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Artículo

# Análisis multitemporal del uso del suelo y vegetación en el Parque Nacional Cumbres de Monterrey

# Multitemporal analysis of land use and vegetation in the *Cumbres de Monterrey* National Park

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**Resumen**

El Parque Nacional Cumbres de Monterrey se caracteriza por su accidentada orografía que determina la distribución de una gran diversidad de ecosistemas, los cuales generan bienes y servicios ambientales como la captura de carbono y el abasto de agua para el Área Metropolitana de Monterrey; sin embargo, está sujeto a una fuerte presión por el avance progresivo de asentamientos humanos, el cambio de uso del suelo con fines agropecuarios e incendios forestales. El objetivo de la presente investigación fue determinar la dinámica de cambio del uso del suelo y de la vegetación, mediante el análisis multitemporal con imágenes satelitales de alta resolución. Los resultados indican que los ecosistemas están experimentando cambios constantes debido a factores tanto naturales como antropogénicos; por una parte, los bosques de pino, encino-pino y encino registran una tasa anual de cambio de 0.406, 0.272 y 0.245, respectivamente que equivalen a una recuperación de cobertura forestal de 3 590.50 ha. En tanto que, ecosistemas como el pastizal, matorral desértico rosetófilo y matorral desértico micrófilo presentan una tasa anual de cambio de -0.954, -0.735 y -0.562 que representan una pérdida de cobertura de 1 919.97 ha. Esta dinámica de uso del suelo pone en riesgo la integridad, capacidad de resiliencia y la multifuncionalidad de los bienes y servicios que proporciona Parque Nacional Cumbres de Monterrey al Área Metropolitana de Monterrey.

**Palabras claves:** Áreas naturales protegidas, cobertura forestal, ecoturismo, multifuncionalidad, reforestación, resiliencia.

**Abstract**

The *Cumbres de Monterrey* National Park is characterized by its rugged orography, which determines the distribution of a great diversity of ecosystems; these provide environmental goods and services, such as carbon capture and water supply for the *Monterrey* Metropolitan Area. However, it has been under strong pressure as a result of the progressive advance of human settlements, land use change for agricultural purposes, and forest fires. The present research aims to determine the dynamics of change in land use and vegetation, through multitemporal analysis with high-resolution satellite images. Results indicate that the ecosystems are experiencing constant changes due to both natural and anthropogenic factors. On the one hand pine, oak-pine and oak forests, exhibit an annual rate of change of 0.406, 0.272, and 0.245 respectively, which is equivalent to a recovery of forest cover of 3 590.50 ha. However, ecosystems such as grasslands, rosetophilic desert scrub, and microphyllous desert scrub show an annual rate of change of -0.954, -0.735 and -0.562, which is equivalent to a loss of coverage of 1 919.97 ha. This dynamic of land use puts at risk the integrity, the resilience abilityity and the multifunctionality of goods and services that they provide to the *Monterrey* Metropolitan Area.

**Key words:** Protected natural areas, forest cover, ecotourism, multifunctionality, reforestation, resilience.

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# Introduction

The *Cumbres de Monterrey* National Park (PNCM, for its acronym in Spanish) is part of the eastern *Sierra Madre* mountain system; it has a wide altitudinal gradient, as well as a diversity of exposure to sunlight and the influence of humid air masses that favor an extraordinary mosaic of ecosystems and biological diversity. Therefore, it is considered the area with the greatest ecological relevance and value in the state of *Nuevo León*, mainly for the Metropolitan Area of *Monterrey*, since it supplies more than 40 % of the water consumed by the population (Cantú-Ayala *et al*., 2013; Rovalo-Merino *et al*., 2013).

3 729 species of flora and fauna are distributed in the PNCM, of which 141 are at risk: mammals (11), birds (32), reptiles (36), amphibians (4), fish (8), plants (42), and fungi (8) (Semarnat-2010; González-Saldivar *et al*., 2013; Naturalista, 2021). Its ecosystems capture 6 113 920 Mg C, which represents a very important contribution to mitigating the effects of greenhouse gas emissions (Jiménez-Pérez *et al*., 2013).

In this regard, the plant communities with the highest figures are pine-oak forests, with an average of 82 Mg C ha$^{-1}$ (Rodríguez-Lagua *et al.*, 2009); oak-pine, with 70 Mg C ha$^{-1}$ (Aguirre-Calderón and Jiménez-Pérez, 2011); pine forests, 62 Mg C ha$^{-1}$ (Pimienta de la Torre *et al.*, 2007); submontane scrub, with 12 Mg C ha$^{-1}$ (Montaño *et al.*, 2016); and grassland, 4 Mg C ha$^{-1}$ (Yerena *et al.*, 2014).

The *Cumbres de Monterrey* National Park is one of the most visited areas in the state of *Nuevo León* due to its natural attractions, which render it ideal for recreation and leisure (Correa-Sandoval and Mayén, 2013). These activities can become a significant factor in conserving the environment, provided that the ecological, social and economic factors of the region are taken into account (Díaz, 2010). However, among other practices, the use of all-terrain vehicles, which has increased in the area, is considered one of the causes of major ecological and hydrological disturbance to river and stream channels (Brenner, 2006; Menchaca and Alvarado, 2011).

The situation described above exerts strong pressure on the available natural resources, with the consequent degradation of vulnerable ecosystems (Rodríguez and Acevedo, 2015). In addition, the communities living in the park have grown, and there is a lack of suitable areas for agricultural crops (Aragón-Palacios, 2013).

Multitemporal analysis is of great importance for monitoring the dynamics of land use and vegetation change, since it allows understanding the factors that trigger the process of ecological succession. These, in turn, affect the recovery of the vital functions of those ecosystems that have been exposed to both natural impacts and the effects of anthropogenic disturbances (Giri *et al.,* 2007; Menchaca and Alvarado, 2011). Likewise, the use of high-resolution satellite images is an important alternative to the evaluation of structural and eco-physiological variables at a regional scale and over time in order to analyze the evolution of forest ecosystems after alterations in their structure and composition (Tirpak and Giuliano, 2010).

Little research has been carried out in the PNCM to assess the dynamics of its plant communities. Most studies have focused on the growth of pine species (González, 2019) and on climate reconstruction by means of dendrochronology (Luna, 2020), without a landscape-level perspective to allow understanding the effect that the exclusion of productive activities has had on the passive restoration of plant communities or on the degradation of post-fire ecosystems.

The objective of this research was to carry out a classification of land use and vegetation in three years: 2000, 2010, and 2018. It was hypothesized that the surface area of plant communities recovers naturally over time, due to the exclusion of productive activities in the PNCM.

# Materials and Methods

PNCM is located in the state of *Nuevo León*, between 26°31'00" N, 100°17'20" W (Figure 1) and borders with the state of *Coahuila*. It is part of RH-24 *Bravo-Conchos* river basin, which is located between the limits of *Allende, García, Montemorelos, Monterrey, Rayones, Santa Catarina, Santiago* and *San Pedro Garza García* municipalities, and has a total surface area of 177 395.95 ha (DOF, 2000).

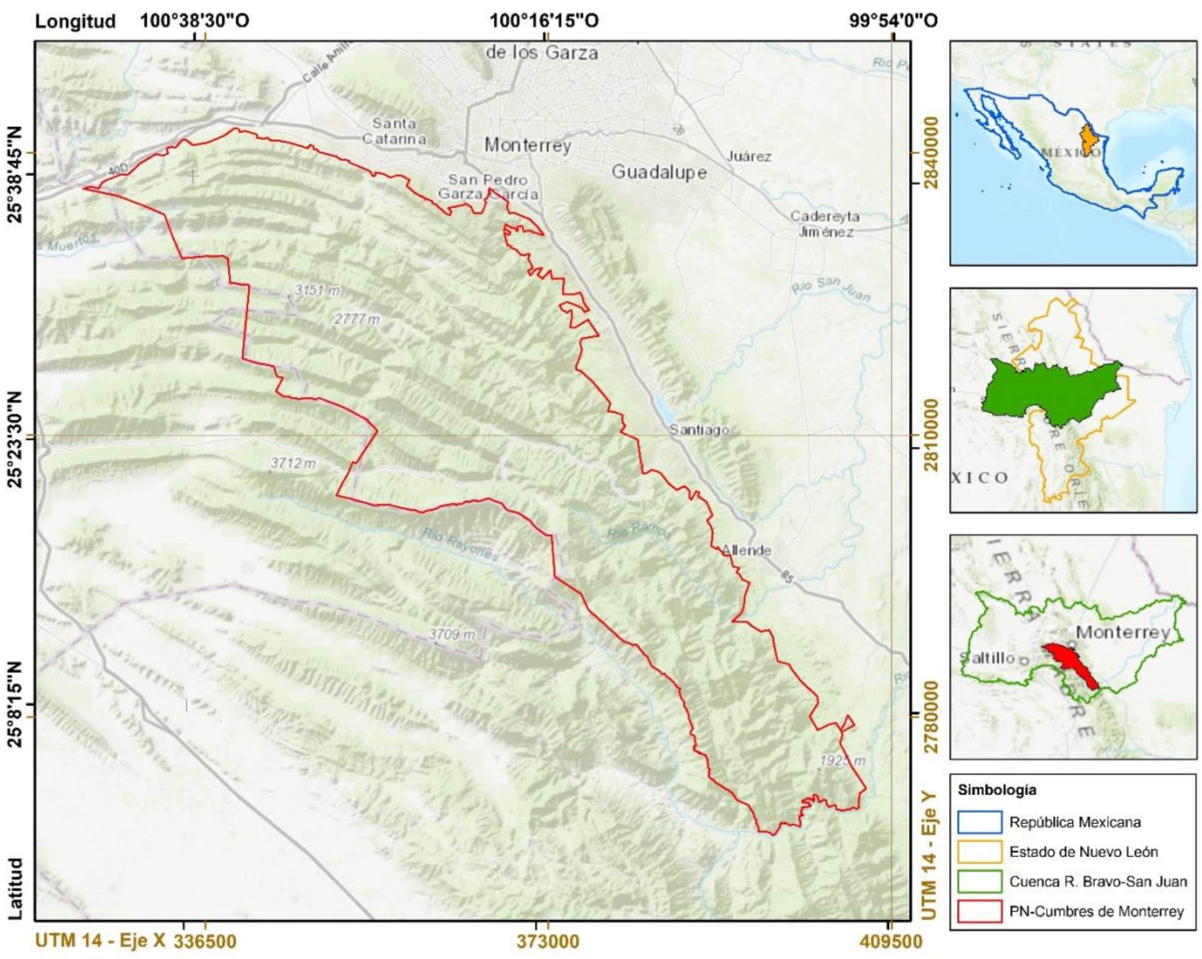



**Figure 1.** Location of the *Cumbres de Monterrey* National Park.

The dominant climates in the PNCM are Semi-warm humid (A)C($w_1$), (A)C($w_2$); Temperate sub-humid C($w_1$); Arid warm BSohw and Semi-arid warm $BS_1$hw. Rainfall varies from 344 mm to 983 mm per year and the average annual temperature ranges from 9 to 24 °C (Cuervo-Robayo *et al*., 2014). The soils are semi-arid, associated with desert vegetation; most are shallow and coarse-textured, and they sometimes have a hard or poorly permeable subsoil. The dominant soils are Leptosol (78.88 %), Pheozem (17.68 %), Fluvisol (1.45 %), Luvisol (0.98 %), Calcisol (0.55 %), Regosol (0.31 %), and Vertisol (0.15 %) (Inegi, 2019).

Surface waters in the study area are drained mainly by the *Santa Catarina* and *Ramos* river sub-basins. Smaller portions of the PNCM correspond to other sub-basins: the northwestern part drains into the *Pesquería* river sub-basin; the southeastern region, into the *Pilón* River, and the central region, towards the northeast, into the *San Juan* river (SIATL, 2020).

## Processing and generation of orthomosaics

In order to identify the optimal resolution for supervised classification processes to determine the rates of land use and vegetation change, a comparison was made between the satellite images most commonly used in this type of analysis: Landsat 8 OLI (Figure 2A) and Sentinel 2A (Figure 2B), compared to orthophotos (Figure 2C), Birdseye (Figure 2D), and Airbus Defence and Space satellite imagery.

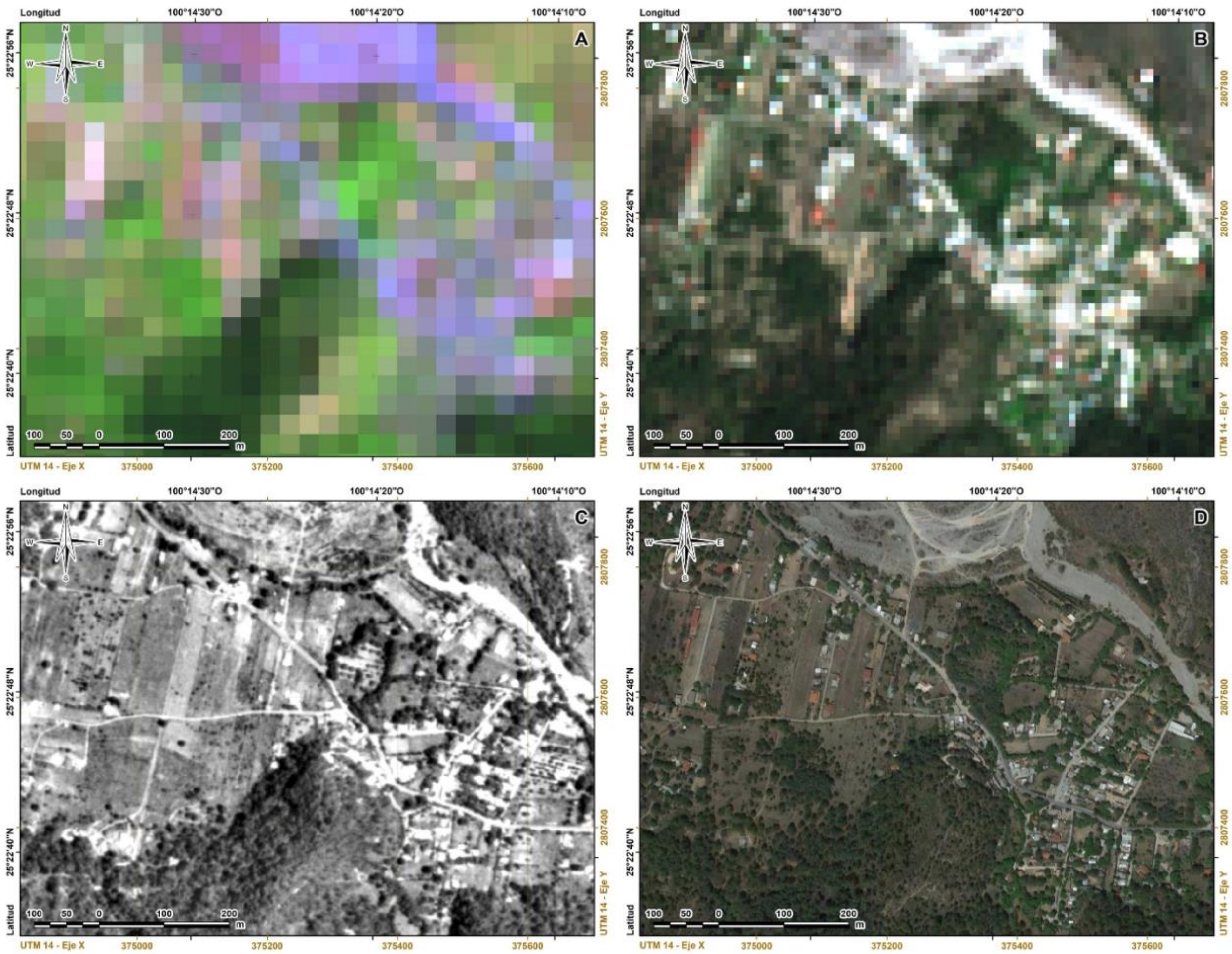


**Figure 2.** Comparison of Landsat 8 OLI (A), Sentinel 2A (B), Orthophotos (C) and high-resolution imagery (D).

According to Earth Observing System (2020), Landsat 8 (30 m/pixel; bands 7, 5, 4) and Sentinel 2 (10 m/pixel; bands 8,4,3) images are classified as medium resolution; while orthophotos (1.5 m/pixel), and Birdseye (0.28 m/pixel) and Airbus Defence and Space satellite images (1.14 m/pixel) are considered high resolution, because they have a resolution below the 5 m/pixel classification of the Earth Observing System.

The processing of high-resolution satellite images is based on georeferencing, radiometric correction, radiometric normalization of the series, and cloudiness percentage (Tirpak and Giuliano, 2010). Therefore, the availability of images with these characteristics was limited to the years 2000, 2010, and 2018.

Medium-resolution satellite imagery was obtained from the U.S. Geological Survey's Earth Explorer platform (USGS, 2020); orthophotos, from the *Espacios y Datos de México* server (Inegi, 2020), and Birdseye and Airbus Defence and Space images, from the SASPlanet software (SASPlanet, 2020).

## Supervised classification

A supervised classification was performed based on the generation of three orthomosaics composed of 27 orthophotos (year 2000; Figure 3A), 578 Birdseye (year 2010; Figure 3B) and 144 Airbus Defence and Space images (year 2018; Figure 3C), which were compared with Landsat (year 2018; Figure 3D) and Sentinel images (2018).

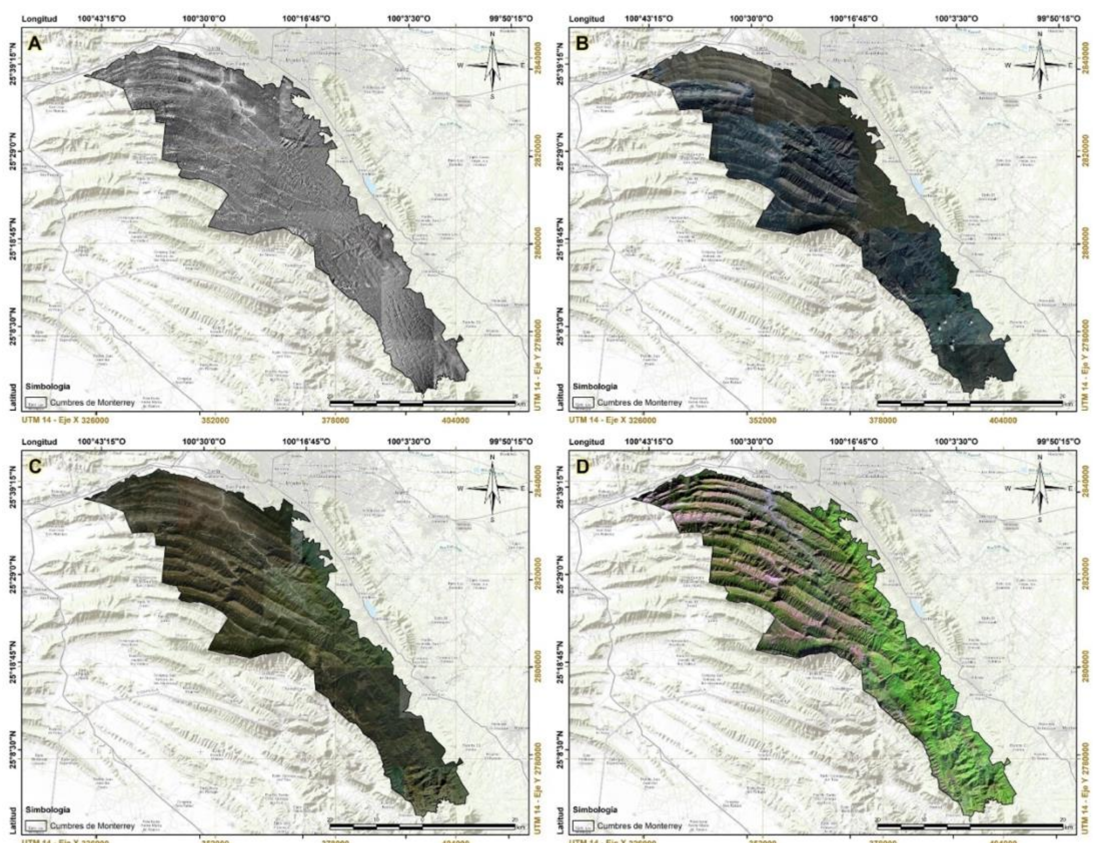



**Figure 3.** PNCM Orthomosaics of the years 2000 (A), 2010 (B), 2018 (C), and Landsat 2018 (D).

The open source QGIS 2.18.25 "*Las Palmas*" software was used for change detection (QGIS Development Team, 2020).

The atmospheric correction to the images of each period was done by cropping them and subjecting them to an unsupervised classification process with the K-means analysis module, which groups the cell values into classes with the multivariate cluster analysis method (Jumb *et al*., 2014; Rashmi *et al*., 2016). The files were then transformed from raster to vector format for supervised classification (Figure 4).

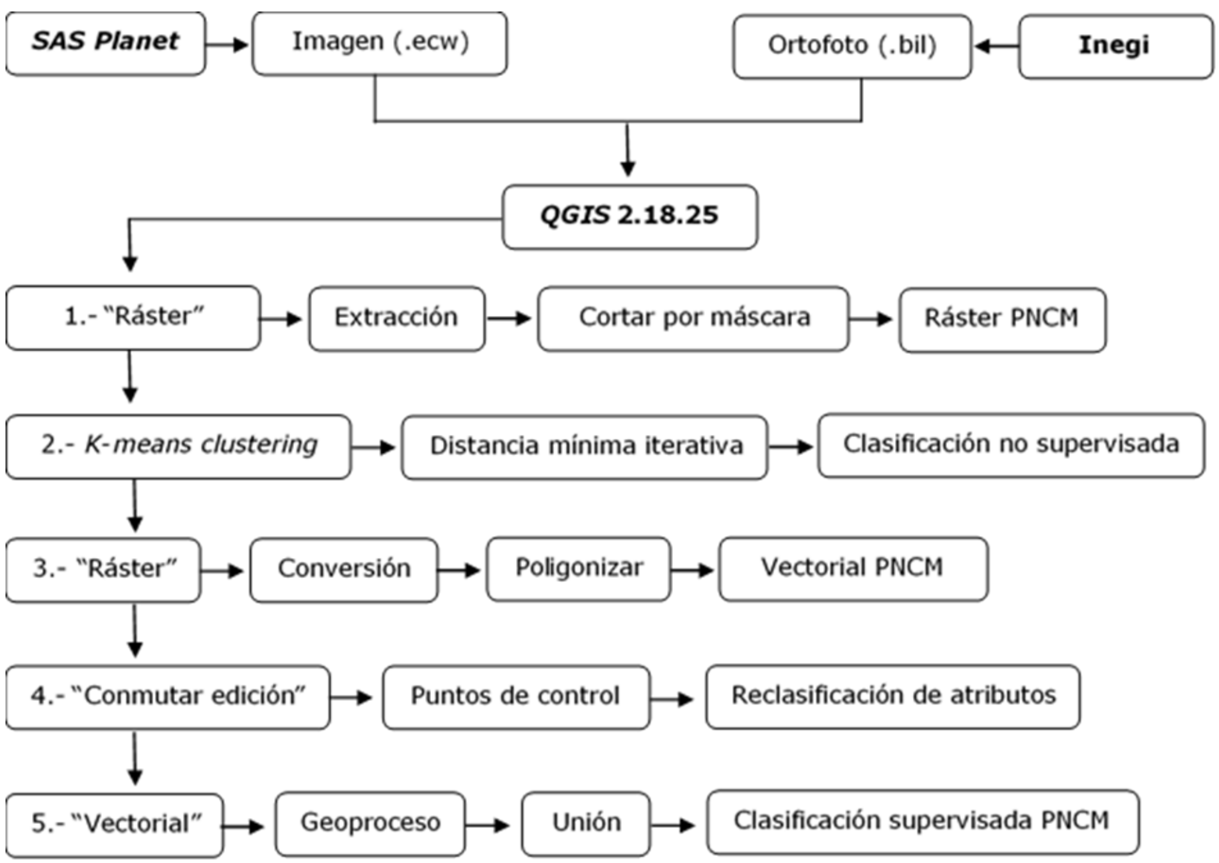



**Figure 4.** Supervised classification process in QGIS*.*

The supervised classification was carried out using control points, which consisted of 148 sites systematically distributed in areas with a high degree of confusion due to image reflectance, exposure, noise and cloud cover.

Information related to the different land uses, vegetation cover and vegetation type was obtained and compared with the information developed by Conafor (2013) and Inegi (2017), and a classification of different land uses (agriculture, human settlements, roads, power transmission lines and rivers) was generated, as well as forest cover (Douglas Fir Forest, Holm Oak, Holm Oak-Pine, Pine, Pine-Oak, Pine-Oak, Microphyllous Desert Scrub, Rosetophile Desert Scrub, Submontane Scrub, Grassland and No Vegetation) distributed in the PNCM (Figure 5).

**Figure 5.** Representative ecosystems of the PNCM.

The agreement and accuracy of the results of the classification of high-resolution satellite imagery was calculated in the *r.kappa* module in GRASS 7.6.0 (QGIS Development Team, 2020), which generates an error matrix and determines Cohen's kappa coefficient.

## Profit and loss determination

The determination of the loss or gain in the restoration process of the different types of vegetation was obtained by constructing transition matrices and rates of change for the years considered in the study, using the equation developed by FAO (1996) and adapted by Palacio-Prieto *et al.* (2004).

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

Where:

$\delta_n$ = Rate of change expressed as a percentage

$s_1$ = Surface area on date 1

$s_2$ = Surface area on date 2

$n$ = Number of years between the two dates

To describe the changes in land use and vegetation, a cross-tabulation of time 1 and time 2 was generated, allowing us to obtain a matrix of change. The diagonal shows the total amount of stable landscape between one date and another, while outside the diagonal are the transitions of the classes between Year 1 and Year 2. A positive rate of change value indicates a gain in restored surface area, while a negative value corresponds to a loss of forest cover.

# Results and Discussion

Fifteen land use and vegetation classes were derived from the supervised classification process; no significant change was observed in the categories of human settlements, roads, power transmission lines or rivers; therefore, the analysis was performed based on the main eleven classifications (Table 1).

**Table 1.** Classification of land use and vegetation in the PNCM.

| Year | 2000 | | 2010 | | 2018 | |
|---|---|---|---|---|---|---|
| **Vegetation** | **ha** | **%** | **ha** | **%** | **ha** | **%** |
| A | 1 550.00 | 0.87 | 1 701.33 | 0.96 | 1 865.57 | 1.05 |
| DFF | 3 600.69 | 2.03 | 3 696.70 | 2.08 | 3 760.52 | 2.12 |
| OF | 20 119.76 | 11.34 | 20 531.17 | 11.57 | 21 035.22 | 11.86 |
| OPF | 15 148.80 | 8.54 | 15 518.38 | 8.75 | 15 915.20 | 8.97 |
| PF | 24 957.86 | 14.07 | 25 999.67 | 14.66 | 26 866.54 | 15.14 |
| POF | 26 276.07 | 14.81 | 26 468.60 | 14.92 | 27 336.31 | 15.41 |
| MDS | 219.14 | 0.12 | 217.51 | 0.12 | 197.79 | 0.11 |
| RDS | 13 664.03 | 7.70 | 12 463.80 | 7.03 | 11 949.78 | 6.74 |
| SMS | 37 452.30 | 21.11 | 37 820.18 | 21.32 | 39 751.12 | 22.41 |
| GL | 1 152.91 | 0.65 | 1 030.07 | 0.58 | 968.54 | 0.55 |
| NV | 25 860.23 | 14.58 | 24 554.38 | 13.84 | 20 355.19 | 11.47 |

A= Agricultural; DFF= Douglas Fir Forest; OF= Oak Forest; OPF= Oak-Pine Forest; PF= Pine Forest; POF= Pine-Oak Forest; MDS= Microphyllous Desert Scrub; RDS= Rosetophile Desert Scrub; SMS= Submontane Scrub; GL= Grassland; NV= No Vegetation.

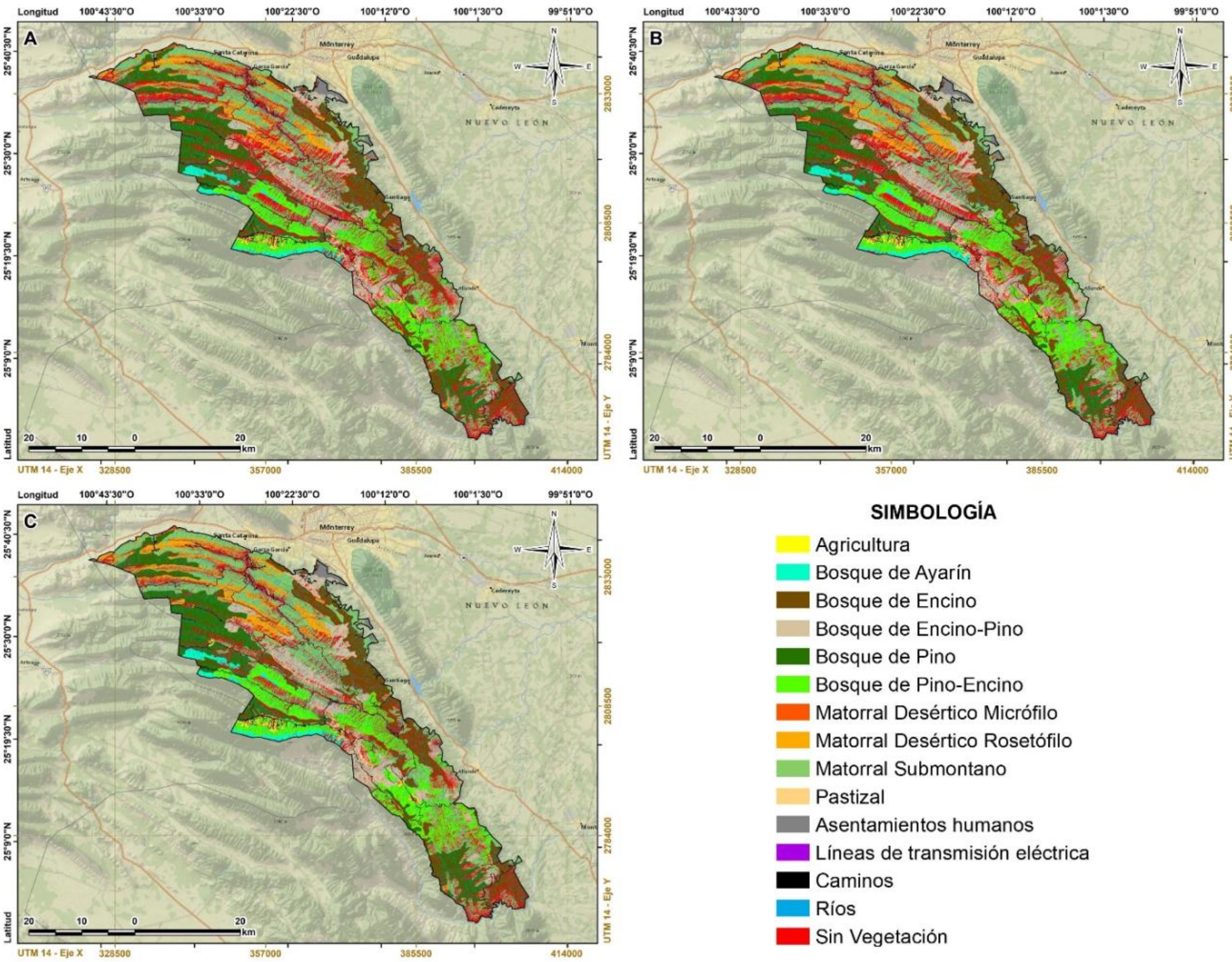
In regard to high-resolution images, the comparative analysis between Landsat 8 OLI and Sentinel 2ª images showed that there is an overestimation of more than 24 % for areas with forest cover. This is because some images showed displacement between the coordinates of the bands, which can produce a systematic error related to overlapping on the same path, but in a different row, in combination with the degree of cloudiness in the images (Cristóbal *et al*., 2004; Astola *et al.,* 2019).

The classification of the high-resolution images presented average Kappa index values of 0.83, which are considered to be within a very good level of accuracy, and were higher than those cited by Mendes *et al.* (2015), who obtained a value of 0.58 for images from the Geoeye-1 satellite.

The PNCM covers an area of 177 395.87 ha, of which, in the year 2018 (Table 1), 81.25 % corresponded to forest cover; 14.58 %, to no apparent vegetation; 3.18 %, to rivers; 0.70 %, to human settlements; 0.19 %, to roads, and 0.10 %, to electric transmission lines. The main vegetation types identified include submontane scrubland (39 751.12 ha), pine-oak (27 336.31 ha), pine (26 866.54 ha), oak (21 035.22 ha), oak-pine (15 915.20 ha), desert rosette scrub (11 949.78 ha), Douglas fir forest (3 760.52 ha), and microphyllous desert scrub (197.79 ha).

In general, there is a process of forest cover recovery in the PNCM; mainly in pine, pine-oak, oak-pine, oak-oak and Douglas fir forests as a result of the resilience of ecosystems to natural or anthropogenic disturbances (Lloret, 2012; Mora-Donjuán and Alanís-Rodríguez, 2016), as well as the restoration efforts made by communities, non-governmental organizations, and public institutions (Rovalo-Merino *et al*., 2013).

However, in ecosystems such as the microphyllous desert scrub, the rosetophile desert scrub, and grasslands, the loss of cover continues due to changes in land use for agricultural and livestock purposes and to the increase in human settlements (Figure 6).




*Agricultura* = Agriculture; *Bosque de ayarín* = Douglas fir forest; *Bosque de encino* = Oak forest; *Bosque de encino-pino* = Oak-Pine forest; *Bosque de pino* = Pine Forest; *Bosque de pino-encino* = Pine-Oak Forest; *Matorral desértico micrófilo* = Microphyllous Desert Scrub; *Matorral desértico rosetófilo* = Rosetophile Desert Scrub; *Matorral submontano* = Submontane Scrub; *Pastizal* = Grassland; *Asentamientos humanos* = Human settlements; *Caminos* = Roads; *Ríos* = Rivers; *Líneas de transmisión eléctrica* = Power transmission lines; *Sin vegetación* = No Vegetation.

**Figure 6.** Land use and vegetation classification from 2000 (A), 2010 (B) and 2018 (C).

## Detection of land use changes

The recovery of vegetation in the PNCM is positive, as can be seen during the 2000-2010 period, when a 13.03 % recovery of the forest cover was recorded, compared to 2000, mainly in those areas covered with pine, Douglas fir, oak-pine, oak, pine-oak, pine-oak and submontane scrub forests. However, there was also a loss of 20.18 % in grasslands, rosetophile desert scrub, and microphyllous desert scrub; agriculture showed an increase of 9.76 % and the areas without an apparent cover showed a decrease of 5.05 % (Table 2).

**Table 2.** Land cover changes in the PNCM from 2000 to 2018.

| Period | Δ 2000 - 2010 | | Δ 2010 - 2018 | | Δ 2000 - 2018 | |
|---|---|---|---|---|---|---|
| Vegetation | ha | % | ha | % | ha | % |
| Agricultural | 151.33 | 9.76 | 164.24 | 9.65 | 315.57 | 20.36 |
| Douglas Fir Forest | 96.01 | 2.67 | 63.82 | 1.73 | 159.83 | 4.44 |
| Pine Forest | 1041.81 | 4.17 | 866.87 | 3.33 | 1 908.68 | 7.65 |
| Pine-Oak Forest | 192.53 | 0.73 | 867.71 | 3.28 | 1 060.24 | 4.04 |
| Oak Forest | 411.41 | 2.04 | 504.05 | 2.46 | 915.46 | 4.55 |
| Oak-Pine Forest | 369.58 | 2.44 | 396.82 | 2.56 | 766.40 | 5.06 |
| Microphyllous Desert Scrub | -1.63 | -0.75 | -19.72 | -9.07 | -21.35 | -9.74 |
| Rosetophile Desert Scrub | -1 200.23 | -8.78 | -514.02 | -4.12 | -1 714.25 | -12.55 |
| Submontane Scrub | 367.88 | 0.98 | 1 930.94 | 5.11 | 2 298.82 | 6.14 |
| Grassland | -122.84 | -10.65 | -61.53 | -5.97 | -184.37 | -15.99 |
| No Vegetation | -1 305.85 | -5.05 | -4 199.19 | -17.10 | -5 505.04 | -21.29 |

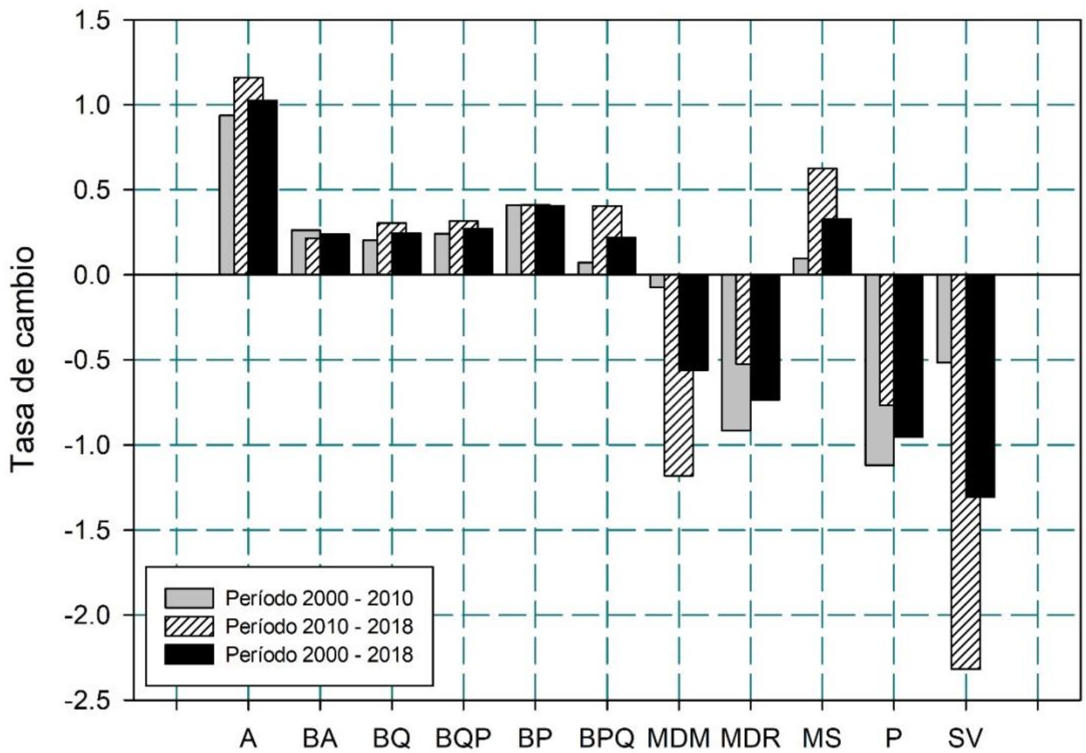
Δ = Cover increase or loss.

These results exhibit a similar trend to those obtained by various studies in protected or exclusion areas, as cited by Flórez-Yepes *et al.* (2017) —who estimated a recovery of 30.44 % for gold mine forests located in Manizales, Colombia—, as well as to those documented by Sanhouse-García *et al.* (2016) in *Sinaloa*, Mexico, where pine-oak and pine forests increased by 38.98 % and 29.56 %, respectively.

As for agricultural vegetation, increases of 9.76 % (2000-2010), 9.65 % (2010-2018), and 20.36 % (2000-2018) were observed. These values are similar to those reported by Kumar *et al.* (2020) in an analysis of cover change on the banks of the Ganges river in Haridwar district, India, for the years 1996, 2003, 2010, and 2017, where agriculture had an increase of 17.32 %. However, they are lower than that obtained by Martin *et al.* (2019) in the Kwakuchinja wildlife corridor of Tanzania, where agriculture increased by 35.6 %.

In regard to the carbon sequestration research conducted in various vegetation types (Pimienta de la Torre *et al.*, 2007; Rodríguez *et al.*, 2009; Aguirre-Calderón and Jiménez-Pérez, 2011; Montaño *et al*., 2016), the recovery of forest ecosystems in the PNCM generates an increase of 86 939.68 Mg C in pine-oak forests, 53 648.00 Mg C in oak-pine forests, 118 338.16 Mg C in pine forests, and 27 585.84 Mg C in submontane scrubland.

The progressive rate of change of agriculture and the negative impact of microphyllous desert scrub, rosetophile scrub, and grassland (Figure 7) threatens the integrity of ecosystems, as well as the provision of such goods and services as the recharge of the water bodies that supply the Metropolitan Area of *Monterrey* (López and Ixtacuy, 2017).

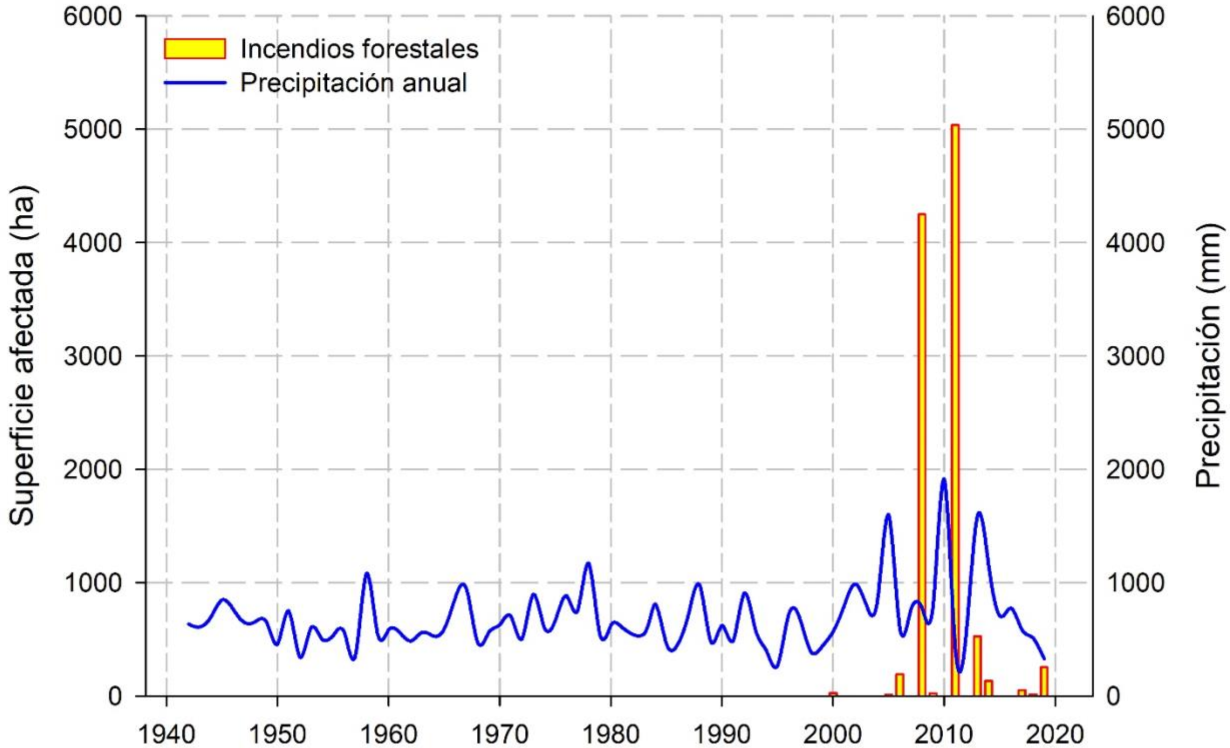



A = Agriculture; BA = Douglas Fir Forest; BQ = Oak Forest; BQP = Oak-Pine Forest; BP = Pine Forest; BPQ = Pine-Oak Forest; MDM = Microphyllous Desert Scrub; MDR = Rosetophile Desert Scrub; MS = Submontane Scrub; P = Grassland; SV = No Vegetation.

**Figure 7.** Dynamics of the rate of change of the soil and vegetation types.

One of the main factors that continue to affect ecosystems are forest fires: in the PNCM, more than 9 085.09 ha have been affected during the period from 2000 to 2011 (Conanp, 2011), and 2 493.68 ha from 2012 to 2019 (Conafor, 2020).

Forest fires are closely related to previous periods of excessive precipitation: those recorded in 2008, when 4 249.31 ha were damaged by fuel accumulation, resulted from the 2005 precipitation (1 600 mm), and those of 2011, which covered an area of 5 037.51 ha (Yerena *et al.*, 2013), followed a precipitation of 1 915 mm in 2010 (Figure 8).




*Superficie afectada* = *Affected area; Incendios forestales* = Forest fires; *Precipitación anual* = Annual precipitation.

**Figure 8.** Forest fires in the PNCM (2000-2019).

# Conclusions

The multitemporal analysis indicates a gradual process of recovery of forest cover —mainly of pine, pine-oak, oak-pine, oak, and Douglas fir forests— as a response to the resilience capacity and the prioritization of ecological restoration strategies in these ecosystems. The opposite situation is observed for the rosetophile desert scrub, the microphyllous desert scrub, and the grassland, which show continuous loss as a result of the change of land use for agricultural purposes.

The rates of change of land use and vegetation in this study indicate the presence of a dynamic in the successional process of the ecosystems of the PNCM. The tendency of this dynamic is similar to that cited for natural protected or exclusion areas where there is a gradual recovery of forest cover with certain types of vegetation, as well as a loss of ecosystems of less economic interest, that are being replaced through the advance of agriculture and of human settlements.

The exclusion of productive activities in natural protected areas does not guarantee the conservation of biodiversity or the optimal functioning of environmental services, since there are external factors that jeopardize the integrity of ecosystems, such as the recurrent presence of forest fires that reduce the resilience capacity and increase the vulnerability of ecosystem services.

The use of high-resolution imagery greatly improves the interpretation of different scenarios of land use and vegetation change, compared to Landsat and Sentinel imagery, and offers a true picture of the loss or gain of forest cover in natural protected areas.

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## Conflict of interests

The authors declare no conflict of interest.

## Contribution by author

Rufino Sandoval-García: design, organization, data analysis, and drafting of the manuscript; Javier Jiménez-Pérez: validation and revision of the manuscript; José Israel Yerena-Yamallel, Oscar Alberto Aguirre-Calderón, Eduardo Alanís-Rodríguez and Marco Vinicio Gómez-Meza: review and editing of the manuscript. All authors contributed to the approval of the final version.

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