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Research article

# Integridad ecológica en un bosque bajo producción maderable del centro de México

# Ecological integrity in a forest under timber production in central Mexico

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**Abstract**

Ecological integrity (EI) is the property of an ecosystem to support and maintain a community of organisms whose composition, diversity, and functional organization is comparable to a natural habitat in the region. This concept is useful to know the degree of conservation of an ecosystem; therefore, it is of interest in forest management. The objective of this study was to develop and apply an Ecological Integrity Index (*EII*) in an area of temperate forest with timber harvesting. The site had four plant associations: three under timber harvesting (*Pinus montezumae*, *P. patula*, and *P. pseudostrobus*), and one corresponding to a conservation area (*Pinus-Quercus*). In order to calculate the index, the structure, composition, and function of the forest were evaluated through 20 markers, corresponding to three ecological attributes: landscape, vegetation, and soil. Four possible categories were established: excellent, good, fair and poor. The highest value of the *EII* was obtained in the conservation area, in the excellent category, while in the associations under harvesting, that of *P. patula* was rated excellent, and those of *P. montezumae* and *P. pseudostrobus* were rated good. In the area under harvesting, observation and minimal intervention are required to maintain and improve EI. The *EII* made it possible to characterize the associations under management, in addition to identifying the markers that require intervention or further research to maintain EI. This generated a baseline of knowledge of EI in the study area, which may be useful for its management.

**Key words:** Species composition, plant diversity, community structure, ecosystem function, Ecological Integrity Index, forest management.

**Resumen**

La integridad ecológica (IE) es la propiedad de un ecosistema para soportar y mantener una comunidad de organismos cuya composición, diversidad y organización funcional sea comparable con un hábitat natural de la región. Este concepto es útil para conocer el grado de conservación de un ecosistema, por lo que es de interés en la gestión forestal. El objetivo fue desarrollar y aplicar un Índice de Integridad Ecológica (*IIE*) en una zona de bosque templado con aprovechamiento maderable. El lugar presentó cuatro asociaciones vegetales: tres bajo aprovechamiento maderable (*Pinus montezumae*, *P. patula* y *P. pseudostrobus)* y una correspondiente a un área de conservación (*Pinus*-*Quercus*). Para calcular el índice, se evaluó la estructura, composición y función del bosque a través de 20 indicadores, correspondientes a tres atributos ecológicos: paisaje, vegetación y suelo. Se establecieron cuatro categorías posibles: excelente, buena, regular y baja. El mayor valor del *IIE* se obtuvo en el área de conservación en la categoría excelente, mientras que en las asociaciones bajo aprovechamiento, la de *P. patula* se clasificó como excelente y las de *P. montezumae* y *P. pseudostrobus* se clasificaron como buenas. En el área bajo aprovechamiento se requiere observación e intervención mínima para mantener y mejorar la IE. El *IIE* permitió caracterizar las asociaciones bajo manejo, además de identificar los indicadores que requieren de intervención o mayor investigación para mantener la IE. Se generó así una línea base del conocimiento de la IE en el área de estudio, que puede ser útil para su gestión.

**Palabras clave:** Composición de especies, diversidad vegetal, estructura de comunidades, función ecosistémica, Índice de Integridad Ecológica, manejo forestal.

# Introduction

Ecological integrity (EI) is the ability of an ecological system to support and maintain a community of organisms with a composition, diversity, and functional organization comparable to those of a natural habitat in the region (Parrish *et al.*, 2003), Tierney *et al.* (2009) define it as a measure of the composition, structure, and function of an ecosystem in relation to the natural range of variation, as well as natural and anthropogenic disturbances.

EI indexes combine different variables in order to characterize an ecosystem and contribute to solving challenges such as ensuring the protection of ecosystems with multiple objectives, problems, uses, and values (Carter *et al.*, 2016). They were developed for the purpose of assessing the condition of the ecosystem and the effectiveness of the management (Tierney *et al.*, 2009), knowing the conservation status of biodiversity in a robust, practical and comparable manner in space and time (Parrish *et al.*, 2003; Santibáñez-Andrade *et al.*, 2015), in order to make management decisions (Gara and Stapanian, 2015), guide monitoring efforts (Wutzerbach and Schultz, 2016), and develop evidence-based policies (Rempel *et al.*, 2016).

Research and environmental monitoring are necessary to understand and manage ecosystems (Haughland *et al.*, 2010), and they are becoming increasingly relevant due to the loss of biodiversity and ecological degradation that they face. Ecosystem assessment should focus not only on recording the loss of surface area but also on recording the current condition of the ecosystem. This knowledge can be useful for monitoring over time, identifying trends, prioritizing sites for conservation or restoration and guiding management actions (Fennessy *et al.*, 2007).

Given that the application of the concept of EI and the development of a protocol for its evaluation in a forest under commercial timber harvesting have been explored in very few studies at the national level, it was considered that its implementation would make it possible to understand how management practices and forestry treatments impact the structural, compositional, and functional components of the forest. In addition, this information will provide a baseline to guide management decisions to reduce negative impacts on the forest ecosystem. The *ejido El Nopalillo,* in the state of *Hidalgo*, was chosen because timber harvesting has been carried out there under a forest management program since 1979, mainly through the Silvicultural Development Method (SDM), which consists in applying a regeneration cut of seed trees, in addition to intermediate treatments such as release cuts, non-commercial thinning, pruning, and two commercial thinnings, in a 50-year rotation. At the time of the evaluation, the *ejido* had the national certification of Sustainable Forest Management (NMX-AA-143-SCFI-2015) since 2017 and the certification of the Forest Stewardship Council (FSC) as of 2018 (Rendón, 2020).

Therefore, the objective of this research was to assess the ecological integrity of a managed temperate forest in the *ejido El Nopalillo*, in the state of *Hidalgo*, Mexico, by developing and implementing a protocol to obtain an Ecological Integrity Index

(*EII*) applicable to the study region. The main hypothesis was that timber harvesting and the applied silvicultural treatments influence the structure, composition, and function of the ecosystem, which would negatively impact the *EII* with respect to that obtained in the conservation forest.

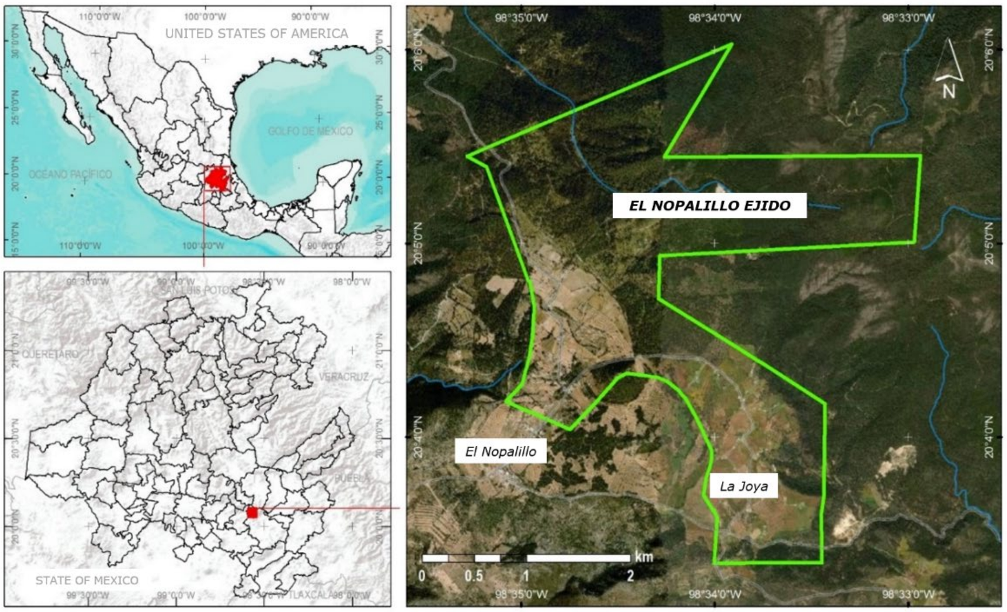
# Materials and Methods

## Study area

The research was carried out in the *ejido El Nopalillo* in the *Epazoyucan* municipality, specifically on *Las Navajas* mountain of the *Sierra de Pachuca* (a section of the Eastern *Sierra Madre*) in *Hidalgo*, Mexico. This is an agrarian nucleus that has had a forestry management program since 1979; the *ejido* covers approximately 550 hectares for timber production using the Silvicultural Development Method (SDM), of which a total of 306 hectares were evaluated with and without forestry intervention.

The altitude gradient of the site ranges from 2 800 to 3 100 m; there are four vegetation associations, three of them under timber harvesting and dominated by (1) *Pinus montezumae* Lamb. (111 ha), (2) *Pinus pseudostrobus* Lindl. (68 ha), and (3) *Pinus patula* Schltdl. & Cham. (66 ha), and (4) a pine-oak (PQ) conservation area (61 ha) that has had no human intervention in at least 50 years. The climate is semi-cold and temperate sub-humid; the soils are Phaeozem and Andosol (Figure 1). The fauna is composed of such birds as woodpeckers (*Sphyrapicus thyroideus*

(Cassin, 1852)) and Mexican Violetear (*Colibri thalassinus* (Swainson, 1827)), mammals like the Mexican red-bellied squirrel (*Sciurus aureogaster* F. Cuvier, 1829), and *armadillos* (*Dasypus novemcinctus* Linnaeus, 1758), and reptiles such as the Mexican small-headed (*Crotalus intermedius* Troschel, 1865) and the racer (*Coluber* spp.) (Rendón, 2020).




*Océano Pacífico* = Pacific Ocean; *Golfo de México* = Gulf of Mexico.

**Figure 1.** Location of the ecological integrity study area in forests under forest management in the *ejido El Nopalillo*, in *Hidalgo*, Mexico.

## Protocol for obtaining the *EII*

The methodological proposal for assessing the EI of the study area consisted of three phases (Table 1), considering EI assessment protocols in the Americas as well as the contribution of authors such as Kapos *et al.* (2002), Parrish *et al.* (2003), Tierney *et al.* (2009), Schroeder *et al.* (2011) and Carter *et al.* (2016).

**Table 1.** Phases and steps for the development of a protocol for the evaluation of the ecological integrity of temperate forests in the *ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

| Phase | Step |
|---|---|
| 1 | 1. Elaboration of the conceptual model |
| | 2. Definition of management objectives |
| | 3. Identification of the ecological attributes |
| | 4. Definition of the scales of analysis |
| | 5. Indicators selection |
| 2 | 6. Evaluation of the indicators and analysis of the information |
| | 7. Identification of an acceptable range of variation for each indicator |
| | 8. Scoring of the indicators to determine whether or not they are within the acceptable ranges of variation |
| | 9. Estimation of the value of the EI index |
| 3 | 10. Report of the results |
| | 11. Use of results to inform, evaluate, and provide feedback on management actions |
| | 12. Systematical repetition of the evaluation |

Adapted from: Tierney *et al.* (2009), Schroeder *et al.* (2011), and Carter *et al.* (2016).

Phase 1 consisted of the theoretical construction of the EI evaluation process, in which the components, attributes, indicators, and measures useful for the evaluation were identified.

A conceptual ecological model was developed (Figure 2), wherein the landscape, vegetation, and soil as the three ecological attributes that play the most important role in maintaining the EI of the ecosystem (Schroeder *et al.*, 2011). These attributes are characterized by 20 indicators (Table 2) which are related to the structure (site occupancy level based on the tree density in the evaluated area), composition (species taxonomy and the ecological indicators of plant species), and function (soil and basal area properties as indicators of carbon sequestration capacity) of the ecosystem.

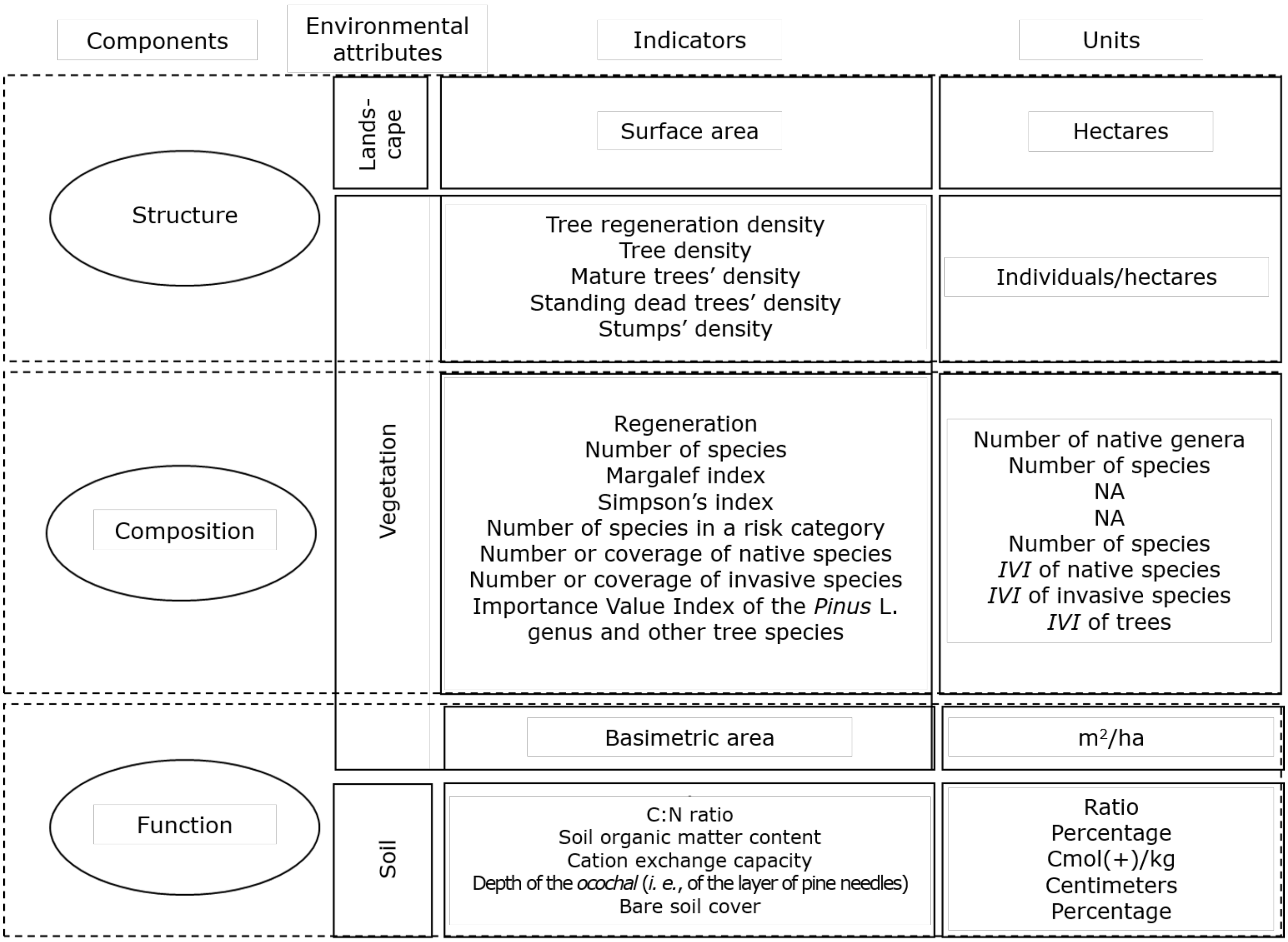


**Figure 2.** Conceptual ecological model for the evaluation of the ecological integrity of the forests of the *Ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

**Table 2.** Results matrix by indicator and plant association in the *ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

| Indicator | PQ | Pmn | Pps | Ppt |
|---|---|---|---|---|
| Surface area (ha) | 60.94 | 111.25 | 68.13 | 65.45 |
| Tree regeneration composition (number of genera) | 4 | 7 | 5 | 6 |
| Number of species (trees, shrubs and herbs) | 39 | 60 | 58 | 62 |
| Simpson's Index (1-D) | 0.8 | 0.7 | 0.7 | 0.8 |
| Margalef Index | 1.6 | 1.4 | 1.4 | 1.6 |
| Species at risk (in NOM-059-SEMARNAT-2010) | 0 | 1 | 0 | 2 |
| *IVI* (Importance Value Index) native species | 100 % | 100 % | 100 % | 100 % |
| *IVI* (Importance Value Index) invasive species | 0 | 0 | 0 | 0 |
| *IVI* (Importance Value Index) *Pinus* sp. | 49 % | 88 % | 88 % | 78 % |
| Tree regeneration (individuals with Normal diameter *ND*<7.5 cm ha$^{-1}$) | 34 | 30 | 47 | 79 |
| Density (trees ha$^{-1}$) | 632 | 448 | 658 | 568 |
| Density of mature trees (*ND*>50 cm and Total Height *H*>25 m) (trees ha$^{-1}$) | 10 | 0 | 0 | 0 |
| Density of standing dead trees (trees ha$^{-1}$) | 18 | 0 | 0 | 1 |
| Stump density (stumps ha$^{-1}$) | 57 | 116 | 238 | 112 |
| C:N ratio | 40.98 | 29.52 | 32.2 | 33.15 |
| Soil Organic Matter (*SOM*) (%) | 25.91 | 28.33 | 15.91 | 21.34 |
| Cation Exchange Capacity (*CEC*) (Cmol(+) kg$^{-1}$) | 59.1 | 63.53 | 37.1 | 55.3 |
| Depth of *ocochal* (cm) | 7 | 5 | 4 | 6 |
| Bare ground cover (%) | 2.9 | 3 | 4.4 | 10 |
| Basimetric area (*BA*) (m$^2$ ha$^{-1}$) | 28 | 17 | 17 | 11 |

PQ = *Pinus-Quercus* association (Conservation area); Pmn = *Pinus montezumae* Lamb. association; Pps = *P. pseudostrobus* Lindl. association; Ppt = *P. patula* Schltdl. & Cham. association (Areas under timber harvesting).

Timber production was identified as the primary management objective, given that any objective in Phase 1 must be related to the attributes whose markers will be measured (Tierney *et al.*, 2009) (Table 1). In this case, the evaluation aimed to assess properties of the ecosystem that are relevant to forest harvesting.

The selection of the indicators met the following criteria: (A) To distinguish an "intact" and functional state from a degraded or highly impacted one, (B) To respond to natural or anthropogenic disturbances, and (C) To be feasible, cost-effective and, as a whole, address the ecosystem's structure, composition and function (Tierney *et al.*, 2009). The selected indicators were obtained at the site level (Figure 2).

Phase 2 involved the collection, processing, and analysis of field data. A base map was prepared from satellite images to validate the polygons registered in the field for the four associations. Data were collected for the different indicators during June-August 2018. A random sampling (1 % intensity) was designed within each plant association, based on the overlapping of a grid of equidistant points every 100 m, for a total of 79 sampling units: 65 in the managed areas and 14 in the conservation zone (Rendón, 2020). For each sampling unit, 400 $m^2$ circular plots were established, nested and in the center of these, a 12.56 $m^2$ circular sub-plot and four 1 $m^2$ square sub-plot were located outside it in the four directions. At each plot, dasometric and ecological variables of trees, shrubs, and herbs were measured and evaluated (Rendón, 2020; Rendón-Pérez *et al.*, 2021).

Additionally, 500 g soil samples were collected from the first 30 cm of mineral soil in 50 % of the sampling units per plant association. Subsequently, a composite sample of 1 kg per association and three replicates were obtained, adding up to a total of

12 samples that were used to obtain the function indicators. General site information, such as geographic coordinates and altitude (Etrex Garmin® GPS), slope (Forestry Pro II Nikon® hypsometer), aspect, leaf litter depth, and percentage of rock cover recorded.

After evaluating the indicators, the natural range of variation (NRV) was established, which refers to the baseline from which it is possible to identify whether or not the indicators in particular or the overall EI of the site are within an acceptable range (Schroeder *et al.*, 2011). Their determination should be based on the contrast with sites where human intervention has been minimal (Stoddard *et al.*, 2006). In this case, the information used was collected in the field from the conservation area with the PQ association, from the scientific literature review, from results of the State Forest Inventory 2014 (Conafor, 2015), and through consultation with experts, to facilitate the identification of an acceptable range of variation for each indicator. As a result, four categories were established: Excellent (A), Good (B), Fair (C), and Low (D), each with a specific score (Table 3).

**Table 3.** Evaluation interval of the indicators by category for the assessment of ecological integrity in the *ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

| Indicator | A (4 points) | B (3 points) | C (2 points) | D (1 point) |
|---|---|---|---|---|
| Absolute surface area (ha) | ≥50 | ≥40, <50 | ≥30, <40 | <30 |
| Tree regeneration composition (number of native genera) | ≥10 | 7-9 | 4-6 | ≤3 |
| Number of tree, shrub, and herbs species | ≥50 | ≥40, <50 | ≥30, <40 | <30 |
| Simpson's Index (1-D) | ≥0.75 | ≥0.50, <0.75 | ≥0.25, <0.50 | <0.25 |
| Margalef Index | ≥1.5 | ≥1, <1.5 | ≥0.5, <1 | <0.5 |
| Species at risk (within NOM-059-SEMARNAT-2010) | ≥5 | 3-4 | 1-2 | 0 |
| *IVI* (Importance Value Index) native species (%) | ≥95 | ≥75, <95 | ≥50, <75 | <50 |
| *IVI* (Importance Value Index) invasive species (%) | 0 | <5 | ≥5, <10 | ≥10 |

| | | | | |
|---|---|---|---|---|
| *IVI* (Importance Value Index) *Pinus* L. genus (%) | ≤60 | >60, ≤80 | >80, ≤90 | >90 |
| Tree regeneration (individuals $ha^{-1}$) | ≥75 | ≥50, <75 | ≥25, <50 | <25 |
| Density (trees $ha^{-1}$) | ≥300 | ≥200, <300 | ≥100, <200 | <100 |
| Density of mature trees Normal diameter *ND*>50 cm, Total height *H*>25 m (trees $ha^{-1}$) | ≥10 | ≥4, <10 | ≥1, <4 | 0 |
| Density of standing dead trees (trees $ha^{-1}$) | ≥10 | ≥4, <10 | ≥1, <4 | 0 |
| Stump density (stumps $ha^{-1}$) | ≤25 | >25, ≤75 | >76, ≤150 | >150 |
| C:N ratio | ≥25 | ≥20, <25 | ≥15, <20 | <15 |
| Soil Organic Matter (*SOM*) (%) | ≥25 | ≥20, <25 | ≥15, <20 | <15 |
| Cation Exchange Capacity (*CEC*) (Cmol(+) $kg^{-1}$) | ≥50 | ≥40, <50 | ≥30, <40 | <30 |
| Depth of the *ocochal* (cm) | ≥5 | 4 a 5 | 1 a 3 | 0 |
| Bare ground cover (%) | ≤5 | ≤10, >5 | ≤15, >10 | >15 |
| Basimetric area (*BA*) ($m^2$ $ha^{-1}$) | ≥25 | ≥20, <25 | ≥15, <20 | <15 |

Each indicator was evaluated to determine the status of its attributes, and based on the category in which it was classified, the corresponding score. Finally, the score for each plant association was calculated by adding them up and standardizing the totals (by the summation by 0.8, given that the maximum possible score was 80) to obtain a value of the *EII* between 0 and 100. *EII* intervals were grouped into four categories: Excellent (A): 76 to 100 points, Good (B): 51 to 75 points, Fair (C): 26 to 50 points, and Low (D): 0 to 25 points (Table 4).

**Table 4.** Rating and interpretation of the categories of ecological integrity of the forest of the *ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

| **Category (*EII* score)** | **Description** |
|---|---|
| Excellent (A): 76 to 100 points | Desirable level of EI, little or no human intervention is required for indicators and attributes to remain within the natural range of variation (NRV). Plant structure and composition indicate high diversity, and function indicators are within the NRV, therefore, the ecosystem is functional. |

| | |
|---|---|
| Good (B):<br>51 to 75 points | Acceptable level of EI with little human intervention needed to maintain it. Structure and composition with moderate impact. Ecosystem function is not compromised; monitoring is required to ensure its continuity. |
| Fair (C):<br>26 to 50 points | Undesirable level of EI impairment, intervention is needed for correction. Several indicators are outside the NRV. Ecosystem functions are compromised and will have negative consequences in the medium and long term. |
| Low (D):<br>0 to 25 points | Strong impact on EI, its current condition is critical and undesirable, requiring immediate intervention to correct it. Most of the indicators are outside the NRV. Ecosystem functions are compromised, and there will be negative environmental consequences in the short term. |

# Results

The forests studied in the *ejido El Nopalillo, overall, exhibited* an EI in the excellent and good categories; although timber harvesting had a negative impact on some indicators of structure and composition, the analyzed ecosystem functions remained within an acceptable range.

The set of indicators showed that forest management activities maintained forest cover and plant species richness, promoting conditions for native species to prevail and resist the potential proliferation of invasive species after timber harvesting. All four vegetation associations obtained high scores for the indicators of area, native species cover, invasive species, tree density, and C:N ratio, indicating a high level of conservation (Table 2, Table 3).

The highest *EII* value (86 points) was obtained for the conservation area (PQ) (Figure 3) and fell within the excellent category with the indicators of structure, composition, and function within the NRV, in which little or no human intervention is required. The *EII* value is the result of the diversity and richness markers (Simpson and Margalef indices), the number of native species and the low or null presence of invasive species, a higher percentage of species of the genus *Pinus* L., a higher density of mature trees, a higher basimetric area (*BA*), and a lower density of stumps. In addition, the function indicators (soil) were the highest (Table 2, Table 3).

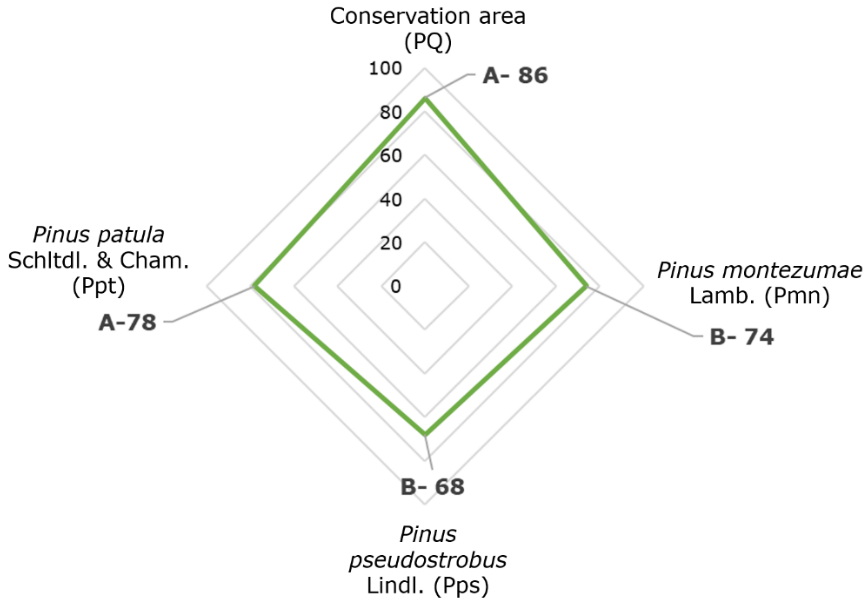



**Figure 3.** Category and Ecological Integrity Index for each type of vegetation association in the *ejido El Nopalillo*, in *Epazoyucan*, *Hidalgo*, Mexico.

On the other hand, in the associations under timber harvesting, the number of species indicator obtained the highest score, while the indicators with the lowest values were the density of mature trees and that of standing dead trees. Particularly, the *P. patula* (Ppt) association achieved highest value for the *EII* (78 points) in the excellent category (Figure 3), and the best rated indicators were richness in tree regeneration, Margalef and Simpson indices, bare soil cover, and depth of the *ocochal* (Table 2, Table 3).

The lowest *EII* value was obtained by the association of *P. pseudostrobus* (Pps) with 68 points and a good category (Figure 3), the level of integrity is considered acceptable, although minimal human intervention is required to maintain or enhance it. There is a moderate impact on structure and composition, and although the ecosystem function is not compromised, monitoring is necessary to ensure its continuity or improvement. The indicators contributing to the lowest values were species at risk, density of mature trees, standing dead trees, and stump density. In the same category, with 74 points, was the association of *P. montezumae* (Pmn) (Figure 3), and the attributes with the lowest score were the same those for Pps, except for stump density (Table 2, Table 3).

# Discussion

Experiences in different parts of the world have demonstrated the usefulness of integrating different variables in order to understand the EI (Hansen *et al.*, 2021), for example, into Canadian parks (Parks Canada Agency, 2011) and some national forests in the northeastern USA (Tierney *et al.*, 2009), or in global landscape-level analyses to capture the conservation status of the forests (Grantham *et al.*, 2020). This was made possible thanks to the increased number and capacity of satellite sensors and research networks for monitoring and assessing the ecosystem integrity (Hansen *et al.*, 2021).

In Mexico, information from the National Biodiversity Monitoring System, the National Forest and Soils Inventory, and satellite data have been integrated to obtain an Ecological Integrity Index at the national level (García-Alaniz *et al.*, 2017), as well as the integrity condition of the landscape considering the top predators (Mora, 2021). Likewise, Mora (2022) introduces a conceptual framework for analyzing forest integrity using indicators of ecological complexity in Mexican forests with attributes such as biodiversity (richness and composition of plant species), structure and development of the canopy, and understory, as well as indicators of human effects on structural complexity.

Although the above examples correspond to spatial scales other than the one used in the present study, Rempel *et al.* (2016), Karr *et al.* (2022), and Mora (2022) agree that the concept of EI along with a conceptual framework for integrating multiple data into a single index is a practical way to concentrate complex information useful for characterizing, reporting, and making decisions related to natural resource management and that it is desirable to have information at the local level.

In addition to the above, the use of multi-metric indices is a consequence of the fact that forest management has evolved from exclusively productive interest to a broader approach, where it is important to sustainably secure a variety of ecosystem goods and services, while simultaneously conserving biodiversity and ecological processes (Lindenmayer and Cunningham, 2013). Therefore, effective management of production forests should maintain yields without reducing their EI (MacDicken *et al.*, 2015) considering elements of disturbance and habitat function (Rempel *et al.*, 2016; Bisbing *et al.*, 2022).

The methodological approach presented herein offers some advantages for forest resource managers. It is practical, since it uses data that are regularly collected in forest inventories and are necessary to implement the management plan; it is also enriched by incorporating some variables that provide an analysis of the degree of conservation of managed forests, especially at the local scale. Complementarily, it is useful because it identifies the conservation status of each indicator, facilitating evidence-based decision-making and recommendations

(Rempel *et al.*, 2016; Karr *et al.*, 2022). In addition, it can be adapted and updated periodically and be used in areas under timber and non-timber harvesting, or exclusively for conservation purposes.

One potential limitation of this proposal is that it was conducted with the current data (*i. e.,* at the time of the assessment); therefore, the disturbance history or previous conditions in the conservation area are unknown as they are not documented. Other reports provide a conceptual framework for selecting feasible reference states by identifying areas with higher biodiversity values relative to other locations within the same ecosystem, irrespective of disturbance history (McNellie *et al.*, 2020), or through, the selection of contemporary areas of low human pressure (Scholes and Biggs, 2005). The area studied met both these criteria insofar as possible.

The areas under management in this study have information from management plans, however, modifications or adaptations or even natural or human disturbances are not identified for each association, as would be advisable for a more detailed evaluation. Even so, these results represent the baseline from which it is possible to detect future changes (Karr *et al.*, 2022).

By incorporating data on the ecosystem structure, composition, and function, it became possible to describe and quantify differences between plant associations and management types (timber harvesting *vs* conservation), that would be difficult to perceive through traditional assessments (Rempel *et al.*, 2016). The conservation area maintains high values of richness and diversity that are important, but not necessarily the only indicators of integrity in an ecosystem (Karr *et al.*, 2022; Mora, 2022); by incorporating the understory (shrubs and herbs) —a stratum that is little considered in both managed and unmanaged areas— in the evaluation of plant diversity (Rendón-Pérez *et al.*, 2021). Forests without recent interventions would have a higher presence of mature trees and also of standing dead trees as indicators of advanced successional stages (Keeton, 2006), as in the case of the PQ area, in addition to a lower density of stumps, an indicator related to forest harvesting. In a similar way, indicators with high native species richness have been found to represent an advantage in maintaining integrity, as they confer resistance to invasion by undesirable species (Pyke *et al.*, 2010).

In the areas under timber harvesting, there were indicators such as a higher percentage of pine species, which was to be expected since one of the objectives of the SDM is the generation of mono-specific even-aged stands, although other tree species are also favored in the area (Rendón, 2020). Consequently, there is little or no presence of mature or dead standing trees, despite the fact that some associations were close to the 50 year old rotation. The higher density of stumps contrasts with that found in the PQ area, but this also reflects the actions of change in structure and composition as a result of forest management (Bisbing *et al.*, 2022).

Among the function indicators, the *BA* is considered a measure of the forest's capacity to produce biomass (Mora, 2022); in areas under management, the values are lower than in PQ, since, in general, areas under management are at juvenile successional stages (Keeton, 2006). In contrast, indicators with high values in these associations were soil organic matter content and its potential to provide essential elements for plants mediated by soil texture, pH, temperature, and humidity (Bot and Benites, 2005). Organic matter also influences the cation exchange capacity or the potential to maintain soil fertility (Thiers *et al.*, 2014), and the depth of the *ocochal* (layer of litter and organic residues) is one of the sources of energy of ecosystems (Tierney, 2009), in addition, it becomes an indicator with a high potential to keep the soil covered and avoid erosive processes (Pellant *et al.*, 2005).

In general, forest management strategies to conserve EI are too complex to be subjected to experimentation (Simberloff, 2001; Drever *et al.*, 2006; Perera *et al.*, 2008; Klenk *et al.*, 2009); therefore, objective forms of evaluation are required to determine whether or not the management approach is conserving the EI

(Carignan and Villard, 2002). The proposal in this work can be used to solve this problem, as the results will provide information on whether to maintain, adapt or reject management strategies.

# Conclusions

The highest Ecological Integrity Index (*EII*) value was found in the conservation area (PQ) when compared to the areas under use, confirming our proposed hypothesis. Therefore, the vegetation associations under timber harvesting obtained lower *EII* values but excellent and good EI categories. This rating was influenced by the deterioration in the indicators related to the structure and composition of the ecosystem due to the implementation of forestry treatments, the objective of which is to obtain a structurally regular forest through its coetaneity.

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**Conflict of interest**

The authors declare that they have no conflict of interest.

**Contribution by author**

Martha Azucena Rendón-Pérez: field data collection, taxonomic determination, data analysis, and drafting of the document; Patricia Hernández-de la Rosa: conceptualization and direction of the research, revision and editing of the document; Valentín J. Reyes-Hernández: revision and editing of the document; Alejandro Velázquez-Martínez: revision and editing of the document; José Luis Alcántara-Carbajal: revision and editing of the document.

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