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Research article

Ecosystem services and indicators for temperate forests in Mexico

Servicios ecosistémicos e indicadores para los bosques templados de México

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Abstract

Ecosystem services (ES) are the direct and indirect contributions of nature to the well-being of society. Their measurement requires indicators for sustainable forest management. The objective was to develop a set of indicators and metrics to assess ES in the temperate forests of Mexico. A systematic review (1990-2025) was conducted, following the Prisma standard (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), analyzing a final *corpus* of 1274 publications (669 global and 605 national). Bibliometric analysis, using the Rayyan and VOSviewer platforms, showed that research on supporting, regulating, and provisioning ES dominates at the national level (48.6 %, 37.3 %, and 12.4 %, respectively): biodiversity, carbon storage and sequestration, water flows, disturbances, timber, and biomass; while cultural ES are underrepresented (1.7 %). Through multi-criteria evaluation and a Delphi panel of 20 experts (95 % global consensus), an operational framework aligned with CICES (Common International Classification of Ecosystem Services) V5.2 was developed, comprising four categories, 19 types of ES, and 43 indicators (25 provision, 10 regulatory, 5 cultural, and 3 supporting). The results highlight the need to employ biophysical metrics validated *in situ*, capable of reflecting the multifunctionality of the ecosystem. The proposed set of ES, indicators, and metrics will serve as an operational tool to guide decision-making and facilitate the inclusion of ES in global environmental accounting frameworks.

Keywords: Bibliometric analysis, carbon sequestration, environmental accounting, temperate ecosystem, indicators, VOSviewer.

Resumen

Los servicios ecosistémicos (SE) son las contribuciones directas e indirectas de la naturaleza para el bienestar de la sociedad. Su medición requiere indicadores para el manejo forestal sustentable. El objetivo fue desarrollar un conjunto de indicadores y métricas para evaluar SE en los bosques templados de México. Se realizó una revisión sistemática (1990-2025), con base en el estándar *Prisma (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)*; se analizó un *corpus* final de 1274 publicaciones (669 publicaciones globales y 605 nacionales). El análisis bibliométrico, mediante las plataformas *Rayyan* y *VOSviewer*, mostraron que las investigaciones sobre SE de soporte, regulación y provisión dominan a nivel nacional (48.6 %, 37.3 % y 12.4 %, respectivamente); biodiversidad, almacenamiento y captura de carbono, flujos hídricos, perturbaciones, madera y biomasa; mientras que los SE culturales están subrepresentados (1.7 %). Mediante una evaluación multicriterio y un panel *Delphi* de 20 expertos (consenso global de 95 %), se construyó la bolsa operativa alineada a CICES (*Common International Classification of Ecosystem Services*) V5.2, que incluye cuatro categorías, 19 tipos de SE y 43 indicadores (25 de provisión, 10 de regulación, 5 culturales y 3 de soporte). Los resultados evidencian la necesidad de emplear métricas biofísicas validadas *in situ*, capaces de reflejar la multifuncionalidad del ecosistema. El conjunto de SE, indicadores y métricas propuesto funcionará como un instrumento operativo para orientar la toma de decisiones y facilitar la inclusión de SE en los marcos globales de contabilidad ambiental.

Palabras clave: Análisis bibliométrico, captura de carbono, contabilidad ambiental, ecosistema templado, indicadores, *VOSviewer*.

Introduction

Global ecosystem degradation has accelerated due to the interaction between human activities and the effects of climate change (Dee et al., 2025). To address environmental functions and benefits that lack a formal market, ecological economics formalized the ecosystem services (ES) framework (Costanza, 2008; Gómez-Baggethun et al., 2010). This framework emerged as a strategy to make visible, economize, and address positive externalities, where ES are operationally defined as those goods and services that people obtain from ecosystems (Costanza, 2008; Mandal et al., 2026). For the classification of ES, the internationally recognized conceptual frameworks are: the Millennium Ecosystem Assessment (MEA, 2005), which establishes the conceptual basis and groups them into four categories (provisioning, regulating, cultural, and supporting), and identifies 17 types of ES; the Economics of

Ecosystems and Biodiversity (Kumar, 2010), which typified 22 ES and reorganized its conceptual classification (including habitat services) to avoid double counting in economic valuation; and the Common International Classification of Ecosystem Services (CICES) V5.2 (Haines-Young, 2023), which does not use a fixed number of ES; this framework is a hierarchical classification for environmental accounting and international comparability, and organizes end-user ES into provisioning, regulating, and cultural, and excludes supporting ES.

Globally, temperate ecosystems provide critical ES such as climate regulation, provisioning (water, timber, forage), and cultural benefits (cultural heritage, aesthetic landscape, sacred sites). Despite their importance, they face severe degradation driven by five global threats: climate change, habitat alteration, overexploitation, pollution, and invasive species (Mandal *et al.*, 2026; Pereira *et al.*, 2022). In the specific case of Mexico, temperate forests play a central role in the territorial provision of these benefits. Based on the conceptual framework of Kumar (2010), Galicia and Zarco-Arista (2014) identified 16 ES: 1) provisioning, 2) food, 3) water, 4) timber, 5) chemical resources, 6) genetic resources, 7) bioenergy, and non-timber forest resources; ES include regulation: 8) climate, 9) water flow regulation, 10) air pollutant purification, 11) soil erosion and landslide prevention, 12) carbon sequestration; cultural services: 13) community, recreational, 14) educational; and habitat support services: 15) primary production, 16) soil formation. To ensure ES, a shift is needed from a reductionist approach, focused on a single ES, towards multifunctionality (Mathieu *et al.*, 2025).

Despite this evident importance and the extensive identification of ES, an operational gap persists in the country between ES research and the implementation of public policies aimed at their conservation, compatibility of provision (Izquierdo-Tort *et al.*, 2025), and economic incentives for the owners of these resources. This disconnect makes it difficult to link ecological conditions with ES provision (Seguin *et al.*, 2026). Furthermore, the historical reliance on remote sensing observations tends to obscure the intrinsic variability of the ecosystem (Kokkoris *et al.*, 2024). Therefore, managers face uncertainties, a lack of standardized data, and temporal mismatches (Hinsch *et*

al., 2024). For this reason, it is vital to compile local databases and establish standardized monitoring methods that reduce subjectivity and bias in ES assessments and measurements (Moreno-Meynard, 2026). To address the lack of standardization in forest monitoring related to ES, ES assessment frameworks have been developed. Among these, the multidimensional analytical matrix proposed by Nahuelhual et al. (2016) stands out. This methodology, tested in Latin America, evaluates environmental indicators using technical, political, and social dimensions. This approach allows for the systematic identification of operational and social feasibility gaps in ES indicators.

ES indicators are tools for quantifying, evaluating, and monitoring them. In Mexico, scientific information on the role of temperate ecosystems in providing ecosystem services is needed, but indicators for their local and standardized assessment and measurement are lacking. Given these limitations, the objective of this study was to develop a set of indicators and metrics to evaluate ecosystem services in Mexico's temperate forests.

Materials and Methods

The methodology was structured in two phases: (1) Systematic review and bibliometric analysis, and (2) Multi-criteria analysis and participatory validation using a Delphi panel to develop the set of evaluation indicators and metrics.

Search strategy and information sources

The research was based on a systematic review structured around: search, quantitative analysis, and qualitative synthesis (Gough et al., 2013). To ensure comprehensive coverage of the literature between 1990 and 2025, four platforms were consulted: Scopus to identify high-impact literature; Dimensions and OpenAlex to broaden interdisciplinary coverage; and ScienceDirect (Elsevier) for full-text retrieval. The search employed Boolean equations at two levels of analysis. At the global level, three conceptual blocks were used: (1) Target ecosystem (temperate forests, *Pinus* and *Quercus* species), (2) Ecosystem service (provisioning, regulating, supporting, and cultural), and (3) Measurement terminology (indicators, metrics, evaluation, indices). At the national level, two blocks were incorporated: (4) Type of service evaluated (*e. g.*, provisioning: food, timber) and (5) Geographic context (Mexico).

Eligibility filter and bibliometric analysis

The process was carried out in accordance with the 2020 Prisma statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page et al., 2021). The Rayyan web platform (Ouzzani et al., 2016) was used for metadata management, enabling the removal of duplicates, double-blind peer review of titles and abstracts, and full-text analysis. Inclusion criteria focused on studies with quantifiable indicators. Prior to the qualitative synthesis, the metadata of the chosen records were processed in the VOSviewer software (van Eck & Waltman, 2010) performing a bibliometric analysis focused on networks of thematic co-occurrence and the dynamics of scientific production and intellectual structure of the field of knowledge.

Geographical contextualization and multicriteria prioritization of ES

The work of Galicia and Zarco-Arista (2014) provided the geographical contextualization to align global frameworks with the national scale, and ES with the greatest social and economic impact were selected. A conceptual standardization was carried out between local ES and the classes proposed by CICES V5.2 to ensure international comparability. ES prioritization was performed using a multicriteria evaluation matrix with equal weighting. Under this scheme, each ES was evaluated against seven specific criteria using a binary scale of presence (1) or absence (0): (1) Ecological value, (2) Level of link with human well-being, (3) Measurability by socioeconomic elements, (4) Importance to the local community, (5) Data availability, (6) Sensitivity to disturbances, and (7) Service category. By assigning equal weight to each criterion (14.3 % of the total value), overvaluation biases were neutralized. Subsequently, the methodological approaches and metrics of the ES were extracted to structure a preliminary set, in which biophysical indicators predominated.

Multidimensional selection of indicators and expert validation

For the final selection of indicators, the multidimensional analytical matrix proposed by Nahuelhual et al. (2016) was adapted. This matrix evaluates quality using 16 sub-criteria across four dimensions (Credibility, Prominence, Legitimacy, and Feasibility). For this procedure, the binary ratings and asymmetric percentage weightings of the original model were replaced by a three-level Likert scale (performance: 1=Low, 2=Moderate, and 3=Optimal) applied uniformly to the sub-criteria (maximum quantitative limit of 48 points per indicator). The scoring matrix underwent

participatory validation using the Delphi method (first workshop on November 28, 2025, and via email from December 2025 to February 2026), with a panel to reach a consensus (85 % threshold) on the relevance of the metrics. The panel consisted of 20 specialists selected for their demonstrable experience in the management and evaluation of temperate forests in Mexico (representativeness: 40 % from the academic sector, 20 % from the government sector, and 40 % from direct users, owners, and providers of forestry technical services). This sample size was determined because the methodological literature suggests that panels of between 15 and 20 participants are optimal for achieving theoretical saturation of responses and consensus (Hsu & Sandford, 2007; Okoli & Pawlowski, 2004).

The process consisted of two rounds. In the first round, each expert independently evaluated the conceptual relevance. Consensus was weighted using the Agreement Index (*AIC*) (von der Gracht, 2012):

$$AIC = \left(\frac{E_a}{n} \right) \times 100,$$

Where:

E_a = Number of experts with a passing grade

n = Total number of evaluators ($n=20$)

In the second round, the results and discrepancies were tabulated and returned to the panel, from which a 95 % overall consensus was reached regarding the feasibility of the metrics. The list of indicators was structured using an analytical framework format.

Data analysis

The systematic literature review under the Prisma standard was analyzed by cleaning metadata and performing double-blind screening using the Rayyan web platform (Ouzzani et al., 2016), while the quantitative syntheses were analyzed using thematic co-occurrence network modeling with VOSviewer software (van Eck & Waltman, 2010). The data from the iterative rounds of the Delphi panel were analyzed using the *AIC* to quantitatively determine saturation and consensus. Finally, the multi-criteria analysis of the metrics was performed using tabulations in Microsoft Excel, calculating the Likert-scale frequency sums for the evaluated sub-criteria.

Results

Global analysis

The systematic review of ES indicators for temperate forests yielded a total of 1 203 documents up to 2025: 525 (43.6 %) from Scopus, 477 (39.7 %) from Dimensions, and 201 (16.7 %) from OpenAlex. The consolidation of this metadata constituted the base document *corpus*. 534 duplicate records were removed, leaving 669 unique records.

Scientific production reflects a notable increase since 2000. To illustrate this accelerating trend, a power-law model was fitted ($y=0.3126x^{1.6277}$, where: y =Number of publications, x =Year; $R^2=0.948$). This reflects the growing interest in the adoption

of ES assessment frameworks (Figure 1). The thematic conceptual network consisted of 169 keywords. Early research prioritized basic concepts ("biodiversity," "biomass"), while recent literature (2020-2025) spatially quantified temperate forests, highlighting "remote sensing" and "LiDAR" technology as key tools (Figure 2). This initial review reveals that the countries with the most publications are the United States (18.5 %), the United Kingdom (14.05 %), Germany (12.04 %), Australia (8.6 %), Switzerland (7.9 %), Sweden (7.3 %), China (7.02 %), Spain (7 %), and Canada (6.1 %), among others. 548 documents that did not meet eligibility leaving 121 records for analysis.

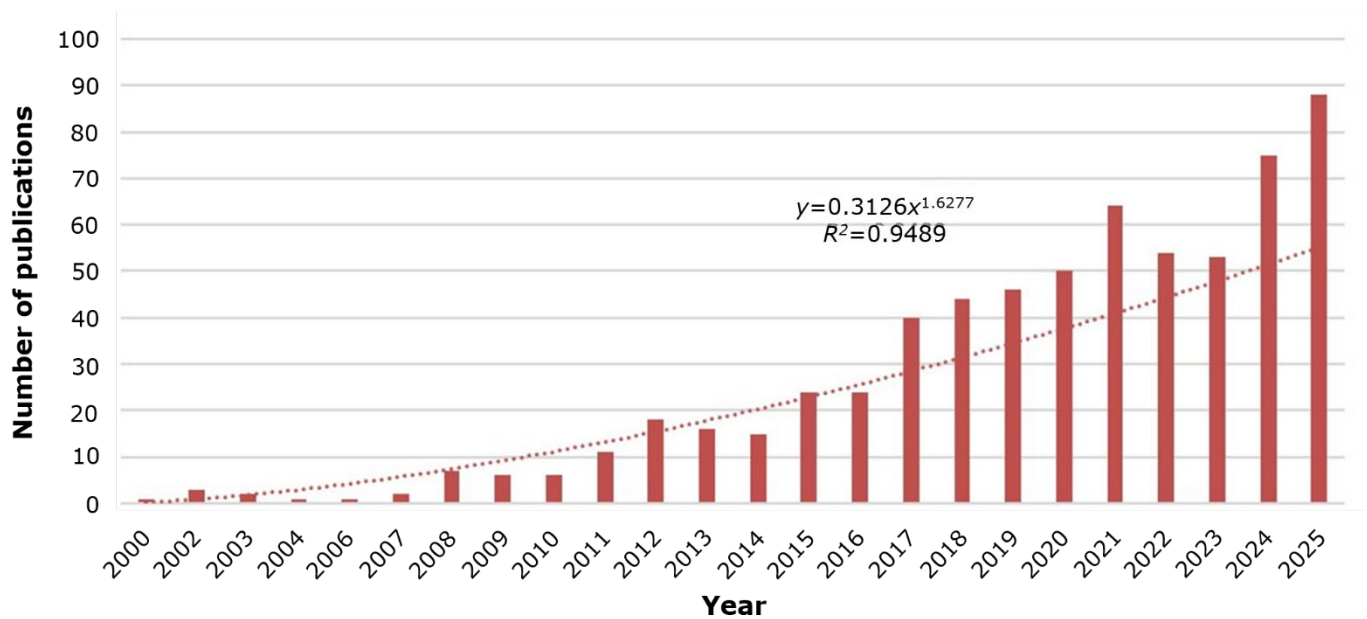


Figure 1. Publications on the topic of ecosystem services indicators, globally.

The distribution of records was highest in supporting ecosystem services (33.2 %, biodiversity metrics), followed by regulating ecosystem services (31.5 %, carbon sequestration and storage, water regulation, and erosion control) and provisioning ecosystem services (28.8 %, tangible goods such as timber, water supply, and crop yields). In contrast, cultural ES were the least studied (6.5 %), confirming the historical bias (Ioan *et al.*, 2025).

Despite the use of biophysical indicators and remote proxies, gaps remain in the measurement of: integration of complex biotic interactions, functional biodiversity, non-tree biodiversity, microbiome, necromass, socio-ecological integration, and cultural perspective. This asymmetry is not due to a lack of indicators, but rather to methodological and economic factors. Provisioning and regulating ecosystem services (*e. g.*, timber, carbon, and plant biodiversity) are prioritized because their functions can be modeled using standardized allometric equations, forest inventories, and remote sensing, which reduces costs and facilitates estimation in monetary units. In contrast, cultural ES require subjective, qualitative assessments in the field, which demand more time and funding. Research has shifted from isolated evaluations (of a single ecosystem service) to a multifunctional analysis that prioritizes quantifying the synergies and trade-offs between ecosystem services.

National analysis

Using data from 1990 to 2025, a total of 605 studies were obtained, distributed by ES: regulation (228 articles), provision (187), support (183), and cultural (7). Exporting the initial database ($n=605$) to the Rayyan platform (Ouzzani *et al.*, 2016) allowed for the elimination of 138 duplicates, resulting in a total of 467 records, with potential growth ($y=0.2576x^{1.3923}$, where: y =Number of publications, x =Year; $R^2=0.917$) that demonstrates the accelerated growth and interest in evaluating ES indicators (Figure 3).

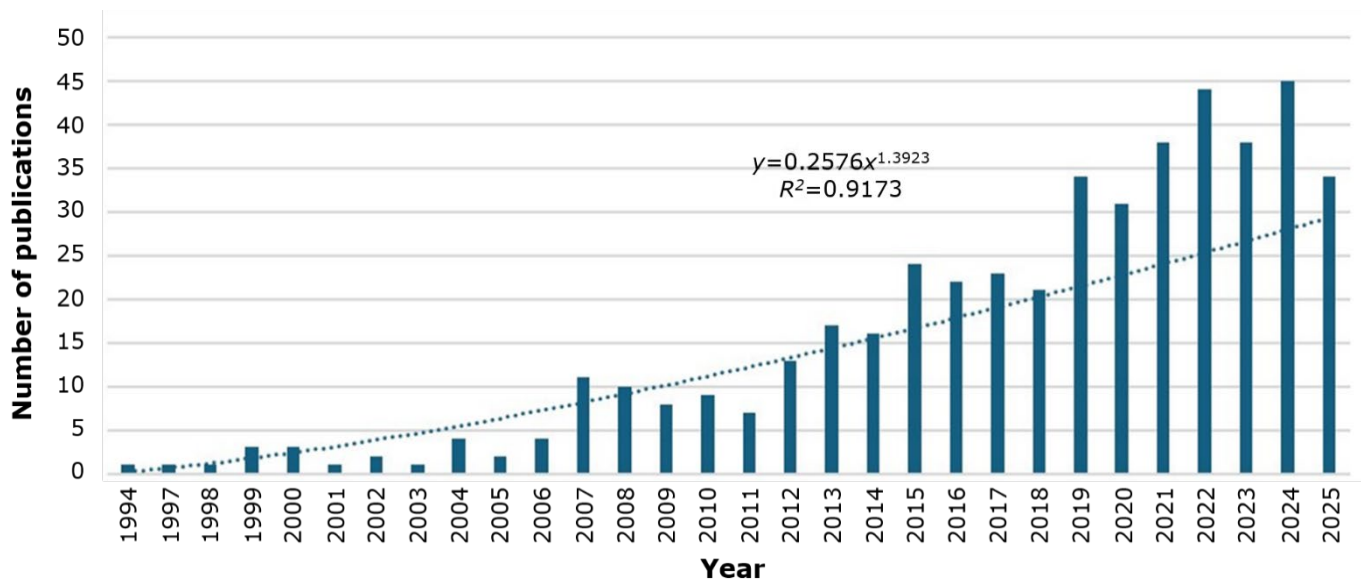
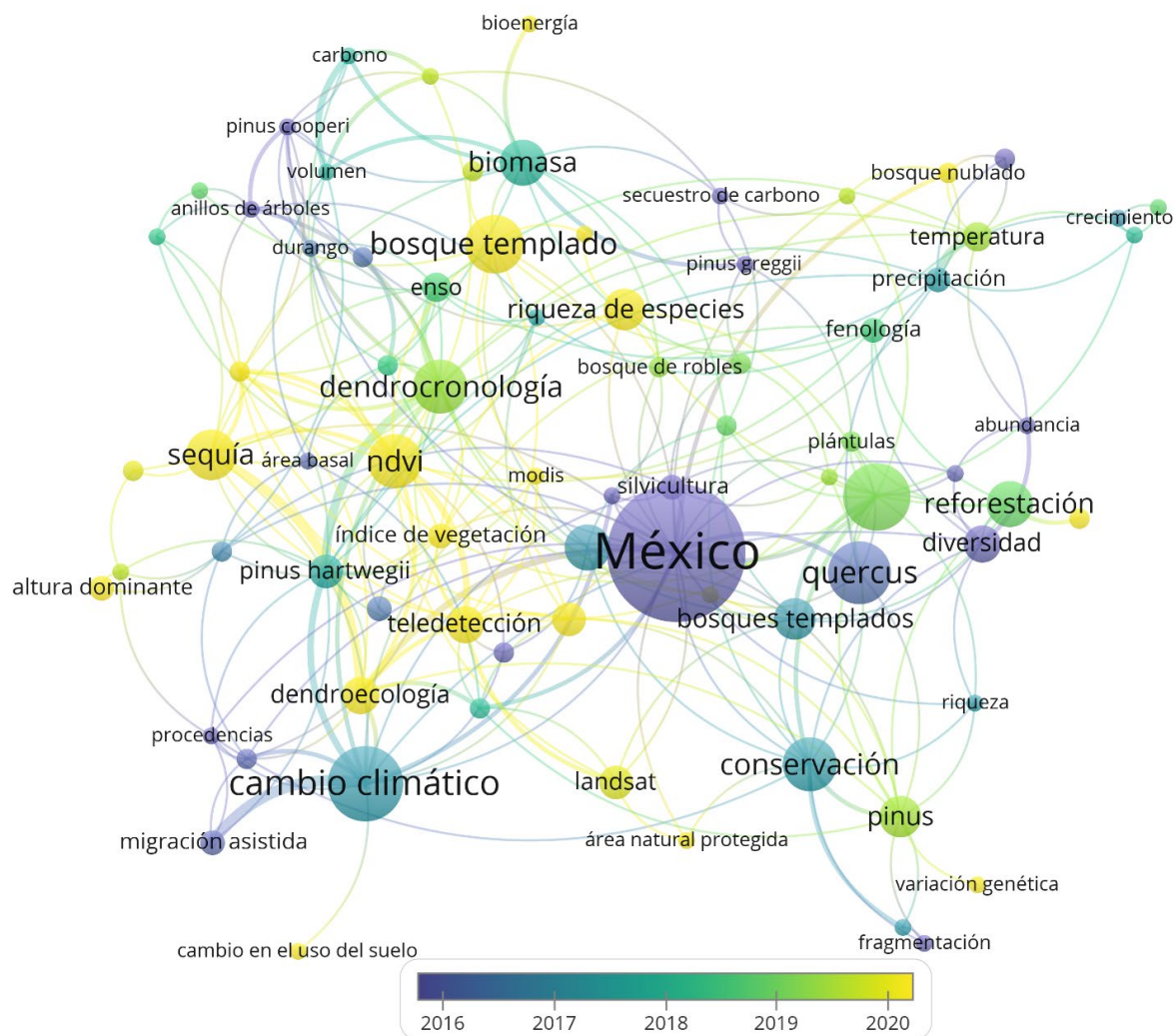


Figure 3. Publications on the topic of ecosystem services indicators at the national level.

The final distribution was highest in support ES (48.6 %), followed by: regulation (37.3 %), provision (12.4 %), and cultural ES (1.7 %). A similar trend to the global level was observed. In Mexico, the most studied ES topics are: biodiversity (35.1 %), climate and air (13.89 %), carbon, primary production, disturbances, and timber (6.6 %); and less studied ES topics (1 %), such as: recreation, bioenergy, chemical resources, and non-timber forest resources. The thematic network showed that supporting and regulating indicators predominate, which contrasts with the few studies on cultural ES (Figure 4).



Bioenergía = Bioenergy; *Carbono* = Carbon; *Pinus cooperi* = *Pinus cooperi* C. E. Blanco; *Volumen* = Volume; *Biomasa* = Biomass; *Anillos de árboles* = Tree rings; *Secuestro de carbono* = Carbon sequestration; *Bosque nublado* = Cloud forest; *Durango* = Durango state; *Bosque templado* = Temperate forest; *Temperatura* = Temperature; *Crecimiento* = Growth; *Pinus greggii* = *Pinus greggii* Engelm. ex Parl.; ENSO = ENSO; *Precipitación* = Precipitation; *Riqueza de especies* = Species richness; *Fenología* = Phenology; *Bosque de robles* = Oak wood; *Dendrocronología* = Dendrochronology; *Sequía* = Drought; *Área basal* = Basal area; *ndvi* = NDVI; *Modis* = Modis; *Silvicultura* = Silviculture; *Plántulas* = Seedlings; *Abundancia* = Abundance; *Índice de vegetación* = Vegetation index; *México* = Mexico; *Reforestación* = Reforestation; *Diversidad* = Diversity; *Pinus hartwegii* = *Pinus hartwegii* Lindl.; *Quercus* = *Quercus*; *Altura dominante* = Dominant height;

Teledetección = Remote sensing; *Bosques templados* = Temperate forests; *Dendroecología* = Dendroecology; *Riqueza* = Richness; *Procedencias* = Provenances; *Cambio climático* = Climate change; *Landsat* = Landsat; *Conservación* = Conservation; *Pinus* = *Pinus*; *Migración asistida* = Assisted migration; *Área natural protegida* = Protected natural area; *Variación genética* = Genetic variation; *Cambio en el uso del suelo* = Land use change; *Fragmentación* = Fragmentation.

Figure 4. Research network on indicators and metrics at the national level.

Based on the territorial anchoring established by Galicia and Zarco-Arista (2014) and its alignment with the 105 classes of CICES V5.2, 27 ES relevant to temperate forests were initially identified. After applying the seven prioritization criteria, nine services were excluded due to a lack of spatial data at the national level (Criterion 5) and their methodological infeasibility for socioeconomic measurement at the community level (Criteria 3 and 4). The ES with the highest overall scores were biodiversity, timber provision, freshwater, climate regulation (carbon capture and storage), erosion control, and cultural services (recreation and ecotourism). The most limiting criterion was data availability and measurability, negatively impacting indicators for supporting and cultural services.

The review yielded a preliminary inventory of 74 indicators, 68 % of which corresponded to strictly biophysical metrics (e. g., $m^3 ha^{-1}$ for timber biomass or $t C ha^{-1}$ for carbon sequestration).

The multidimensional analysis showed that provisioning ES had the highest scores, maximum viability, and legitimacy, given their socioeconomic linkages and data availability. Regulating ES stood out for their ecological sensitivity but had lower viability due to their high technical complexity. Cultural ES showed low viability due to the need for direct, *in-situ* data collection. Supporting ES presented maximum relevance as a structural foundation, lower legitimacy due to low socioeconomic perception, and lower viability due to their technical complexity (Table 1).

Table 1. Dimensionality and evaluation subcriterion for each ecosystem service.

Dimension	Evaluation subcriterion	ES Provision (Timber, Fodder, Food)	ES Regulation (Carbon, Water regulation)	ES Culturales (ICF, Recreation)	ES Support (Diversity, Biomass, Soil)
Credibility	1. Certainty	3	3	2	3
	2. Spatio-temporal realism	3	3	2	3
	3. Coherence	3	3	2	1
	4. Conceptual congruence	3	3	3	1
	Subtotal Credibility:	12	12	7	7
Prominence- Relevance	5. Ecological value of the ES	2	3	2	3
	6. Exposure to climate change	2	3	1	3
	7. Sensitivity to climate change	2	3	1	3
	8. Exposure to land use	3	3	3	3
	9. Sensitivity to land use	3	3	3	3
	Subtotal Prominence:	12	15	10	15
Legitimacy- Acceptability	10. Link to human well-being	3	3	3	1
	11. Importance for communities	3	2	3	1
	12. Potential for economic mediation	3	2	3	1
	13. Understandability	3	1	3	1
	Subtotal Legitimacy:	12	8	12	4
Viability	14. Data availability	3	2	1	2
	15. Ease of evaluation	3	2	2	1
	16. Generality	3	2	2	2
	Subtotal Viability:	9	6	5	5
Score	Total (Maximum 48 points):	45	41	34	31

ICF = Physical Quality Index

A mapping of equivalences between local SEs and the CICES V5.2 (Haines-Young, 2023) and MEA (2025) classification classes was carried out to ensure international comparability (Table 2).

Table 2. Classification of forest ecosystem services adapted to the CICES typology V5.2 (Haines-Young, 2023) and the waterfall model (Haines-Young & Potschin, 2016).

Service type	1 and 2. Ecological structure and Function (Condition)	3. Final ES (CICES Flow)	4. Socioeconomic benefit
Support (Condition accounts)			
1. Primary production	Woody growth and active photosynthesis in the stand	Basal support. No final ES in CICES	Maintenance of the food web and life cycles
2. Soil formation	Soil properties, soil chemistry, and mesofauna	Basal support. No final ES in CICES	Baseline fertility for productive activities
3. Biodiversity	Population dynamics and taxon richness	Basal support. No final ES in CICES	Genetic resilience of the ecosystem
Provision service			
4. Food	Food web, soil fertility, and habitat availability	Biomass supply for consumption	Local food security and commercial value
5. Freshwater	Drainage network and soil infiltration capacity	Freshwater supply for consumptive use	Human supply and reservoir capacity
6. Timber	Secondary growth of <i>Pinus</i> and <i>Quercus</i>	Supply of wood fibers	Construction and manufacturing materials
7. Bioenergy	Accumulation of necromass and lignocellulosic material	Supply of biomass for energy purposes	Energy security and local heating
8. Non-timber, chemical, and genetic resources	Plant secondary metabolism and understory diversity	Supply of resins, forage, extracts, and germplasm	Chemical, pharmaceutical, and livestock inputs
Regulatory services			
9. Climate regulation	Leaf area, canopy architecture, and vegetation indexes	Microclimate regulation and GHG sequestration	Mitigation of thermal extremes and climate change
10. Water flow regulation	Topography, runoff, and canopy retention	Regulation of liquid flow dynamics	Flood prevention and drought regulation
11. Water quality	Hydraulic conductivity and soil filtration capacity	Retention of dissolved pollutants	Provision of clean, toxin-free water
12. Erosion-sediment control	Soil stability through root systems and cover (%)	Control of erosion rates	Protection against landslides and dam siltation
13. Pest and disease management	Natural biological control and predator diversity	Mitigation of epidemic outbreaks	Forest health
14. Fire management	Fuel and spatial structure of biomass	Fire prevention and suppression	Reduction of the risk of catastrophic fires
15. Natural disaster management	Systemic resilience of the ecosystem to extreme events	Mitigation of the impacts of hurricanes/storms	Protection of infrastructure and human lives

Cultural services			
16. Spiritual and religious value	Presence of unique geographical features and flora	Support for characteristics that foster spirituality and identity	Sense of belonging and cultural heritage
17. Recreational-ecotourism	Ecological integrity and visual quality of the landscape	Physical support for leisure and recreation	Mental health, recreation, and economic benefits
18. Educational	State of conservation of pristine habitats and biodiversity	Support for spaces for research and teaching	Scientific development and environmental education

Although the international trend, led by classification frameworks such as CICES V5.2 (Haines-Young, 2023) and the United Nations Ecosystem Accounting Framework (SEEA EA), proposes the exclusion of supporting ecosystem services to avoid double counting, this study, and specifically for Mexico, retained the supporting ecosystem services principle. This decision responds to the urgent need to monitor the structural biophysical base and resilience of temperate forests to disturbances caused by climate change. In the national context, supporting ES ensure the ecological processes that sustain forest productivity. Furthermore, omitting these ES in Mexico would mean ignoring 48.6 % of the scientific evidence.

Consolidation of the indicator set

Finally, the definitive structure of ES and indicators underwent participatory validation using the Delphi method in a workshop with 20 experts (academia: 40 %, government: 20 %, and forestry sector [service providers and producers]: 40 %). In the first stage (workshop), 100 % of the experts validated the principles of provision and regulation as critical axes for forest management in Mexico. In a second round of evaluation (via email), a consensus of over 80 % was reached on 28 indicators. However, an adjustment was required for the cultural ES: it was recommended to

merge the ES of spiritual values with community identity to facilitate its measurement. Forest resource owners and technical service providers showed a marked preference for indicators that are easy to measure in the field, while academics prioritized metrics with greater scientific robustness (e. g., Alpha and Beta diversity indices). Finally, an overall agreement level of 95 % was achieved on the relevance of the 19 prioritized ES.

The technical evaluation of the 43 indicators using the multilevel matrix yielded outstanding scores in the Credibility dimension ($\bar{x} = \frac{11}{12}$) for the carbon and biomass indicators. However, a critical initial feasibility issue was identified in the Genetic resources and Freshwater supply indicators, due to the dispersion of official data and the implications for field data collection.

As a result, three theoretical indicators (continuous monitoring of groundwater flows, direct measurement of gas flows, and contingent valuation/willingness to pay) were replaced with remote sensing proxies and inventory data (Normalized Difference Vegetation Index, pollutant removal models based on Satellite leaf area index, and direct economic spillover metrics, respectively). The process culminated in the unanimous approval of the "Ecosystem Services and Indicators Exchange," guaranteeing a technical tool ready for implementation in forest monitoring programs. At the institutional level, this proposal can complement the National Forest and Soil Inventory of the National Forest Commission (*Comisión Nacional Forestal, Conafor*), and at the farm level, it can be integrated into Forest Management Programs, based on the forest mensuration data that foresters already collect in the field. Finally, it can be incorporated into payment schemes for environmental services and certification of good forest management at monitoring points. Table 3 shows the resulting exchange, which includes the type of ES, indicators, and unit of measurement or metric.

Table 3. Ecosystem service, type of service, indicator and metric to monitor and evaluate ecosystem services in the temperate forests of Mexico.

Type/Section /Class	Selected indicator/Benefit	Unit of measurement or valuation metric
<p>Support: ensure the fundamental ecological processes that sustain the life and productivity of the forest. Or, reclassify as Ecosystem Condition Accounts, so as not to contradict CICES, since they determine the ecosystem's "capacity" to deliver services.</p>		
1. Primary production	Forest biomass	t ha ⁻¹ , t ha ⁻¹ año ⁻¹ . Accumulated biomass (storage) and biomass generation (net primary productivity)
2. Soil formation	Cyclical service of nutrients, organic matter, and characteristics of the soil mesofauna	kg ha ⁻¹ año ⁻¹ , t ha ⁻¹ , %, individuals m ⁻² . Cyclic nutrient service (flow of N, P, K through leaf litter fall or mineralization), soil organic matter, soil mesofauna.
3. Biodiversity	Vegetation diversity indexes	m ² , %. Diversity index values. Spectral indexes. Alpha diversity (Species richness, Shannon-Wiener <i>H'</i> , Simpson <i>D</i> , Margalef <i>DMg</i>), Beta diversity indices (Similarity: Jaccard index, Sørensen index), Importance Value Index. Normalized Difference Vegetation Index. Enhanced vegetation index. Canopy structural indexes
<p>Provisioning Service: ensuring the sustainable supply of tangible goods from the forest.</p>		
4. Food	Crop production (multiple subcategories)	kg ha ⁻¹ año ⁻¹ , t ha ⁻¹ año ⁻¹ , kg fisherman ⁻¹ h ⁻¹ . Biological yield per unit area. Harvest index. Animal carrying capacity of the ecosystem, measured in Animal Units (AU) per hectare (AU ha ⁻¹).
	Meat production (multiple subcategories)	Value of aquaponics production (MXN ha ⁻¹). Water recirculation and replenishment rate. Production and efficiency of the integrated aquaponics system. Catch per unit effort in water bodies within forested areas (<i>e. g.</i> , dams, mountain rivers)
	Aquaponics production	
	Fish catch	
	Number of wild species used as food	Number of edible species, number of species ha ⁻¹ , kg ha ⁻¹ , t ha ⁻¹ . Richness of wild edible species. Yield of edible mushrooms and fruits. Annual extraction rate of edible wild plant products
	Hunting performance	Number of species, individuals species ⁻¹ year ⁻¹ . Game fauna. Sustainable harvest rates per species
	Value of agricultural production	MXN ha ⁻¹ . Economic value of agricultural production estimated using local market prices
5. Freshwater	Value of livestock production	MXN ha ⁻¹ year ⁻¹ , MXN AU ⁻¹ year ⁻¹ . Economic value
	Water supply/population benefited by water resources, water quality parameters	m ³ ha ⁻¹ year ⁻¹ , L hab ⁻¹ d ⁻¹ , Water Quality Index (<i>WQI</i>), pH, Turbidity (<i>NTU</i>), Conductivity (dS m ⁻¹), Dissolved Oxygen (mg L ⁻¹), Total Suspended Solids (mg L ⁻¹), nutrients, temperature (°C). Volume of surface water supply derived from watersheds. Amount of water available per inhabitant per day supplied by the ecosystem. Water Quality Index: physicochemical values (pH, conductivity, turbidity, etc.)
	Water storage capacity	m ³ d ⁻¹ , mm year ⁻¹ , m ³ . Total water retention capacity of infrastructure within the forest. Duration of water storage. Infiltration rate that replenishes underground reservoirs
6. Timber	Roundwood production	

	Fiber and firewood production	$m^3 \text{ ha}^{-1}$, m^3 , m^2 . Commercial timber volume ($m^3 \text{ ha}^{-1}$), diameter at breast height (<i>DBH</i> , <i>cm</i>), total height (<i>TH</i> , <i>m</i>), and stem quality (straightness/soundness). Current annual increment, mean annual increment. General dendrometry (basimetric area, density, etc.)
	Biomass for fuel	
	Value of forest products (categories)	MXN ha^{-1} , %. Product distribution (primary, secondary, cellulosic, and waste)
7. Forage	Forage biomass balance	$t \text{ ha}^{-1}$, Kilograms of forage per kilogram of live weight. ($kg \text{ kg}^{-1}_{PV}$). Forage production. Amount of forest forage converted into livestock feed
8. Chemical resources	Number of species with chemical potential	<i>Number of species</i> . Richness of species with pharmacological potential (terpenes, phenols, alkaloids) or industrial interest
	Resin production	$kg \text{ face}^{-1} \text{ year}^{-1}$, faces ha^{-1} . Resin yield per individual. Number of active resin-tapping faces per hectare
	Value of resin production	$\text{MXN ha}^{-1} \text{ year}^{-1}$. Annual gross income derived from the sale of raw resin. Opportunity cost of non-timber forest products <i>versus</i> final timber harvesting
9. Genetic resources	Number of species converted into commercial products	Number of species. Native species diversity. Forest species integrated into industrial value chains (cellulose, resin, essential oils, sources for seed production, ethnobotanical value). Species listed under protection categories (NOM-059)
	Seed production	$kg \text{ t}^{-1}$. Clean seed yield per unit of cone weight. Seed viability
	Value of the genetic resources	$\text{MXN ha}^{-1} \text{ year}^{-1}$. Market price of forest germplasm
10. Bioenergy	Firewood production	$m^3 \text{ ha}^{-1}$. Volume of harvest residues, calorific value. Biomass quantification. residual lignocellulosic and determination of the thermochemical potential
	Value of firewood production	$\text{MXN ha}^{-1} \text{ year}^{-1}$. Revenue from firewood sales, subsequent processing
11. Non-wood Forest Resources (NWFR)	Non-wood forest production	m^3 , L, $kg \text{ ha}^{-1} \text{ year}^{-1}$, $t \text{ ha}^{-1} \text{ year}^{-1}$. Specific products (wild mushrooms, forest soil, ornamental foliage) in fresh and dry weight
	Value of non-wood forest production	$\text{MXN ha}^{-1} \text{ year}^{-1}$. Revenue from the marketing of non-wood forest products (NWFR)

Regulatory Service: Maintaining the capacity of forests to regulate ecological and environmental processes.

12. Climate regulation and purification of atmospheric pollutants	Forest attenuation capacity (temperature, humidity, wind, radiation). Dendrochronological analysis	Microclimatic buffering capacity: Thermal ($\Delta \text{ }^\circ\text{C}$) and hygrometric ($\Delta \%$) attenuation, wind speed reduction (m s^{-1}), and solar radiation interception (W m^{-2}). Gross Radial Growth (mm year^{-1}) and Tree Ring Width Index (<i>RWI</i>) for chronologies
	Atmospheric gas flux. Air pollutant removal models	Atmospheric gas flux (Net Ecosystem Exchange): Evaluated at the microscale in flux towers ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) or scaled to the forest landscape ($t \text{ ha}^{-1} \text{ year}^{-1}$). Atmospheric pollutant removal models ($\text{PM}_{2.5}$, PM_{10} , O_3 , NO_2 , SO_2): rate at which the forest canopy "cleans" these pollutants through mass interception ($kg \text{ ha}^{-1} \text{ year}^{-1}$ or $g \text{ m}^{-2} \text{ year}^{-1}$)
13. Erosion regulation	Sediment transfer and loading	$t \text{ ha}^{-1} \text{ year}^{-1}$, mg L^{-1} , % coverage. Soil loss rate, modeled using the Universal Soil Loss Equation with vegetation cover factor. Total load of suspended sediments in watercourses

14. Carbon sequestration-accumulation	Carbon sequestration and capture capacity	t C ha ⁻¹ , t C ha ⁻¹ year ⁻¹ . Total organic carbon content, aboveground biomass, soil organic carbon, and carbon in necromass. (leaf litter and detritus)
15. Regulation of water flows and water quality	Water flow monitoring. Water balance	mm year ⁻¹ , distribution %, m ³ ha ⁻¹ year ⁻¹ , L year ⁻¹ . Precipitation distribution (runoff, stem runoff, interception, and net precipitation). Water balance (watershed volume)
	Water yield (harvested water or infiltration).	mm ha ⁻¹ year ⁻¹ , cm ha ⁻¹ year ⁻¹ , m ³ ha ⁻¹ year ⁻¹ , mm year ⁻¹ , cm year ⁻¹ , m ³ year ⁻¹ , mm year ⁻¹ . Volume of freshwater that the forest watershed delivers to or recharges the system. Infiltration capacity
16. Regulation of pests and diseases, fires, and natural disasters	Area and frequency of pests and diseases	ha year ⁻¹ , % year ⁻¹ , events year ⁻¹ , years. Area damaged (pests, diseases, fires, and disasters) in a given period. Absolute and relative area. Frequency of disturbances
	Area and frequency affected by fires	
	Area affected by natural disasters	
	Economic losses due to natural disturbances	MXN event ⁻¹ , MXN ha ⁻¹ year ⁻¹ . Estimated economic losses.
Cultural Service: recognizing and conserving the intangible and social values associated with the forest.		
17. Spiritual value-community identity	Áreas with spiritual and religious value	ha, number of sites, or number of species. <i>Informant Consensus Index (ICF)</i> , Use Value Index (<i>IVU</i>). Presence of sacred sites, richness of species with symbolic-ritual value
18. Recreational	Number of visitors	Visitors year ⁻¹ . Tourist influx over a period
	Recreation and ecotourism area	ha, Likert scale. Area designated for ecotourism and perceived aesthetic quality (perception indexes)
	Recreational value	MXN year ⁻¹ , MXN ha ⁻¹ year ⁻¹ . Total or distributed economic impact in the area
19. Educational	Areas for educational use	ha, projects year ⁻¹ , sites km ⁻² , % of conservation. Area for educational use, number of research projects, density of educational use areas, and conservation status of culturally important habitats

The qualitative analysis of the discarded indicators and metrics revealed three decision patterns derived from the perspective of local stakeholders: cost-effectiveness constraints, required technology, an preference for metrics with monetary capacity, and ease of field data collection. For example, highly accurate but costly metrics such as continuous monitoring of groundwater flows or trace gas measurement using covariance towers were ruled out by forestry technical service providers and forest owners due to their lack of financial and technological viability at the property level.

Discussion

The research conducted at the national level aligns with the most recent global literature, demonstrating that provisioning ES (45 points in multidimensional analysis) obtained the highest score, in contrast to the low scores of cultural (34) and supporting (31) ecosystem services. This finding supports Chen's (2025) assertion that tangible goods such as timber and freshwater continue to dominate assessments due to their feasibility for direct quantification and monetization. In a similar way, the scarcity of indicators for regulatory and cultural ES is due to their methodological complexity and subjective valuation, as noted by Ioan et al. (2025) and Seguin et al. (2026). The results of this research confirm Chen's (2025) argument that the lack of indicators and metrics stems from the technical difficulty in quantifying intangible, experiential benefits that are dependent on the local sociocultural context—a pattern that explains the low representation of cultural ES in the national context (1.7 %).

As recent literature reviews warn (Kokkoris et al., 2024; Seguin et al., 2026), a large proportion of current global assessments rely on indirect methods based on land use and land cover (LULC) mapping, erroneously assuming that the mere presence of a forest guarantees the provision of ES (Seguin et al., 2026). This reliance on land cover-based substitutes, without integrating the actual ecological condition, masks the functional variability of ecosystems and generates potential biases by overestimating the provision of ES in seemingly intact or unmanaged areas (Seguin et al., 2026). The research results reflect this limitation, which explains why the assessed national indicators that relied on indirect data obtained significantly lower viability scores (Table 1). Therefore, and in accordance with the proposed indicators, several researchers postulate that the current context should move towards *in situ* biophysical measurements and field-based functional approaches, which are capable of reflecting the structural integrity of the forest ecosystem (Leveau et al., 2025; Seguin et al., 2026).

The shift observed in the literature towards multifunctionality analysis is highly relevant for temperate forests in Mexico. Historically, forest management programs have had a reductionist approach focused on maximizing the timber service due to its economic value. The importance of documenting this change lies in the fact that the set of indicators will allow decision-makers to visualize the multifunctionality of the ecosystem by evaluating synergies and trade-offs (for example, how timber extraction affects carbon sequestration or water recharge). Foresters and institutions will be able to design adaptive silvicultural strategies that optimize multiple ES and ensure the ecosystem's resilience to climate change. The concentration of national studies on supporting services reveals that research in Mexico remains confined to descriptive ecology, without evaluating end-flow services and payments for ES. This gap necessitates the design of environmental policies based on global assumptions. Documenting this asymmetry justifies implementing the proposed set of indicators to measure historically overlooked ES.

The application of indicators is essential for analyzing trade-offs and synergies in the adaptive management of temperate forests (Liu et al., 2026). While timber extraction is often the ES prioritized by commercial management, maximizing this benefit generates compromises that reduce other ES, such as biodiversity conservation and climate change mitigation (Ioan et al., 2025). This explains why the provisioning indicators received the highest ratings, as their methodological maturity is the result of decades of forest inventories and mensurations focused on quantifying tangible goods and services. Simultaneously evaluating multiple ES using indicators facilitates the implementation of technologies that allow forest managers to design multifunctional and sustainable silvicultural strategies (Baskent & Yilmaz, 2026).

In the Mexican context, the operationalization of the proposed catalog of indicators and metrics has profound implications for environmental governance, establishing homogeneous technical criteria that reduce subjectivity in resource allocation. Adopting a hybrid approach that integrates multispectral modeling validated with *in situ* data or biophysical indicators brings transparency and effectiveness to economic compensation schemes (Yang et al., 2026). This technical certainty is imperative for

integrating the country's temperate forests within the recent global frameworks of the System of Environmental and Economic Accounting–Ecosystem Accounting (SEEA EA) (Seguin et al., 2026), allowing the true value of natural capital to be internalized in national macroeconomic planning.

The qualitative weightings of the Delphi panel and the operational calibration of the metrics were primarily based on the structure and dynamics of temperate forests in Central and Northern Mexico. Their direct applicability in locations with different socio-ecological conditions will require a validation process or local adjustments.

Conclusions

The study generated a set of ecosystem services, indicators, and metrics for temperate forests in Mexico. This framework, structured through systematic identification and validated by the Delphi panel consensus, demonstrates the feasibility of standardizing biophysical and socioeconomic variables in a single operational instrument. The integration of the provisioning, regulating, cultural, and supporting categories (the latter of which can be reclassified as ecosystem condition accounts) provides a direct tool to reduce reliance on indirect estimates.

The findings showed that forest assessments and monitoring prioritize ES indicators that are easy to measure and have economic value in their estimation. Assessments in Mexico have focused on quantifying supporting, provisioning, and regulating ES. This contrasts with the measurement of cultural ES, whose evaluation is methodologically more complex and subjective.

The operational implementation of the proposed catalog for measuring ES lies in its capacity to serve as input or a technical baseline to support economic valuation

methods and natural capital accounting systems, such as the System of Environmental and Economic Accounting–Ecosystem Accounting (SEEA EA), in order to link financial compensation mechanisms for the conservation and provision of ES.

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Conflict of interest

The authors declare no conflict of interest. José Carlos Monárrez-González declared that he did not participate in the editorial process of the article.

Contribution by author

José Carlos Monárrez-González: data curation, application of the methodology, information analysis, and drafting of the original manuscript; Carlos Mallén Rivera: conceptualization of the research, data collection, results monitoring, manuscript review and correction.

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