period (1960s and 1970s).
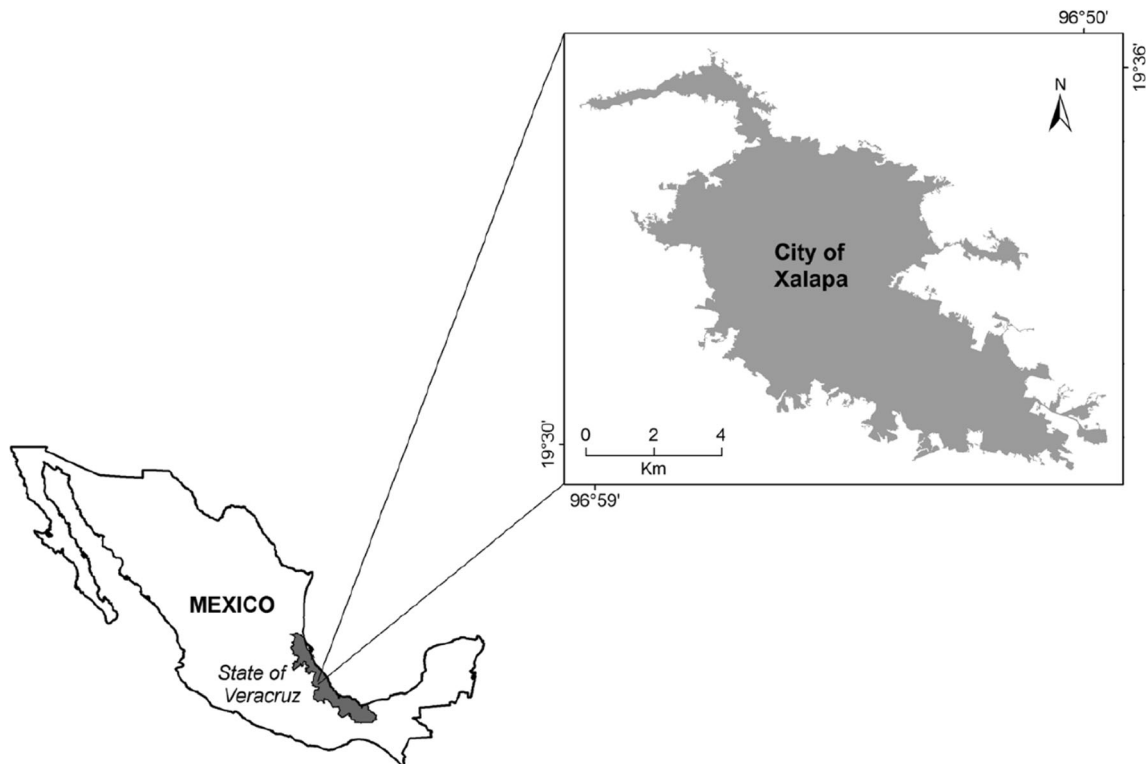
Fig. 1 Location of the city of Xalapa, Veracruz

Digital image processing

Remotely sensed data used for this study included two digital panchromatic aerial photographs (years: 1956, 1980; INEGI 1956, 1980), digital ortho-photography with a spatial resolution of 2 m (year: 1996; INEGI 1996), and two SPOT 5 panchromatic images with a spatial resolution of 2.5 m (years: 2004, 2011; ERMEXS/SEMAR 2011). In order to minimize the distortion effects on the geoposition of features in the imagery caused by complex terrain, all images were ortho-rectified. The 1996 digital ortho-photography, projected to UTM zone 14, was used as the reference for ortho-rectification of the remaining images. The 1956 and 1980 aerial photographs were ortho-rectified in ILWIS 3.4, resulting in ortho-photographs with spatial resolutions of 2 m and 5 m, respectively, due to their scales. SPOT 5 images were received at the 1A processing level, allowing for ortho-rectification using the OrthoEngine module in PCI Geomatics 2012. At least 20 control points were used on each image for the ortho-rectification process, and an ASTER version 2.0 digital elevation model (METI/NASA 2011) was used for input of elevation values. In all cases, the positional error achieved was <1 pixel, ensuring sufficient geographic matching between images. To minimize contrast due to different atmospheric conditions between digital images from different dates, histogram matching was applied to ensure valid comparison between digital images.

Delimitation of the urban area

The polygons of the urban area from the different decades were screen-digitized on each image. The criteria used to distinguish urban areas were the continuity of infrastructure, connectivity (through paved roads), and spatial aggregation of development features (>3 adjacent features) visually identified on the digital images. Areas and perimeters of the urban polygons were computed to measure the magnitude of city growth.

Classification of urban green areas

A supervised object-oriented classification approach (i.e., image segmentation) was used to distinguish urban green areas and urban developed areas. This method takes into account, in addition to the spectral response of objects on the ground, the contextual and spatial characteristics of neighboring pixels, such as size, texture, and shape (Benz et al. 2004; Jensen 2005). This classification detects groups of adjacent pixels (extracted objects) formed in growing regions with similar contextual characteristics, to which a corresponding class is assigned (Perea et al. 2009). The supervised classification requires sample data (i.e., pixels) with similar characteristics to train the classification algorithm and obtain a classified image. In total, 650 training areas, representative of both urban green areas and urban areas, and enough to include different types of elements in the image (i.e., urban, non-urban classes), were

distributed on each digital image. The accuracy of the classification was assessed using validation points randomly distributed in the classified images. The number of points on the most recent image was 150, and the number of validation points on each classified image was chosen to be proportional to the area occupied by the polygons of the city, giving a total of 432 validation points. Classification accuracy was determined for each image based on the proportion of successfully classified points contained in an error matrix.

Inter-decade sprawl areas

Urban polygons were merged in pairs from the 1980s–2010s images to obtain the differences in urban area between successive decades (1980s and 1990s, 1990s and 2000s, and 2000s and 2010s). A polygon of the inter-decade sprawl was then created for each of the three decade-to-decade study periods. The digital image from the 1950s was not used for this analysis, as there were no remotely sensed data for the first two decades, which prevented analysis of sprawl areas over the periods 1950s–1960s and 1960s–1970s. Land uses within each of the three inter-decade sprawl areas were classified using the object-oriented classification approach (described above), into: (1) woody vegetation, (2) cropland, and (3) urban areas. A multi-temporal analysis of land use changes was then conducted within the inter-decade sprawl areas to identify change dynamics (i.e., type, magnitude and direction of changes) from the 1980s to 2010s. Classification accuracy was assessed using 180 validation points for the three periods of analysis within an error matrix.

Landscape analysis and degree of urban sprawl

To quantify the landscape characteristics and pattern, four metrics were used to describe the spatial and temporal dynamics of land use types within the sprawl areas described above. The selected metrics were the percentage of landscape, patch density, largest patch index and connectance index (Table 1), and were computed using the FRAGSTATS version 4.1 program (McGarigal and Marks 1995). Entropy was used to examine the degree of urban sprawl, by exploring whether land development in Xalapa was dispersed or compact within sprawl areas. Shannon's entropy (Hn) can be used to measure

the degree of spatial concentration or dispersion of a geographical variable (x_i) among zones (Thomas 1981). To carry out the entropy analysis, the city of Xalapa was divided into eight zones in relation to the cardinal and half-cardinal directions: N, NE, E, S, SE, SW, W and NW; these zones had their origin at the centroid of the city's polygon. Entropy value ranges from zero to log (n); if the distribution is concentrated in one zone, the lowest value, zero, will be obtained. An evenly dispersed distribution among the zones will give the maximum value of log (n). Relative entropy can be used to scale the entropy value into a value that ranges from 0 to 1 to allow for temporal comparisons. Relative entropy was computed according to Thomas (1981).

Results

Urban sprawl of Xalapa

The sprawl of Xalapa since the 1950s (city area = 10.22 km^2) experienced two main growth episodes during the study period: (1) slow growth of ~14 km^2 in the first three decades (1950s–1980s), and (2) faster growth of ~17 km^2 in the next decade (1980s–1990s; Fig. 2). During the subsequent decades, city growth was slower, reaching an area of 65.54 km^2 in the 2010s. Although the growth of the city in the past six decades had a significant fit to a linear model (r^2 = 0.93, p = 0.008), it showed a better fit to the quadratic model (r^2 = 0.99, p = 0.01; Fig. 3). The city has grown in different directions over the study period. During the period 1950s–1990s, the city grew mainly northward, while later, in the 1990s–2010s, the city grew mainly to the southeast, and to a lesser extent also toward the northwest (Fig. 2).

During the period 1950–1990, urban growth gave rise to 57 neighbourhoods, many of them established illegally, located in areas with a high landslide risk, and some of the neighbourhoods invaded protected natural areas. Additionally, 10 collective housing units (apartment building complexes) and a residential development were built in the north of Xalapa-Banderilla. This growth pattern toward the north was mostly triggered by the improvement of the transportation corridor Boulevard Xalapa-Banderilla, running north–south in the urban area, which in turn promoted

Table 1 Description of landscape metrics used in the study

Landscape index	Description
Percentage of landscape	Relative area of a specific patch type in the landscape (%)
Patch density	Number of patches per 100 ha
Largest patch index	Percentage of landscape occupied by largest patch (%)
Connectance index	Maximum possible connectance given the number of patches. It equals 100 when every patch of the focal class is connected (%).

Fig. 2 Urban sprawl of the city of Xalapa in the last six decades
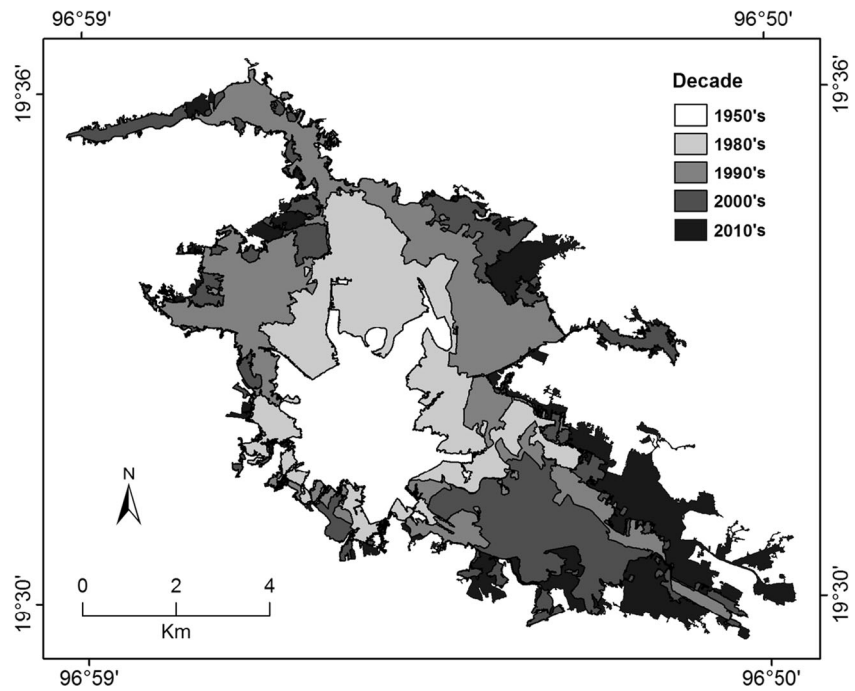
commercial land use along the northern section of the boulevard. During the period 1990–2010, 35 neighbourhoods, 17 residential developments and 11 collective housing units were appended to the urban area. Most of these developments were located in the south-eastern and north-eastern portions of the city. During this period, the direction of urban growth shifted from north to south-east because of the presence of physical barriers in the north of the city (e.g., mountainous terrain and steep slopes) that prevented further urban development toward the north. The substantial growth toward the south was due to the construction of several centers of population attraction such as supermarkets, malls, hospitals, schools and universities, which increased land values. Although many illegal settlements were established in this period, widespread development of residential areas with high economic value took place in the city.
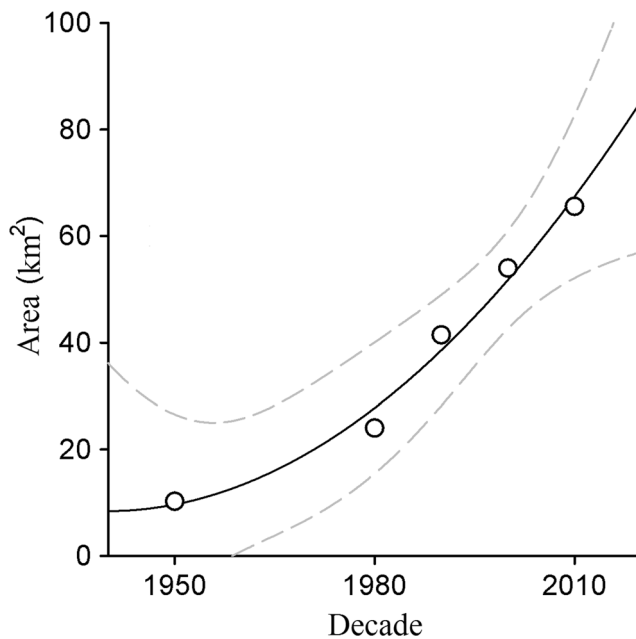
Shifts in green areas within the City

Classification accuracy of urban green areas was 82%. The results of the analysis showed that Xalapa has undergone constant change in its green areas during the last six decades (Fig. 4), declining in the first part of the period (1950s–1980s), increasing in the 1980s–2000s, and decreasing again in the last decade of the study period (2000s–2010s). Preexisting urban green areas decreased as consequence of infill urbanization, while new green patches were surrounded by the city as it expanded, which has led to the percentage of woody cover in the city in the 2010s being almost the same as in the 1990s. There is only one large patch of vegetation that has been conserved throughout the entire period; the Cerro de Macuiltépetl (29 ha), an extinct volcano located at the center of the current city polygon. This patch is a protected ecological park that preserves remnants of the original vegetation of the area and is highly appreciated by inhabitants as it is used for running, picnicking and leisure activities. Two other significant green areas were embedded by the city during the 2000s in the south (Parque Natura) and in the north (Cerro

Fig. 3 Size increase of the urban area of the city of Xalapa in the six study decades. The solid black line indicates a quadratic fit, while the gray segmented lines show the 95% confidence intervals. No remotely-sensed data were available for the 1960s or 1970s
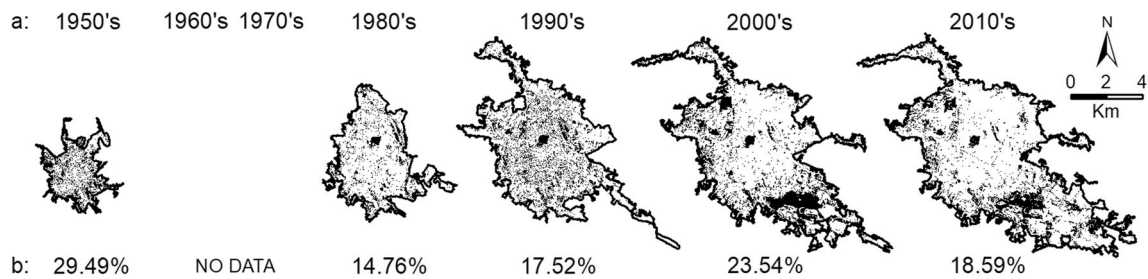
Fig. 4 Woody vegetation cover in the city of Xalapa expressed as percentage of woody vegetation cover in relation to the size of the city (obtained with data provided by ERMEX-inecol-ver02 2011)

de la Galaxia). Although these two parks are protected areas, they had been fragmented and occupied in some parts by irregular settlements, which reduced them from 235 ha to 227 ha (Parque Natura) and 40 ha to 36 ha (Cerro de la Galaxia) from the 2000s to the 2010s. Most of the other embedded green areas of lesser area were intensively occupied by irregular settlements.

Inter-decade sprawl

Overall classification accuracy of urban, woody vegetation and cropland was 89% for the three periods of analysis. The expansion of the city of Xalapa in the last six decades occurred mostly in areas formerly occupied by woody vegetation. From the 1980s to the 2000s (30.07 km^2 growth), woody vegetation areas were mainly converted to cropland, and from the 2000s to the 2010s (11.27 km^2 growth) woody vegetation areas changed directly to urban areas without a transition through the cropland phase (Table 1). We also found areas with no land use changes (stasis), with woody vegetation cover heading the list (in terms of area), followed by cropland, and previously established human settlements (Table 2).

Table 2 Land use changes and stasis (km^2; in bold) in the sprawl areas of Xalapa

Decades	Woody cover	Cropland	Urban
1980s–1990s			
Woody cover	**3.06**	4.49	3.60
Cropland	0.47	**1.46**	1.23
Urban	0.07	0.31	**0.41**
1990s–2000s			
Woody cover	**3.27**	2.77	2.59
Cropland	0.28	**1.34**	1.03
Urban	0.12	0.77	**1.29**
2000s–2010s			
Woody cover	**2.40**	1.20	2.39
Cropland	0.77	**1.29**	1.86
Urban	0.17	0.48	**1.05**

Numbers marked in bold indicate areas with no change

Landscape dynamics and degree of sprawl

Landscape analysis indicated that the area of woody vegetation in Xalapa decreased by 10% from 1990 to 2000 compared to 1980–1990, but increased 20% in the period 2000–2010 compared to 1980–1990 (Fig. 5a). The density of patches of woody vegetation was highest in 1980–1990, and decreased in 1990–2000, but increased in 2000–2010 (Fig. 5b). The largest patch of woody vegetation was found in 1990–2000, being three times larger than during 1980–1990 but it decreased in 2000–2010 (Fig. 5c). Connectivity among woody vegetation patches decreased overall during the study period (Fig. 5d).

The percentage of urban area decreased from decade to decade, especially in 2000–2010 (Fig. 5a). The density of urban patches decreased in 1990–2000, but in the decade 2000–2010, patches of urban area became denser than in the previous decade (1990–2000) (Fig. 5b). The largest patches of urban area decreased over the study period, with sizes ranging from 3% to 5% of the landscape (Fig. 5c). Similarly to woody vegetation patches, connectivity among patches of urban areas decreased over the study period (Fig. 5d).

Croplands increased in total area in 1990–2000 compared to 1980–1990, but decreased in 2000–2010 (Fig. 5a). On average, croplands had higher patch density than either urban or woody vegetation areas and had the highest patch density in 2000–2010 (Fig. 5b). Croplands also had the lowest value of the largest patch index as compared to other land use types; the largest patch of cropland covered from 1% to 3% in the study period (Fig. 5c). Connectivity of cropland patches followed a similar trend to that of woody vegetation patches and decreased with time over the period of study (Fig. 5d). Shannon's relative entropy showed values of 0.58 in 1980–1990, 0.63 in 1990–2000 and 0.73 in 2000–2010, exhibiting an increasing, dispersed pattern of urban infrastructure over time (Fig. 6).

Discussion

Urban sprawl is a global concern, as it is occurring at a rapid rate, which represents a challenge for urban planning and
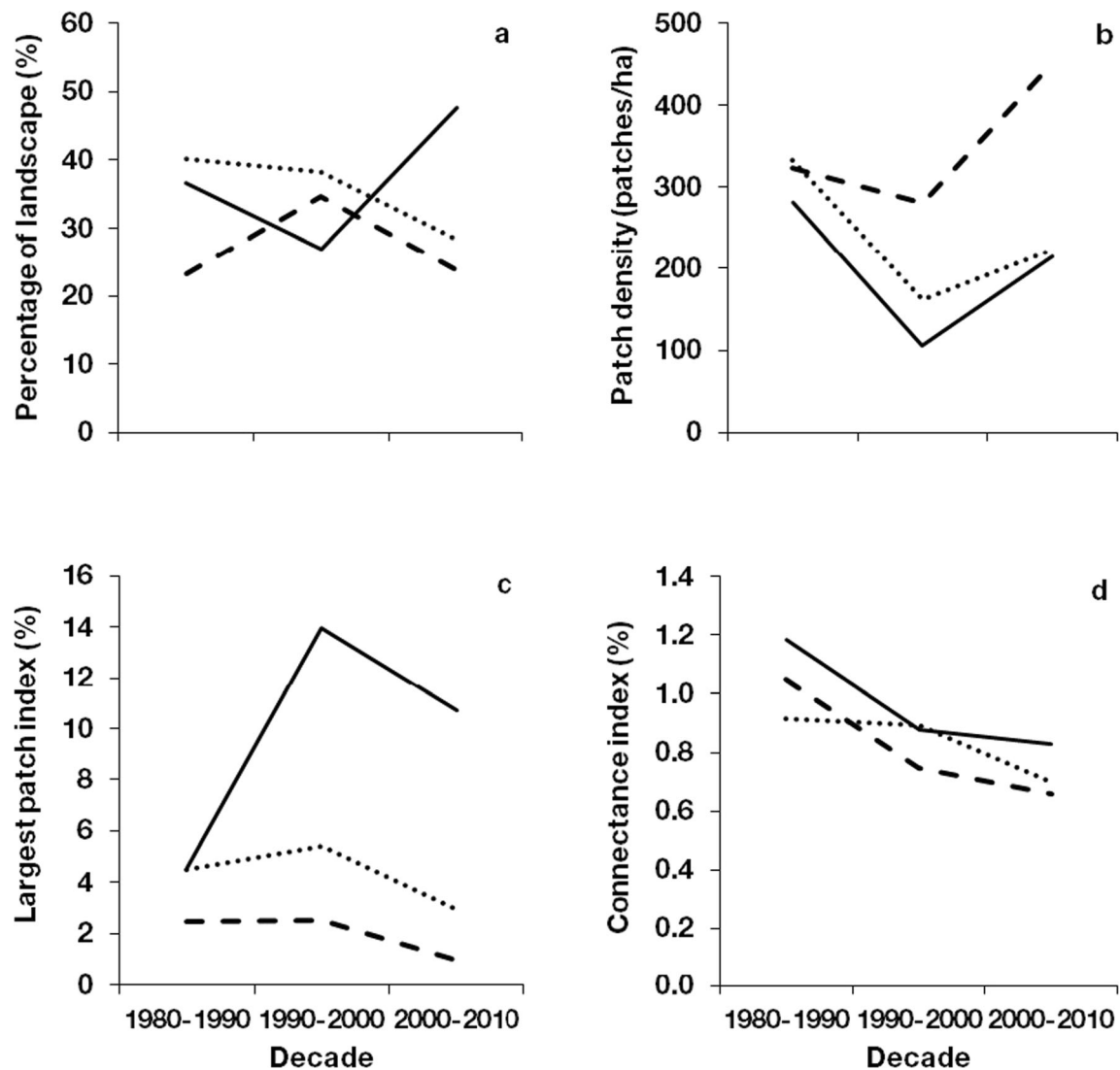
Fig. 5 Landscape metrics computed from the sprawl areas of the city of Xalapa (1980–2010). **a** Percentage of landscape, indicating the relative area of each specific patch type; **b** Patch density; the number of patches per area unit; **c** Largest patch index; the percentage of the landscape occupied by the largest patch; **d** Connectance index; maximum possible connectance among patches, equals 100 when every patch of the focal class is connected. Solid line depicts woody vegetation, dashed line agricultural lands and dotted line urban infrastructure

policy implementation (Hasse and Lathrop 2003; Poelmans and Van Rompaey 2009). Little is known about the spatiotemporal dynamics of urban sprawl in medium-sized Mexican cities (Álvarez de la Torre 2011). The growth of cities can take place under different spatial contexts. In Mexico, topographic features and economic activities are factors that shape urban sprawl, often through synergistic interactions (Ávila-Sánchez 2009). The city of Xalapa had concentric growth until the 2000s, with 7–18 km^2 growth per decade, and the largest growth occurring from the 1980s to the 1990s. Similar growth has been reported for several medium-sized Mexican cities (Álvarez de la Torre 2011). Independently of the factors determining urban growth, two Mexican cities that had a similar size to Xalapa in the 1950s have now increased their area by 237% (city of Querétaro; PNUMA 2008) and 159% (city of

Morelia; López et al. 2001) with respect to their respective areas in the 1950s. Thus, our results show that Xalapa has sprawled less than some other similar Mexican cities, following a quadratic-linear growth pattern.

The growth magnitude and orientation of the city of Xalapa in the last six decades has shown no ordered urban planning, mainly due to social factors (e.g., economical activities, availability of basic services, housing cost; Benítez 2011). Values of Shannon's relative entropy support this claim, as it reveals a moderately high degree of dispersion of the urban infrastructure, and indicates that sprawl is taking place and increasing in Xalapa over time and causing landscape fragmentation. During the first period of analysis (1950–1990), the city of Xalapa-Banderilla grew to the north; this direction of growth had already been identified by Dredge (1995), who
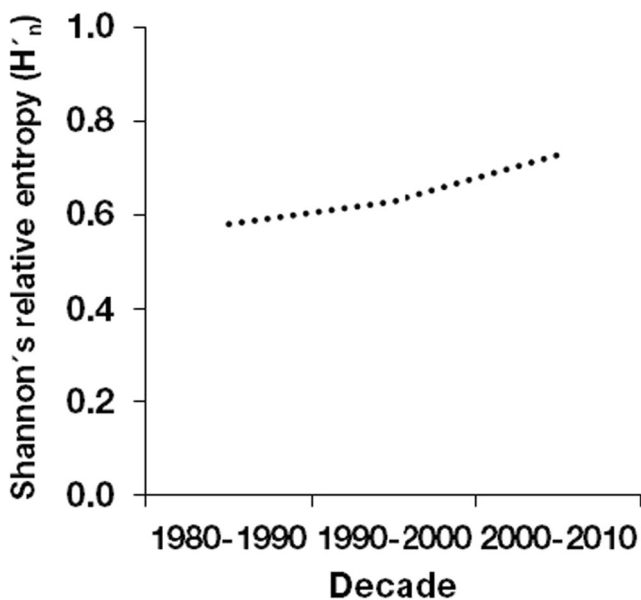
Fig. 6 Shannon's relative entropy for urban areas within the sprawl areas of the city of Xalapa (1980–2010)

pointed out that the city of Xalapa-Banderilla had physical limitations impeding its growth in other directions, which, along with some socio-economic factors, promoted growth towards the north. However, from 1990 on, the direction of growth shifted towards the south, and currently it appears that Xalapa will grow southward due to the topographic barriers located to the north, east and west of the city's boundaries. This growth will replace significant areas of woody vegetation and cropland found in these areas. Thus, for urban planning purposes, the expected growth of the city must take into account the potential loss of large surrounding vegetated areas, and examine how to preserve a proportion of these areas and to incorporate new green areas into Xalapa.

The landscape analysis showed the spatial characteristics of the areas covered by the three land uses and vegetation types and their changes over the period 1980–2010. The growth dynamics of the city of Xalapa and its green areas have been driven mainly by the incorporation of vegetation patches from surrounding areas into the city. In the last decade in the study period, an increase in woody vegetation in the landscape as well as a decrease in urban areas as a consequence of infill urbanization were observed; this was the result of the inclusion of new woody vegetated areas that are embedded as the city expands its boundaries. This effect has also meant that the single largest patches are of woody vegetation, as large green parks have been added to the city, especially in the sprawl areas. However, these patches of vegetation have also been subject to fragmentation and their connectivity has been modified, which has changed their ecological properties and potential to provide ecosystem services. It is clear that the designation of urban green areas as protected parks has enabled partial conservation of such areas. Nevertheless, local

government must put stronger efforts into the regulation of land use change within these areas. On the other hand, it is important to protect preexisting urban green areas from infill urbanization, consolidating most of them as protected areas. Preexisting inner-city green areas have decreased, basically due to the preferential designation of urban land use (e.g., housing developments, shops, roads) throughout the city, including sprawl areas. The urbanization process in the areas surrounding Xalapa has caused constant land use changes, mainly of woody vegetation areas, which in turn have been converted to cropland (1980s–1990s) and urban land use areas (1990s–2000s, 2000s–2010s) as a consequence of the increased demand for residential sites. All land use and vegetation types exhibited the same increasing trend in patch density in the last study decade, which along with a trend of decreasing patch connectivity is evidence of fragmentation. During this process of change, the areas covered by cropland have had the highest degree of fragmentation, indicating considerable replacement of primary production activities by dispersed urban infrastructure.

The direct change from woody vegetation to urban cover (without a transition to cropland) has been documented in several cases where urbanization of surrounding city areas has taken place illegally (Ávila-Sánchez 2009). We suggest that woody vegetated areas located to the south of Xalapa will form part of the city in the near future; thus, it is important to exercise sufficient management of these areas. Particularly, it is vital to maintain the vegetation in the areas surrounding the city, as it provides important benefits: (1) preserved forest areas, (2) environmental services to the city, (3) habitat for wildlife species, and (4) a source of agricultural income (Pisanty et al. 2009).

Most of the studies focusing on urban sprawl and resulting land use change have been conducted on large cities. However, there is a lack of data describing land change processes in smaller cities; these cities may represent centers of development that attract people, increasing their growth rates. The patterns of urban sprawl measured with Shannon's entropy in Xalapa exhibit similar sprawl patterns to those found for some large cities analyzed over similar time periods (Sun et al. 2007; Kumar et al. 2008; Bhatta 2009; Tewolde and Cabral 2011). Thus, urban sprawl rates can be as high as for large cities, and need to be characterized to aid in regional planning. Additionally, the growth pattern of Xalapa was consistent with decreasing largest patch values and urban infrastructure connectivity; that is, a smaller area of the largest urban patch and less connectivity among urban patches, which in turn reflects urban sprawl.

Our study integrates remote sensing with easy-to-obtain data, geographic information systems and landscape metrics to characterize spatiotemporal patterns of urban growth and land use in the medium-sized urban area of Xalapa, Mexico. Our results enable an understanding and monitoring of how

patterns of urban growth (i.e., landscape organization) and processes (i.e., urban sprawl; land use change) occur and how they shift over time in a medium-sized city. By using similar data, urban planners in comparable cities can infer and characterize specific patterns of residential use, informal settlements and urban green areas in a cost-effective way. Hence, our approach facilitates the interpretation of trends in urban systems and the related ecological and urban planning implications, which constitute an important basis for guiding management practices. Particularly for the urban area of Xalapa, our results underline the need for comprehensive ecology-based urban planning, including strategies directed at conserving the city's vegetation. Such strategies should include the creation and maintenance of green areas and their spatial connectivity, paying special attention to the cloud forest zones located to the east and southeast of the city to guarantee ecological functioning.

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