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ARTICLE

RESEARCH ARTICLE

Recovery of forest cover and connectivity in a mountain ecosystem: evidence from Cofre de Perote National Park

Recuperación de la cobertura forestal y la conectividad en un ecosistema de montaña: evidencia del Parque Nacional Cofre de Perote

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Abstract: *Aim of study:* To assess changes in land-use and landscape connectivity in Cofre de Perote National Park (CPNP), Mexico, from 2017 to 2024, and to understand how different management subzones influence land-use and forest-connectivity dynamics. Knowing more about these processes is essential to guide adaptive management in protected areas facing landscape dynamics due to anthropogenic activities. *Area of study:* This study was carried out in a high-altitude protected area located in the center of the state of Veracruz, Mexico, including its designated buffer zone. *Material and methods*: We classified the land use and vegetation cover of the CPNP using Sentinel-2 satellite imagery at 10 m from 2017 to 2024, applying a Random Forest algorithm for classification. We assessed land use and land cover changes, as well as forest connectivity, across the park's internal management subzones (22,330.47 ha), including forest restoration areas, traditional use, and public use zones, as well as a buffer zone located outside the park boundaries, using the Integral Index of Connectivity. *Main results:* From 2017 to 2024, forest cover increased by 1,290 ha within the park and 386 ha in the buffer zone, primarily replacing grasslands and, to a lesser extent, agricultural lands. Connectivity analysis showed significant improvements in forest cover connectivity values in the park, especially within the forest recovery subzone. However, traditional use and buffer zones exhibited mixed connectivity trends, with some areas experiencing declines due to land cover changes. *Research highlights:* Gains in forest cover and improved connectivity in key subzones represent an opportunity to increase ecosystem integrity and resilience in the face of threats posed by human activities around the CPNP. However, the situation in the buffer zone underscores the urgent need to implement integrated landscape management strategies that include the CPNP and adjacent areas to ensure long-term sustainability and resilience to current landscape dynamics.

Keywords: forest management; integral index of connectivity; protected areas; Random Forest; Sentinel; zonification.

Resumen: *Objetivo del estudio*: Evaluar los cambios en el uso del suelo y la conectividad del paisaje en el Parque Nacional Cofre de Perote (PNCP), México, entre 2017 y 2024, y comprender como las diferentes subzonas de gestión influyen en la dinámica del uso de suelo y la conectividad forestal. Conocer más sobre estos cambios es fundamental para orientar la gestión adaptativa en áreas protegidas que enfrentan dinámicas del paisaje derivadas de actividades antrópicas. Área de estudio: El estudio se llevó a cabo en el PNCP, un área natural protegida de alta montaña ubicada en el centro del estado de Veracruz, México, así como su zona de amortiguamiento. *Material y métodos*: Se clasificó el uso del suelo y la cobertura vegetal del PNCP utilizando imágenes satelitales Sentinel-2 a 10 m de los años 2017 y 2024, aplicando el algoritmo Random Forest. Se evaluaron los cambios en el uso y la cobertura del suelo, así como la conectividad forestal, en las subzonas de manejo interno del parque (22.330,47 ha), incluyendo áreas de restauración forestal, zonas de uso tradicional y de uso público, así como una zona de amortiguamiento ubicada fuera de los límites del parque, utilizando el Índice Integral de Conectividad. *Resultados principales:* Entre 2017 y 2024, la cobertura forestal aumentó en 1.290 ha dentro del parque y 386 ha en la zona de amortiguamiento, reemplazando principalmente pastizales y, en menor medida, tierras agrícolas. El análisis de conectividad mostró mejoras significativas en los valores de conectividad de la cobertura forestal en el parque, especialmente en la subzona de recuperación forestal. Sin embargo, las zonas de uso tradicional y de amortiguamiento mostraron tendencias de conectividad dispares, con algunas áreas experimentando disminuciones debido a los cambios en la cobertura del suelo. *Aspectos destacados de la investigación:* El aumento de la cobertura forestal y la mejora de la conectividad en subzonas clave representan una oportunidad para aumentar la integridad y la resiliencia de los ecosistemas ante las amenazas que representan las actividades humanas en el parque. Sin embargo, la situación en la zona de amortiguamiento subraya la urgente necesidad de implementar estrategias integradas de gestión del paisaje que incluyan el PNCP y las áreas adyacentes para garantizar la sostenibilidad a largo plazo y la resiliencia ante la dinámica actual del paisaje.

Palabras clave: áreas naturales protegidas; índice integral de conectividad; gestión forestal; Random Forest; Sentinel; zonificación.

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Supplementary information ↓

1. INTRODUCTION

In recent decades, effective biodiversity and ecosystem conservation have become increasingly relevant in the face of rapid global environmental change (Dudley, 2008; Donaldson et al., 2017; CBD, 2020). Protected Areas (PAs) are crucial in preserving natural habitats and enhancing landscape connectivity, essential for sustaining ecological processes and ensuring species resilience (Saura et al., 2018; Escobar-Ocampo et al., 2023). A global assessment by Saura et al. (2019) revealed that connectivity between PAs in the Americas has been increasing continuously since 2010, with most of these increases occurring in South America, while connectivity between PAs declined in North America. In Mexico, although connectivity between PAs has shown slight improvements, less than 4% of Mexico's PAs meet the conservation indicators, falling short of the Aichi Target 11 of achieving at least 17% connectivity among protected areas (CBD, 2020).

Changes in connectivity patterns respond primarily to the prevailing processes of land use and land cover change (LULCC). Therefore, understanding the processes of LULCC within and around PAs is a priority and constitutes a task that requires an integrated approach for effective management and conservation planning (Leberger et al., 2020; García-Cuevas et al., 2024). Many factors, including human activities, influence the land-use dynamics of PAs, leading to changes in forest cover and habitat fragmentation, which affect biodiversity and ecosystem functionality (Almeida-Rocha & Peres, 2021). To slow down the change process, it is necessary to design management strategies within the PAs and the broader landscape context that encompasses their buffers or interaction zones (Williams et al., 2005; DeFries et al., 2010; Ward et al., 2018), aspects often overlooked in many studies (Almeida-Rocha & Peres, 2021).

High-altitude forest areas tend to be less susceptible to the intense changes observed in foothills or plain regions (Thomas & Gillingham, 2015), where economic activities are more widespread. Although PAs serve as a buffer against transformation processes and prevent habitat fragmentation and loss of connectivity (Santini et al., 2016), mountainous PAs commonly have circular boundaries and are surrounded by less steep terrain, making them especially vulnerable to turning into ecological islands when habitat fragmentation occurs in their surroundings, particularly in tropical regions where such fragmentation significantly affects biodiversity and ecosystem functions (Collinge, 1996). Despite these challenges, local communities recognize the importance of mountain ecosystems and have developed a close dependency on the goods and services they provide (Pineda-López et al., 2017).

In Mexico, preserving biodiversity is a significant national priority, underscored by establishing and managing 232 PAs nationwide (CONANP, 2025). These efforts align with global conservation goals, promoting various management regimes with specific conservation objectives and zoning criteria (Stolton et al., 2013; CBD, 2020), designed according to the management regimes and land tenure dynamics (Dudley, 2008; Ward et al., 2018; DOF, 2024). As critical tools for conservation, PAs are designated for various reasons, including the urgent need to conserve priority ecosystems and species or even to confront the effects of climate change (Gillingham et al., 2015; Thomas & Gillingham, 2015). Guided by national policies and legislation, the General Law of Ecological Balance and Environmental Protection (Ley General del Equilibrio Ecológico y Protección al Ambiente, LGEEPA; DOF, 2024) provides a structured framework for classifying, managing, and protecting different types of PAs. This framework ensures the preservation of natural heritage while considering the livelihoods of local communities. Consequently, conservation efforts are suited to regions with a particular ecological, geographic, and socioeconomic context, resulting in diverse objectives and management strategies to effectively conserve Mexico's unique ecosystems and species (DOF, 2024).

National Parks in Mexico belong to one of the nine categories of PA described in the LGEEPA (DOF, 2024). They are characterized by representing ecosystems that stand out for their scenic beauty and for the presence of diverse species of flora and fauna, equivalent to the National Park IUCN designations that fall into the II management category (Dudley, 2008). This means they protect large-scale ecological processes while integrating environmental, cultural, recreational, and scientific opportunities (Stolton et al., 2013; Leberger et al., 2020; DOF, 2024). The Cofre de Perote National Park (CPNP) stands out for its ecological significance and its strategic location within a biodiverse region in the eastern extreme of the Mexican Transition Zone, the border between the Neartic and Neotropic realms (SEMARNAT & CONANP, 2015). CPNP is a mountain embedded in a tropical landscape, crucial for providing ecosystem services in central Veracruz (Román-Jiménez et al., 2016; Pineda-López et al., 2017). Furthermore, CPNP contributes to the connectivity of the regional PA network, enhancing the ecosystem resilience to disturbances (García-Alaniz et al., 2017; Saura et al., 2019; Barnett et al., 2021). Unfortunately, according to Espinoza-Guzmán et al. (2023), the forest cover in CPNP has been affected mainly by extractive activities within the park. These activities have led to changes in the landscape configuration and, consequently, in the ecological connectivity of the forest cover. It is necessary to analyze these processes to identify the direct and underlying causes of these pressures and to develop management strategies to mitigate their effects (DeFries et al., 2010).

In this study, we analyzed land-use and forest-cover connectivity changes in CPNP from 2017 to 2024. Specifically, we examined these dynamics at two spatial scales: 1) the entire park and its surrounding buffer zone, and 2) individual management subzones, defined by the different conservation strategies established in the park's management program. By incorporating both scales, we aimed to elucidate how distinct management regimes influence LULCC patterns and forest-connectivity dynamics within the protected area.

2. MATERIAL AND METHODS

2.1. Study area

Cofre de Perote National Park (CPNP) is located in the intertropical zone of the Northern Hemisphere, within the Trans-Mexican Volcanic Belt. It covers 11,530 ha and ranges from 3,000 to 4,250 m above sea level, occupying the upper portion of Cofre de Perote, the eighth-highest mountain in Mexico, between 19°29'21.98" N and -97°09'00.44" W (SEMARNAT & CONANP, 2015). The park encompasses fractions of the municipalities of Perote, Xico, Ixhuacán de los Reyes, and Ayahualulco, and is part of the physiographic subprovinces Lagos y Volcanes del Anáhuac and Chiconquiaco. CPNP vegetation is dominated by temperate forests composed primarily of *Pinus hartwegi*i L., *Pinus Montezumae* L., *Pinus pseudostrobus* L., *Abies religiosa* K., and *Juniperus* species, forming vegetation mosaics that range from open canopy woodlands to mature, closed forests. CPNP follows a classical altitudinal and succession gradient and is subject to different management regimes.

Although CPNP was established in 1937 (SEMARNAT & CONANP, 2015), it did not have a management program (MP) until 2015. The MP aims to provide conservation and restoration management guidelines and establish the park's administration's activities, actions, and basic guidelines (SEMARNAT & CONANP, 2015). The MP has established zoning of the CPNP polygon according to the degree of conservation and ecosystem representativeness. There are currently three administrative zones with different management regimes: 1) Traditional Use Subzone (TU). This zone includes areas traditionally used for subsistence agricultural activities by local communities. Permitted activities include farming and livestock in pre-existing areas, extractive activities for self-consumption, low-impact tourism, non-extractive use of natural resources, and research. Prohibited activities include creating new population centers, expanding urban infrastructure, and using material banks. 2) Public Use Subzone (PU). This zone features a main cobblestone road, a network of roads and trails for visitors, and telecommunications infrastructure. Permitted activities include maintaining visitor concentrations, constructing facilities for tourism support, research, environmental monitoring, and environmental education. Camping, scientific collecting, bonfires, infrastructure maintenance, trail signage, and low-impact tourism are allowed. Prohibited activities include agriculture, new trail openings, extractive uses, and livestock. Lastly, 3) Forest Recovery Subzone (FR). This zone ensures long-term maintenance and allows scientific activities, environmental education, scientific collection, low-impact tourism, and forest cover management. Prohibited activities include landscape modification or extractive activities.

Since there is no officially declared buffer zone in the CPNP, the PA statute under the LGEEPA requires the establishment of a zone of influence. This area should include landscapes like those within the PA, but with different degrees of land use transformation or human occupation. Due to the interactions with the economic, social, and environmental factors, productive activities in these influence areas tend towards sustainability, allowing the continuity of the ecosystems' evolutionary processes within the National Park. In this sense, the zone of influence of the CPNP extends two kilometres around the three-thousand-meter line and includes an area of 10,922 hectares, equivalent to a Buffer zone (BZ) (Figure 1).

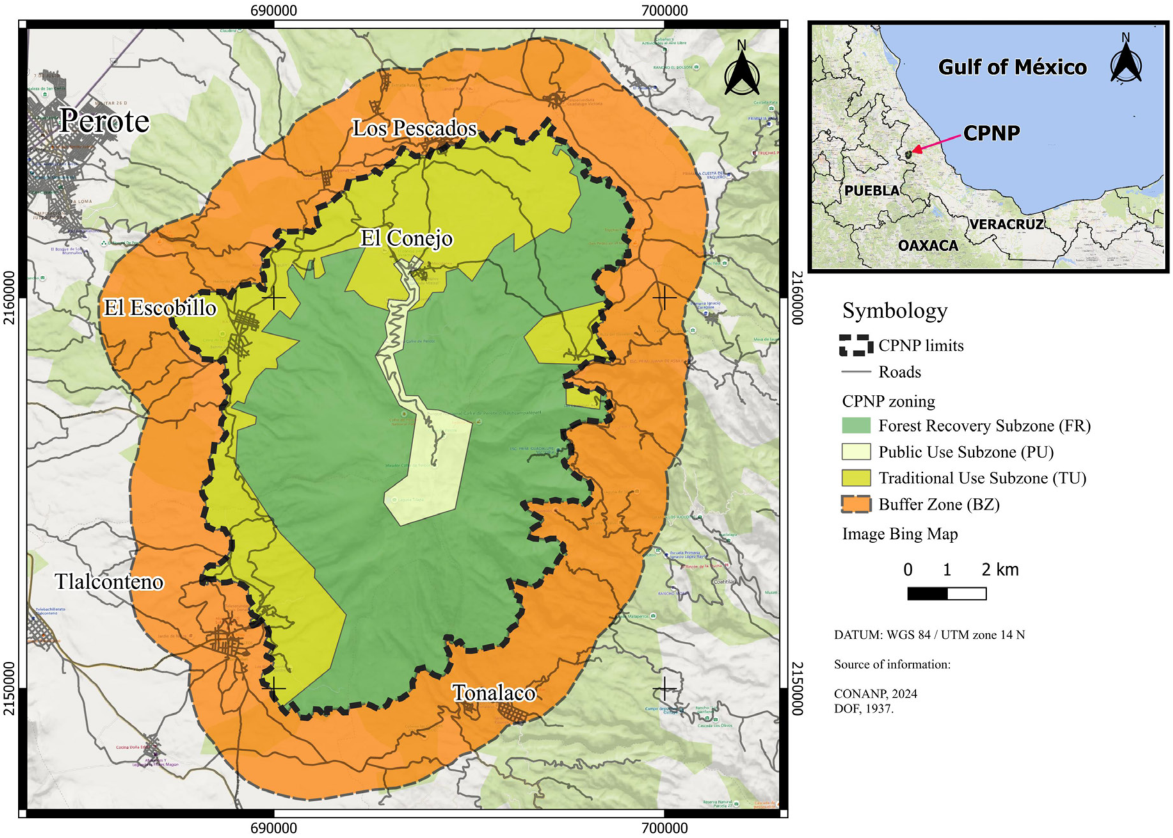


Figure 1. Location of the Cofre de Perote National Park (Mexico) and the conservation zoning.

2.2. Dynamics of Land use - Land cover change

To determine the changes in land use and forest cover in the CPNP, we used two multispectral scenes from the Sentinel-2 satellite at 10 m, dated February 23, 2017, and April 22, 2024. These scenes, sourced from the Copernicus Open Access Hub (https://www.sentinel-hub.com). The study area is mainly in the T14QPG image, and a small portion is in the T14QQG scene, so a “mosaic” was made, which has the first scene as a reference. The satellite images correspond to the dry season in the study area and were chosen for their minimal cloud cover (less than 10%). We made this choice to facilitate the process of interpretation and the accuracy of our analysis. Radiometric correction was then applied through the SNAP program’s automatic Sen2Cor algorithm, with the most appropriate aerosol type (rural) for a mid-winter latitude and ozone concentration of 331 Dobson units, which prevents underestimating the reflectance in multispectral bands (Congedo, 2021). The selection of the aerosol type (in this case, rural) is essential for accurately modeling the scattering and absorption of solar radiation in the atmosphere. We chose this aerosol because of its similarity to representative land uses in the area. In the case of atmospheric correction, it is necessary to know the amount of ozone present because it absorbs radiation in certain spectral bands (ACRI-ST, 2024).

We then developed the supervised land use and vegetation classification using 1,050 reference points obtained from other studies conducted in the study area (Espinoza-Guzmán et al., 2023). This georeferenced information was processed using the QGIS 3.28 program, in which we created land use and vegetation reference points and generated the spectral signatures corresponding to 13 land use and land cover (LULC) categories: 1. Water bodies, 2. Rainfed agriculture, 3. Agricultural (irrigation), 4. Cropland (no vegetation cover), 5. Urban, 6. Forests (coniferous and broadleaf), 7. Zacatonal (high mountain grassland), 8. Burned areas, 9. Shade (cloud and topographic), 10. Tepetzilera, 11. Induced grassland, 12. Natural grasslands, 13. Bare soil. Land use in the Tepetzilera category refers to simple or stratified pyroclastic deposits of lapilis pumitico (tepetzil) (Geissert & Meza, 2016). We then used the Semi-Automatic Classification Plugin (SCP) module version 3.0 (Congedo, 2021) to classify each scene. In the SCP, we generated a composition of bands (8, 4, 3, 2) of the Sentinel-2 satellite with the corresponding band centers (SUHET, 2015). This combination makes it easy to obtain an image in realistic natural colors (commonly called “true color”). It is very useful in thematic analysis and visualization for environmental, agricultural, and land-use interpretation. The band centers represent the spectral midpoint of each sensor band, defining the central wavelength at which that band is most sensitive to capturing radiation reflected or emitted by the Earth’s surface. Subsequently, with the “SCP dock” plugin (Congedo, 2021), we created 537 regions of interest (ROIs), with 296 for the 2017 images and 241 for the 2024 images.

The Sentinel-2 scenes for 2017 and 2024 were classified using the supervised machine learning algorithm Random Forest (RF), a widely used method in classification and regression (Belgiu & Drăguţ, 2016). This algorithm provides accurate and fine-scale separation of pixel groups by considering spatial autocorrelation and non-parametric data, building decision trees on different samples, considering majority vote for classification, and averaging in case of regression, allowing for better-informed decisions based on larger-scale data (Genuer et al., 2010; Schonlau & Zou, 2020; Yin et al., 2023). Using the RF algorithm available in the SCP plugin of QGIS, we performed the supervised classification based on the ROIs and ground truth points for the images from 2017 and 2024, as indicated by Congedo (2021). The RF processing parameters included 3,000 training samples and 1,000 random trees, with the classifier evaluated for each Sentinel-2 scene.

We then applied a smoothing process to the image resulting from the RF algorithm in “tiff” format. The process replaces isolated pixel values with the value of the largest neighboring patch to generate more homogeneous regions that facilitate the interpretation of the classification (Jensen, 1996). This is useful for removing small patches from a classification through the SIAVE Classification option of the SCP console in the QGIS 3.28 program with a threshold size of two. Subsequently, the smoothed image was recategorized to reduce noise from 13 categories into eight classes: 1) water, 2) shadow, 3) bare soil, 4) forest, 5) grassland, 6) urban, 7) agriculture, and 8) burned, using the reclassification by table tool available in the QGIS 3.28 toolbox. In this case, the rainfed and irrigated agriculture categories were combined into a single agricultural class, and herbaceous and shrub species, such as grasslands and tepetzil, were added to another class. This new categorization was validated with random point and Accuracy Assessment and Area Estimation Using Thematic Maps (ACATAMA) methodology proposed by Olofsson et al. (2014), as well as the Accuracy Assessment methodology proposed by Belgiu & Drăguţ (2016). The parameters indicated in the ACATAMA plugin for sample calculation used a standard error of 0.025, while the distance between samples was 500 meters. The pixel aggregation was 8, the minimum. With the parameters mentioned above, it was found that 346 verification sites were used in 2017, while 390 samples were used in 2024.

Subsequently, we analyzed the resulting layers with the TERRSET (CLARKU, 2025) program using the Land Change Modeler for Ecological Sustainability, a module developed to obtain information on the net changes and their spatial location in the studied area, facilitating the establishment of action plans and future scenarios to ensure resource conservation. We also calculated landscape metrics to obtain information about patches and their edges using the Patch Analysis module in ArcMap (ESRI, 2014). Next, the trajectories and rates of change in land uses and forest covers between the two dates were determined to clarify the dynamics of transformation in the study area. Finally, we determined the rates of change according to the formula proposed by Puyravaud (2003):

Equation 1

$$\mathrm{r} = \left[\left(\frac{1}{\mathrm{t1}-\mathrm{t2}}\right)\right] \ln\left(\frac{\mathrm{A2}}{\mathrm{A1}}\right)$$

where r corresponds to the annual percentage of forest cover loss calculated from the extension of the area of land use covers (A1 and A2) at separate times (t1 and t2). This formula provides more precise information and is more intuitive than that used by the FAO (1995) to calculate exchange rates, because it calculates relative and comparable rates of change between regions and periods, with a more robust mathematical basis based on the exponential model (Puyravaud, 2003).

2.3. Connectivity analysis

To estimate connectivity between forest patches in the CPNP, we used the graph-based "Conefor Sensinode 2.6" program (Saura & Torné 2009). We calculated the Integral Index of connectivity (IIC) for the two dates described above (2017 and 2024). In this index, each forest patch is represented as a node, and potential dispersal pathways between pairs of patches are represented as edges (links) whenever the Euclidean edge-to-edge distance between them is equal to or less than a user-specified threshold. Thus, we selected a distance threshold ≤ 1,000 m. This value has been used in other studies as a practical convention or threshold that seeks to include most dispersal events, including long-distance dispersal events that are key to the long-term dynamics of landscapes (Hämäläinen et al., 2019; Tiang et al., 2021; Hernández et al., 2024). According to Nathan (2006), this threshold also provides a robust approximation of overall connectivity among vegetation patches. Patch size (area; in ha) was used as the attribute value assigned to each node, thereby weighting connectivity calculations by habitat availability. Patch size (area, in ha) was used to assign attribute values to the nodes, thereby weighting connectivity calculations by habitat availability at the landscape scale. Additionally, we estimated the delta Integral Index of Connectivity components (dIICintra, dIICflux, and dIICconnector), which decompose the contribution of each patch to overall landscape connectivity (Saura & Rubio, 2010). Specifically, dIICintra reflects the contribution of patch k to habitat availability through its area (independently of its connections), dIICflux corresponds to the area-weighted potential dispersal flux between patch k and all other patches (i.e., how well patch k is connected to the rest), and dIICconnector quantifies the role of patch k as a stepping stone facilitating connectivity between other patches (topological importance in the network) (Saura & Torné, 2009; Saura & Rubio, 2010). Finally, we classified patch contributions into three categories of connectivity change (high, moderate, and low) based on the Jenks natural breaks method in QGIS 3.28. These breaks were calculated for the first date (2017) and then duplicated into the second one (2024) to make them comparable. To detect changes in connectivity raw values between years, we used the raster calculator to obtain positive values (indicating increases in connectivity) and negative values (indicating decreases) between years.

2.4. Topographic correction

Given the intricate topographic characteristics of CPNP, which may lead to underestimated surface area measurements by overlooking terrain roughness, we conducted a topographic correction (TC) across the entire study area. We employed an arithmetic distance method (Equation 2) that incorporates the cosine slope value in radians for each pixel multiplied by its planimetric area derived from a digital elevation model (DEM) at a scale of 15 m. The Mexican Elevation Continuum (INEGI, 2013) served as our DEM source.

Equation 2

$$\mathrm{TC} = \left(cos\ cos \left(\frac{slope\ DEM^{*}\pi}{180} \right) \right) \mathrm{s}^2$$

where *s* = pixel side.

3. RESULTS

The changes analysis showed a significant increase in forest cover over the last seven years, with gains of 1,290 ha (topographic) and 1,214 ha (planimetric), indicating a recovery trend (Table 1). Forests have primarily replaced grasslands and, to a lesser extent, agricultural areas. On the other hand, grasslands showed marked losses, decreasing by 2,242 ha (topographic) or 2,162 ha (planimetric), with changes mainly directed towards agricultural activities and forest cover recovery. The decrease in areas without vegetation is evident, particularly where they have been converted to croplands (Figure 2).

Table 1. Differences (DR dif) in surfaces and deforestation rates (DR) in Cofre de Perote National Park (Mexico) between 2017 and 2024. The table includes planimetric and topographic calculations. LU = Land use, AG = Agriculture, HS = Human settlements, FO = Forest, GL = Grassland, BU = Burned, BS = Bared soil

LU	**Planimetric** (P)				**Topographic** (T)				**P vs. T**
	2017 (ha)	**2024** (ha)	**Gain (+) Loss (-)**	**DR**	**2017** (ha)	**2024** (ha)	**Gain (+) Loss (-)**	**DR**	(**DR dif**)
AG	298.63	2,861.12	+2,562.49	32.31	301.37	2,919.75	+2,618.38	32.47	0.16
HS	258.64	273.14	+14.50	0.78	261.29	275.19	+13.90	0.74	-0.04
FO	12,079.49	13,293.09	+1,213.60	1.37	12,982.91	14,272.85	+1,289.94	1.35	-0.01
GL	6,752.24	4,590.57	-2,161.67	-5.52	7,027.39	4,786.27	-2,241.13	-5.49	0.03
BU	58.14	59.22	+1.08	0.26	58.22	59.75	+1.52	0.37	0.11
BS	2,749.77	1,097.28	-1,652.49	-13.14	2,827.65	1,125.30	-1,702.34	-13.18	-0.04

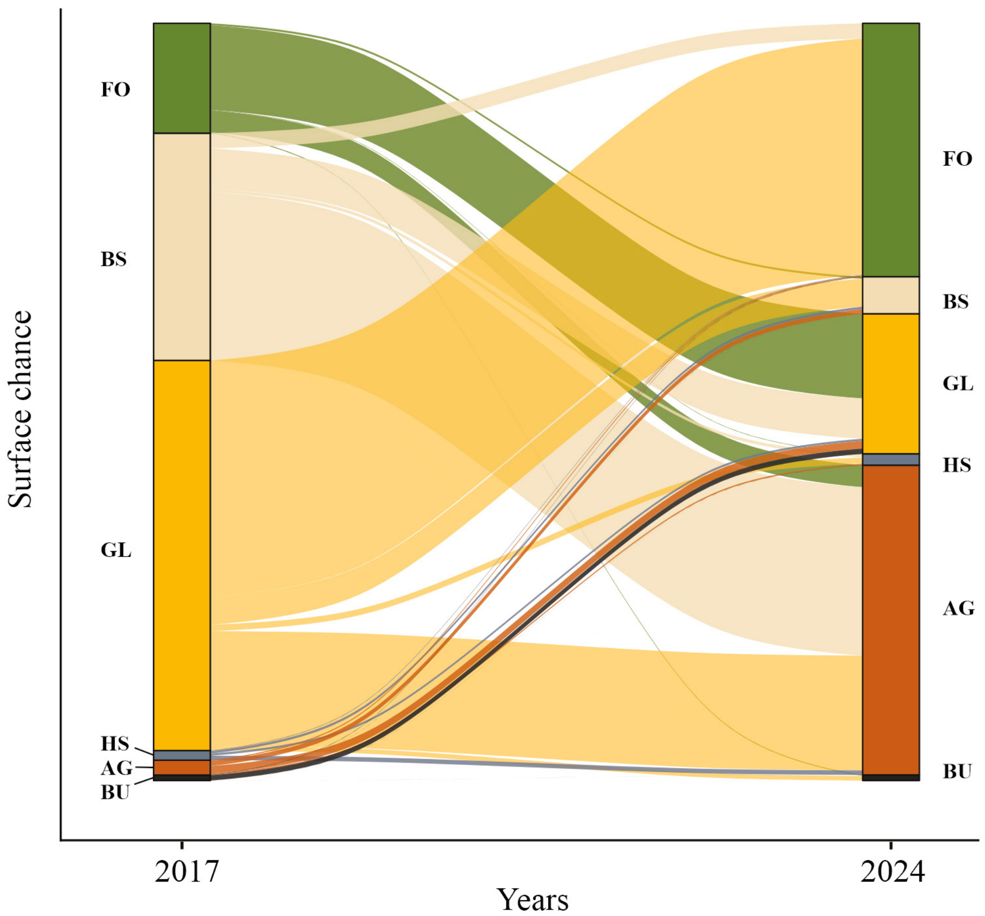


Figure 2. Land Use - Land Cover Change between 2017 and 2024 in Cofre de Perote National Park (Mexico). AG = Agriculture, BS = Bared soil, BU = Burned, FO = Forest, GL = Grassland, HS = Human settlements. Two additional categories (Water bodies and Shade) were included in the analysis but are not shown here, as they had no detectable change or too few pixels, and were omitted to improve visual clarity.

The differences between the two estimation methods were most evident in forest (+980 ha difference) and grasslands (+196 ha difference) categories. Agricultural land showed substantial growth of +2,618 ha (topographic) and +2,562 ha (planimetric) largely in burned, bare-soil, and grassland areas. Forests expansion was also consistent across both methods, although slightly higher in the topographic calculation (Table 1). Annual deforestation rates indicate a high transformation in agricultural lands (32.31) and areas with bare soil (-13.14). Regarding the difference in deforestation rates between planimetric and topographic surfaces, the largest occurred in land uses classified as burned (0.11) and agriculture (0.16) (Table 1).

The LULCC analysis within the CPNP showed distinct dynamics across its management regimes (Supplementary material Table S1). In the FR zone, the most significant changes were grassland converting to forest, totalling 908 ha (planimetric) or 986 ha (topographic), consistent with reforestation efforts. Additionally, grassland conversion to agriculture covered only 19 ha, while bare soil converted to forest covered 73 ha. In contrast, the PU zone underwent slight transformations, including the conversion of grassland to forest, which covered up to 33 ha. The TU underwent significant changes, particularly in converting grassland to forest (307 ha / topographic) and bare soil to agriculture (542 ha / topographic). The BZ displayed the most extensive land use changes, particularly the conversion from grassland to forest (807.42 ha planimetrically and 836.08 ha topographically) and from bare soil to agriculture (919.35 ha planimetrically and 935.36 ha topographically). Regarding landscape metrics, the results indicate that forest and grassland areas reduced their patch count, while forests also increased their average patch size. Agriculture increased patch size but reduced patch count, which could suggest that agricultural areas are now more concentrated. On the other hand, edge density decreased in both grassland and forest areas (Table 2).

Table 2. Landscape metrics of Land Use - Land Cover (LULC) of Cofre de Perote National Park (Mexico) between 2017 and 2024. AG = Agriculture, BS = Bared soil, BU = Burned, FO = Forest, GL = Grassland, HS = Human settlements

	NumP		**MPS**		**TE**		**ED**	
LULC	**2017**	**2024**	**2017**	**2024**	**2017**	**2024**	**2017**	**2024**
AG	3014.00	2763.00	0.10	1.04	424260.00	1802540.00	18.98	80.70
BS	4870.00	2280.00	0.57	0.48	1311640.00	850580.00	58.69	38.08
BU	130.00	153.00	0.44	0.39	36200.00	41580.00	1.62	1.86
FO	4763.00	2184.00	2.54	6.10	3024860.00	2734380.00	135.34	122.42
GL	9293.00	6872.00	0.73	0.67	3643740.00	2917780.00	163.03	130.63
HS	884.00	429.00	0.29	0.63	196540.00	192160.00	8.79	8.60

In the park area, connectivity increased by 14,184 ha (topographic surface), mainly in forest and agricultural covers, reducing the overall fragmentation within the park. On the other hand, we recorded a loss of connectivity in 3,432 hectares of the total PA area, distributed across different management regimes. This loss was particularly concentrated in the BZ, which is not formally included in the decree, and in the TU zone, one of the less restrictive management areas. In Figure 3, high-connectivity areas expanded notably between 2017 and 2024, especially across the central and northern regions of the CPNP, indicating improved structural connectivity. The changes observed in the individual components of the dIIC (dIICintra, dIICflux, and dIICconnector) are presented in Suppl. Figure S1 (1, 2, 3) in the appendix, which show patterns of improvement in local habitat, stability of flow with slight expansions, and an increase in key connection patches on the periphery of the park. Taken together, these results point to stable or slightly improved connectivity across the landscape, with some patches becoming more important in maintaining forest connectivity. Specifically, in the case of dIIC*connector*, which measures the role of each patch as a stepping stone linking other patches. We observed a clear increase in the area of patches functioning as key connectors, particularly at the periphery of the CPNP. This reflects the fact that some new or growing patches are contributing more strongly to forest connectivity.

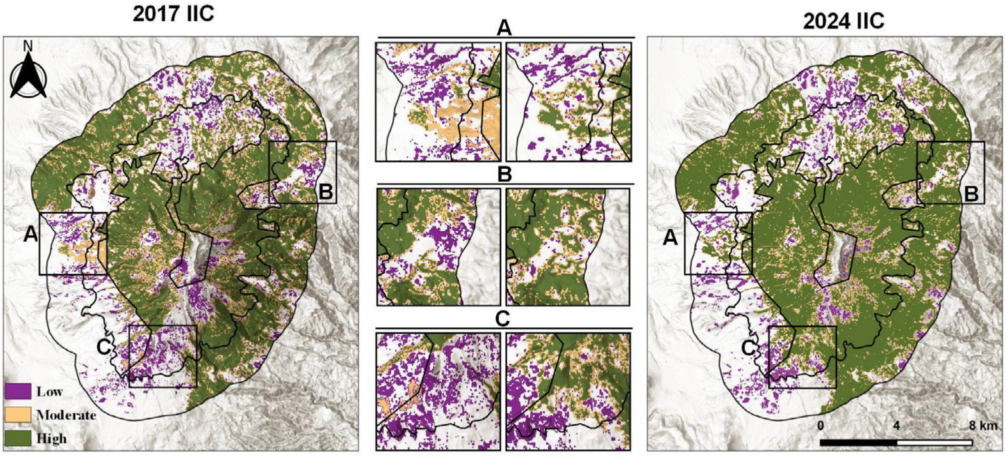
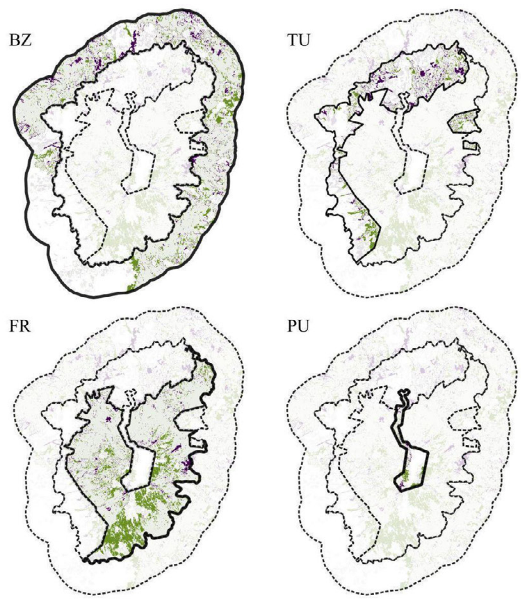
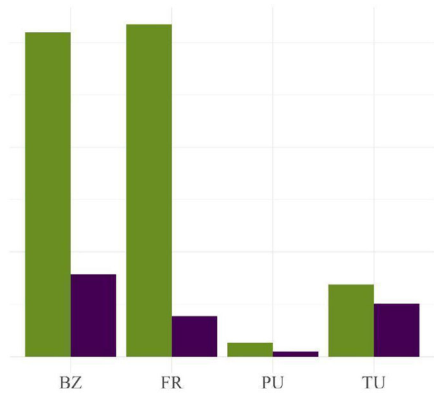


Figure 3. Spatial contribution of forest patches to overall connectivity by the Integral Index of Connectivity (IIC) for 2017 and 2024 in Cofre de Perote National Park (Mexico). Each date includes windows (labelled **A**, **B**, and **C**) that provide zoomed-in views of selected areas.

Regarding the management regimes, the increase in connectivity was particularly significant in the FR subzone, reflecting the effectiveness of conservation strategies in this area. In contrast, the BZ and TU subzones exhibited variable connectivity trends, with certain areas improving and others declining. These contrasting patterns likely reflect differences in land-use pressures and management practices within the BZ and the TU subzones (Figure 4). We observe that the areas that have experienced connectivity decreases are primarily small, scattered patches, mainly located in the northern and northeastern parts of all management regimes near El Conejo, Los Pescados, and El Llanillo Redondo communities, except for the PU and FR categories, which experience connectivity decreases in central patches (Figure 4). Although the BZ has experienced the highest loss in quantity, it generally shows small decreases in connectivity values. Conversely, we found the most significant losses regarding higher values in the area shared between the BZ and TU (northern region). On the other hand, the increase in connectivity is more concentrated in the southern and southwestern parts of the CPNP, with some large and continuous patches mainly located in the FR management regime and its adjacent areas.





	Management category	Planimetric		Topographic	
		In	De	In	De
BZ	Buffer zone	5,762	714	6,193	1,568
TU	Traditional use	1,263	504	1,375	1,018
FR	Forest recovery	5,699	316	6,349	744
PU	Public use	225	42	267	102

Figure 4. Surface area of increase and decrease in connectivity values by management regime in Cofre de Perote National Park (Mexico). The figure shows areas in planimetric and topographic measurements. The surface area with increased connectivity is green, the areas with decreased connectivity are purple, and all values are in hectares. In = Connectivity increase, De = Connectivity decrease. Bar graphs correspond to topographic estimations.

4. DISCUSSION

In Mexico and North America, temperate and tropical dry forests have the highest deforestation rates related to land use- land cover change (Bonilla-Moheno & Mitchell, 2020; Gutiérrez-Hernández et al., 2021; López-Mendoza et al., 2022). Therefore, the significant increase in forest cover in the CPNP exemplifies the positive outcomes of targeted management strategies aimed at reducing deforestation rates and enhancing landscape connectivity (SEMARNAT & CONANP, 2015). As an example, the Restoration Subprogram outlined in the MP proposes strategies of ecological restoration through both active and passive activities. These include soil conservation practices, reforestation with native species, and hydrological rehabilitation. Complementary initiatives, such as restoration facilitation techniques (Sánchez-Velásquez et al., 2016) and the implementation of the national "Payment for Environmental Services" program (CONAFOR, 2021), have further incentivised forest conservation by providing financial support to local landowners inside the PA. Over the past seven years, these coordinated interventions have enabled the recovery of 1,445 hectares of forest cover within the PA and an additional 879 hectares in its BZ. This forest expansion contributes directly to improved ecological connectivity across the landscape, a trend already documented in other regions of Mexico (Galindo-Cruz et al., 2024; García-Cuevas et al., 2024).

The analysis of land use-land cover changes and the calculation of landscape metrics across different periods provided relevant information on how the patterns changed over time. When generating the land use and vegetation classification with Random Forest (RF), a certainty of 0.993 was obtained, in relation to the ground truth (or reference) points. These results are consistent with the standards set by Belgiu & Drăguţ (2016), as well as the evaluation suggestions by Olofsson et al. (2014) for thematic maps. As has been proven in previous works, RF is well-known for its consistency and robustness in analyzing high spatial resolution remote sensing images (Sheykhmousa et al., 2020). Furthermore, the connectivity index (IIC, dIICflux, dIICintra, and dIICconnector) provides relevant information for conservation management decision-making, as these graph-based metrics allow both the overall connectivity of the landscape to be assessed and individual habitat patches to be prioritized (Saura & Rubio, 2010; Santini et al., 2016; Saura et al., 2018). These indices provide a solid basis for conservation planning, and they can be complemented, where appropriate, with additional approaches based on species-specific models to refine conservation strategies, mainly when focusing on the habitat requirements of focal species (Neel et al., 2014; Santini et al., 2016; López-Mendoza et al., 2022).

Additionally, topographic correction reduces bias in surface calculations, providing more accurate information about changes in land use - land cover and connectivity in the study area. Traditional planimetric calculations assume a flat surface, which systematically reduces the estimated extent of vegetation cover in mountainous regions (Hoechstetter et al., 2008; Ghandehari et al., 2019; Galindo-Cruz & Rojas-Soto, 2023). By correcting surface area to account for slope and terrain heterogeneity, the estimates of forest cover change and connectivity become more realistic and spatially accurate. This refinement is critical in rugged landscapes such as the PNCP, where topography strongly influences both the distribution of vegetation and the functional connectivity of habitats. Incorporating surface area correction, therefore, provides a more reliable baseline for monitoring LULC dynamics and supports more robust conservation planning.

Land use – land cover change is the principal driver for fragmentation, loss of connectivity, and edge increase, which promote species isolation and, eventually, local extinction (Sawyer et al., 2011). In the CPNP, afforestation rates (~1.35) are favourable and similar to those reported by García-Cuevas et al. (2024) for the Flora and Fauna Protection Area "Nevado de Toluca" (~ 2.0), another mountain PA in Mexico. This similarity supports that effective zoning and land-use planning are crucial for biodiversity conservation and land-use management within protected areas (Dudley, 2008; SEMARNAT & CONANP, 2015). CPNP's zoning scheme, which delineates areas for strict conservation, restoration, and sustainable use, can be refined to improve connectivity. For instance, authorities should also manage the BZ to avoid fragmentation by encouraging reforestation and restricting land uses that lead to habitat degradation (Almeida-Rocha & Peres, 2021). Connectivity metrics can support zoning adjustments and can optimize conservation outcomes by aligning management practices with ecological connectivity objectives (García-Alaniz et al., 2017). In the case of protected areas, such changes can be incorporated by stakeholders into management programs, which, under Mexican law, must be reviewed every five years (DOF, 2024).

The resulting landscape metrics support this management perspective, showing connectivity increases within CPNP, particularly in the TU and FR subzones, suggesting an enhanced ability of the park's administration to support ecological processes. Forest and grassland areas reduced their patch count, with forests also increasing their average patch size, reflecting habitat consolidation and recovery of connectivity. Agriculture, conversely, displayed fewer but larger patches, indicating a more concentrated expansion that could compromise ecological integrity. Edge density declined in both forest and grassland areas, further indicating reduced fragmentation. These structural changes are also consistent with connectivity outcomes. For example, the improvement in forest connectivity in the CPNP is likely a result of the conversion of grasslands and agricultural areas to forest cover. Increases in dIIC*intra* values indicate greater habitat availability contributed by individual patches, either through larger patch size or improved quality, while stable or slightly increasing dIIC*flux* values indicate consistent ecological flow, meaning that focal patches remain well connected to their surroundings. The dIIC*connector* values increase highlight patches that have gained importance as stepping stones, strengthening their role in linking new parts of the landscape network. All these results suggest that targeted conservation efforts and natural regeneration processes enhance landscape connectivity and habitat restoration. This enhancement is consistent with findings that indicate effective conservation strategies should prioritize connectivity to ensure ecological networks are maintained, allowing species to adapt to changing environments (Neel et al., 2014) and also with broader conservation goals, such as the Aichi Biodiversity Targets, which aim to enhance habitat connectivity globally to support the critical role of landscape connectivity in supporting ecological process and species resilience (Saura et al., 2018; CBD, 2020).

One of the problems of PAs is that the polygons that delimit them remain static over time, making them less resilient to landscape changes and the effects of climate change (Belote et al., 2017). Conserving landscape connectivity is critical for maintaining biodiversity and ecological processes across fragmented landscapes (Leija & Mendoza, 2021; López-Mendoza et al., 2022; Escobar-Ocampo et al., 2023). For this reason, current conservation trends focus on complementing PAs with areas that enhance species connectivity, contributing to resilience against climate change impacts and reducing the effects of deforestation (Donaldson et al., 2017; CBD, 2020). Over long periods, changes in species ranges are expected to take place (Thomas & Gillingham, 2015), emphasising the need to maintain forest connectivity in the adjacencies to PAs or promote dynamic reserves to prevent the PA from becoming ecological islands (Gillingham et al., 2015).

Although conservation biology theory constantly states that circular reserves are more effective than elongated ones (Donaldson et al., 2017), this refers to the core ratio more than the edges *per se*. However, PAs with circular boundaries, such as mountain PAs, can be particularly susceptible to becoming ecological islands due to their geometric isolation (Collinge, 1996), which often limits the movement of species between the protected core and surrounding habitats. The connectivity of PA networks depends significantly on the strategic placement of key connectors within the landscape, which uphold ecological fluxes and sustain native biota's long-term viability (Saura et al., 2018, 2019). Thus, severe fragmentation in the BZ of CPNP can lead to isolation from other ecological zones, hindering species dispersal and reducing ecological resilience, increasing the risk of genetic and demographic extinction (Williams et al., 2005; Sawyer et al., 2011). This phenomenon has been observed in several ecological studies in which the geographic shape of a protected area can influence its ecological connectivity and overall conservation effectiveness (Collinge, 1996; Donaldson et al., 2017). Different studies examine the effectiveness of protected areas, pointing out that large areas with stricter management can be more effective in safeguarding species (Li et al., 2024), for example, Maiorano et al. (2008) point out that the ability to resist changes in land use is related to size and that the smaller they are, the less viable they will be in the future.

According to Barnett et al. (2021), the CPNP acts as an ecological bridge connecting several protected areas along the Sierra Madre Oriental (Garcia-Alaniz et al., 2017), the Transmexican Volcanic Belt, and the Altiplano, with potential links or bridges to the Sierra Madre Occidental and Sierra Madre del Sur networks. Our results show gains in forest cover and improved connectivity within the CPNP, strengthening the role of the park as a stepping stone by reducing fragmentation and enhancing the park's ability to sustain ecological flows beyond its boundaries. Strengthened connectivity within the park and in its buffer areas thus increases the likelihood of maintaining functional links between PAs in the states of Puebla, Tamaulipas, Coahuila, San Luis Potosí, Durango, and even southern Texas as part of a regional PA network. Therefore, maintaining and improving connectivity between CPNP and surrounding habitats is crucial to prevent isolation. This can be achieved through targeted conservation strategies and improved land management practices, such as designing or implementing ecological or biological corridors (e.g., CESMO; García-Alaniz et al., 2017; López-Mendoza et al., 2022).

Safeguarding the integrity of the BZ against perturbations is essential to avoid fragmentation of the regional network and ensure species' mobility (DeFries et al., 2010; Barnett & Belote, 2021). Thus, understanding socio-ecological dynamics stands as a key factor in the success of effective conservation planning. Participatory environmental zoning enhances sustainability by aligning conservation initiatives with communities' needs and cultural values, thereby avoiding land tenure conflicts (Ward et al., 2018). Involving local communities in participatory decision-making can improve governance and ensure sustainable resource management within the park and its buffer zone. Engaging local communities in conservation governance is crucial for the long-term success of PAs. Participatory approaches involving stakeholders in decision-making promote a sense of ownership and responsibility toward conservation efforts. Furthermore, the concept of the interaction zone (DeFries et al., 2010) should be considered beyond the influence area of the PA, as it includes the social dynamics that constantly interact with the edges of protected areas. This broader consideration can help understand and manage the socio-ecological interactions that influence the sustainability of conservation efforts. In the case of CPNP, involving local communities in reforestation and land management practices could ensure that conservation actions are more effective and resilient. For that reason, in the future, we propose working on participatory environmental zoning to promote connectivity under a governance scheme that encourages the co-management of resources within the park boundaries and its buffer zone.

The results indicate a recovery of forest cover within the CPNP, improving internal connectivity patterns. However, changes are intensifying in its area of influence, which increases the risk of protected area isolation. Using satellite images and analysis methods to determine the dynamics of land use – land cover changes and connectivity on different dates is a clear alternative to evaluating management actions and proposing new strategies in the context of the CPNP, other PAs, or ecological corridors. Specifically, we suggest implementing and reinforcing management and conservation strategies that involve people in communities around the buffer zone to guarantee that it retains long-term connectivity around and inside the park.

Supplementary information ↑

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Supplementary material

Table S1 and Figure S1**:** accompanies the paper on *Forest Systems*' website.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Authorship contribution statement

Marco Antonio Espinoza-Guzmán: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Alejandra Galindo-Cruz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Francisco Javier Sahagún-Sánchez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

The authors employed Grammarly / ChatGPT to support language editing, grammar correction, and translation tasks. These tools were employed to enhance clarity, improve readability, and refine the overall structure of the manuscript during preparation. Final content was critically reviewed and approved by the authors. Following their use, the authors assumed full responsibility for the publication's content and reviewed and edited it as necessary.

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