



Research Article

Future urban growth scenarios and ecosystem services valuation in the Tepic-Xalisco Metropolitan area, Mexico

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Abstract

Currently, there is a need to establish new territorial planning instruments focused on sustainable development. The simulation of spatial scenarios is an essential tool to evaluate different alternatives for urban planning. The objective of this work was to explore future urban growth through the analysis of landscape patterns and the economic quantification of ecosystem services of three prospective scenarios, simulated towards the horizon year 2045. Each scenario was formulated, based on the application of different socioeconomic, political and environmental development strategies whose actions have a direct impact on land-use changes. The starting point was an urban growth simulation model, based on Cellular Automata with Markov Chains (CA-Markov), developed from previous work for the study area. Three scenarios were constructed with the intention of showing the spatial characteristics of three different alternatives of the evolution of future urban growth and through them, quantify the economic value and the consequences that would occur in the territory due to the effect of the different decisions taken. Landscape metrics were applied to detect the spatial processes and patterns of urban growth for each

of the simulated scenarios and, finally, the costs of ecosystem services associated with the loss or gain of territory (that each of the different land covers and land uses would contribute) were quantified. The three simulated scenarios revealed that the Tepic-Xalisco Metropolitan Zone (MZ) will be in a process of urban coalescence in the next 30 years; and that the path designed to move towards an Industrialisation Scenario (ES2-IN) estimates economic losses of more than \$31 million dollars per year for the ecosystem services associated particularly with the reduction of forest cover.

Keywords

CA-Markov, spatial planning, landscape metrics, future scenarios, ecosystem services valuation

1. Introduction

Urban areas in most developing countries in the world have been expanding at a very rapid pace (ONU 2018a). Before the 20th century, urban settlements evolved naturally and spontaneously without any type of management or planning. This situation has provoked a series of environmental, social, economic and cultural impacts (UN-Habitat. 2020), with serious effects (ONU 2018b) on environmental ecosystems and biogeochemical cycles (Karmanova et al. 2022), with overexploitation of natural resources (Lampert 2019), fragmentation and loss of habitat (Rybicki et al. 2019), deforestation (Bologna and Aquino 2020) and environmental pollution (Juan et al. 2021). Therefore, there is a need to establish new land-use planning instruments focused on sustainable development.

In this sense, the simulation of spatial scenarios is an essential tool for evaluating different alternatives in urban planning. Urban planning through the use of scenarios refers to the process of creating multiple plausible futures that can be used as territorial planning tools with a focus on sustainable development (Avin and Goodspeed 2020). The application of this methodology has proven to be an indispensable tool for decision-making (Schmidt 2020), by allowing us to obtain images of possible future situations (Barredo et al. 2003; Avin and Goodspeed 2020; Barredo et al. 2003; Avin and Goodspeed 2020) and to increase adaptive capacity of urban development plans (Aguilera et al. 2011; Chakraborty and McMillan 2015). These will enable the evaluation of different alternatives for the probable, possible and/or desirable future in order to have a clear vision of the consequences that implementation of one or another decision would have on the territory (Gómez et al. 2014; Gómez et al. 2014; Gounaridis et al. 2018; Kim et al. 2020).

Scenarios are not in themselves future predictions of urban growth (Jahanishakib et al. 2018), but state possible situations that urban growth may have (Aguilera et al. 2010). In this context, knowing the changes that may happen in past, present and possible future situations, plays an important role in decision-making processes (Shafizadeh and Helbich 2013). Understanding the urban dynamics and simulating scenarios can contribute to anticipating these outcomes, managing the establishment of actions that influence the

desired scenarios (Dreborg 2004; Börjeson et al. 2006; Chakraborty and McMillan 2015 Dreborg 2004).

The use of scenarios and the application of models to simulate those scenarios have been widely field-tested in some European countries (Aguilera et al. 2011); but, to our knowledge, in Latin American countries, especially in Mexico, these tools and methodologies are not yet applied in territorial planning processes. However, the use of models is currently spreading by a large number of studies in the scientific literature (Tong and Feng 2020; Aburas et al. 2021 Tong and Feng 2020 Aburas et al. 2021); these models have been developed to simulate urban growth scenarios, based on the observed historical trend (Avalos et al. 2019; Kantakumar et al. 2019) to evaluate the influence and calibration of some driving factors (Barreira et al. 2017; Feng et al. 2019 Barreira et al. 2017) or based on other methodologies where certain restrictions are applied to limit urban growth or ecological protection (Osman et al. 2016; Liao et al. 2019 Osman et al. 2016 Liao et al. 2019). All those studies showed the great usefulness of these models in the processes, planning practices and decision-making.

Given these circumstances, it is evident that the decision-making process for territorial planning and the formulation of scenarios must move towards sustainable development. For this, it is necessary to evaluate, amongst other aspects, the ecological integrity of future scenarios; for example, by guaranteeing the ability of future generations to access ecosystem services (Assessment 2004). In this sense, it is clear that ecosystem services (ES) are essential for the human well-being, such as health, livelihood and survival (TEEB 2010; TEEB 2018), because they provide the materials to obtain products, goods and services from the different natural ecosystems directly or indirectly exploited by humans for our well-being (Costanza et al. 1997; Douglas 2015 Costanza 2020; Costanza 2020) and the maintenance of our vital functions.

The ecosystem services valuation (ESV) has become an important tool to quantify the benefits provided by natural resources (Costanza et al. 2014), to help planners raise awareness and convey the value and importance of ecosystems and biodiversity (de Groot et al. 2012), as well as to establish land-use planning policies, this being one of the paths towards sustainable development (Anderson et al. 2017).

In this same context, landscape metrics have taken great relevance in the urban environment due to their ability to analyse the structure and configuration of the landscape (McGarigal and Marks 1995; McGarigal et al. 2012; McGarigal et al. 2013); to identify patterns (Riitters et al. 1995) and spatial processes (O'Neill et al. 1999); as achieved in studies by Seto and Fragkias (2005), Aguilera et al. (2011), and Zubair (2020) when analysing the structure or integrity of urban growth scenarios, as well as to detect patterns in future scenarios, such as those studies carried out by Rozas et al. (2014), Mugiraneza et al. (2019) and Mohamed and Worku (2020), amongst others.

The objective of this work is to explore future urban growth through the analysis of landscape patterns and the economic quantification of ecosystem services in three prospective scenarios, simulated towards the 2045 horizon. Each scenario was formulated,

based on the application of different socioeconomic, political and environmental development strategies whose actions have a direct impact on future urban land-use changes. The starting point was an urban growth simulation model, based on Cellular Automata with Markov Chains (CA-Markov). Three exploratory scenarios were built with the intention of showing three different alternatives for the evolution of future urban growth and its spatial characteristics. They were then evaluated using landscape metrics to compare the effects and consequences for each scenario and, finally, the changes occurred were economically quantified by linking the value of ecosystem services with the different land covers and land uses. The results obtained constitute a valuable source of information for decision-making when evaluating different land-use planning alternatives, as well as providing a first approximation of the economic value of the ecosystem services that subsist in the Tepic-Xalisco Metropolitan Zone (MZ). The methodology proposed in this paper is intended to be a contribution in the sense of evaluating the sustainability of prospective scenarios that can be replicated in the search for sustainable urban planning.

2. Materials and methods

2.1 Study area and baseline data

Fig. 1 shows the MZ, the area where the simulation model, based on CA-Markov, was validated and applied to explore future urban growth through three simulated scenarios towards the year 2045 and which was delimited by a 900 km² quadrant, containing a total of 30 locations that have experienced significant urban growth in the last 30 years.

The settlements in the MZ date back to the 16th century, particularly Tepic (26), which was officially founded in 1532, with a concentric urban layout, based on a main square. In Mexico's colonial period (1960), the Guadalajara-Tepic-Mazatlán highway was built, producing new functions for the urban layout, as an obligatory communication route to the northern (Sinaloa) and southern (Jalisco) zones of the country. Therefore, Tepic City became the centre of attraction of its State, due to its housing and permanent employment services and also became a centre of supply and distribution of products, mainly agricultural and livestock products (PDU 2000). In recent years, with the intense exchange of goods and services, urban growth has accelerated towards the southwest and east of the Tepic, between the location of Xalisco (30) and La Cantera (13). This expansion of the capital city was beyond the administrative limits, leading to a partnership with Xalisco for a formalised conurbation process known as the Metropolitan Zone (MZ) in 2003 (CONAPO 2005). Currently, this situation has spread to the south with San Cayetano (23) and to the north with El Aguacate (7), Las Delicias (18) and Lo de Lamedo (19), surpassing natural limits of ecological importance, such as aquifer recharge zones (wetlands) and biological corridors (Metropolitan Ecological Park) that provided diverse ecosystemic services to the MZ. This area is affected by a continuous process of environmental deterioration, mainly because there is no proper control in urban planning and no concern about the value of natural resources.

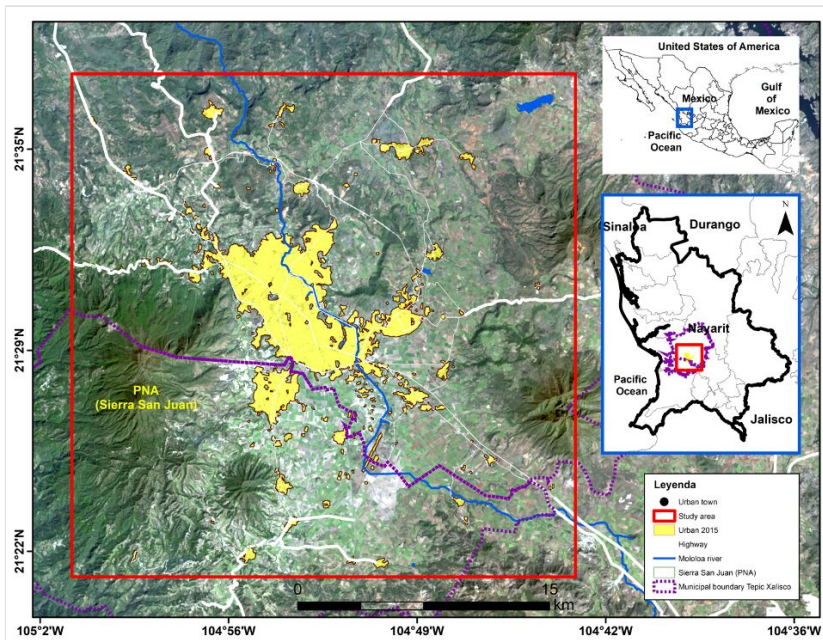


Figure 1.

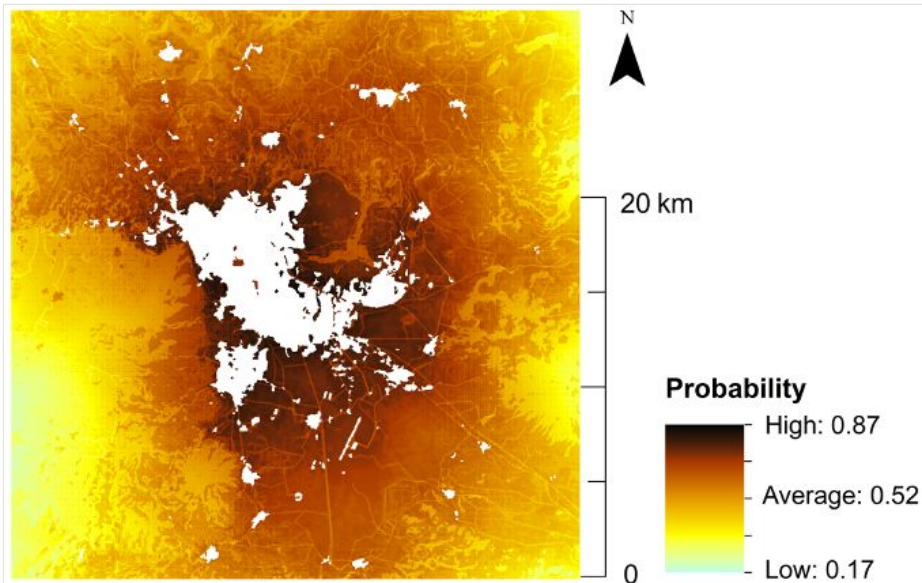
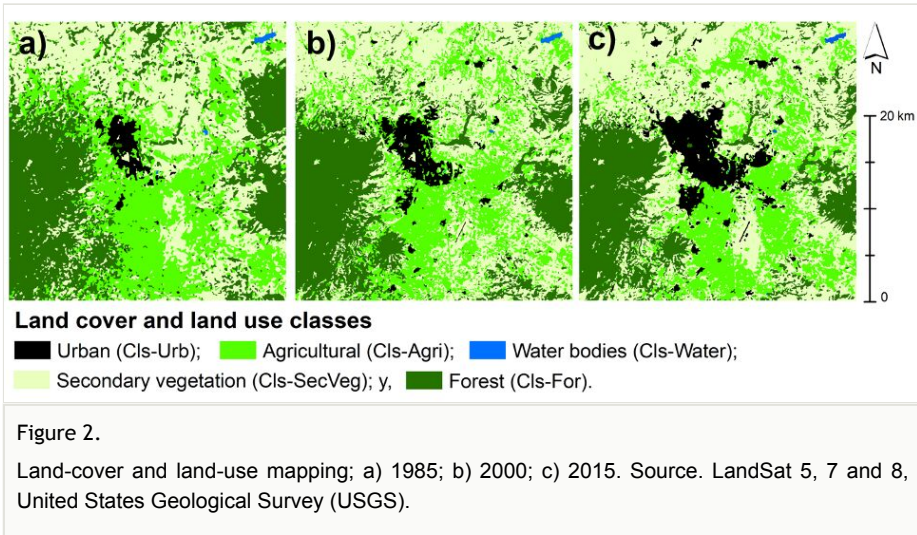
Location and delimitation of the study area. Source: Our own elaboration using data from National Institute of Statistics and Geography of Mexico (“Instituto Nacional de Estadística y Geografía”, INEGI). Base map: LandSat Image 8 (OLI) 2015 of the United States Geological Survey (USGS), natural composition (Bands 432).

We started from the data obtained in previous works by Avalos et al. (2019); specifically for the study area, the land-use mapping obtained for the years 1985, 2000 and 2015 was used through the classification of LandSat 5, 7 and 8 satellite images, for the corresponding time periods. The five land-cover and land-use classes indicated in Fig. 2 were considered and the Conditional Probability Image (CPI) for urban land use was used as shown in Fig. 3. The Transition Probability Matrix (TPM) and Transition Area Matrix (TAM) are shown in Fig. 4. Model data indicate the change from each type of land cover and land use to another and which constitute the urban growth trend of the MZ, over a period of 30 years.

The urban growth simulation model was developed in previous works by Avalos et al. (2019), where particularly the CA-Markov model was tested for the past and managed to obtain the best model fit with a degree of agreement (kappa index) of 75%, the highest value of the three models used, this being due to its ability to analyse the spatial neighbourhood and consider the randomness factor (uncertainty factor associated with the study of complex phenomena) that determines the areas of greatest potential for urban growth.

The core of the CA-Markov model was to obtain the Markov chains used to generate the Transition Probability Matrix (TPM), the Conditional Probability Image (CPI) and the

Transition Area Matrix (TAM) for the land-use classes, all of which are necessary to design and configure the different scenarios to be simulated. The model used was built from the 1985-2000 land use mapping, to simulate urban growth towards 2015 and was subsequently validated by comparing it with the actual urban mapping of 2015 (30-year analysis period that was established as the time horizon).



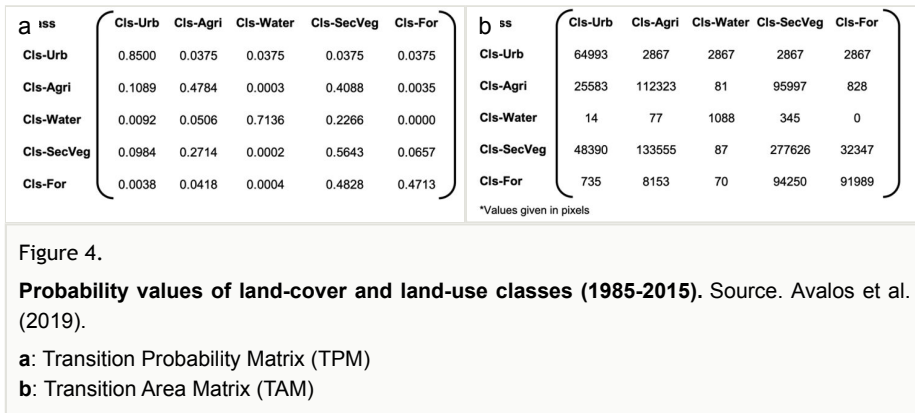


Figure 4.

Probability values of land-cover and land-use classes (1985-2015). Source. Avalos et al. (2019).

a: Transition Probability Matrix (TPM)

b: Transition Area Matrix (TAM)

2.2. Methodology

The methodology followed for the simulation of scenarios, analysis of spatial processes and quantification of ecosystem services were established for the two stages described in Fig. 5, starting from the execution of the simulation model built, based on CA-Markov; in the first stage A), three scenarios were designed and simulated in order to evaluate different alternatives for urban growth, based on the application of different strategies and public policies that have direct consequences on the different land covers and land uses. The design of the scenarios was developed under a panel of experts who constructed the descriptive basis (Storyline) and the Configured Matrix of Transition Areas (CMTA) associated with the different policies and strategies that were applied for each scenario; and, in stage B), the results of the three scenarios were analysed through the application of landscape metrics to identify the processes of change and patterns of urban growth; then the economic value of ecosystem services was quantified by linking the different classes of land cover and land use with the value of the global ecosystem in order to compare the effects and possible environmental consequences with respect to the starting status established in 2015.

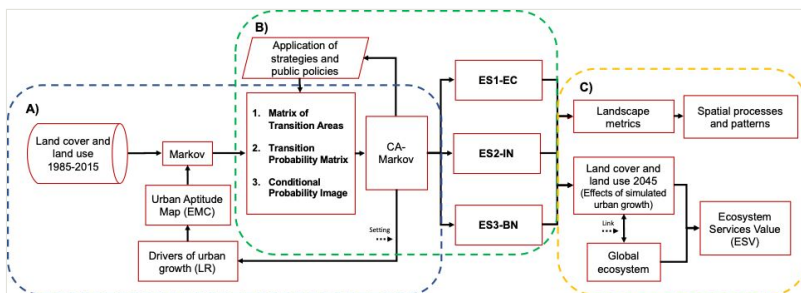


Figure 5.

Methodological process to explore urban growth through the simulation of future scenarios. A) Urban growth simulation model; B) Simulation of three alternative future scenarios; C) Exploration and analysis of future scenarios. Source. Own elaboration.

2.2.1. Design and simulation of future scenarios

Three alternatives were formulated as the minimum options necessary for proper exploration and comparison of the different decisions implemented (Durance and Godet 2010; Amer et al. 2013). Each scenario was formulated through the consensus of a panel of experts composed of a group of research professors, with areas of research focused on the evaluation and management of natural resources and environmental planning and with experience in the elaboration of Ecological Management Programmes (“Programas de Ordenamiento Ecológico, POE”) and environmental impact assessments. A round-table discussion group was organised and the experts gave their opinion on a series of strategies and public policies that (under their experience) have repercussions on the changes in land use in the MZ in the future, in the context of the three scenarios explained in this section.

Ecological Conservation Scenario (SC1-EC). The environmental situation is considered to be of great importance through strict enforcement of environmental laws. In this scenario, Mexico’s economic situation is expected to strengthen, enabling greater federal support for programmes and actions aimed at environmental care and protection. Local strategies and public policies focus on the conservation of sites of scenic and ecological value, including forests and bodies of water (such as the Mololoa River), promoting the creation of biological corridors for wildlife activities, greater conservation of watercourses and bodies of water by protecting the rivers and run-offs that are part of the natural drainage system. Ecological restoration through the reforestation of areas of scenic value and the integration of the urban aspect into the natural landscape is promoted. Sustainable agricultural use is considered, maintaining the trend of change of the current stable agricultural surface, the real protection of protected natural areas is promoted, with a tendency towards the sustainable use of natural resources, limiting urban growth.

Industrialisation Scenario (SC2-IN). Strategies and public policies promote productive activities in areas of high industrial and agricultural production, with greater provision of equipment and urban infrastructure. The generation of industrial corridors is promoted and the territorial reserve is increased to intensify mining extractive activities. Environmental protection restrictions are eliminated, allowing uncontrolled exploitation of natural resources with imminent overexploitation of aquifers and bodies of water to supply industrial and agricultural activities. This scenario considers the intensive use of forests with considerable loss of surface area and, on the other hand, the increase in urban and industrial areas that are reflected in the replacement of secondary vegetation and agricultural areas by industrial and service activities.

Northern Bypass Scenario (SC3-NB). This scenario involves the expansion and improvement of the road structure through the construction of new communication routes, such as the Libramiento Norte Highway. In this scenario, the urban growth trend of recent years is maintained, giving continuity to environmental regulation without further investment in local environmental programmes. Urban growth continues with the trend registered in the last 30 years, displacing agricultural land and eliminating forest vegetation (Avalos et al. 2019).

Each of the different policies and strategies considered above were assessed by the same panel of experts to form the Transition Area Allocation Matrix (TAAM) in Table 1, whose data indicate the percentage change in area of each land cover and land use that will directly influence the results of each simulated scenario.

Table 1.
Transition Area Allocation Matrix (TAAM) for the design of the three future scenarios. *Sign (+) Indicates increase; and, (-) Reflects reduction of surface area.* Source. Own elaboration.

Land cover and land use classes	Land use surface transition														
	SC1-CE					SC2-IN					SC3-NB				
	Cls-Urb	Cls-Agri	Cls-Water	Cls-SecVeg	Cls-For	Cls-Urb	Cls-Agri	Cls-Water	Cls-SecVeg	Cls-For	Cls-Urb	Cls-Agri	Cls-Water	Cls-SecVeg	Cls-For
Cls-Urb	0	0	0	0	0	+25%	0	0	0	0	+10%	0	0	0	0
Cls-Agri	0	0	0	0	0	0	+10%	0	0	0	0	+5%	0	0	0
Cls-Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cls-SecVeg	0	0	0	-20%	0	0	0	0	-15%	0	0	0	0	-15%	0
Cls-For	0	0	0	0	+20%	0	0	0	0	-20%	0	0	0	0	0

The simulation for each of the three scenarios designed was developed through the execution of the Markov CA model using the starting data (TPM, CPI and TAM) and the Configured Matrix of Transition Areas (CMTA), which was obtained by combining two matrices: the Transition Area Matrix (TAM) containing the trend values of transition areas and the Transition Area Allocation Matrix (TAAM) elaborated from the values agreed upon by the panel of experts for each scenario designed.

In particular, the CMTA was constructed by converting the values of percent area change contained in the TAM into area quantity (number of pixels) with respect to the total area of the landscape and these values were then added to the TAAM of the trend model. The allocation of the number of areas established in the CMTA will indicate an increase or decrease in the surface area of each land cover and land use in the landscape, directly impacting the process of allocating the number of areas during the execution and allocation of pixels in the CA-Markov model, while, on the other hand, the CPI will determine the location of the change, leading to the generation of each of the scenarios proposed.

2.2.2. Scenario evaluation and ecosystem services valuation (ESV) with landscape metrics

Landscape metrics were applied to evaluate and quantify the spatial characteristics of each simulated scenario through the analysis of patches or tessellations in the landscape mosaic (McGarigal 2014). The metrics application was carried out through the software Fragstats v. 4.2, to obtain the differences between the metrics of each scenario and, through their comparison, to evaluate the processes and spatial patterns of urban growth that would occur in the future; six metrics described in Fig. 6 were applied; three to analyse

the composition of the landscape ("NP"; "PLAND" and "SHAPE") and three to measure landscape configuration ("AREA_MN"; "ENN_MN" and "CONNECT"); all were calculated at the class level for the purpose of analysing changes for each of the land covers and land uses, all metrics being obtained from McGarigal et al. (2012), where more references can be found.

No.	Métrica	Formula	Interpretación	Valores
1	NP	NP = N	>NP } <AREA_MN } FRAGMENTATION >NP } >ENN_MN } DISPERSION >AREA_MN }	1 al ∞ 1 = 1 patche
2	PLAND	$PLAND = \frac{\sum_{j=1}^n a_{ij}}{A} (100)$	>PLAND } >AREA_MN } DIFFUSION <ENN_MN }	0 to 100 0 = Rare patch
3	SHAPE_MN	$SHAPE_MN = \frac{\sum_{j=1}^n \frac{p_{ij}}{\min p_{ij}}}{n_{ij}}$	>SHAPE } >AREA_MN } COMPLEXITY	> 1 1 = 1 square patch
4	AREA_MN	$AREA_MN = \frac{\sum_{j=1}^n a_{ij}}{n_i}$	>NP } <AREA_MN } FRAGMENTATION >NP } >AREA_MN } COALESCENCE	> 0
5	ENN_MN	$ENN_MN = \frac{\sum_{j=1}^n h_{ij}}{n_i}$	>ENN_MN } >NP } DISPERSION >AREA_MN } >ENN_MN } <NP } COALESCENCE >AREA_MN }	> 0 0 = 1 patche
6	CONNECT	$CONNECT = \left[\frac{\sum_{j \neq k} c_{ijk}}{n_i (n_i - 1)} \right] (100)$	<NP } >CONNECT } COALESCENCE >ENN_MN }	0 to 100 0 = No connectivity 100 = Full focal connectivity

Figure 6.

Metrics applied to analyse landscape patterns. * Increase, Decrease. Source. Own elaboration.

A review of the literature identified the phases of: Diffusion (Álvarez 2016); Coalescence (Pascual et al. 2019); Dispersion (González and Larralde 2018) and Fragmentation (Maure 2017) as the four main spatial processes currently occurring in various urban settings (Martellozzo and Clarke 2011; Shrestha et al. 2012; Dietzel et al. 2016; He et al. 2017; Monkkonen et al. 2018). Fig. 7 describes these processes, the associated urban growth pattern and the interpretation in terms of the changing trend of landscape metrics, which were considered for the purpose of evaluating the spatial evolution of each simulated scenario and detecting the spatial processes and patterns associated with each scenario due to the effects of urban growth.

The ESV was developed according to the proposal of Costanza et al. (1997) and Costanza et al. (2014), to quantify, in monetary units, the economic value of the ecosystem services present in the MZ, linking each type of land cover and land use with the global ecosystem value established by the Millennium Ecosystem Assessment (Assessment 2004) and The Economics of Ecosystems and Biodiversity (TEEB 2012; TEEB 2018).

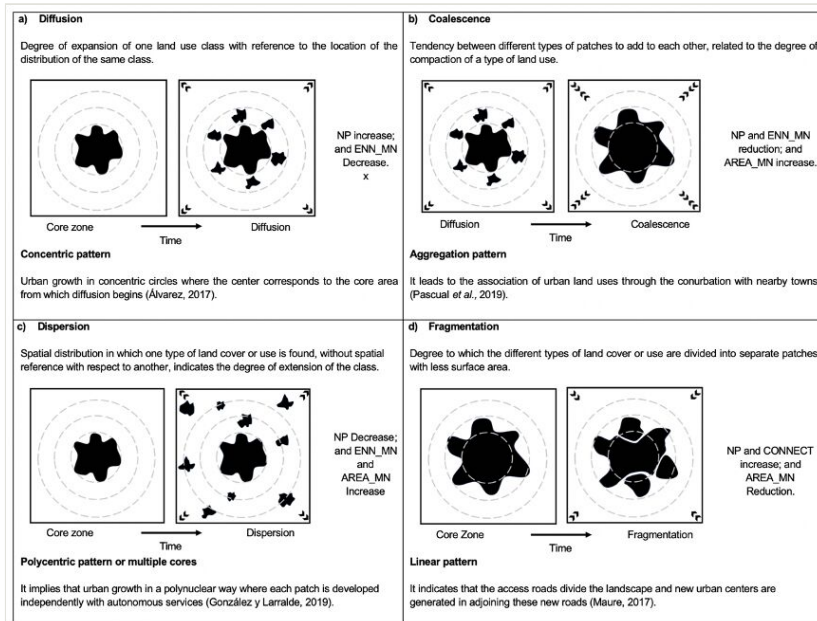


Figure 7.

Processes and spatial patterns of urban growth considered in the landscape analysis for the simulated scenarios. a) Diffusion; b) Coalescence; c) Dispersion; d) Fragmentation. Source. Own elaboration.

The estimation value was obtained through the ecosystem service value estimation function according to equation 1.

$$ESV = \sum_{i=1}^n CA_i UV$$

Where, ESV is the ecosystem service value, "CA_i" is the class area in patch "i" expressed in ha, "n" the number of patches per class area and "UV" the unit value of the ecosystem service expressed in USD.

The process to estimate the value was developed through the direct association of the biome or global ecosystem with the type of land cover or land use present in the MZ. This estimate was obtained for the three simulated scenarios and for 2015; this year was used as a starting point for the comparison and evaluation of the changes in value between the different periods.

Table 2 shows the link between ecosystem services and the different land-cover and land-use classes in the MZ, where urban land use corresponds to the built-up area (housing and industrial use) whose ecosystem services are associated with the provision of habitat for the population. Agricultural land use represents the agricultural production zone of the main crops of sugarcane, corn, mango, jicama and avocado grown in the study area and the

secondary vegetation land cover, generally composed of grasses and shrubs. Water bodies are linked as sources of water supply and climate regulation, as well as the forest cover that provides the greatest amount of ecosystem services to the population, associating eleven of the eighteen ecosystem services classified by Assessment (2004), representing the coverage with the greatest functional value in the study area.

Table 2.

Linkage of ecosystem services with land-cover and land-use classes present in the MZ. Source: *List of ecosystem services adapted from Costanza et al. (1997); Assessment (2004); TEEB (2010).

Classification	Ecosystem service	Land cover and use of the ZM				
		Cls-Urb	Cls-Agri	Cls-Water	Cls-SecVeg	Cls-For
Services of regulation	Air quality regulation (1)*					X
	Climate regulation (2)			X		X
	Regulation of disturbances (protection of natural hazards) (3)					X
	Regulation of the water cycle (4)			X		X
	Sewage and waste treatment (9)	X				X
	Soil formation (7)					
	Pollination (10)					X
	Biological control (11)					X
Provisioning services	Food production (13)		X		X	
	Water supply (5)			X		
	Raw Materials (14)		X			X
	Genetic resources (15)					X
	Medicinal resources (15)				X	X
Habitat services	Refuge (12)	X		X		X
	Nutrient cycle (8)			X		X
	Erosion control and sediment retention (6)			X		X
Cultural services	Recreation and ecotourism (16)	X		X		X
	Cultural diversity (17)	X				

3. Results

3.1. Simulated future urban growth scenarios

Fig. 8 shows the three simulated scenarios, presenting an urban growth of about twice the current area, with the ES2-IN scenario having the highest growth with almost 130 km² and

ES1-CE having the lowest urban growth with an area of 108.95 km². This situation is consistent with the rate of change considered for the design of the different scenarios.

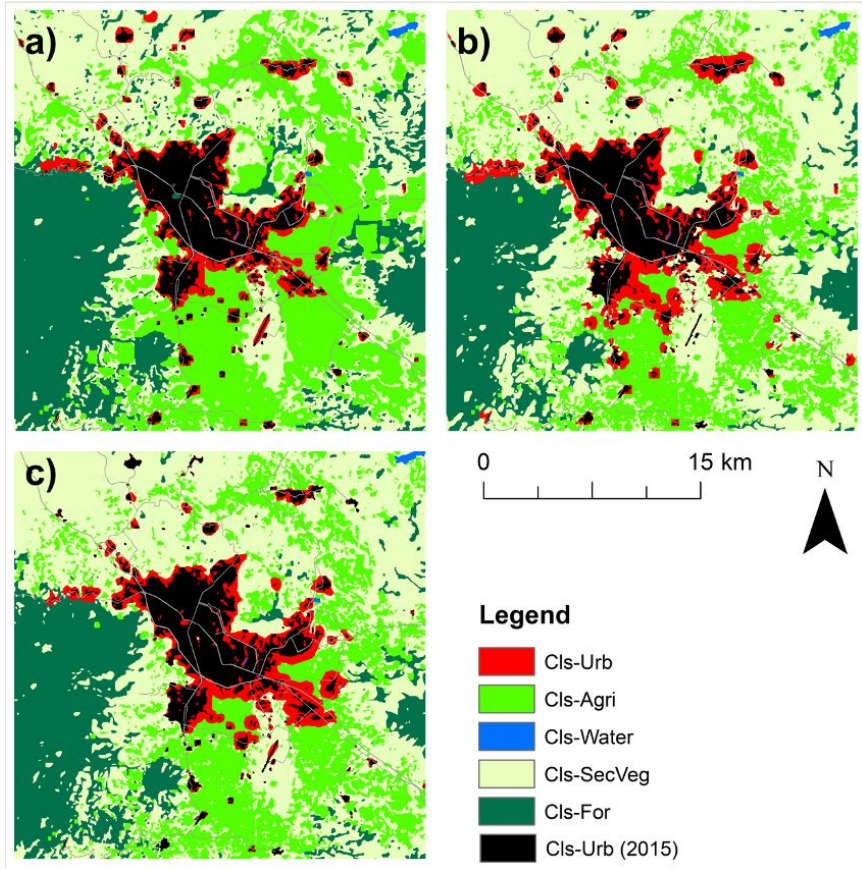


Figure 8.

Future urban growth scenarios (year 2045) with respect to land cover and land use; a) Ecological Conservation Scenario (ES1-CE); b) Industrialisation Scenario (ES2-IN); c) Northern Bypass Scenario (ES3-LN). Note: Land-cover and land-use classes: Urban (Cls-Urb), Agricultural (Cls-Agri), Water bodies (Cls-Water), Secondary vegetation (Cls-SecVeg) and Forest (Cls-For). Source. Own elaboration.

Similarly, Fig. 9 represents the changes in land cover and land use due to urban growth for each simulated scenario, from which it can be inferred that the area of agricultural use is the one that suffers the greatest transition to urban land use. The analysis of surface change obtained through cross-tabulation indicates a loss of agricultural use of more than 20 km² for the ES1-CE and ES3-LN scenarios and almost 40 km² loss in the ES2-IN scenario, particularly in the southeast direction of the MZ. Forest cover also undergoes transitions to urban use, but to a lesser extent, with the ES2-IN scenario being the most affected, by ceding an area of 4.69 km² to urban use.

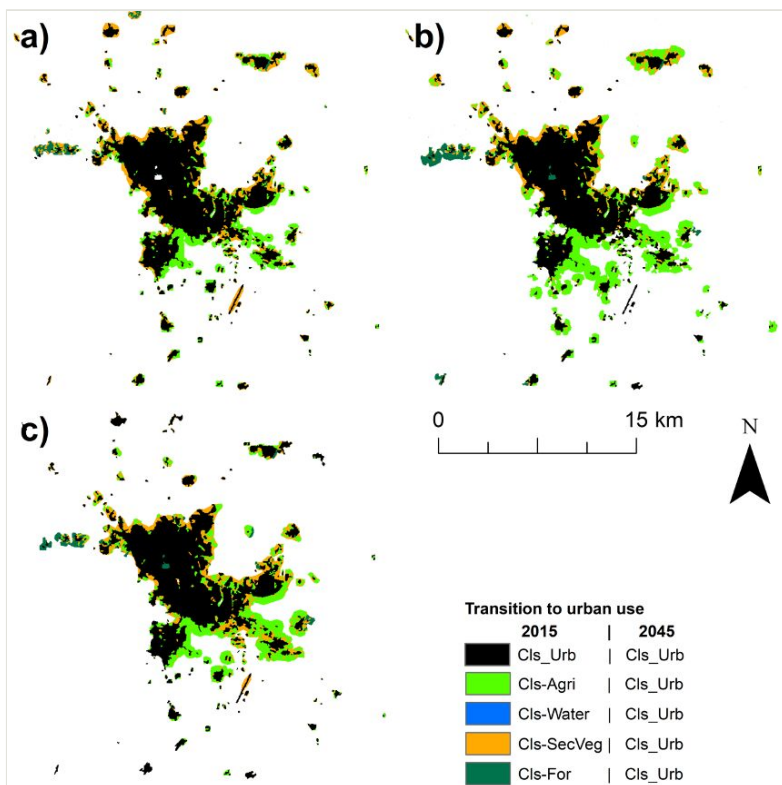


Figure 9.

Land-cover and land-use change to urban use 2015-2045. a) Ecological Conservation Scenario (ES1-CE); b) Industrialisation Scenario (ES2-IN); c) Northern Bypass Scenario (ES3-LN). Land-cover and land-use class: Urban (Cls-Urb), Agricultural (Cls-Agri), Water bodies (Cls-Water), Secondary vegetation (Cls-SecVeg) and Forest (Cls-For). Source. Own elaboration.

3.2. Evaluation of scenarios and ESV

The evaluation of the simulated scenarios through the exploration of the processes and spatial patterns of urban growth was obtained with the application of the landscape metrics whose results were analysed with the standard index (standard z) estimated from the mean and standard deviation; a method used to bring the absolute values of the metrics obtained to the same unit of measurement and to enable them to be comparable for the purpose of analysing the composition of the different land-cover and land-use classes of the landscape with respect to each type of land cover and land use in 2015. Fig. 10 indicates the standardised values obtained for each landscape metric for each simulated scenario.

The analysis of the applied landscape metrics suggests that the three simulated alternatives assume similar processes and spatial patterns of urban growth in the future,

with only some variations in the amount of surface change. The values obtained indicate that the amount of "NP" for the urban land use class is reduced, with respect to 2015, revealing that the patches for urban land use will be in a process of Coalescence, where, specifically for urban use, the tesserae dispersed will become a conurbation with nearby localities, thus forming larger urban patches. This characteristic is similar for the other land-use classes and, when compared with respect to "AREA_MN", it is observed that "NP" decreases, while "AREA_MN" increases; due to this behaviour, it is inferred that there is a reduction in the degree of fragmentation of the landscape.

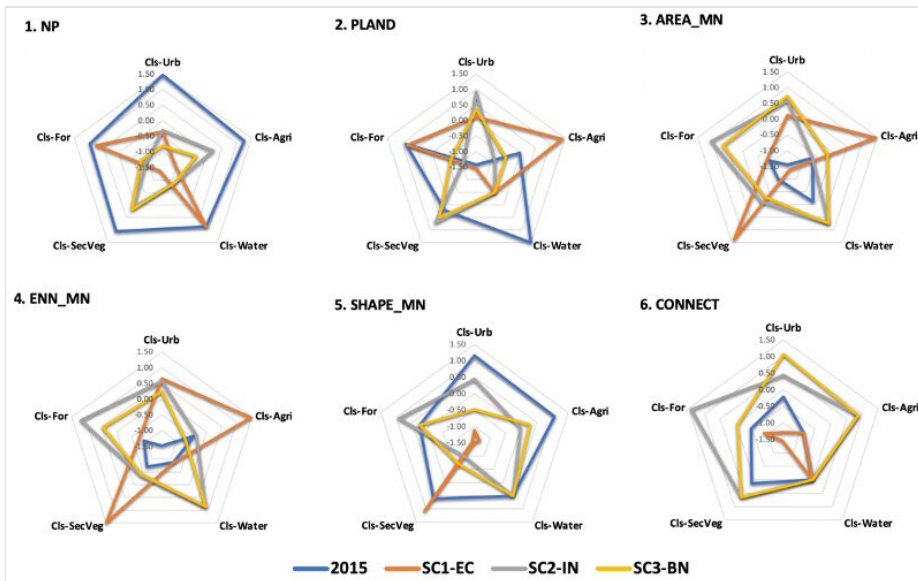


Figure 10.

Standard value of metrics applied for land-cover and land-use class for each simulated scenario. Land-cover and land-use class: Urban (Cls-Urb), Agricultural (Cls-Agri), Water bodies (Cls-Water), Secondary vegetation (Cls-SecVeg) and Forest (Cls-For).

Source. Own elaboration with standardised values of landscape metrics.

Together, the landscape metrics show that the "NP" decreases in comparison with the "ENN_MN" of the same land-use class where the latter increases at the same rate as the "AREA_MN". This corroborates that there is a pattern of aggregation for the urban use classes, particularly in the three simulated scenarios. In the case of the "SHAPE_MN" index, there is a decrease for urban and agricultural use in the three scenarios, which implies that, since there is an aggregation between patches, there is also a greater homogeneity in the shapes of the patches.

On the other hand, Table 3 describes the link between the land covers and uses present in the MZ, which is the equivalent comparison between each class and the global ecosystem services. The base value calculated for 2015 was \$449.38 million dollars, which increased slightly to \$453.53 million dollars by 2045, the highest cost for the ES2-IN scenario,

associated with the increase in urban land use and the decrease in forest cover. The ES3-LN scenario shows an increase in value of \$3.89 million dollars due to the increase in urban use and the ES1-CE scenario, although it has the lowest increase in urban land use which also achieves an increase in the value of ecosystem services with a difference of more than \$16 million dollars with respect to the base value, this scenario implying the greatest loss of secondary vegetation cover with almost 180 km².

Table 3.

Cost of ecosystem services as a function of the link to the global ecosystem. Source. Own elaboration.

Global ecosystem	Equivalent ecosystem in the ZM	Estimated value (USD / ha / year)	Base value for 2015 (Millions of USD)	Value of Scenarios to the year 2045 (Millions of USD)			Net change 2015-2045 (Millions of USD)		
				SC1-EC	SC2-IN	SC3-BN	SC1-EC	SC2-IN	SC3-BN
Urban systems	Cls-Urb	6.661	45.69	72.57	86.33	76.99	26.88	40.64	31.29
Farmland	Cls-Agri	5.567	121.66	147.82	106.65	113.18	26.16	-15.00	-847
Lakes / rivers	Cls-Water	12.512	1.81	1.61	1.60	1.61	-0.20	-0.21	-0.20
Grass / pasture	Cls-Sec_Veg	4.166	167.35	131.69	177.74	173.29	-35.66	10.39	5.94
Tropical forest	Cls-For	5.382	112.87	112.01	81.20	88.19	-0.86	-31.67	-24.67
Total		35.689	449.38	465.71	453.53	453.27	16.33	4.15	3.89

The ESV is particularly affected by the loss of forest area, the base value of which is the highest and by 2045 a reduction of up to 60 km² is quantified, which implies economic losses of almost \$32 million dollars.

4. Discussion

The joint application of the different tools used in this study to explore future scenarios and their evaluation through the application of metrics revealed that the MZ will be in a process of urban coalescence in the next 30 years, associated with a pattern of aggregates between urban land-use patches through the conurbation of the closest contiguous localities to the MZ, such as Pantanal (20) and San Cayetano (23) in a south-southeast direction (see Fig. 1), this condition being characterised according to the change trends of the applied metrics; these results can be contrasted with works that have been developed by Dietzel et al. (2016) and Martellozzo and Clarke (2011), whose results share similarities in detecting spatial patterns associated with diffusion and coalescence of urban land use, as well as those studies developed by He et al. (2017), who also identified different degrees of diffusion and coalescence for a set of 363 cities. In this sense, the results of the

present study show that the MZ is currently undergoing a process of urban sprawl diffusion towards surrounding areas.

In the context of ESV determination, various methods have been applied in the scientific literature to value ecosystem services; Liu et al. (2020) indicate three methods: energy value analysis, physical assessment and value assessment. The first two methods require input parameters and calculation processes that are still complicated to obtain, while value assessment is done through the linkage of equivalent reference value tables (Xie et al. 2017). Value assessment is the simplest value transfer function by averaging spatial variation with the economic value of ecosystem services (Schmidt et al. 2016) and the most widely used method in the scientific literature, which is why it was applied in the present work.

In this sense, Costanza et al. (1997) were the first to establish economic values for ecosystem services and, therefore, for natural resources at a global level (Turner et al. 2020). In 1995, they estimated an average value of \$33 billion dollars per year, considering a set of 16 biomes and 17 ecosystem services and, later in 2011, de Groot et al. (2012) and Costanza et al. (2014) updated the amount in global unit values, reaching a value of \$145 billion dollars per year. Although the values proposed for each of the biomes and ecosystem services considered by Costanza (1997 and 2014) do not represent the exact characteristics of the existing ecosystems in the study area, their application is effective and represents the first approximation for obtaining monetary values for the MZ. Results of the present work can be contrasted with other studies where the value of ecosystem services has been obtained, such as those carried out by Tolessa et al. (2016) who manage to determine a 68% reduction in ESV from 53 to 16.71 million dollars (1973-2014), due to forest and shrublands deforestation. Likewise, Mugiraneza et al. (2019) manage to estimate losses of 69 million dollars (USD) for ecosystem services associated with degradation of farmland due to urban growth.

Each geographic region in the world is different and heterogeneous, with topography, climate and vegetation features that configure unique and varied ecosystems, in which determining the economic value can be subjective and depend on the geographic region in which they are found. The lack of information regarding the specific economic value for each ecosystem present in the study area implies a variation in the real economic quantification; however, it is necessary to have a first approach on the economic estimation of the ecosystem services of the MZ. In this sense, the recommendation for future research would be directed in two directions: the first one aimed at establishing an adaptation of the global ecosystem value equivalence coefficients for the study area, just as Su et al. (2020), Mendoza et al. (2012) and Hu et al. (2020) did, by taking the equivalent coefficients of the regional ecosystem to adapt them to a local ecosystem. Camacho and Ruiz (2016) also adapted a region closer to our study area (Sinaloa, Mexico). The second recommendation would be focused on the application of scientific knowledge for the generation of a database of the economic value of ecosystem services linked to the different land covers and land uses of the MZ (at a local scale).

The limitations of this study involve the considerations of the starting data, since the results will be biased depending on the degree of agreement between the classification of the different land-cover and land-use classes obtained, with the existing land uses (actual uses) impacting on the degree of fit (kappa index) of the simulation model and, therefore, on the level of certainty of the projected scenarios; moreover, the geographic scale and particularly the spatial resolution of analysis will impact the generation of landscape patterns and might modify the characteristics of the patches and the value of the landscape metrics.

In this sense, it is recognised that, for the study area, there are some small areas that still have the characteristics of wetland ecosystems and that were not analysed or valued in this study due to the level of scale developed and the type and number of land-cover and land-use classes classified and used as starting data. Further studies can improve and expand the characterisation of the different types of land cover and land use and perform a detailed scale level analysis (reducing the Minimum Mappable Unit) that allows the study of reduced surfaces that can include areas of wetlands, run-off and urban ecological parks, considered to have the greatest economic value according to the global estimate of the value of ecosystem services and, therefore, the richest ecosystems available in the MZ.

5. Conclusions

This article explores three alternative simulated future scenarios for the ZM, based on the application of a set of different socioeconomic, political and environmental development strategies; on the analysis and identification of processes and spatial patterns of future urban growth through landscape metrics; and on the ESV linked to changes in land cover and land use, the application of this methodological proposal could contribute to generate awareness in decision-makers about the consequences and impacts on the territory due to the application of some or other decisions and, based on this knowledge, to rethink alternative scenarios for planning and management the territory that allow us to proceed to sustainable urban development in the future.

The simulation model implemented manages to be an efficient tool for evaluating alternative urban growth scenarios (different scenarios to those developed in this work), with the possibility of configuring the different factors that condition urban growth according to the different decisions and public policies established by those in charge of planning. The model also could contribute to a better urban planning, enhancing the creation of new municipal or state programmes for urban development (“Programas de Desarrollo Urbano”, PDU). Urban growth scenarios, presented in this article, are also a valuable source of information for the knowledge of the consequences on the territory in the event that the areas could be occupied by urban land use in the future.

From the ESV results, it is concluded that there is an increase in the economic value for the three simulated scenarios due to the variation in growth for urban land use; this increase implies the reduction of other land covers, such as forest and agricultural use with the imminent loss of ecosystem services. ES2-IN represents the scenario with the highest

economic value by associating land cover and land use with ecosystem services; however, it is also the one that suffers the greatest impact in the reduction of forest area; if this condition were to occur in the future, ecosystem services would have serious effects on the vitality of the population of the MZ due to the imminent lack of provision of basic services. The ESV was able to quantify economic losses for the ES2-IN scenario of almost \$32 million dollars with the loss of the ecosystem services of climate regulation, water cycle regulation, reduction in the provision of raw materials, refuge for fauna species and nutrient cycling, amongst others, with a reduction of almost 60 km² of forest cover. In the same way, losses of \$15 million were determined, linked to the reduction in agricultural production capacity.

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Author contributions

AAJ Designed, developed and wrote the present article; FFV, FAB, MGD and ONG reviewed, analysed the data and approved the article.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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