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## Dynamics of change in urban and peri-urban ecosystems in the metropolitan area of Monterrey, Mexico

### Dinámica de cambio en ecosistemas urbanos y periurbanos en el área metropolitana de Monterrey, México

### Dinâmica de mudança nos ecossistemas urbanos e peri-urbanos na área metropolitana de Monterrey, México

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#### ABSTRACT

The loss of forest ecosystems due to urbanization has numerous impacts on environmental and social services, which is why a detailed monitoring system for the fragmentation process of the two ecosystems is necessary. The objective of this research



was to determine the rate of change in land use and the availability of urban and peri-urban ecosystems in the metropolitan area of Monterrey, Mexico. A multi-temporal analysis was carried out in QGIS 2.18.25, by means of a supervised classification of high-resolution satellite images from 1994 to 2020, and the availability of green areas per inhabitant ( $\text{m}^{-2} \text{inhab}^{-1}$ ) was obtained from the surface of the urban ecosystems and population growth by municipality. The results indicate that over a 26-year period, the Monterrey metropolitan area lost 33 % of two urban ecosystems and 13 % of two peri-urban ones, at an average rate of -1.53 and -0.93, respectively. The availability of green areas per inhabitant increased from 68 to 32  $\text{m}^{-2} \text{inhab}^{-1}$  and the trend indicates that in less than ten years some municipalities will have only 15  $\text{m}^{-2} \text{inhab}^{-1}$ . For that reason, it would be necessary to prioritize strategies of ecological restoration to regulate microclimatic conditions, mitigate the impacts of heat islands and maintain the provision of environmental services that these ecosystems provide to the Monterrey metropolitan area.

**Keywords:** Green areas; Heat islands; High resolution satellite images; SASPlanet and Ecosystem Services.

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## RESUMEN

La pérdida de ecosistemas forestales por la urbanización tiene innumerables impactos en los servicios ambientales y sociales, por lo cual, se requiere de un sistema de monitoreo detallado del proceso de fragmentación de ecosistemas. El objetivo de la presente investigación fue determinar la tasa de cambio del uso del suelo y la disponibilidad de ecosistemas urbanos y periurbanos en área metropolitana de Monterrey, México. Se realizó un análisis multitemporal en QGIS 2.18.25, mediante una clasificación supervisada de imágenes satelitales de alta resolución de año 1994 al 2020 y la disponibilidad de áreas verdes por habitante ( $\text{m}^{-2} \text{hab}^{-1}$ ) se obtuvo de la superficie de los ecosistemas urbanos y crecimiento poblacional por municipio. Los resultados indican que en un periodo de 26 años el área metropolitana de Monterrey ha perdido el 33 % de ecosistemas urbanos y 13 % de periurbanos, a una tasa promedio de -1.53 y - 0.93 respectivamente. La disponibilidad de áreas verdes por habitantes pasó de 68 a 32  $\text{m}^{-2} \text{hab}^{-1}$  y la tendencia indica que en menos de diez años algunos municipios dispondrán únicamente de 15  $\text{m}^{-2} \text{hab}^{-1}$ , por lo que se requieren la priorización de estrategias de restauración ecológica para regular las condiciones microclimáticas, mitigar los impactos de las islas de calor y mantener la provisión de servicios ambientales que brindan estos ecosistemas al área metropolitana de Monterrey.

**Palabras clave:** Áreas verdes; Imágenes satelitales de alta resolución; Islas de calor; SASPlanet y Servicios ecosistémicos.

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## RESUMO

A perda de ecossistemas florestais devido à urbanização tem inúmeros impactos nos serviços ambientais e sociais, razão pela qual é necessário um sistema de monitoramento detalhado do processo de fragmentação dos ecossistemas. O objetivo desta pesquisa foi determinar a taxa de mudança do uso da terra e a disponibilidade de ecossistemas urbanos e periurbanos na área metropolitana de Monterrey, México. Uma análise multitemporal foi realizada no QGIS 2.18.25, por meio de uma classificação



supervisionada de imagens de satélite de alta resolução de 1994 a 2020, e a disponibilidade de áreas verdes por habitante ( $\text{m}^{-2} \text{hab}^{-1}$ ) foi obtida da superfície de os ecossistemas, crescimento urbano e populacional por município. Os resultados indicam que em um período de 26 anos, a área metropolitana de Monterrey perdeu 33% dos ecossistemas urbanos e 13 % dos periurbanos, a uma taxa média de -1,53 e -0,93, respectivamente. A disponibilidade de áreas verdes por habitante passou de 68 para 32  $\text{m}^{-2} \text{hab}^{-1}$  e a tendência indica que em menos de dez anos alguns municípios terão apenas 15  $\text{m}^{-2} \text{hab}^{-1}$ , razão pela qual é necessária a priorização de estratégias. de restauração ecológica para regular as condições microclimáticas, mitigar os impactos das ilhas de calor e manter a prestação de serviços ambientais que esses ecossistemas prestam à área metropolitana de Monterrey.

**Palavras chave:** Áreas verdes; ilhas de calor; imagens de satélite de alta resolução; SASPlanet e Serviços de ecossistemas.

## INTRODUCTION

The elimination of forest cover, for the establishment of human settlements, infrastructure, industry and shopping centers, has reduced the availability of urban and peri-urban ecosystems at an accelerated speed. Those factors have modified the natural processes of runoff and increases the risk of flooding, it reduces the recharge of aquifers, loss of biodiversity and degradation of ecosystems (MacGregor-Fors *et al.*, 2009).

Urban ecosystems (green areas) are a set of natural resources that include: water, soil, landscapes, agricultural areas, forests, gardens and associated organisms, which generate a microclimate in cities, contribute to reducing the effect of heat islands by reducing the flow of sensible heat and air temperature due to plant transpiration (Meza and Moncada, 2010).

They improve air quality by filtering polluting particles, insulate noise, sequester carbon, protect the soil against erosion, control solar radiation, provide wildlife with shelter and generate a positive psychological effect that improves physical and mental health of residents (Nowak *et al.*, 2006).

Urban developers, forestry experts, politicians, residents and environmentalists are responsible for the establishment and maintenance of green areas; however, they are not always accepted or considered during planning because they compromise spaces for capitalist development (Bascuñán *et al.*, 2009).

In order to make decisions in the planning of urban areas and prioritization of critical areas where to implement ecological restoration strategies and landscaping practices, it is essential to have a monitoring system that allows understanding the process of loss and fragmentation of green areas (Giri *et al.*, 2007).

Satellite images have become a tool with high potential and importance for multi-temporal monitoring of forest ecosystems and the growth of large cities (Ardila *et al.*, 2012). Due to the high level of detail with which natural resources can be observed, the use of high-resolution images (30 cm at 5 m/pixel) greatly improves the interpretation of the different land use change scenarios (Everitt *et al.*, 2007).



Through multi-temporal analyzes with these images, it is possible to obtain a real picture of the loss of urban and peri-urban ecosystems, with spatially explicit and statistically representative information from individual trees or groups (Azzari *et al.*, 2017).

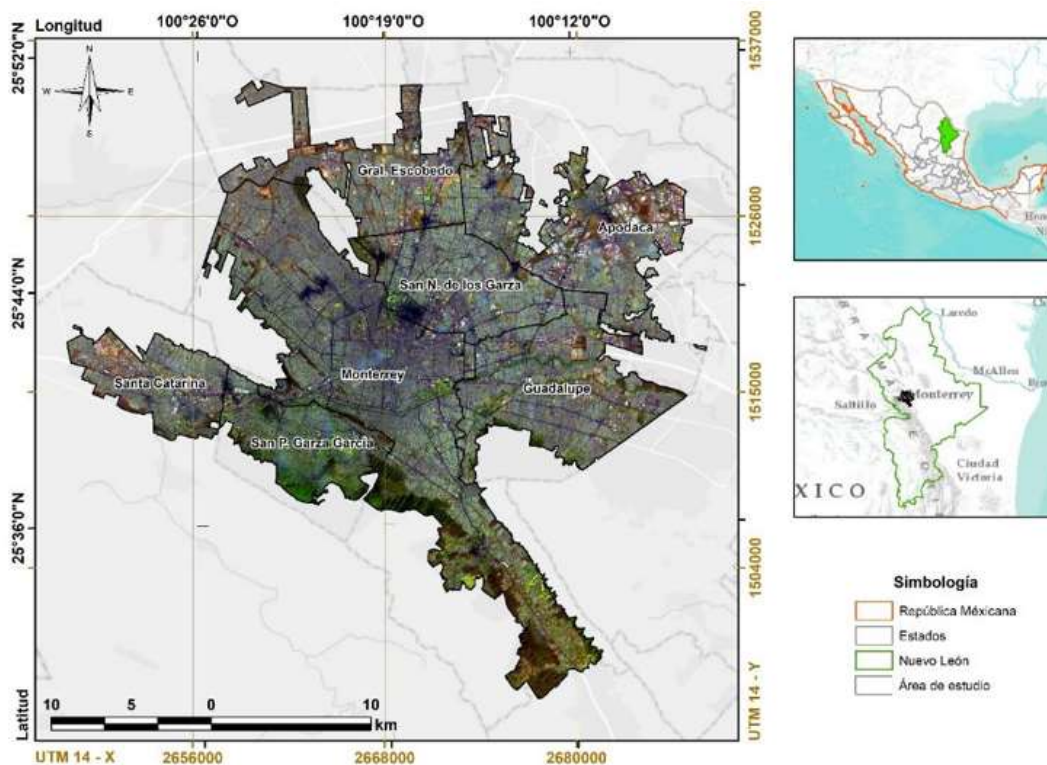
The objective of this research was to determine the rate of land use change and the availability of urban and peri-urban ecosystems in the metropolitan area of Monterrey, Mexico, to identify and prioritize critical areas for ecological restoration and urban planning. The proposed hypothesis indicates that population growth affects the loss of urban and peri-urban ecosystems in the metropolitan area of Monterrey.

## MATERIALS AND METHODS

### Location of area of study

This study was conducted in the metropolitan area of Monterrey, Mexico, contemplating seven municipalities: General Escobedo, Guadalupe, Monterrey, San Nicolás de los Garza, San Pedro Garza García, Santa Catarina, and Apodaca (Figure 1).

The municipalities as a whole have a total population of 7,549,298 inhabitants, in an area of 60,296.76 hectares (ha), where industrial parks and shopping centers are concentrated and the main economy of northern Mexico is developed.

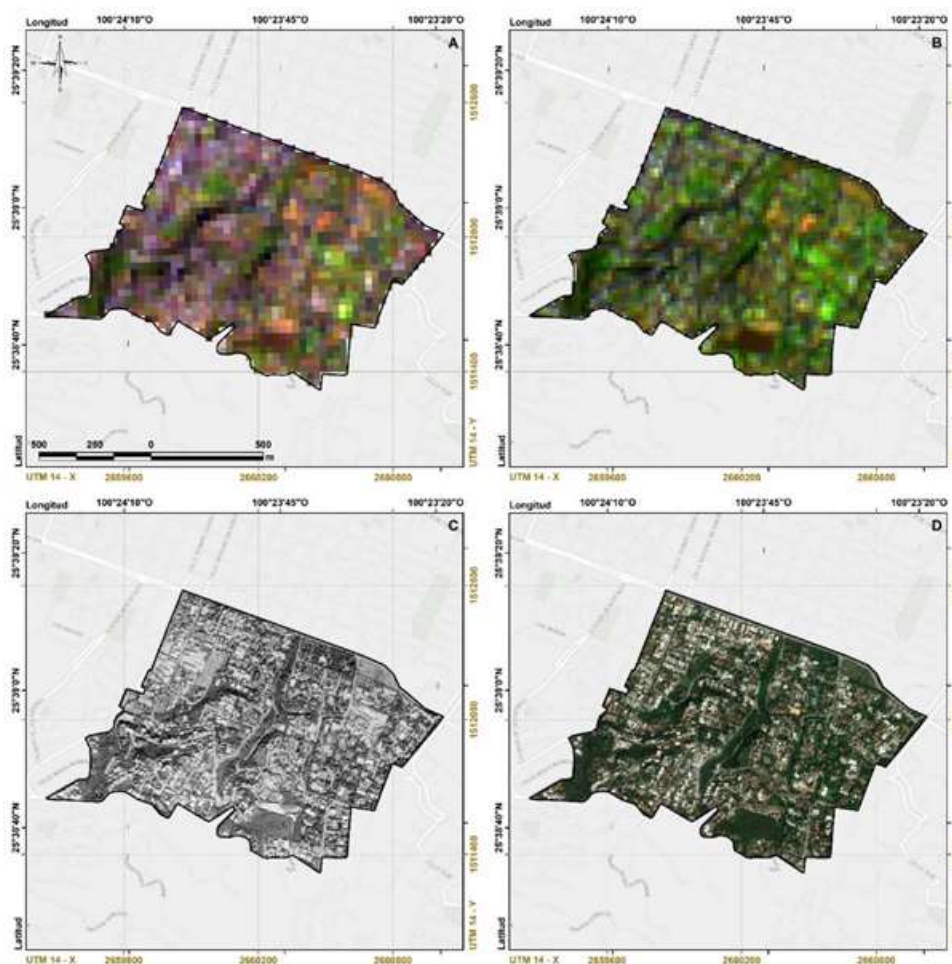


**Figure 1.** - Location of the metropolitan area of Monterrey, Mexico



## Processing and generation of orthomosaics

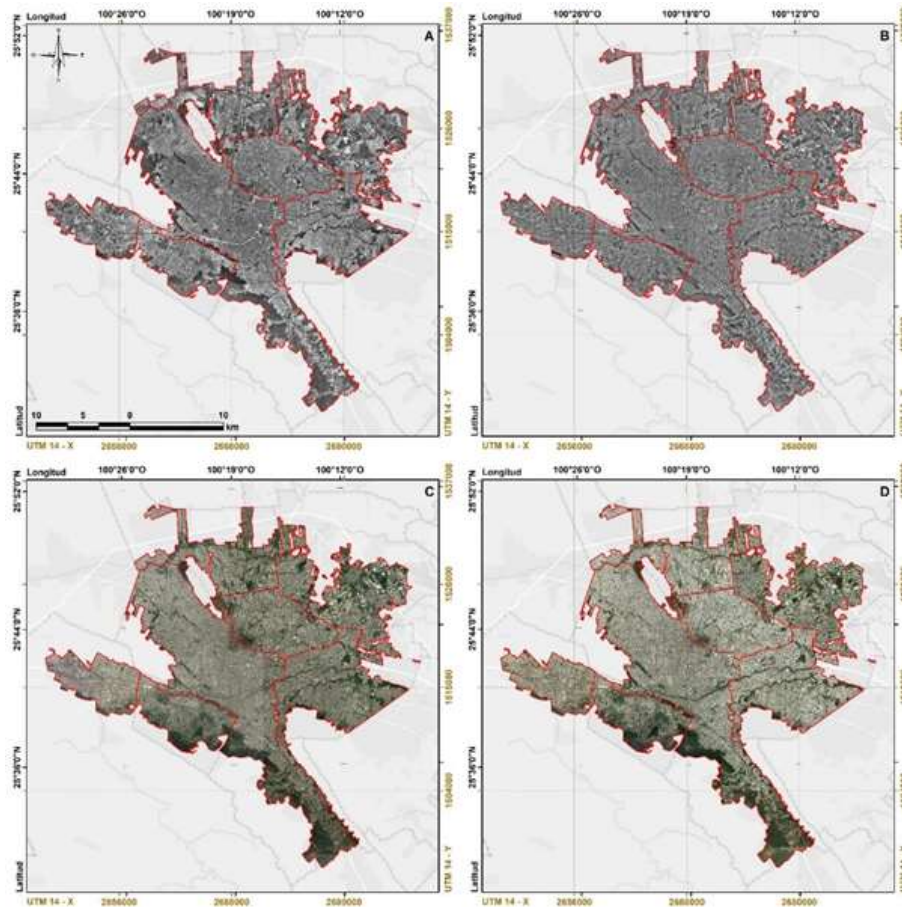
The Landsat 8 (30 m/pixel, Figure 2A) and Sentinel 2 (10 m/pixel, Figure 2B) satellite images present a bias in the calculation of surfaces. For that reason, a comparison was made with orthophotos (1 m/ pixel; Figure 2C) and Birdseye images (0.28 m/pixel; Figure 2D), which are considered high resolution.



**Figure 2.** - Comparison of Landsat (A), Sentinel (B), Orthophoto (C) and Birdseye (D) images

Four orthomosaics composed of 9 orthophotos, (1.5 m/pixel; year 1994, Figure 3A), 31 orthophotos (1 m/pixel; year 2004, Figure 3B), 48 of Airbus Defense and Space (1.14 m/pixel; year 2020, Figure 3C) and 193 Birdseye images (0.28 m/pixel; year 2010; Figure 3D), were processed and generated.





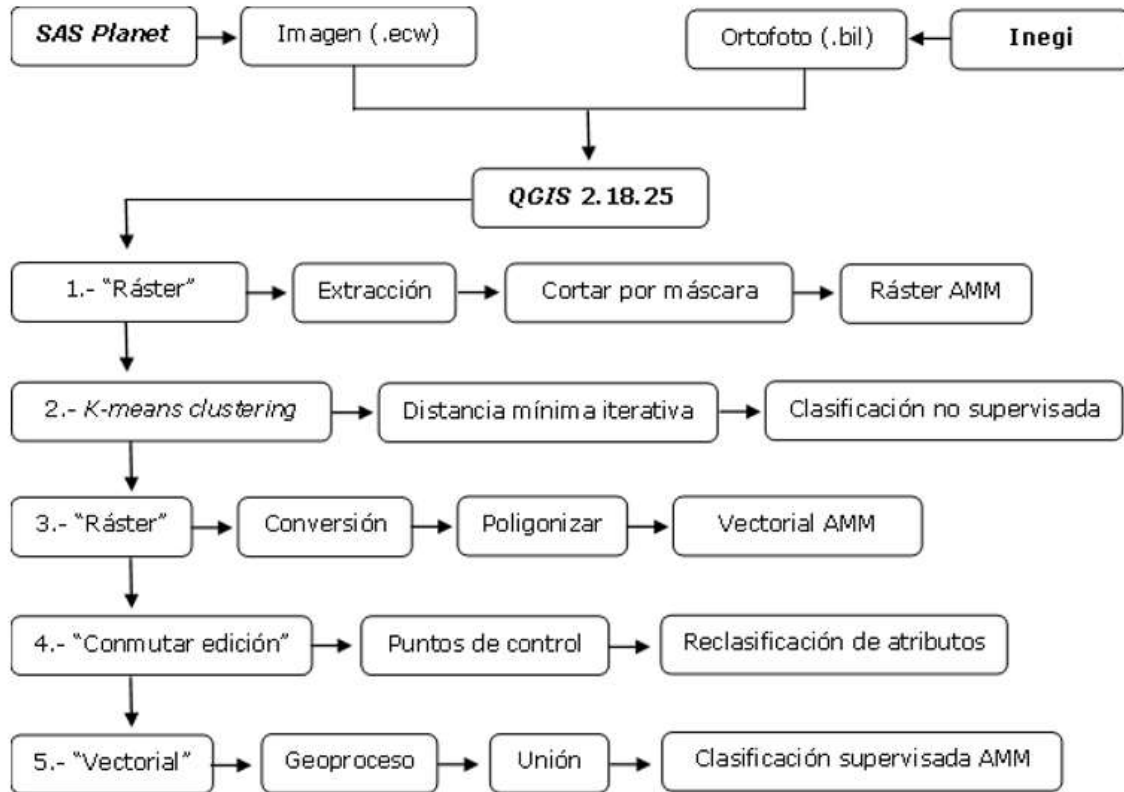
**Figure 3.** - Orthomosaics of the year 1994 (A), 2004 (B), 2010 (C) and 2020 (D)

The Landsat and Sentinel images were obtained from the free access platforms Earth Explorer of the United States Geological Survey (USGS, 2021). The orthophotos of Space and Mexico Data of the National Institute of Statistics and Geography; as well as the images of Airbus Defense and Space and Birdseye of the SASPlanet software.

### Supervised classification

For the detection of changes, the open source software QGIS 2.18.25 "Las Palmas" was used, since it is the most stable version. An atmospheric correction was made to the images of each year, which were cropped and subjected to an unsupervised classification process with the "K-means analysis" module that groups the cell values into classes, with the analysis method of multivariate data clusters (Rashmi *et al.*, 2016).





**Figure 4.** - Supervised classification process in QGIS 2.18.25

Subsequently, the files were transformed from raster to vectorial format, for a supervised classification (Figure 4), through control points with information obtained in the field (Figure 5), in 100 sites distributed in a systematic way, in areas with a high degree of confusion by the reflectance of the images, exposure, noise and cloudiness (Jumb *et al.*, 2014).



**Figure 5.** - Urban and peri-urban ecosystems of the Monterrey metropolitan area





The agreement and precision of the classification results of the high-resolution satellite images were calculated in the "r.kappa" module in GRASS, which generates an error matrix and determines Cohen's kappa coefficient.

### Determination of land use change rate

The determination of the rate of change of land use and vegetation was obtained through the equation adapted by Palacio-Prieto *et al.* (2004) (Equation 1).

$$\delta_n = [((s_2/s_1)^{(1/n)}) - 1] * 100 \quad (1)$$

Where:

$\delta_n$

= Rate of change expressed as a percentage.

$S_1$ = Surface of date 1.

$S_2$ = Surface of date 2.

$n$ = Number of years between the two dates

### Determination of green areas per inhabitant

The determination of green areas per inhabitant was calculated using the formula adapted by Ballinas and Barradas (2015), considering only the urban ecosystems and the total population per municipality in the different years, which was obtained from the Territorial Information Consultation System (INEGI), 2021b) (Equation 2).

$$AV = (Sup/Hab) \quad (2)$$

Where:

$AV$ = Green area per inhabitant ( $m^{-2}$  inhab $^{-1}$ ).

$Sup$ = Green area surface ( $m^{-2}$ ).

$Hab$ = Number of inhabitants (inhab $^{-1}$ ).

## RESULTS AND DISCUSSION

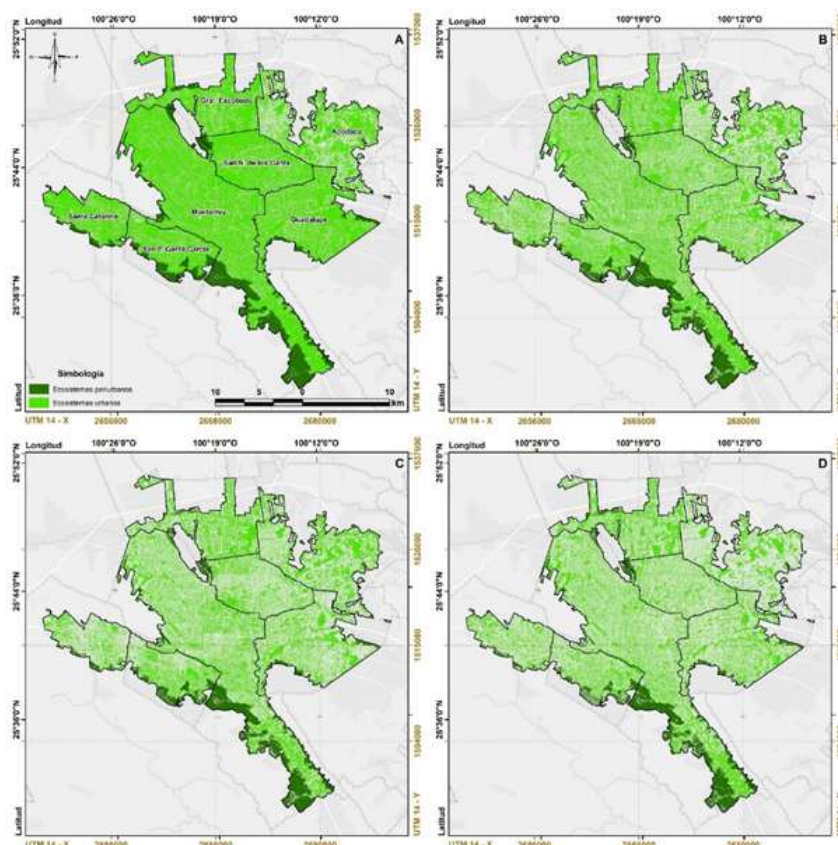
The comparative analysis between satellite images showed that there is an overestimation of more than 38 % with Landsat 8 OLI and 22 % with Sentinel 2A, compared to high resolution images that presented average values of kappa index of 0.82, considered within of a very good level of precision. That is similar to the reports of Arenas *et al.* (2011) and Mendes *et al.* (2015) for Quickbird (2.4 m/pixel) and Geoeye-1 (1.65 m/pixel) images.

In the metropolitan area of Monterrey, by the year 2020, a total of 10,657.9 ha of urban ecosystems have been lost, representing 33 % and 13 % of peri-urban ecosystems. Representing an equivalent of 673.8 ha and meaning that the municipalities with the greatest loss are Apodaca with 39.6 %, San Nicolas de los Garza (37.4 %) and Santa Catarina (37.2 %) of the coverage they had in 1994 (Figure 6; Table 1).



**Table 1.** - Urban and peri-urban ecosystems of the Monterrey metropolitan area

Municipalities	Urban ecosystems (ha)				Peri-urban (ha)			
	1994	2004	2010	2020	1994	2004	2010	2020
<b>Monterrey</b>	11,640.4	8,321.6	8,313.8	7,779.6	3,491.7	3,323.0	3,260.8	3,210.3
<b>Guadalupe</b>	4,794.4	4,139.7	3,577.8	3,501.4	295.4	268.1	263.0	248.7
<b>San Nicolas de los G.</b>	3,502.2	3,026.9	2,413.8	2,181.5	97.3	81.3	74.4	73.3
<b>General Escobedo</b>	3,271.7	3,130.5	3,069.5	2,334.6	197.7	182.4	174.7	151.7
<b>Saint Peter G. Garcia</b>	2,361.9	2,267.9	1,923.3	1,747.9	754.4	743.5	680.0	537.6
<b>St. Catarina</b>	2,369.3	1,886.2	1,502.7	1,467.1	214.3	199.9	181.2	155.5
<b>Apodaca</b>	4,372.5	3,439.4	2,925.8	2,642.2				
<b>Total</b>	32,312.2	26,212.2	23,726.7	21,654.3	5,050.8	4,798.2	4,634.2	4,377.0



**Figure 6.** - Urban and peri-urban ecosystems in 1994 (A), 2004 (B), 2010 (C) and 2020 (D)

The availability of green areas per inhabitant in the Monterrey metropolitan area for the year 2020 is 20.1 to 66.1 m<sup>2</sup> inhab<sup>-1</sup> (Table 2), which is above the optimal levels, recommending 9 to 15 m<sup>2</sup> inhab<sup>-1</sup>. The results being similar to those reported in Santiago de Chile and Curitiba, Brazil with values of 26.1 and 51.5 m<sup>2</sup> hab<sup>-1</sup> respectively (Mejía

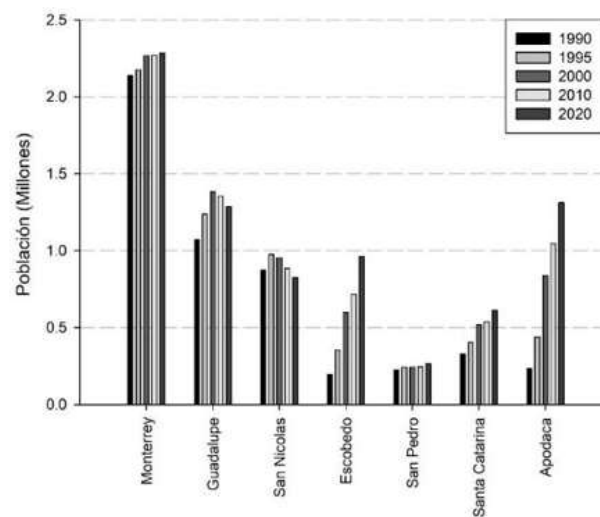


and Gómez, 2015), higher than Fuenlabrada, Almería and Reggio di Calabria, Italy with 3 and 4 m<sup>-2</sup> inhab<sup>-1</sup> and less than Liege, Belgium and Oulu, Finland that have more than 300 m<sup>-2</sup> inhab<sup>-1</sup> (Fuller and Gastón, 2009).

**Table 2.** Green areas (m<sup>2</sup>) per inhabitant in the metropolitan area of Monterrey

Municipality / Year	1994	2004	2010	2020
Monterrey	53.5	36.7	36.6	34.0
Guadalupe	38.7	29.9	26.4	27.2
San Nicolas de los Garza	35.9	31.7	27.2	26.5
General Escobedo	92.5	52.3	42.9	24.3
San Pedro Garza García	97.7	92.9	78.4	66.1
St. Catarina	58.6	36.3	27.9	23.9
Apodaca	99.8	41.1	27.9	20.1
Average	68.1	45.8	38.2	31.7

Among the municipalities of the metropolitan area of Monterrey, San Pedro Garza García presents the greatest availability of green areas per inhabitant, due to the fact that population growth has been maintained steadily for more than 30 years on average with 244,336 inhabitants. For that reason it is considered the richest municipality in Mexico and Latin America. Unlike Apodaca, that has the lowest availability of green areas per inhabitant as a result of exponential growth, which went from a population of 232,310 in 1990 to 1,313,074 by 2020. The municipality of General Escobedo has a similar situation since went from 196,398 to 962,458 inhabitants (Figure 7).



**Figure 7.** - Population growth of the Monterrey metropolitan area

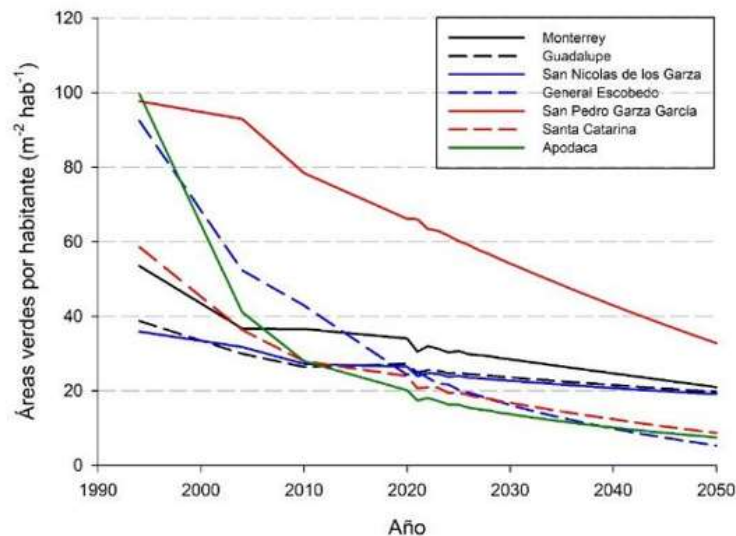


Regarding the municipalities of Guadalupe and San Nicolas de los Garza, they present a negative trend of population growth, as a response to the limited availability of optimal spaces for urban development. In contrast, Monterrey has concentrated the largest population since 1990 with 2,138,501 inhabitants, reaching a maximum growth in 2005 with 2,267,640. Subsequently population growth is minimal, however, it maintains a continuous rate of loss of urban ecosystems and peri-urban (Table 3).

**Table 3.** - Rate of change of green areas in the metropolitan area of Monterrey

Municipality / Year	1994-2004	2004-2010	2010-2020	1994-2020
Monterrey	-3.30	-0.02	-1.65	-1.54
Guadalupe	-1.46	-3.58	-0.54	-1.20
San Nicolas de los Garza	-1.45	-5.50	-2.50	-1.80
General Escobedo	-0.44	-0.49	-6.61	-1.29
San Pedro Garza Garcia	-0.40	-4.04	-2.36	-1.15
St. Catarina	-2.25	-5.52	-0.60	-1.83
Apodaca	-2.37	-3.96	-2.52	-1.92
Average	-1.67	-3.30	-2.40	-1.53

The metropolitan area of Monterrey, in general, presents a gradual trend of loss of urban and peri-urban ecosystems, coupled with the exponential population growth of some municipalities. It is estimated that by the year 2026 the municipality of Apodaca will have  $15 \text{ m}^{-2} \text{ inhab}^{-1}$ . Whereas that will happen for Escobedo in 2031 and for Santa Catarina in 2033 (Figure 8), minimum recommended values, being considered as priority municipalities for the implementation of ecological restoration strategies that allow reversing this process and guaranteeing the life quality of the inhabitants.



**Figure 8.** - Projection of loss of green areas in the metropolitan area of Monterrey



## CONCLUSIONS

The results of the present investigation indicate that the municipalities of Apodaca, General Escobedo and Santa Catarina, present the greatest loss of green areas, in contrast to those municipalities whose population growth has gradually decreased and included a process of migration towards municipalities and adjoining states.

The rate of change of the urban and peri-urban ecosystems of the Monterrey metropolitan area indicates a negative trend that gradually contributes to the loss of environmental services.

High-resolution images allow identifying priority areas for the implementation of ecological restoration strategies, thus allowing a real panorama of the degradation process of forest ecosystems.

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**Conflict of interests:**

The authors declare not to have any interest conflicts.

**Authors' contribution:**

The authors have participated in the writing of the work and analysis of the documents.



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