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Threatened Trees Characteristic of Mexican Tropical Montane Cloud Forests

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Abstract: In this study, we document the distribution, current knowledge, and conservation of twenty-six tree species of gymnosperms (four species) and angiosperms (twenty-two species) characteristic of the Mexican cloud forests and most endemic to Mexico. Many species are threatened and included in international and national Red Data List, such as the IUCN, and the Mexican Official Norm (NOM-059-SEMARNAT-2010). Distribution maps of these 26 species were generated based on information from herbarium specimens, specialized literature, web databases, and our own field surveys. All records were displayed on a map of the Mexican territory divided into grid cells of 15 × 20 min of latitude/longitude (a spatial resolution of approximately 27.75 km × 36.75 km) to obtain the richness patterns. Additionally, these records were displayed on the map of the current Mexican System of Natural Protected Areas (NPAs) to evaluate their representativeness in these areas of in situ conservation. We also include information on populations and the habitat status of these tree species in some Mexican locations. Most species studied here require particular policies for their conservation due to the problems affecting their natural populations and habitat. Our results indicate that three species are not represented in the Mexican System of NPAs and that some are underrepresented.

Keywords: IUCN Red List; endemism; threatened species; Natural Protected Areas

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1. Introduction

The most recent estimation of the native vascular flora of Mexico [1] indicates that this flora is represented by 23,314 species and 2854 genera, with nearly 50% of the species being endemic. Approximately 2800 species of these vascular plants inhabit the Mexican tropical montane cloud forest (TMCF) [2]. These species constitute 10% of the total number of vascular plants estimated in Mexico, representing a high species richness in a relatively small area, considering that these forests cover less than 1% of the territory, an area equivalent to 8809 km^2 [3]. Additionally, more than 82% of the country's plant families are found in this ecosystem [2].

The Mexican TMCF represents the northernmost extension of the montane cloud forests in the New World [4], exhibiting an archipelagic or discontinuous distribution pattern that is also fragmented by land use change through humid mountain slopes, ravines, and gorges and diagnosed as threatened due to its small extent and fragility. This forest commonly comprises populations of few or scarce individuals located in a few isolated patches [4,5]. They are best developed between 1000 and 1750 m above sea level and are characterized by the cloud layer's persistence and seasonality [6,7]. These forests occur in environments that combine relatively high annual rainfall (mainly 1500–3000 mm), irregular topography, and mild to cool temperatures [4,6]. Unfortunately, the intensive land-use change due to high deforestation rates and activities related to human settling clearance, agriculture, and animal husbandry exacerbates the fragmentation of the TMCF [4,5,8–10]. The term "tropical" refers to the geographical distribution of this vegetation type in the mountains from the Neotropics [11]. The TCMF usually prospers in conditions with an annual temperature average above 22 °C and the highest monthly temperature between 18 and 22 °C. In eastern Mexico (the Gulf of Mexico slope), the TMCF prevails in tropical pluvial bioclimates, but on the western side (the Pacific slope), it extends above a 2000 m elevation in pluvial seasonal bioclimates [12]. On the Pacific slope, the mist condenses at a higher level than on the Atlantic slope. The floristic composition of the TMCF includes, in the canopy, typical taxa that are represented in Mexican temperate forests [13,14].

The richness of tree species in the Mexican TMCF constitutes approximately 25% of the total vascular plant diversity [2]. In this vegetation type, the tree associations are about 15 to 30 m tall, although some species can reach 40 to 60 m. A multistratified canopy is presented, where trees define the forest structure and contribute to the forests' ecological function and resilience [2,4]. Many of the component tree species are severely threatened or in danger of extinction [2,5,8,10], and most of them have low frequencies due to the patchy distribution of this vegetation type [2,5,7]. The Mexican TMCF is expected to be among the ecosystems most affected by global climate change, including the tree species inhabiting these forests; many are in some risk category [2,9,10].

Previous studies analyzing the distributional patterns related to the richness, phylogenetic composition, biogeography, and floristics of vascular plants inhabiting the Mexican TMCF have been performed, and many of the products come from our own research, e.g., [4,5,11,15–25]. Furthermore, our previous research included vegetation structure investigation of the arboreal stratum, where several endangered trees have their place [26–33]. In addition, some other studies are related to the impact of climate change on endangered tree species of the Mexican TMCF [9,10,33–40]. First, however, it is necessary to integrate, update, and expand the knowledge of these Mexican TMCF diagnostic trees using a detailed geographic scale, allowing us to recognize areas with high concentrations of these species and distributional information gaps.

We aimed to contribute to the ecological and biogeographical knowledge of some selected tree species that are frequent elements of the Mexican TMCF along a wide distribution range. All these species are considered diagnostic or characteristic of this vegetation type. We also intend to promote their in situ conservation, evaluate the geographic distribution of these diagnostic species, and determine the accuracy of the current protected areas, intending to evaluate their diversity according to the Mexican Natural Protected Areas (NPAs). Finally, we proposed incorporating or changing some species into the Red List of the IUCN using the GeoCAT web tool [41].

2. Material and Methods

We chose a set of 26 tree species for this study, including twenty-two angiosperms and four gymnosperms most endemic to Mexico and well-represented in the Mexican mountains of the Mexican Transition Zone sensu Morrone [42]. These tree species are frequent, characteristic, or diagnostic elements of the Mexican TMCF [13,21]. Most species are included in different extinction or endangered risk categories in the Mexican Official Norm NOM-059-SEMARNAT-2010 [43] and the IUCN Red List [2]. Methods went along with the following diagram (Figure 1).

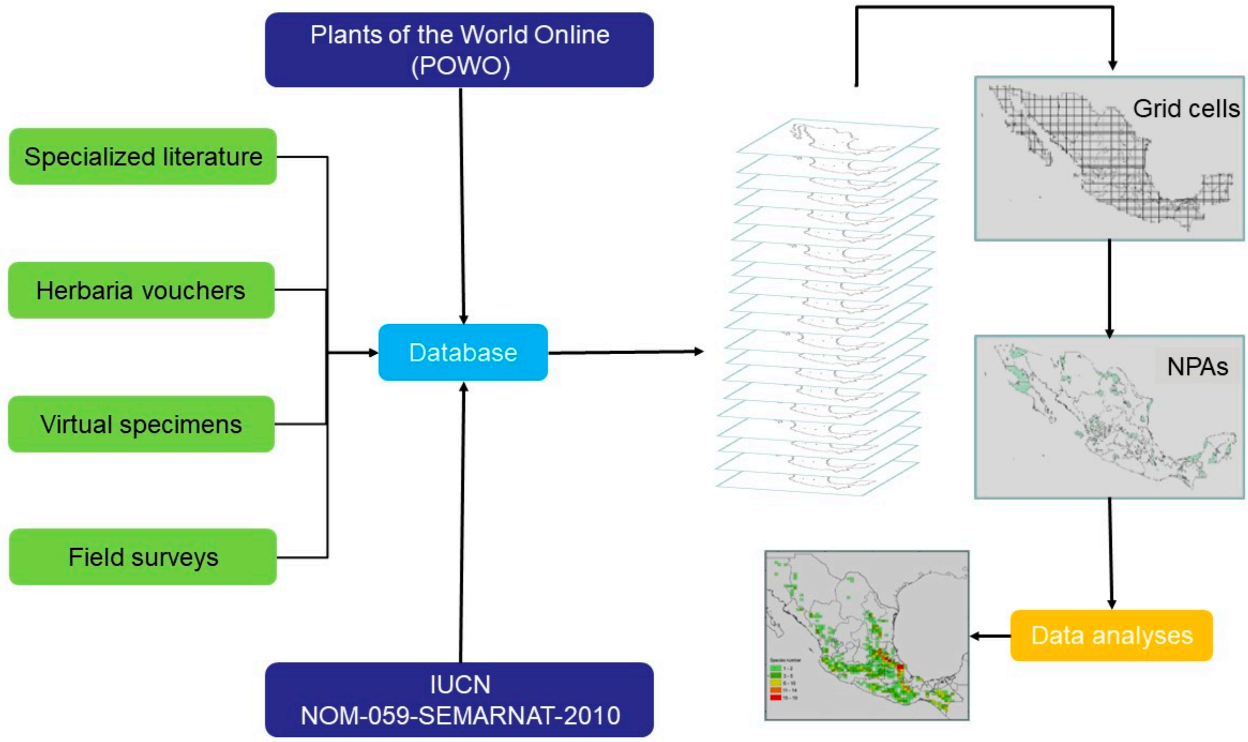

Figure 1. Methodology diagram. Sources of database construction. The taxa names followed the Plants of the World Online (POWO) nomenclature. Risk categories of the taxa agreed with the IUCN Red List and NOM-059-SEMARNAT-2010. Distributional maps of each tree species were generated using ArcGIS software and then overlapped on a grid cell system of 15 $\times$ 20 min latitude/longitude and the Mexican NPAs.

Distributional data of vascular plants inhabiting the Mexican TMCF have been obtained from more than 30 years of field surveys, revision of herbarium specimens in different Mexican herbaria, and revision of monographic and taxonomic studies of vascular plants of the TMCF, resulting from several floristic and biogeographic projects. We prepared a general Mexican TMCF database comprising 5624 records of these 26 tree species from this information. In addition, the central floristic and revisionary studies related to the selected tree species were reviewed to acquire information concerning their distribution and ecology [2,8,17,18,44–49]. We decided to follow the nomenclatural and taxonomic proposals published on the Plants of the World Online webpage [50] to distinguish and homogenize the names of the species, avoiding nomenclatural confusion.

We revised the available herbarium vouchers of the studied tree species in the following botanical collections: National Herbarium of the Instituto de Biología, UNAM (MEXU), Herbarium of the Escuela Nacional de Ciencias Biológicas, Instituto Politécnico Nacional (ENCB), Herbarium of the Missouri Botanical Garden (MO), Herbaria of the Instituto de Ecología A.C. in Xalapa City (XAL) and Pátzcuaro City (IEB), Herbarium of the Universidad Autónoma Metropolitana, Unidad Iztapalapa (UAMIZ), Herbarium of the Facultad de Ciencias, UNAM (FCME), Herbario Nacional Forestal (INIF), Herbarium of the Instituto Tecnológico de Ciudad Victoria, Tamaulipas (ITCV), Herbarium of the Universidad de Guadalajara (IBUG), Herbarium of the Departamento de Bosques, Universidad Autónoma Chapingo (CHAP), Herbarium of the Centro Interdisciplinario para el Desarrollo Integral Regional, Unidad Oaxaca, Instituto Politécnico Nacional (OAX), and Herbarium of the Universidad Autónoma de Querétaro (QMEX) (acronyms sensu Thiers [51]). In addition, the species identity was verified for each voucher examined, the nomenclature was updated to the latest taxonomic revisionary study [50], and the geographical coordinates were revisited and updated accurately for each database record. In addition, we revised the National Herbaria databases compiled by the CONABIO (Comisión Nacional para el

Conocimiento y Uso de la Biodiversidad). Finally, we conducted botanical field surveys in the Mexican states of Hidalgo, Querétaro, Estado de México, Veracruz, Tamaulipas, and Oaxaca to obtain field data and to obtain field observations of natural populations of these tree species. Based on our expertise and previous research [5,14,18,19,28], we conducted vegetation and floristic studies to evaluate the representativeness of these tree species, their ecological importance, and their contribution to the vegetational structure of the Mexican TMCF.

With all this information, we generated distributional maps of each 26 tree species using ArcGIS software [52] and then overlapped them on digital 1:1,000,000 scale maps of Mexico. The Mexican territory was divided using a grid system with a 1:50,000 scale, composed of 2313 grids of 15 × 20 min latitude/longitude with a spatial resolution of approximately 27.75 km × 36.75 km produced by the Comisión Nacional para el Uso y Conocimiento de la Biodiversidad [53].

Using ArcGIS [52], we intersected the maps of the localities of the species with the grid system, including all the species, to obtain the richness of each grid cell. Next, we selected those areas with more species richness (more than 10 living sympatrically). Then, we overlapped them on the Mexican System of Natural Protected Areas (NPAs) map of the Comisión Nacional de Áreas Naturales Protegidas decreed by the Mexican Federal Government [54] and the Mexican State System of Natural Protected Areas map [55] to determine the effectiveness of the current NPA system for in situ conservation and to determine the diversity of threatened tree species recorded within each Federal and State NPA.

Moreover, we reviewed the Official Mexican Norm NOM-059-SEMARNAT-2010 [42] to recognize how many of the tree species analyzed here are listed and assess the corresponding risk category for each species. The NOM-059-SEMARNAT-2010 is the official document generated by the Mexican Government encompassing the environmental protection of the wild flora, fauna, and fungi species native to the country. This document includes the specifications for including and analyzing those species in some risk categories. Some categories in both the IUCN Red List and the Mexican Norm NOM-059-SEMARNAT-2010 official lists can be considered equivalent, such as the threatened category in the Mexican Norm NOM-059-SEMARNAT-2010 to the vulnerable category of the IUCN [56]. In addition, the special protection category (Pr) of the NOM-059-SEMARNAT-2010 includes some minor categories of the IUCN [57].

To reevaluate the category of the studied species, we determined the conservation status (according to IUCN categories and criteria [56]), the extent of occurrence (EOO), and the area of occupancy (AOO) criteria of the studied species using the Red List threat assessments with the GeoCAT [41] browser-based tool. This webpage is updated constantly, see https://www.kew.org/science/our-science/projects/geocat-geospatialconservation-assessment-tool (accessed on 9 November 2022) [56]. Following the IUCN suggestion, we selected the highest risk category for each tree species.

We graphed the frequency of the species on the grid cells to establish a geographic rarity assessment as a risk criterion. Then, following the proposal of Gray et al. [58] and Nunes et al. [59] based on Preston's octaves, we applied a binning method to assess the distribution of the species studied related to the number of grid cells where they occur. We used a modified $\log_2$ classes binning system where bin 1 = the number of species occurring in one grid cell, bin 2 = the number of species occurring in 2–3 grid cells, bin 3 = 4–7 grid cells, bin 4 = 8–15 grid cells, and so on. The interval is on a $\log_2$ scale [58] which considers those species in the first three classes of the octaves as rare [59].

3. Results

We present here a new distribution map of the Mexican TMCF, improved from the INEGI version [3]. The geographic location of the TMCF patches resulted from the revision of published floristic literature, our field expertise of several years in the Mexican TMCF, and herbarium labels of poorly mappable forest patches (Figure 2). This is the case for some large and isolated patches located in the area of the Sierra Gorda in the northeastern portion of the state of Querétaro that are not entirely included in the INEGI map [3], and neither are the studies of González-Espinosa et al. [2] and Ochoa-Ochoa et al. [60], among others. The same occurs with some isolated patches of San Luis Potosí and Tamaulipas. Furthermore, our studies [22,23,33] and herbarium vouchers of some species (e.g., *Cupressus lusitanica*, *Diospyros conzattii*, *Magnolia rzedowskiana*, *Podocarpus matudae*, *Taxus globosa*, *Ternstroemia huasteca*, and *Tilia mexicana*) confirm the existence of the TMCF in other areas not charted by the INEGI [3].

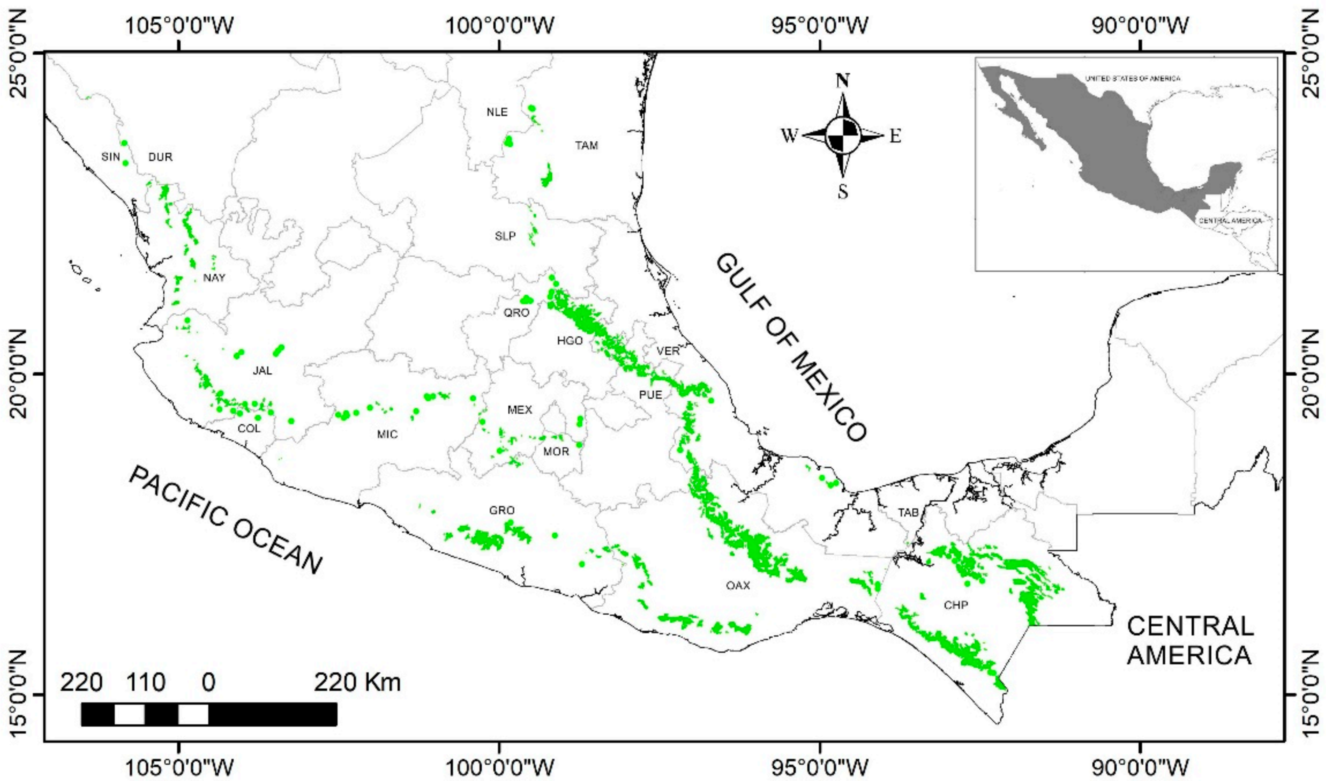

Figure 2. A map of Mexico showing the geographic location of the TMCF (modified from the INEGI [3]). Mexican state abbreviations are as follows: CHP, Chiapas; COL, Colima; DUR, Durango; GRO, Guerrero; HGO, Hidalgo; JAL, Jalisco; MEX, México; MIC, Michoacán; MOR, Morelos; NAY, Nayarit; NLE, Nuevo León; OAX, Oaxaca; PUE, Puebla; QRO, Querétaro; SIN, Sinaloa; SLP, San Luis Potosí; TAB, Tabasco; TAM, Tamaulipas; and VER, Veracruz.

The 26 tree species and the vegetation types where each tree species occurs are presented in Table 1. These species mainly inhabit temperate forests, such as pine–oak, oak, pine forests, and TMCFs, especially in temperate climates, in altitudinal ranges from 850 to 3600 m, but mainly between 1000 and 2800 m. Few of these species inhabit broad altitudinal and latitudinal ranges (e.g., *Litsea glaucescens* and *Pinus chiapensis*). These tree species generally inhabit humid slopes where TMCF prospers with abundant atmospheric moisture. Most of the tree species analyzed are key elements in the different strata of the forests where they grow (Table 1).

Figure 3 shows the distribution of these species in a grid system with a spatial resolution of 15 × 20 min of latitude/longitude. Based on herbarium specimens examined, web databases, and samples collected during fieldwork, we obtained a database with 5624 accession georeferenced records corresponding to twenty-six tree taxa, four gymnosperms, and twenty-two angiosperms. The tree species studied here are mainly distributed in the Mexican Transition Zone sensu Morrone [42] (Sierra Madre Occidental, Sierra Madre Oriental, Trans-Mexican Volcanic Belt, Sierra Madre del Sur, and the Chiapas Highlands), characterized by its montane temperate humid conditions, mainly in TMCF, oak, pine–oak, and pine forests (Figure 3).

Interestingly, all grid cells with ten or more species are in the Mexican Transition Zone (sensu Morrone [42]), predominantly in the Sierra Madre Oriental. These grid cells join with the Trans-Mexican Volcanic Belt and Oaxaca Highlands, represented by the most extensive and continuous patches of the Mexican TMCF (Figures 2 and 4). The richest grid cells are in the biogeographically complex areas of the Karst Huaxteco and the Oaxaca Highlands.

The geographic distribution of the tree species studied here demonstrated that most are endemic to the country (Table 1). However, their presence in grid cells showed different patterns, from narrow to wide ranges from 1 to 194 grid cells (Table 1). For example, *Magnolia nuevoleonensis* (Nuevo León) and *M. alejandrae* (Tamaulipas) are restricted to one and two grid cells, respectively. Other tree species recorded in less than eight grid cells were *Quercus meavei* (4), *Magnolia dealbata* (5), *M. rzedowskiana* (5), *Cleyera velutina* (7), *M. vovidesii* (7), and *Fagus grandifolia* subsp. *mexicana* (7). In contrast, four species were recorded in more than 100 grid cells (Figure 5), e.g., *Litsea glaucescens* (194), *Cupressus lusitanica* (135), *Carpinus tropicalis* (127), and *Ostrya virginiana* (112).

Concerning the risk categories of the NOM-059-SEMARNAT-2010 [43], seventeen of the tree species are included in a risk category: four as threatened (A), seven in the special protection category (Pr), and six in danger of extinction (P). Twenty-five species are included in the IUCN Red List [56]: nine in the less concern category (LC), eight in endangered (EN), five in vulnerable (VU), two nearly threatened (NT), and one as critically endangered (CR) (Table 2). No species are included in the CITES checklist of wood or endangered species. Unfortunately, some species are not included yet in any risk category and need to be assessed for their inclusion in the Mexican Norm NOM-059-SEMARNAT-2010 (nine species) and the IUCN Red List (one species).

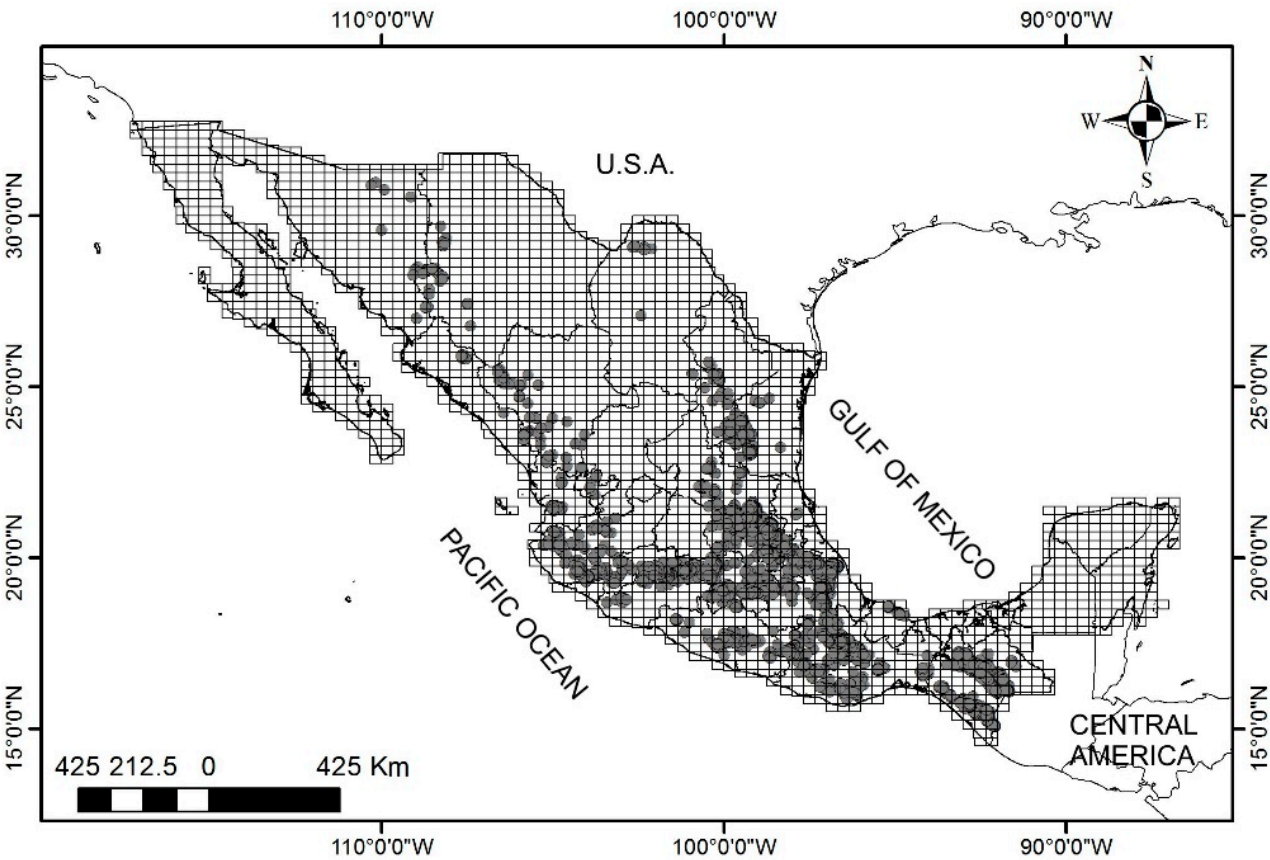

Figure 3. Geographic distribution of the 26 species that were studied using a grid system of Mexico by CONABIO [54] with a spatial resolution of 15 × 20 min of latitude/longitude.

Table 1. Geographic distribution of studied species (number of states/number of grid cells). Vegetation type, altitudinal range, and forest strata are where they occur. Vegetation types follow Rzedowski [6].

Species	Distribution	Vegetation Type	Altitudinal Range	Forest Strata
Acer negundo subsp. *mexicanum* (DC). Wesm.	Mx (21/35)	PF, PQF, TMCF	1200–2900	Medium or high arboreal layers
Carpinus tropicalis (Donn. Sm.) Lundell	Mx (23/127), CA	PF, PQF, TMCF	850–3600	Medium and high arboreal layers
Cleyera velutina B.M. Barthol.	Mx (3/7)	PQF, TMCF	1300–2500	Low arboreal layer
Cupressus lusitanica Mill.	Mx (29/135), CA	FF, PF, PQF, QF, TMCF	900–3600	Medium and high arboreal layers
Diospyros conzattii Standl.	Mx (8/28)	QF, TMCF	900–3000	Medium arboreal layer
Fagus grandifolia subsp. *mexicana* (Martínez) A.E. Murray	Mx (6/7)	PQF, TMCF	1200–2100	Medium and high arboreal layers
Juglans pyriformis Liebm.	Mx (13/25)	PF, PQF, TMCF	1000–2900	Medium and high arboreal layers
Litsea glaucescens Kunth.	Mx (26/194), CA	FF, PF, PQF, QF, TMCF	850–3100	Low and medium arboreal layers
Magnolia alejandrae García-Mor. and Iamonico	Mx (1/2)	PQF, TMCF	1500–2200	Medium arboreal layer
Magnolia dealbata Zucc.	Mx (2/5)	PQF, TMCF	1200–2000	Medium arboreal layers
Magnolia nuevoleonensis A. Vázquez and Domínguez-Yescas	Mx (1/1)	TMCF	1500–1700	Medium and high arboreal layers
Magnolia rzedowskiana A. Vázquez, Domínguez-Yescas and R. Pedraza	Mx (4/5)	PQF, TMCF	1450–2100	Medium arboreal layer
Magnolia schiedeana Schltdl.	Mx (6/27)	PQF, QF, SAP, TMCF	700–2500	Medium and high arboreal layers
Magnolia vovidesii A. Vázquez, Domínguez-Yescas and L. Carvajal	Mx (1/4)	PF, TMCF	1500–1900	Medium arboreal layer
Matudaea trinervia Lundell	Mx (7/21)	PF, PQF, QF, TMCF	900–2900	Medium arboreal layer
Ostrya virginiana (Mill.) K. Koch	Mx (23/112), CA, E-USA	PF, PQF, QF, TMCF	900–3000	Medium arboreal layer
Pinus chiapensis (Martínez) Andresen	Mx (5/36)	PF, PQF, TMCF	900–2500	Medium and high arboreal layers
Podocarpus matudae Lundell	Mx (14/76), CA	PF, PQF, TMCF	1000–2500	Medium and high arboreal layers
Quercus meavei Valencia-A, Sabas and O. J. Soto	Mx (2/4)	PF, PQF, TMCF	1300–2000	Medium and high arboreal layers
Symplocos coccinea Bonpl.	Mx (5/25)	PF, PQF, TMCF	900–2700	Low and medium arboreal layers
Symplocos speciosa Hemsl.	Mx (4/22)	PF, PQF, TMCF	1100–3000	Low and medium arboreal layers
Taxus globosa Schltdl.	Mx (10/42), CA	FF, PF, PQF, QF, TMCF	900–3100	Low and medium arboreal layers
Ternstroemia huasteca B.M. Barthol.	Mx (5/15)	PQF, QF, TMCF	1000–2100	Low and medium arboreal layers
Ternstroemia sylvatica Schltdl. and Cham.	Mx (14/54)	PF, PQF, TMCF	1000–2800	Low arboreal layer
Tilia mexicana Schltdl.	Mx (21/82)	PF, PQF, QF, TMCF	900–2800	Medium and high arboreal layers
Zinowiewia concinna Lundell	Mx (9/27)	PQF, QF, TMCF	900–2500	Medium and high arboreal layers

Abbreviations. Distributions are CA, Central America; E-USA, eastern United States; and Mx, Mexico. Vegetation types are FF, fir forest; PF, pine forest; PQF, pine–oak forest; QF, oak forest; SAP, tropical rain forest; and TMCF, tropical montane cloud forest. The six richest grid cells contain 14-19 of the studied species (and are in the Mexican states of Hidalgo, Puebla, and Veracruz (Figure 4). Other grid cells with high diversity (orange grid cells with 10–13 species) are in (1) El Cielo, Tamaulipas; (2) the Sierra Gorda in the boundaries of San Luis Potosí, Querétaro, and Hidalgo; (3) the Molango, Tlanchinol, and Hidalgo areas; and (4) the Oaxaca Highlands, represented by the Sierra de Zongolica, Sierra Mazateca, and Sierra de Juárez.

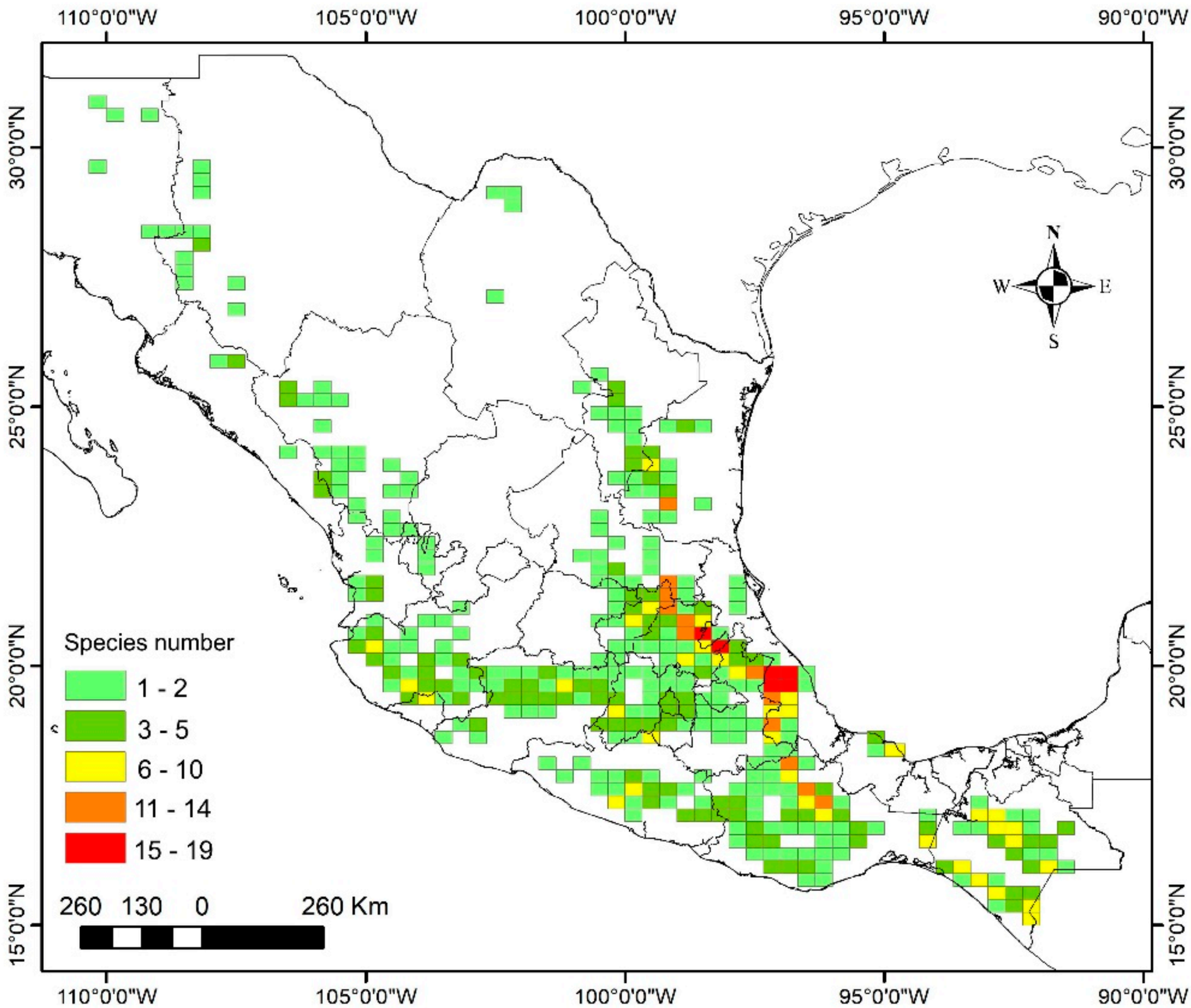

Figure 4. Species richness in the grid cells (15 × 20 min longitude/latitude) located in the Mexican TMCF.

Our analysis of the studied species (based on herbaria specimens, specialized literature, web databases, and our field surveys) concerning the map of the Mexican National System of Natural Protected Areas (NPAs) [54] and the State System of Natural Protected Areas [55] detected that three of the taxa studied are not integrated within protected areas (Figure 6); e.g., *Cleyera velutina*, *Magnolia dealbata*, and *M. vovidesii*. In addition, some other species are recorded only in one or two Mexican NPAs, such as *Fagus grandifolia* subsp. *mexicana*, *Magnolia alejandrae*, *M. nuevoleonensis*, *Magnolia rzedowskiana*, *Quercus meavei*, and *Ternstroemia huasteca*. In contrast, other tree species are represented in many NPAs, such as *Carpinus tropicalis* and *Cupressus lusitanica*, recorded in 34 NPAs, and *Litsea glaucescens* in 44 NPAs (Figure 6).

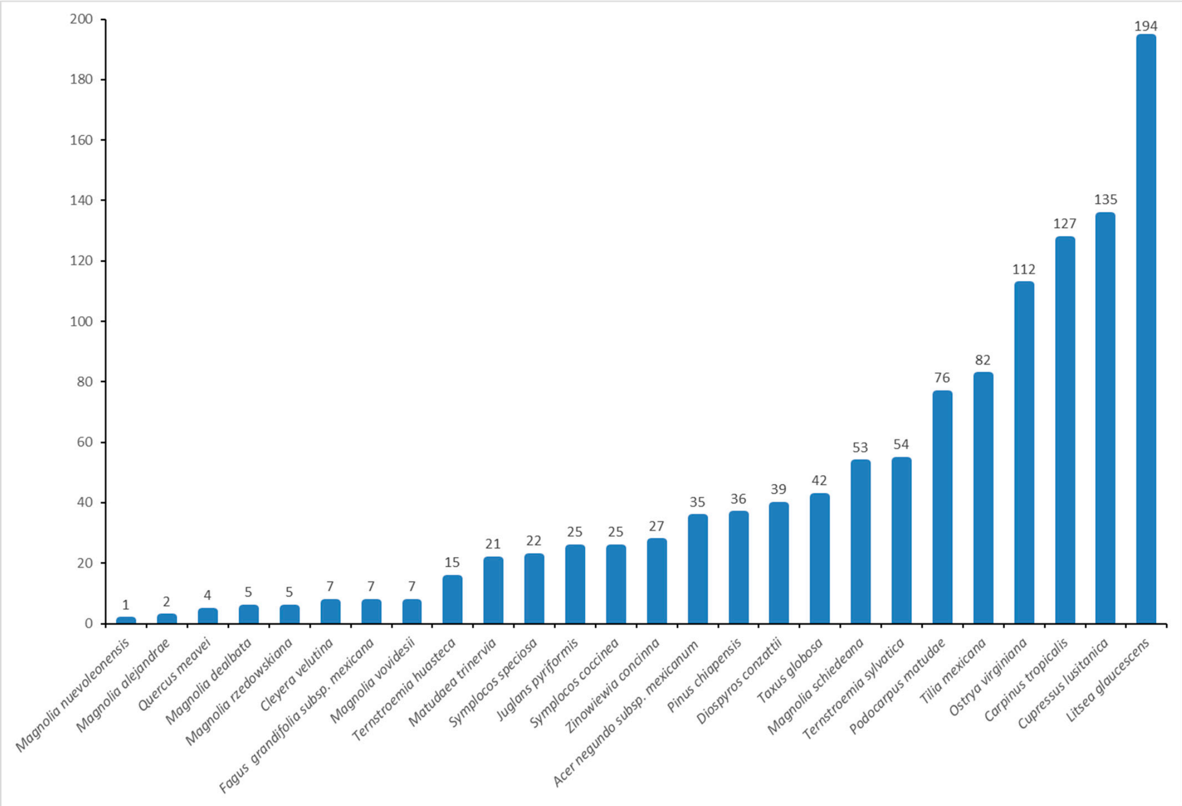

Figure 5. The number of grid cells occupied by each species studied.

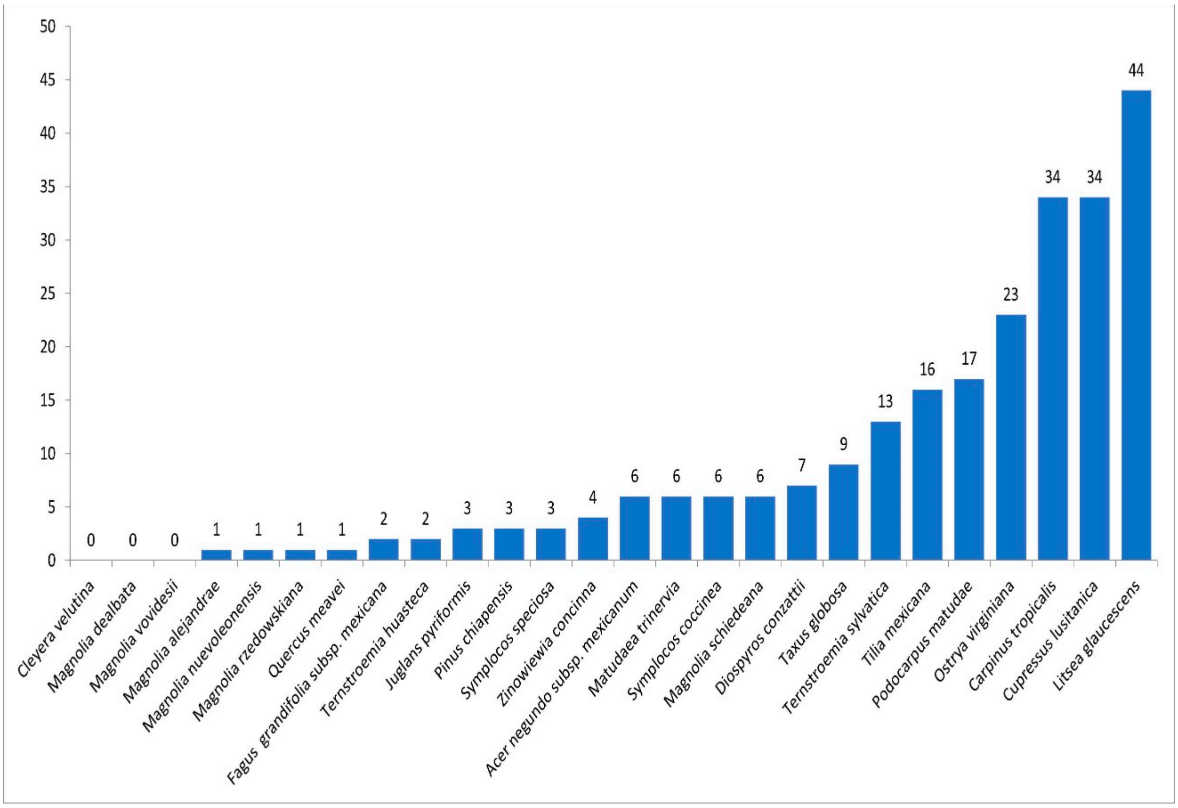

Figure 6. The number of Mexican protected areas (federal and state NPAs) where each tree species occurred.

Table 2. Risk categories of the tree species studied in NOM-059-SEMARNAT-2010 [43] and IUCN [56]. Reevaluated categories of these species following the Red List threat assessments with GeoCAT [41].

Tree Species	NOM-059-SEMARNAT-2010	IUCN	EOO	AOO
Acer negundo subsp. *mexicanum* (DC.) Wesm.	Pr	VU	LC	**EN**
Carpinus tropicalis (Donn. Sm.) Lundell	A	LC	LC	**NT**
Cleyera velutina B.M. Barthol.	ND	CR [1]	VU	**EN**
Cupressus lusitanica Mill.	Pr	LC	LC	**VU**
Diospyros conzattii Standl.	P	LC	LC	**EN**
Fagus grandifolia subsp. *mexicana* (Martínez) A.E. Murray	P	LC	NT	**EN**
Juglans pyriformis Liebm.	A	EN [2]	LC	**EN**
Litsea glaucescens Kunth.	P	LC	LC	**NT**
Magnolia alejandrae García-Mor. and Iamonico	ND	EN	**CR**	EN
Magnolia dealbata Zucc.	P	NT	EN	**EN**
Magnolia nuevoleonensis A.Vázquez and Domínguez-Yescas	ND	EN	CR	**CR**
Magnolia rzedowskiana A.Vázquez, Domínguez-Yescas and R. Pedraza	ND	EN [2]	VU	**EN**
Magnolia schiedeana Schltdl.	A	VU	LC	**EN**
Magnolia vovidesii A.Vázquez, Domínguez-Yescas and L. Carvajal	ND	EN [2]	VU	**EN**
Matudaea trinervia Lundell	A	LC	LC	**EN**
Ostrya virginiana (Mill.) K. Koch	Pr	LC	LC	**VU**
Pinus chiapensis (Martínez) Andresen	Pr	EN [1]	LC	**VU**
Podocarpus matudae Lundell	Pr	VU [2]	LC	**VU**
Quercus meavei Valencia-A., Sabas and O.J.Soto	ND	VU	VU	**EN**
Symplocos coccinea Bonpl.	Pr	NT	LC	**EN**
Symplocos speciosa Hemsl.	ND	ND	LC	**EN**
Taxus globosa Schltdl.	Pr	EN [1]	LC	**VU**
Ternstroemia huasteca B.M. Barthol.	ND	VU	VU	**EN**
Ternstroemia sylvatica Schltdl. and Cham.	ND	LC	LC	**VU**
Tilia mexicana Schltdl.	P	LC	LC	**VU**
Zinowiewia concinna Lundell	P	EN [2]	LC	**EN**

Abbreviations. Risk categories of the NOM-059-SEMARNAT-2010. (A) Threatened, (Pr) special protection; and (P) endangered. The IUCN includes (LC) less concern category, (CR) critically endangered, (EN) endangered, (VU) vulnerable, (NT) near threatened; and (ND) species not yet evaluated. Categories in bold were preliminarily selected as the most accurate. [1] Categories in a high risk than the obtained with the spatial analysis. [2] Categories identical to the one obtained with the spatial analysis.

Based on geographic criteria, we reevaluated the conservation status (according to IUCN categories and criteria [56]), applying the extent of occurrence (EOO) and area of occupancy (AOO) of the studied species through GeoCAT [41]. The EOO and AOO criteria obtained were different, except for one species with highly restricted distribution (*Magnolia nuevoleonensis*). In the case of the 22 tree species analyzed, the risk category obtained with GeoCAT [41] was higher than the current IUCN category. Finally, in the case of *Cleyera velutina*, *Pinus chiapensis*, and *Taxus globosa*, the current IUCN category was of higher risk than the one obtained in our analysis.

4. Discussion and Conclusions

The Mexican TMCF represents an invaluable ecosystem due to its environmental services, such as being a water reserve, its use for carbon capture, its use for timber production, and the goods generated and obtained by local people [2]. These forests have exceptional biodiversity, with over 2800 vascular plant species recorded. The tree species represent approximately 25% of this plant diversity [2,4,13]. The species analyzed here are dominant canopy members and contribute to high density, basal area, frequency, tree crown cover, and relative importance values [7,36]. These trees promote the forest's ecological function and resilience [2].

Unfortunately, the Mexican TMCFs are severely threatened [2,7]. Land-use change is a critical problem impacting the Mexican TMCF at spatial scales ranging from local to regional [9], mainly due to deforestation and agriculture associated with corn and coffee plantations [7,14]. As a result, these forests are among the most threatened ecosystems in the world [4,35]. Habitat destruction promoted by animal husbandry, illegal clearance, and urban expansion is the central pressures that have reduced the forest size and floristic composition [7].

Another current and crucial threat is global climate change, which is modifying and decreasing many species' biological diversity and populations. As a result, local extinctions are expected, fragmenting the populations [35]. In this sense, studies of threatened tree species of the TMCF using ecological niche models contribute to determining which climatic factors constrain the geographic distribution of these species and how these circumstances will change in the future under scenarios generated by the IPCC [9,10,34,35,61]. Furthermore, these studies reinforce the widely accepted idea that significant distribution changes in tropical mountains will occur in this century, predicting upward migrations of certain trees to higher elevations, extinctions, and drastic distribution contractions of species inhabiting the TMCF [9,10,34].

In the last two decades, scientific knowledge of some of the tree species that inhabit the TMCF has increased [2,5,9,10,28,34,35]. As a result, it is necessary to establish conservation strategies for many plant species that inhabit these forests, mainly those with relictual distribution, endangered species, microendemics, and small populations [2,5,36]. However, the conservation strategies for the Mexican TMCF represent a complex process [60,61].

The TMCF is a highly discontinuous vegetation type essential for the survival of many species studied, such as *Fagus grandifolia* subsp. *mexicana* [8,62] and some species of *Magnolia* [24,32], which are dominant species in some parts of eastern Mexico. Furthermore, because many of the TMCFs isolated patches are not protected, their situation is critical since agriculture and animal husbandry expansion are constant threats [5,7].

There are 18 Mexican grid cells with the highest richness (red = 14 to 19 species and orange = 10 to 13 species), all located along the Gulf of Mexico slope in the Sierra Madre Oriental. Two of these red grid cells are located on the southern border of the Pánuco River in the Karst Huaxteco. The other four red richest grid cells are located on the boundaries of the states of Veracruz and Puebla, where the flora of the Sierra de Chiconquiaco (that belongs to the southern part of the Karst Huaxteco) converges with the Oaxaca Highlands. Evidently, the northern and southern parts of the Pánuco River harbor different floras, representing a biogeographically complex area where the richness is increased (representing a panbiogeographic node sensu Croizat [63]).

A rarity analysis based on the binning method of Preston's octaves following the methodology of Gray et al. [57] and Nunes et al. [59] showed that species that fell in the first three frequency classes are geographically rare. These species occupy less than eight grid cells, such as *Cleyera velutina*, *Fagus grandifolia* subsp. *mexicana*, *Magnolia alejandrae*, *M. nuevoleonensis*, *M. rzedowskiana*, *M. vovidesii*, and *Quercus meavei*.

Some tree species analyzed here meet the criteria to be considered in some risk category (restricted distribution, low-density populations, and sensitive habitat to reduction by indirect and direct human impact) to be included in the Mexican NOM-059-SEMARNAT-2010 [43] and the IUCN [56]. For these reasons, we suggest that candidate species are *Cleyera velutina*, *Magnolia alejandrae*, *M. nuevoleonensis*, *M. rzedowskiana*, *M. vovidesii*, *Quercus meavei*, *Symplocos speciosa*, and *Ternstroemia huasteca*. However, detailed population and genetic studies are required to evaluate the proper protection category of these taxa. Some species were described after the revision of the Mexican NOM-059-SEMARNAT-2010 published in 2019 [43], such as many of the *Magnolia* species analyzed by García-Morales et al. [24], Vázquez-García [64–66], and Chávez-Cortázar et al. [67].

The reevaluation of the conservation status employing the AOO and EOO area thresholds followed a geographic framework. In most cases (17 species), this analysis increased the risk category status of the species. In the case of *Cleyera velutina*, *Pinus chiapensis*, and

Taxus globosa, the category obtained was of lower risk than the current IUCN category, suggesting all these species need a detailed evaluation of other parameters included in the Red List Assessment of the IUCN [56]. Previous studies showed that the EOO and AOO values are identical when the species have a highly restricted distribution [68]. In our study, *Magnolia nuevoleonensis* is the only known species from three localities [64].

Some of the taxa analyzed here constitute species complexes without a recently published phylogenetic analysis. This is the case of *Tilia mexicana* (Terrazas pers. com) and *Litsea glaucescens* (Rico-Arce pers. com.). The nomenclatural and taxonomical status of *Fagus grandifolia* ssp. *mexicana* must be switched according to the recent species concept proposed by De Queiroz [69] and the worldwide phylogenetic framework on the genus *Fagus* proposed by Jiang et al. [70], such as *Fagus mexicana* Martínez. Therefore, we suggest equaling the worldwide conservation status of this taxon as endangered for the IUCN Red List as proposed by the Mexican Official Norm NOM-059-SEMARNAT-2010 [43].

Most species of the selected genera preferentially inhabit the TMCF [13]. Other genera to analyze are *Clethra*, *Chiranthodendron*, *Dendropanax*, *Meliosma*, and *Oreommunea*, the conspicuous canopy members. Other genera belonging to the medium strata are *Cornus*, *Oreopanax*, *Persea*, *Prunus*, and *Styrax*. Many species of these genera are preferent or/characteristic inhabitants, allowing us to recognize and add some important TMCF isolated patches to the previous land use and vegetation map [3].

Our study contributed to the knowledge of endangered trees of the TMCF, increasing the information carried out in different countries related to spatial patterns, rareness, and conservation of vascular plants [71–73]. This last consideration demonstrates that many tree species worldwide are threatened due to their limited geographic distribution, restriction to a single habitat, reduced local abundance, or even a combination of these factors [5,72].

Tree ferns represent another frequent and characteristic component in the TMCF, especially in southeastern Mexico [5,7,13]. The mountain regions of tropical America, mainly the TMCF, harbor most of the species richness of American tree ferns [74]. These vascular plants are critically endangered and face the current environmental crisis and global climate change [7,74]. However, we do not include them in our analysis because our present study is focused on tree seed plants. These species have been analyzed in previous papers based on spatial analysis and conservation efforts [5,74].

Currently, more than 680 NPAs are recorded in Mexico [54,55] among state and federal protected areas. However, some Mexican states include less than 10 NPAs (e.g., Colima) and others have more than 50 (e.g., Chiapas [75]). We documented 19 of the studied species in less than 10 NPAs along the Mexican territory, showing low representativeness in these areas coinciding with other organisms composing the Mexican biota [76].

Peterson et al. [77] pointed out that in the past, most Mexican NPAs were created based on criteria such as fresh-water reservoirs for urban settlements, natural monuments, recreational areas, or historical meaning. As a result, essential areas based on biodiversity conservation have been left out. Fortunately, the delimitation of Mexican NPAs has recently incorporated different biodiversity parameters [54], such as threatened species presence, high species richness, endemism, complementarity richness among regions, and surface areas covered by particular ecosystems [78,79]. In this context, the conservation in situ of some of the tree species analyzed here is more reliable and feasible in the Mexican System of NPAs.

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