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Research article

Multitemporal analysis using high-resolution images in a Tamaulipan Thornscrub

Análisis multitemporal mediante imágenes de alta resolución en un Matorral Espinoso Tamaulipeco

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Abstract

In Northeastern Mexico, a biodiversity conservation area was established within an industrial complex, where a reforestation program with native species was implemented in 2010. The objective of this paper was to quantitatively assess, through multitemporal analysis of high-resolution images, the effectiveness of an ecological restoration project in the Tamaulipan Thornscrub, based on spatial changes in vegetation cover and land use recorded between 1995 and 2024. The results indicated a linear increase (R^2=0.92) in vegetation cover over time. In 1995, it occupied 32.22 % of the conservation area, and in 2024, 62.67 %. In contrast, the area used for agriculture decreased from 38.5 % in 1995 to 12.6 % in 2008, and was zero from 2014 onwards. Likewise, the grassland cover decreased from 27.1 % in 1995 to 17.1 % in 2024. The results of the study show a recovery in vegetation cover as a result of the implementation of the ecological restoration program over an area of 83 ha. This included the planting of 69 537 individuals from rescues and 18 500 individuals from local nurseries, with a survival rate of 85 % by 2024 for at least 10 species of ecological interest. The findings confirm the effectiveness of these strategies in restoring vegetation, which can serve as a basis for the design and implementation of larger-scale restoration projects.

Keywords: Agriculture, land use change, supervised classification, biodiversity conservation, reforestation, ecological restoration.

Resumen

En el noreste de México, se estableció un área de conservación de la biodiversidad dentro de un complejo industrial, donde a partir del año 2010 se implementó un programa de reforestación con especies nativas. El objetivo fue evaluar cuantitativamente, mediante análisis multitemporal de imágenes de alta resolución, la efectividad de un proyecto de restauración ecológica en el Matorral Espinoso Tamaulipeco, en función de los cambios espaciales en la cobertura vegetal y el uso de suelo registrados entre 1995 y 2024. Los resultados indicaron un aumento lineal (R^2=0.92) de la cobertura de la vegetación conforme transcurrió el tiempo. En 1995 ocupaba 32.22 % del área de conservación y en 2024, 62.67 %. En contraste, la superficie con agricultura disminuyó de 38.5 % en 1995 a 12.6 % en 2008, y fue nula a partir de 2014. Asimismo, la cobertura de pastizal se redujo de 27.1 % en 1995 a 17.1 % en 2024. Los resultados del estudio evidencian una recuperación de la cobertura vegetal como consecuencia de la implementación del programa de restauración ecológica en una superficie de 83 ha. Este incluyó la plantación de 69 537 individuos provenientes de rescates, 18 500 individuos de viveros locales; con una supervivencia de 85 % al año 2024, para al menos 10 especies de interés ecológico. Los hallazgos confirman la efectividad de dichas estrategias en el restablecimiento de la vegetación, que puede servir como base para el diseño e implementación de proyectos de restauración a mayor escala.

Palabras claves: Agricultura, cambio de uso del suelo, clasificación supervisada, conservación de la biodiversidad, reforestación, restauración ecológica.

Introduction

Globally, various categories of protected natural areas have been established in order to conserve biodiversity and restore degraded plant communities (Arneth et al., 2023). In Mexico, at the federal level, there are biosphere reserves, national parks, natural monuments, areas designated for the protection of resources, flora, and fauna, as well as sanctuaries (Reyna-Rojas et al., 2021). In addition to these areas under government protection, there are conservation areas on privately owned land, where those responsible implement strategies to protect the country's biological capital (Cámara de Diputados, 1988; Patiño-Flores et al., 2019).

In Northeastern Mexico, in the state of *Nuevo León*, a Wildlife Conservation Area is designated to conserve biodiversity and restore degraded plant communities (Patiño-Flores et al., 2019). Since 2010, various reforestation programs with woody species have been implemented in this area to restore the vegetation cover (Alanís-Rodríguez et al., 2016).

Previous studies have evaluated the plantation planting density and canopy cover in the area (Alanís-Rodríguez et al., 2016, 2021; Alcalá-Rojas et al., 2025). Although specific reforestation actions have been documented in these areas, no multitemporal monitoring and analysis have been conducted to assess the dynamics of vegetation-cover recovery over time. Only the number of individuals planted has been recorded, but the behavior of land-use change over time has not.

In multitemporal studies, vegetation indices derived from high-resolution multispectral images acquired by satellites and unmanned aerial vehicles (UAVs) have proven to be effective tools for monitoring ecosystems (Gutiérrez-Barrientos et al., 2022; Mao et al., 2020). This methodology allows data to be obtained quickly, consistently, and in a manner applicable to areas that are difficult to access, thereby reducing the time and costs associated with efficient field assessments for ecosystem monitoring (Doi, 2021).

Within this context, it was proposed to quantitatively evaluate, through multitemporal analysis of high-resolution images, the effectiveness of an ecological restoration project in the Tamaulipan Thornscrub, based on the spatial changes in vegetation cover and land use recorded between 1995 and 2024. The aim is to provide information on the dynamics of vegetation cover recovery resulting from the ecological restoration project in this type of vegetation and to generate inputs for the management and planning of strategies focused on its conservation.

Materials and Methods

Study area

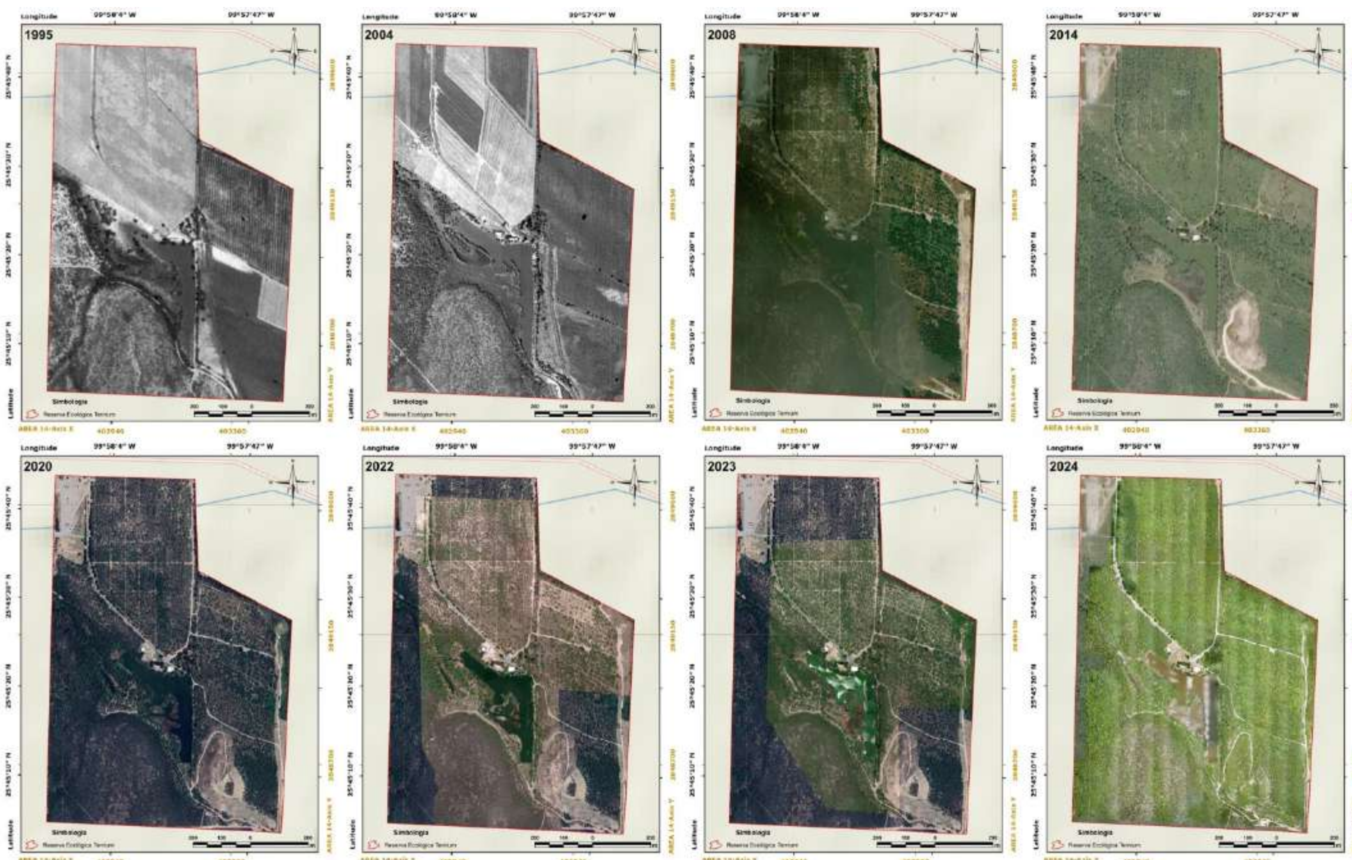
The study area covered 83.72 ha and was located in *Pesquería* tmunicipality, state of *Nuevo León*, Mexico (Figure 1), at 25°45’94.99” N and 99°57’43.61” W, with an altitude of 305 m. The region's climate is classified as dry-semi-warm (BWhw) under the Köppen classification modified by García (García & Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio], 1998). The predominant soil type is pelic Vertisol (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2014). The characteristic vegetation corresponds to the Tamaulipan Thornscrub (MET by its Spanish acronym) (Alanís-Rodríguez et al., 2021).

Figure 1. Location of the study area in *Pesquería* municipality, state of *Nuevo León*, Mexico.

Image acquisition

The classification of land cover used a 2 m pixel orthophoto (year 1995) and a 1.5 m pixel orthophoto (year 2004), both obtained from the *Espacios y Datos de México* platform (Instituto Nacional de Estadística y Geografía [Inegi], 2024), as well as six high-resolution satellite images from Airbus Defence and Space with a pixel size of 1.14 m (year 2008), 22 images from GeoEye-1 with a pixel size of 0.28 m (year

2014), and 22 Birdseye images with a resolution of 0.28 m (year 2020) from the SASPlanet platform (SASPlanet Development Team, 2024). Both sources are freely accessible and open source. The images from 2022, 2023, and 2024 were obtained from one flight per year with a Wingtra® One RGB61 Unmanned Aerial Vehicle (UAV), in autopilot mode at an altitude of 120 m, which generated approximately 446 images of 0.05 m pixels with a 70/60 % overlap and processed with Pix4D version 4.8.4 software (Pix4D, 2023) (Figure 2).



Simbología = Key; *Reserva Ecológica Ternium* = Ternium Ecological Reserve.

Figure 2. Orthomosaics of the conservation area located in *Pesquería* municipality, state of *Nuevo León*, Mexico (1995-2024).

Cover classification

Prior to processing and using the satellite images, including the orthophotos obtained by the UAV, a geometric correction was performed by taking identifiable control points. In order to do this, a mathematical transformation (polynomial or similar) was applied, and a digital elevation model was used for orthorectification, followed by resampling to assign new pixel values using methods such as nearest neighbor or cubic convolution. The result was a georeferenced image ready for analysis.

The sites are systematically distributed in areas with a high degree of confusion due to image reflectance, exposure, noise and cloud cover (Figure 3).

A = Resolution of 0.28 m pixel; B = Resolution of 0.05 m pixel.

Figure 3. Example of resolution of 0.28 m pixel and 0.05 m pixel.

The detection of changes was performed with the Quantum GIS QGIS 3.36.0 software "Maidenhead" using the open-source SAGA (System for Automated Geoscientific Analyses) processing toolbox (QGIS Development Team, 2024), through unsupervised classification with the K-Means Cluster Analysis module, which performs cluster grouping using the iterative refinement technique (Jumb et al., 2014). Subsequently, a supervised classification method was applied, based on converting raster-format files to vector format, using training sites derived from field data, with a total of six land-use and vegetation classes (Rashmi et al., 2016).

Information validation

To calculate the concordance and accuracy of the classification of high-resolution satellite images and UAV-derived images, the r.kappa module of the GRASS 7.6.0 extension for QGIS 3.36.0 was used (QGIS Development Team, 2024). An error matrix was generated, and the Kappa coefficient was determined using the following Equation (Quezada et al., 2022):

$$K = \frac{Po - Pe}{1 - Pe} \qquad (1)$$

Where:

K = Kappa coefficient

Po = Observed agreement

Pe = Expected random agreement

$1-Pe$ = Maximum non-random potential agreement

The Kappa coefficient was 0.85, which, according to Landis and Koch (1977), indicates that the images match almost perfectly, guaranteeing a high degree of similarity when replicating the study. The information was validated against land-use records and field surveys, from which 40 control points were obtained.

Multitemporal analysis

Changes (increases or losses) in forest cover and land use were estimated by cross-tabulating eight different periods: 1995-2004, 2004-2008, 2008-2014, 2014-2020, 2020-2022, 2022-2023, 2023-2024, and 1995-2024. For this purpose, Equation 2 was used as developed by the Food and Agriculture Organization of the United Nations (FAO, 1993) and adapted by Palacio-Prieto et al. (2004).

$$\delta_n = \left[\left(\frac{S_2}{S_1}\right)^{\frac{1}{n}} - 1\right] \times 100 \qquad (2)$$

Where:

δ_n = Exchange rate 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

Using the data obtained from the classification of the images, the annual deforestation rate was calculated by comparing the land cover of the same site in two different periods. Equation 3, proposed by Puyravaud (2003), was used for this purpose, where a positive "r" value indicates an increase in vegetation cover, while a negative value indicates a loss of cover.

$$r = \left(\frac{1}{t_2 - t_1}\right) \times ln\left(\frac{A_2}{A_1}\right) \times 100 \qquad (3)$$

Where:

A_1 = Vegetation cover or land use in the initial period

A_2 = Vegetation cover or land use at the end of the period

t_1 = Initial period

t_2 = Final period

Restoration actions in the area

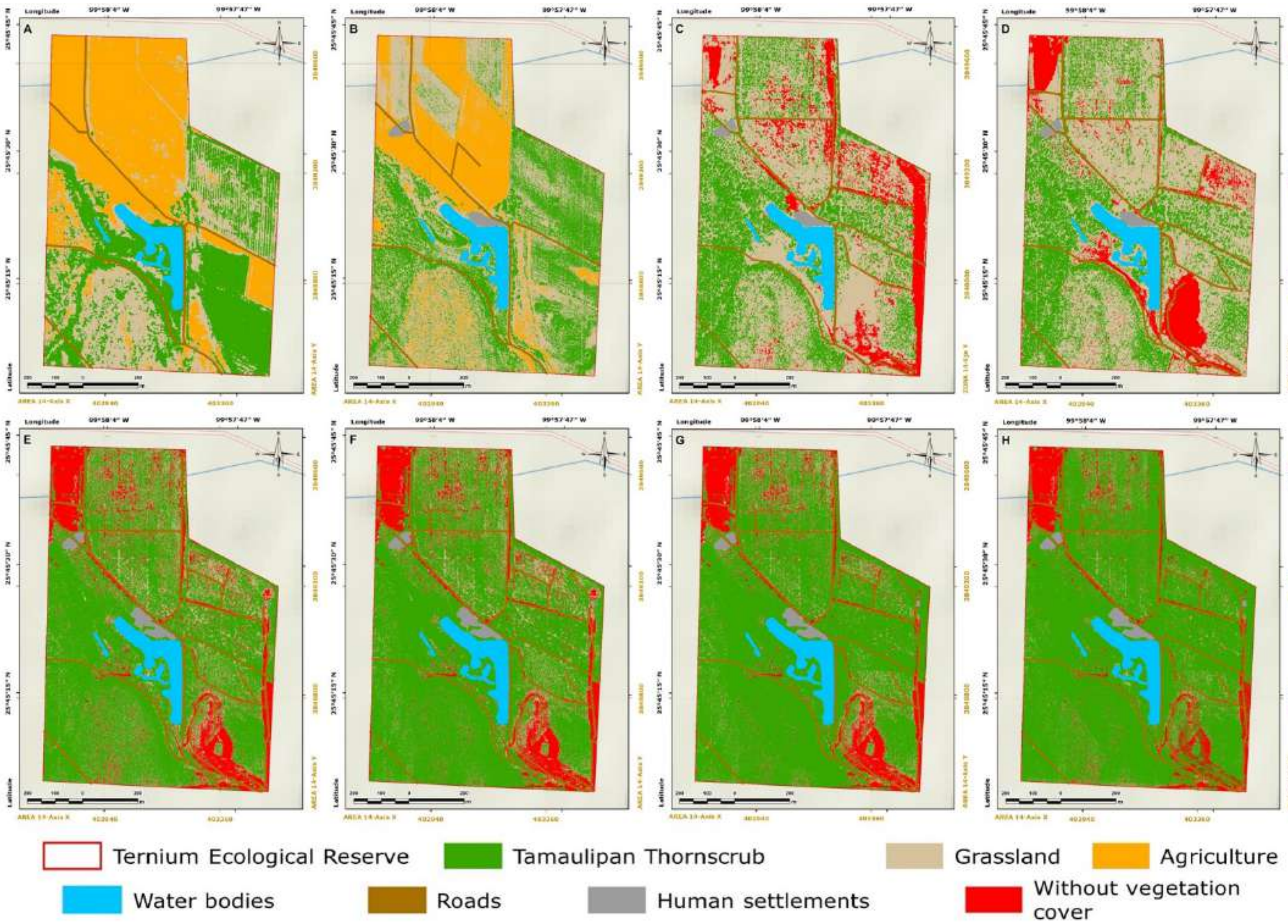
The ecological restoration process began in April 2010, when the area was excluded from livestock grazing and reforested by stages with native woody species between 2010 and 2024. Individuals from local forest nurseries and specimens rescued from areas undergoing land-use change were utilized. A triangular layout was used for planting, with a distance of 1.5 m between individuals and rows to achieve a density of 992 plants per hectare (n ha^{-1}).

In addition, maintenance actions were implemented to eliminate exotic grasses, with the aim of reducing competition for resources and promoting the establishment of native vegetation. Over time, the success of the removal of exotic grasses became apparent, as by 2024, their presence was scarce, occurring only under the cover of the plantation, where they reached heights of up to 3 m. Support irrigation was also applied using a tanker truck once a week for the first four months after planting and once every two weeks for the following eight months (Alanís-Rodríguez et al., 2021).

Finally, dead seedlings were replaced in the years following planting, with the aim of ensuring the establishment and formation of the plant community and maintaining a survival rate of 85 % by 2024. To this end, 88 106 specimens of at least 10 different native species were planted.

Results

Multitemporal processing of high-resolution images allowed us to quantify land use and vegetation cover transitions in the study area during the period 1995-2024, as a basis for evaluating the effectiveness of the ecological restoration project (Figure 4).



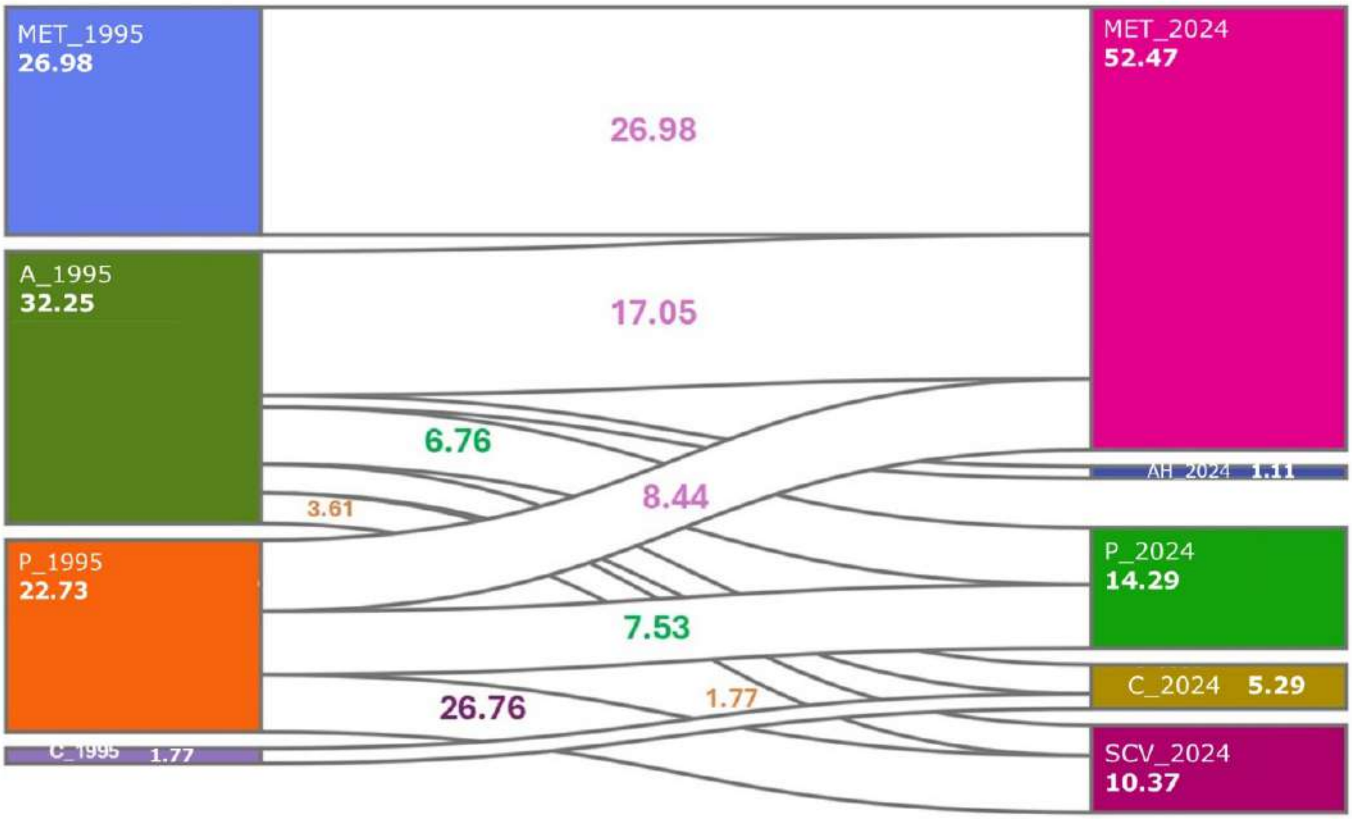
Land use: A = 1995; B = 2004; C = 2008; D = 2014; E = 2020; F = 2022; G = 2023; H = 2024.

Figure 4. Land use change from 1995 to 2024.

The results indicated that the cover of the MET (Tamaulipan Thornscrub) was dominant and stable, while agriculture and grassland were more dynamic, mainly due to conversion processes to MET.

Figure 5 shows the change in land use by comparing between 1995 and 2024; it shows the conservation of 26.98 ha of the MET; the 32.25 ha of agriculture became 20.2 ha of MET, 8.22 ha of grassland, 1.11 ha of human settlements, and 2.72 ha of roads; 22.73 ha of grassland became 5.29 ha of MET, 2.15 ha without vegetation cover while 14.29 ha remained as grassland, 0.21 ha of roads, and 0.29 ha of human settlements.

Finally, of the 1.77 hectares of roads, 1.7 hectares were preserved, and the rest was added as a result of the change from grassland to agriculture.



MET = Tamaulipan Thornscrub; P = Grassland; A = Agriculture; C = Roads; AH = Human settlements; SCV = Without vegetation cover.

Figure 5. Sankey diagram for the period 1995 to 2024

When analyzing the rate of change and permanence by period, it was evident that, from 2020 onwards, land-use permanence remained unchanged, with the greatest change occurring in the 2008-2014 and 2014-2020 periods, which corresponded to the start of restoration, reforestation, and plantation establishment. Table 1 shows the behavior of these changes.

Table 1. Rate of change/permanence of land use from 1995 to 2024.

Period	Changed surface area (ha)	Permanente area (ha)	% change	% permanece
1995→2004	11.61	72.12	13.87	86.13
2004→2008	10.10	73.62	12.07	87.93
2008→2014	15.58	68.14	18.61	81.39
2014→2020	16.35	67.37	19.53	80.47
2020→2022	3.47	80.26	4.14	95.86
2022→2023	1.10	82.63	1.31	98.69
2023→2024	1.55	82.18	1.85	98.15

Land uses with positive changes in all periods were the MET, roads, and human settlements, with average values of 2.45 %, 5.25 %, and 3.18 %, respectively. The largest negative changes were observed in agriculture for the 2004-2008 period, with -15.48 %, and pastureland with -10.03 % in the 2014-2020 period (Figure 6).

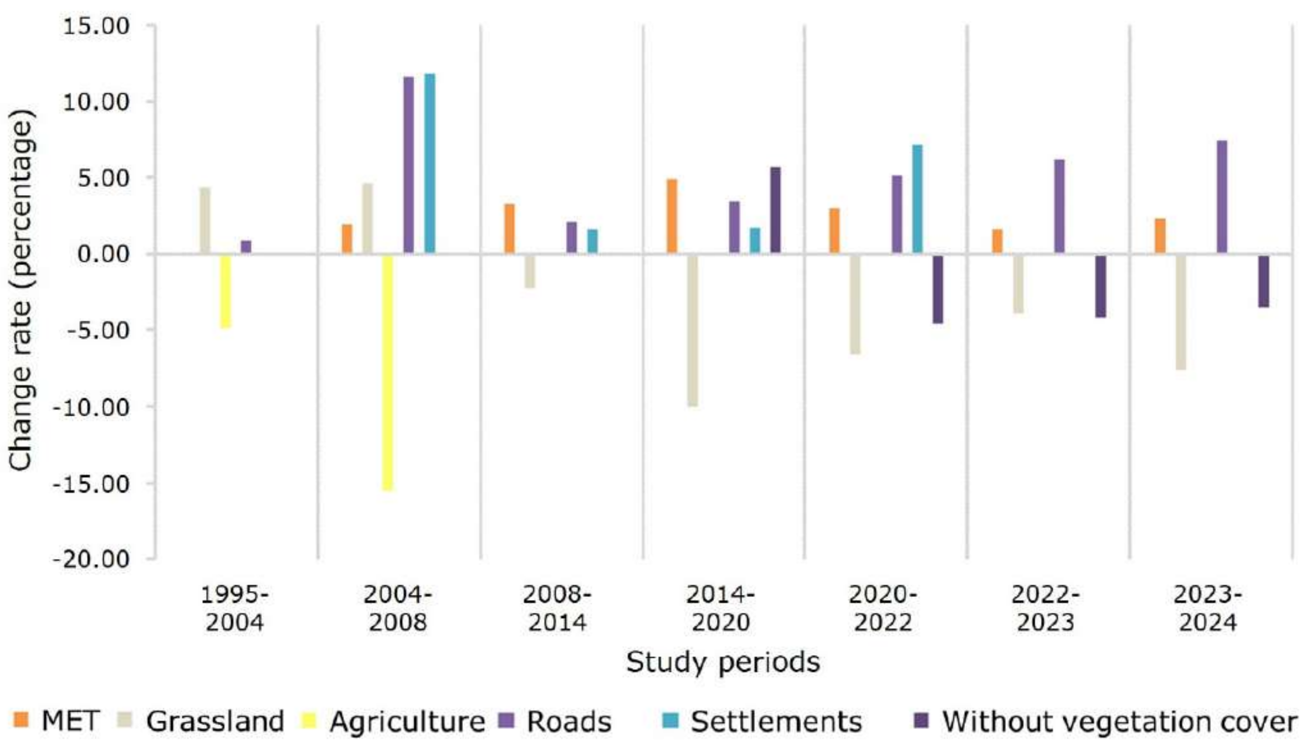


Figure 6. Rate of change in the area assessed during the 1995-2024 period.

The analysis of the information for the MET shows a linear increase (R^2=0.91) over time. In 1995, it occupied 32.22 % of the 83 ha conservation area, and by 2024, it had grown to 62.67 %. The area of grassland increased from 1995 to 2008, but after restoration it decreased from 2008 to 2024; agriculture declined from 1995 to 2008, reaching zero by 2014.

The MET area remained virtually stable from 1995 to 2008 and began to increase from 2014 onward, owing to reforestation efforts undertaken in 2010. The greatest increase was observed from 2020 onward, as planting continued from 2010 to 2024 and the specimens grew larger, thereby increasing the vegetation cover. These changes in vegetation cover were the result of restoration actions, and not of the natural regeneration process. Alcalá-Rojas et al. (2025) evaluated natural regeneration in 18 ha, which are within the 83 ha where this study was conducted, and, although the plantation has created the conditions for natural regeneration, its growth has not been significant, amounting merely to 3.8 m^3 ha^{-1}, while the plantation has values of 15 m^3 ha^{-1}.

Agricultural activity ceased in the study area and was replaced by exotic grass cover. Subsequently, this cover was removed from the site to begin the restoration process by establishing native species. While there was no intervention, the grassland area showed an upward trend. However, starting in 2009, when restoration activities began, this cover began to decline. Since 2020, this reduction has remained stable; as a result, the grassland is preserved only in specific areas designated for soil protection and conservation.

Discussion

To evaluate the effectiveness of ecological restoration projects, it is essential to adopt a systematic, comprehensive approach that enables monitoring of plant community dynamics (León & Vargas-Ríos, 2021). However, traditional monitoring based on on-site assessments has limitations, especially in hard-to-reach locations or large-scale restoration projects (Gutiérrez-Barrientos et al., 2022; Mao et al., 2020). Within this context, the use of remote sensing images offers significant advantages, as it enables the assessment of the recovery of vegetation cover over time and across large areas, facilitating the detection of changes that would be difficult to observe through field sampling (Doi, 2020; Liu et al., 2019).

Although this research did not cover a large area, the objective was to establish a methodological approach that would lay the foundation for its application at a larger scale, thereby improving the monitoring of ecological restoration projects and generating more robust information for decision-making in ecosystem management.

The results of this research indicate that vegetation cover in the Tamaulipan Thornscrub has increased over time. This increase is attributed to reforestation actions implemented as part of the ecological restoration project in the study area (Alanís-Rodríguez et al., 2021; Molina-Guerra et al., 2023). In these areas, Alanís-Rodríguez et al. (2021) documented that recovery was reflected in a canopy cover of 9 298 m^2 ha^{-1}, with a density of 1 033 individuals ha^{-1}, and Alcalá-Rojas et al. (2025) cited a density of 1 129 individuals ha^{-1}. In addition, Alcalá-Rojas et al. (2025) evaluated natural regeneration of woody plants under the canopies of reforested species and recorded 1 513 small seedlings, indicating that natural regeneration is underway. Similar findings have been reported by Sandoval-García et al. (2021), who documented a 6.6 % increase in forest cover in the *Mixteca Alta Oaxaqueña* region between 1995 and 2016 attributable to ecological restoration strategies. In a similar way, Hernández-Cavazos et al. (2023) recorded a 12.83 % recovery in the cover of the Tamaulipan

Thornscrub in *Linares* municipality, state of *Nuevo León*, during the 1995-2021 period. This information suggests that ecological restoration strategies can be effective in recovering vegetation cover in semi-arid ecosystems, although monitoring must continue in order to assess their long-term stability.

The results indicate that the area devoted to agriculture decreased between 1995 and 2008, with 0.00 ha in 2014. This change is attributed, in principle, to the fact that agricultural activities ceased after the ecological restoration actions implemented in these areas, which have been transformed into plant communities in the Tamaulipan Thornscrub. In contrast, Alanís-Rodríguez et al. (2021) evaluated a community without restoration treatment in the same locality and observed limited recovery of canopy cover, attributed to slow natural regeneration under conditions of high competition with exotic herbaceous plants.

The area without vegetation cover increased in 2014 as a result of the establishment of a zone designated for the accumulation of soil material generated by land use change activities. This process involved the removal of existing vegetation, which created bare areas that altered the continuity of vegetation cover in the study area.

As for the area occupied by induced grassland, it is mainly dominated by the invasive alien species *Cenchrus ciliaris* L. Between 1995 and 2008, its coverage increased from 22.73 % to 39.86 %, indicating its high invasiveness. Subsequently, as a result of restoration efforts, this coverage was reduced to 14.29 %. In the study area, work was carried out to remove this grass and replace it with *Cynodon dactylon* (L.) Pers. to prevent soil erosion. Currently, *Cenchrus ciliaris* is found only in isolated patches under vegetation cover. However, the natural recovery of the native plant community under conditions of competition with *C. ciliaris* tends to be slow, due to the strong interspecific competition exerted by this grass, which monopolizes the cover and limits the establishment of native species (Alanís-Rodríguez et al., 2023; Arriaga et al., 2004; Marshall et al., 2012).

One of the fundamental objectives of ecological restoration projects is to assist areas devoid of native vegetation in developing functional communities composed of native taxa (Pequeño-Ledezma et al., 2016). This approach seeks to halt the causes of degradation, restore the ecosystem's native vegetation and fauna, and facilitate ecological succession processes that promote natural regeneration (Alcalá-Rojas et al., 2025).

Conclusions

Analysis of the collected data indicates that restoration activities have been effective: vegetation cover has increased, and conditions for natural regeneration have been established; over time, these conditions will contribute to further increases in cover. It is advisable to continue monitoring these conditions. Multitemporal analysis using high-resolution images made it possible to quantitatively evaluate the effectiveness of the ecological restoration project in the Tamaulipan Thornscrub, based on spatial changes in vegetation cover and land use between 1995 and 2024. The most significant result is the sustained increase in scrub cover from 32.22 % to 62.67 %, with a positive linear trend (R^2=0.91), demonstrating a significant recovery attributable to the restoration actions initiated in 2009. In addition, the conversion of agricultural and induced grassland areas to communities dominated by native vegetation and the reduction of grassland associated with *Cenchrus ciliaris* reinforce the effectiveness of reforestation strategies, disturbance exclusion, and exotic species control. Taken together, these results confirm that high-resolution remote sensing is a robust tool for evaluating the effectiveness of ecological restoration projects in semi-arid ecosystems and establish a replicable methodological basis for monitoring, planning, and decision-making in larger-scale restoration initiatives.

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Conflict of interest

The authors declare that they have no conflict of interest. Eduardo Alanís-Rodríguez declares that he did not participate in the editorial process of the manuscript.

Contribution by author

Alejandro Alcalá-Rojas and Eduardo Alanís-Rodríguez: research design, fieldwork, integration, and first draft of the manuscript; Rufino Sandoval-García: image acquisition, information analysis and table generation; Oscar Aguirre-Calderón and Gerardo Cuéllar-Rodríguez: validation of information and drafting of the Introduction and Conclusions; Israel Yerena-Yamallel: validation of information and drafting of the Results. All the authors revised and approved the final version of the manuscript.

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