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Research article

Potential distribution and bioclimatic profile of mistletoes in *Quercus* L. forests in *Durango*

Distribución potencial y perfil bioclimático del muérdago en bosques de *Quercus* L. en *Durango*

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Abstract

Oak forests have been subject to agroforestry practices that have caused serious problems with disease (severe infections by parasitic plants), notably mistletoes of the genera *Arceuthobium* and *Phoradendron*, which cause deformities and tree death. For *Durango*, information on the potential distribution of mistletoes, linked to biotic and abiotic variables, is considered scarce. This research generated potential distribution models of both types of mistletoe (*Arceuthobium* spp. and *Phoradendron* spp.) on the genus *Quercus* and established the variables that influence their dispersal within the state of *Durango*, and in this way project areas with high predisposition and facilitate their control. For this purpose, 19 bioclimatic variables and oak presence data were used and analyzed with the MaxEnt®. To validate the model, response curves (omitting/commission analysis) and sensitivity analysis (Receptor Operated Curve [*ROC*]-Area under the curve [*AUC*]) were used to measure the effect of each variable. An estimated 48 000 hectares (high suitability) could be affected by *Phoradendron* spp., due to its high dispersal. Furthermore, the most important variables for modeling the analyzed species were temperature (minimum temperature of the coldest month [°C]) and precipitation (precipitation of the coldest quarter [mm]), as these directly influenced their spread.

Keywords: *Arceuthobium* M. Bieb., forest disease, MaxEnt®, infestation levels, oaks, *Phoradendron* Nutt.

Resumen

Los bosques de encino han sido objeto de un aprovechamiento agroforestal que ha provocado graves problemas de presencia de enfermedades (infecciones severas por plantas parásitas), entre las que destacan los muérdagos de los géneros *Arceuthobium* y *Phoradendron* causantes de deformaciones y muerte del arbolado. Para Durango la información sobre la distribución potencial de los muérdagos vinculada a variables bióticas y abióticas se considera escasa. En la presente investigación se generaron modelos de distribución potencial tanto para *Arceuthobium* spp. como para *Phoradendron* spp. sobre el género *Quercus* y se identificaron las variables que inciden en su dispersión dentro del estado, para proyectar zonas con alta predisposición y facilitar su control. Para ello, se utilizaron 19 variables bioclimáticas y datos de presencia de los encinos, los cuales se analizaron con *MaxEnt*®. El modelo se validó mediante curvas de respuesta (análisis de omisión/comisión) y análisis de sensibilidad Curva operada por el receptor (*ROC*)-Área bajo la curva (*AUC*), lo que permitió medir el efecto de cada variable. Se obtuvo un aproximado de 48 mil hectáreas (idoneidad alta) que pueden ser afectadas por *Phoradendron* spp., debido a su alta dispersión. Por otra parte, las variables más importantes para la modelación de las especies analizadas fue la temperatura (temperatura mínima del mes más frío [°C]) y precipitación (precipitación del trimestre más frío [mm]), debido a que influyeron de manera directa en su propagación.

Palabras clave: *Arceuthobium* M. Bieb., enfermedad forestal, *MaxEnt*®, niveles de infestación, encinos, *Phoradendron* Nutt.

Introduction

The largest distribution of woody plants in the world is represented by the Fagaceae family, specifically the genus *Quercus* L., commonly known as oak, which constitutes a significant part of the mountainous regions of Mexico. Various plant associations, such as pine-oak or oak-pine forests, provide different ecosystem services, either directly or indirectly, at local and global levels, including provisioning, regulation, and cultural services (Hernández-Pérez, 2020). Furthermore, oak wood is considered highly resistant and durable. In Mexico, most species of the genus *Quercus* have high commercial value due to the quality of their wood and the products obtained from them, such as charcoal, tannins, dyes, and cork (Gorgonio-Ramírez et al., 2017). Their uses are primarily for fuel, railroad ties, ships, flooring, and some furniture (Balvanera, 2012). At the ecosystem level, oak trees provide protection to watersheds, vegetation cover, erosion reduction, and carbon sequestration (Cavender-Bares et al., 2011). However, these ecosystems are being affected by ongoing anthropogenic activities triggered by climate change.

According to Backs and Ashley (2021), approximately 15 % of species in the genus *Quercus* will be genetically affected by climate change. The genus *Quercus* comprises approximately 500 species (Moreno-Rico et al., 2010) in the Northern Hemisphere, of which 135 to 150 are found in Mexico; their distribution ranges from the United States to Colombia (Sarkar et al., 2009). The state of *Durango* exhibits most of the diverse vegetation types found in Mexico, due to factors that determine its diversity, such as the convergence of two biogeographic regions, its physiography, and climatic diversity. Oak forests in *Durango* represent 16 % of the total area, and among the most common species associations are *Quercus rugosa* Neé, *Q. sideroxyla* Bonpl., *Q. laeta* Liebm., and *Q. durifolia* Seemen *ex* Loes. (González-Elizondo et al., 2006).

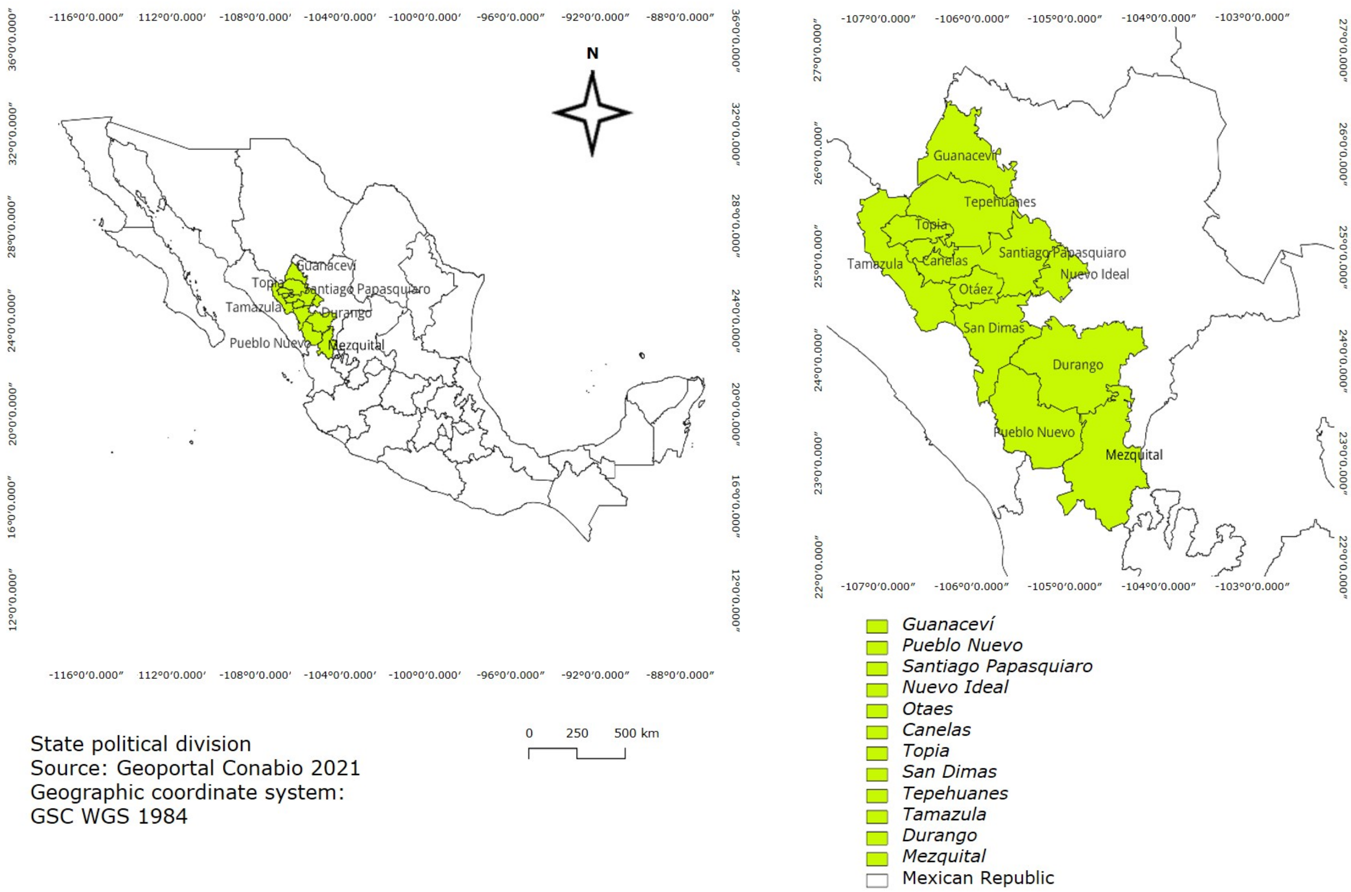
For several decades, it has been observed that oak forest ecosystems are undervalued and their health is inadequate, which favors the emergence of pests and diseases (Uribe-Salas et al., 2019). One of the main diseases affecting oaks is caused by hemiparasitic plants, which are divided into two types: dwarf mistletoe and true mistletoe, and are considered the second leading cause of damage in forest areas. It is estimated that 18 million hectares are infested by these plants (Vázquez-Collazo et al., 2006). When their seeds germinate, they produce a root known as a haustorium that attaches to the tree trunk and causes the formation of woody tumors (Arce-Acosta et al., 2016; Díaz-Limón et al., 2016). The hemiparasitic plants of the genera *Phoradendron* Nutt. and *Arceuthobium* M. Bieb. are obligate pathogens belonging to the Santalaceae family (Correoso-Rodríguez, 2022). Mistletoes of the genera *Phoradendron* and *Arceuthobium* are known as true mistletoe and dwarf mistletoe respectively and cause weakness in host trees and reduce their growth (height, diameter and volume), which can potentially lead to negative consequences for biodiversity and, in some cases, even cause the death of the trees (Chávez et al., 2025; Geils et al., 2002; Ramón et al., 2016).

Geographic Information Systems (GIS) enable the development of predictive distribution models for certain biotic factors. These models project and correlate study sites with a set of environmental factors (bioclimatic variables). Any statistical classifier deemed appropriate (such as BIOCLIM, GARP, or MaxEnt®) can be used depending on the type of variable being modeled: dichotomous for presence/absence data and continuous for abundance data (Felicísimo et al., 2012; Mateo et al., 2011). Predictive models of species geographic distributions are important for a variety of applications in ecology and conservation. This research generated potential distribution models of both types of mistletoe (*Arceuthobium* spp. and *Phoradendron* spp.) on the genus *Quercus* and established the variables that influence their dispersal within the state of *Durango*, and in this way project areas with high predisposition and facilitate their control. This information could be used as a tool for decision-making regarding the use, control, and sanitary management of forest ecosystems in *Durango*, and thus predict mistletoe trends in the study region, which are influenced by various bioclimatic variables that directly affect its dispersal.

Material and Methods

Study area

The study was conducted in *Durango*, Mexico, within the areas encompassing the *Sierra Madre Occidental* from the municipality of *Guanaceví* located in the North of the state to the Southern area of *Mezquital*, passing through 11 of the 39 municipalities of the state (Figure 1). The dominant vegetation types are temperate forests (4 700 000 ha), followed by scrublands (2 900 000 ha), grasslands (1 000 000 ha), agriculture (1 300 000 ha), lowland rainforests (500 000 ha), and the remaining area (2 000 000 ha) of other vegetation types (Návar-Cháidez, 2011). It presents the greatest diversity of pine, oak, and strawberry tree associations worldwide. The area's climate corresponds to semi-cold sub-humid and temperate sub-humid (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2008, 2015).



Guanaceví = *Guanaceví* municipality; *Pueblo Nuevo* = *Pueblo Nuevo* municipality; *Santiago Papasquiaro* = *Santiago Papasquiaro* municipality; *Nuevo Ideal* = *Nuevo Ideal* municipality; *Otaes* = *Otaes* municipality; *Canelas* = *Canelas* municipality; *Topia* = *Topia* municipality; *San Dimas* = *San Dimas* municipality; *Tepehuanes* = *Tepehuanes* municipality; *Tamazula* = *Tamazula* municipality; *Durango* = *Durango* municipality; *Mezquital* = *Mezquital* municipality. Prepared: Edwin Yael Bueno Vazquez.

Figure 1. Geographical distribution of mistletoe in some municipalities of the state of *Durango*, Mexico.

Record of mistletoe presence and bioclimatic variables

The records indicating the presence of the genera *Arceuthobium* spp. and *Phorandendron* spp. were obtained from the National Forestry Commission and totaled 1 550 records (Comisión Nacional Forestal [Conafor], 2023), according to the sanitation notifications issued by the institution. These records correspond to the 2018-2022 period and, before analysis, were verified to ensure there were no duplicate records and that their distribution matched the forested areas.

From these records, data located within the study area were selected, in addition to filtering those found on the host *Quercus* spp., bioclimatic, physiographic, and soil variables for modeling.

For the study, 19 variables available on the website (WolrldClim, 2020) were used with a resolution of 1 km^2 (Table 1). In addition, the digital elevation model (30 m) was used and the exposure was generated to produce the potential distribution models of the mistletoe species analyzed. The cartographic variables with a scale of 1:250 000, edaphology Series II (INEGI, 2011) and land use and vegetation Series VI (INEGI, 2015), which were converted to raster format to homogenize them (1:250 000) (Sosa-Díaz et al., 2018). The data were cleaned based on the suggestions of Cobos et al. (2018), eliminating duplicate records, low precision, with identification errors, etc.

Table 1. WorldClim bioclimatic variables used to generate the potential distribution models of mistletoe.

Key	Variable name
BIO1	Average annual temperature (°C)
BIO2	Mean diurnal range (monthly average ($°C\ max - °C\ min$))
BIO3	Isothermality $\left(\left(\frac{\text{BIO2}}{\text{BIO7}}\right)100\right)$
BIO4	Seasonality of temperature ($standard\ deviation \times 100$)
BIO5	Maximum temperature of the warmest month (°C)
BIO6	Minimum temperature of the coldest month (°C)
BIO7	Annual temperature range (°C) ($BIO5 - BIO6$)
BIO8	Average temperature of the wettest quarter (°C)
BIO9	Average temperature of the warmest quarter (°C)
BIO10	Average temperature of the driest quarter (°C)
BIO11	Average temperature of the coldest quarter (°C)
BIO12	Annual precipitation (mm)
BIO13	Precipitation of the wettest month (mm)
BIO14	Precipitation of the driest month (mm)
BIO15	Seasonality of precipitation (coefficient of variation %)
BIO16	Precipitation of the wettest quarter (mm)
BIO17	Precipitation of the driest quarter (mm)
BIO18	Precipitation of the warmest quarter (mm)
BIO19	Precipitation of the coldest quarter (mm)

Source: WorldClim (2020).

Once the rasters were obtained, they were adjusted using ArcMap software (Version 10.8) of the ArcGis® package (ESRI, 2021), to subsequently convert them to ASCII format and thus be able to process the information in the Maximium entropy algorithm (MaxEnt® 3.4.4) (Carrillo-Aguilar et al., 2021).

Potential distribution models for *Arceuthobium* spp. and *Phoradendron* spp. in *Durango*

To generate the distribution models for *Arceuthobium* spp. and *Phoradendron* spp., the Maximium entropy (MaxEnt® 3.4.4) algorithm (Phillips & Dudik, 2008) was used to create a logistic model with a probability of 0-1, where 0 indicates pixels that do not represent habitat and values close to 1 represent a higher probability of mistletoe species presence (Carrillo-Aguilar et al., 2021). Due to the limited presence records and in accordance with the methodology proposed by Giménez et al. (2015), ten replicates were run to generate the models.

The biologically significant variables derived from monthly temperature and precipitation values were then selected, representing annual trends. According to the National Forestry Commission records (Conafor, 2025) 40 records of the *Arceuthobium* spp. species were found within the study area, and 30 records of *Phoradendron* spp. were found, so the models were generated with different characteristics (Table 2).

Table 2. Characteristics of the models generated in MaxEnt®.

Species	Model type	Iterations	Test percentage (%)	Background points	Replicas
Arceuthobium spp.	Logistic	1 200	35	10 000	10
Phoradendron spp.	Logistic	1 000	30	10 000	10

Model evaluation

This methodology was based on the one proposed by Avalos-Jiménez et al. (2023), who stated that to achieve greater modeling accuracy, the "Jackknife" test should be performed to determine the independent behavior of each bioclimatic variable and thus establish its weight and degree of participation in model creation. The graphical output provided by MaxEnt® 3.4.4 , such as the Area under the curve (*AUC*), is a fit statistic and can vary between 0 and 1. The best model would be one with a sensitivity close to 1 and a false negative rate of zero. An *AUC* value above 0.7 is generally considered to indicate a good and valid fit (Townsend-Peterson et al., 2011). After obtaining the result in an ASCII file, the layer was exported to ArcMap® and the values were reclassified (Villaseñor et al., 2014) using as minimum value the of "Minimum presence in training" generated in the MaxEnt® algorithm (Radosavljevic & Anderson, 2014).

Results and Discussion

The synergy between climate change and soil degradation has created an optimal scenario for the spread of *Phoradendron* spp. and *Arceuthobium* spp. in *Durango*, thus requiring comprehensive forest management strategies that address both the parasite and the restoration of soil health (Aitken et al., 2008). In addition, Conafor (2023) reports that approximately four or five species of *Quercus* (*Q. durifolia*, *Q. sideroxyla*, *Q. convallata* Trel. and *Q. viminea* Trel.) were attacked by the mistletoe *Phoradendron villosum* (Nutt.) Nutt. *ex* Engelm., *P. bolleanum* (Seem.) Eichler, *Arceuthobium nigrum* (Hawksw. & Wiens) Hawksw. & Wiens and *A. rubrum* Hawksw. & Wiens in *Durango*, due to the increase in degraded soils in forest areas, a finding that coincides with Uribe-Salas et al. (2019). Furthermore, the attack by fungal diseases or mistletoe in some oak species is directly related to the continuous modification of factors such as: climate change, droughts, fires, etc. (Keča et al., 2016), in addition to the above they are affected by the low quality of forest soils of water, which today is more common to see sick oaks with high levels of infestation caused by mistletoe in *Durango*. Based on the results reported by Conafor (2023), shows the total affected area of 11 333.77 ha in *Durango* up to 2023. Furthermore, the municipalities reporting the highest presence of mistletoe (dwarf and true) are *Pueblo Nuevo*, *San Dimas*, *Guanaceví*, and *Durango*.

A growing infestation has also been observed within the municipality of *Durango*, attributed to the varying responses within forest dynamics to stochastic events, both natural and anthropogenic (tree removal, branch pruning, and road construction, as well as arson). This suggests that mistletoes represent a variable system and are sensitive to fluctuations in climatic and anthropogenic activities (Queijeiro-Bolaños & Cano-Santana, 2015; Queijeiro-Bolaños et al., 2014).

Important environmental variables and ecological profile

The bioclimatic profile of species is of utmost importance for understanding their climatic tolerances (Méndez-Encina et al., 2020); however, few studies present it. The results obtained from the Jackknife test show that the most important variable associated with the model for *Phoradendron* spp. is exposure and precipitation (*BIO19*), which suggests the importance of the presence of the host *Quercus* spp. for its distribution. On the other hand, for *Arceuthobium* spp., the variable land use and vegetation increases the gain, as does temperature, which is consistent with Brandt et al. (2005), who mention that precipitation and temperature directly influence seed dispersal capacity by up to 95 %. On the other hand, for *Arceuthobium* spp., the distribution is strongly influenced by land use and vegetation (LUV) at 23.1 %, followed by aspect o sun exposure (21.1 %). Climatic variables also play a critical role, notably the minimum temperature of the coldest month (*BIO 6*) at 17.6 % and the diurnal temperature range (*BIO 2*) at 17.1 %. Taken together, these data suggest that this genus depends on a balanced interaction between the available host type and specific thermal conditions. In contrast, for *Phoradendron* spp., the dominant variable is aspect o sun exposure (28.8 %), considerably exceeding LUV (19.5 %). Unlike *Arceuthobium* spp., this genus shows greater sensitivity to seasonal precipitation, with precipitation during the coldest quarter (*BIO 19*) contributing 18.4 % (Table 3). Therefore, the variables that explain the distribution of the analyzed species vary according to each genus. Analysis of the percentage contribution of environmental variables reveals significant differences in the factors that determine the distribution of both genera of parasitic plants. *Phoradendron* spp., being a hemiparasite with greater photosynthetic activity, prefers South- and Southwest-facing slopes, which tend to be warmer, to maximize its energy balance, while *Arceuthobium* spp. disperses more uniformly, which is consistent with the findings reported by González-Hidalgo et al. (2013) and Geils et al. (2002).

Table 3. Variables that contribute to the dispersal and establishment of mistletoe in *Durango*, Mexico.

Contribution of the five main variables (%)	
***Arceuthobium* spp.**	***Phoradendron* spp.**
LUV 23.1	Exposure 28.8
Exposure 21.1	LUV 19.5
BIO6 17.6	*BIO19* 18.4
BIO2 17.1	*BIO17* 9
BIO19 17.7	*BIO10* 7.4

LUV = Land use and vegetation; *BIO2* = Mean diurnal range (monthly average ($°C\ max - °C\ min$); *BIO6* = Minimum temperature of the coldest month (°C); *BIO10* = Mean temperature of the driest quarter (°C); *BIO17* = Precipitation of the driest quarter (mm); *BIO18* = Precipitation of the warmest quarter (mm); *BIO19* = Precipitation of the coldest quarter (mm).

While *Arceuthobium* appears to be limited by biotic and thermal factors, *Phoradendron* responds more strongly to topographic and hydrological factors. This divergence in ecological niches allows both genera to coexist in similar regions but occupying distinct microhabitats, which coincides with what was reported by Mathiasen et al. (2008).

Potential distribution of mistletoes

Mistletoes are present in *Durango*, and based on the analyzed records, it was observed that the *Arceuthobium* genus on *Quercus* spp. has a smaller potential distribution compared to the mistletoe of the *Phoradendron* genus. This is mainly due to the climatic contrast between the different regions and the fact that the state has the largest forest area under optimal conditions for defoliators, bark beetles, and mistletoes (Sosa-Díaz et al., 2018). On the other hand, land use conditions, combined with climate change, have modified the ecological context of mistletoe because by altering the nutrient cycle and its interactions with its hosts and mutualists, it modifies the spatial structure of mistletoes (Baranowska et al., 2025; Walas et al., 2022).

The spatial distribution of the studied taxa was reclassified into three probability strata (low, medium, and high) according to the criteria of Sosa-Díaz et al. (2018), identifiable in Figure 2 by their coding in green, yellow, and red. The geographic analysis reveals a significant presence of *Arceuthobium* spp. in the region encompassing *Durango*, *Tepehuanes*, *Mezquital*, *Pueblo Nuevo*, and *San Dimas*; while for *Phoradendron* spp., the probability model highlights critical areas in the municipalities of *Durango*, *Pueblo Nuevo*, *Santiago Papasquiaro*, *Tepehuanes*, *San Dimas*, and *Guanaceví*. A higher probability of dispersion in terms of hectares was observed for mistletoe of the genus *Phoradendron*.

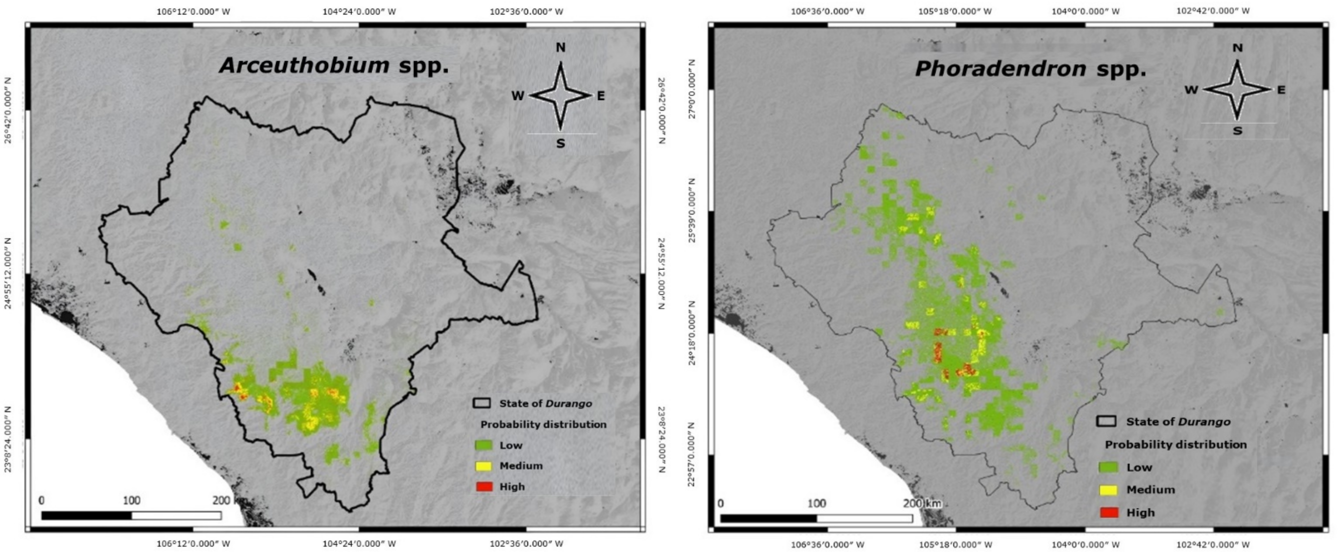


Figure 2. Potential distribution model of mistletoe (*Arceuthobium* spp. and *Phoradendron* spp.) in municipalities of *Durango*, Mexico.

Analysis of the potential distribution area of the studied species

For *Arceuthobium* spp., the area with the highest probability of distribution was 45 605.16 ha, while for *Phoradendron* spp. it was 48 512.07 ha. Therefore, the data suggest that the analyzed ecosystem is under constant pressure from hemiparasites. *Phoradendron* represents the greatest threat in terms of geographic extent, while the *Arceuthobium* outbreaks appear to be more localized but significant (Table 4). The greater overall probability area for *Phoradendron* spp. in *Durango* can be explained by its broad ecological plasticity and host range. Unlike *Arceuthobium* spp., which is almost exclusively limited to conifers (mainly of the genus *Pinus* L.), *Phoradendron* spp. can infect both gymnosperms and a vast diversity of angiosperms, including oaks (*Quercus*) and leguminous trees (Mathiasen et al., 2008). This generalist capacity allows it to occupy a greater diversity of ecosystems in *Durango's* rugged topography, from xerophytic scrublands to temperate-cold forests.

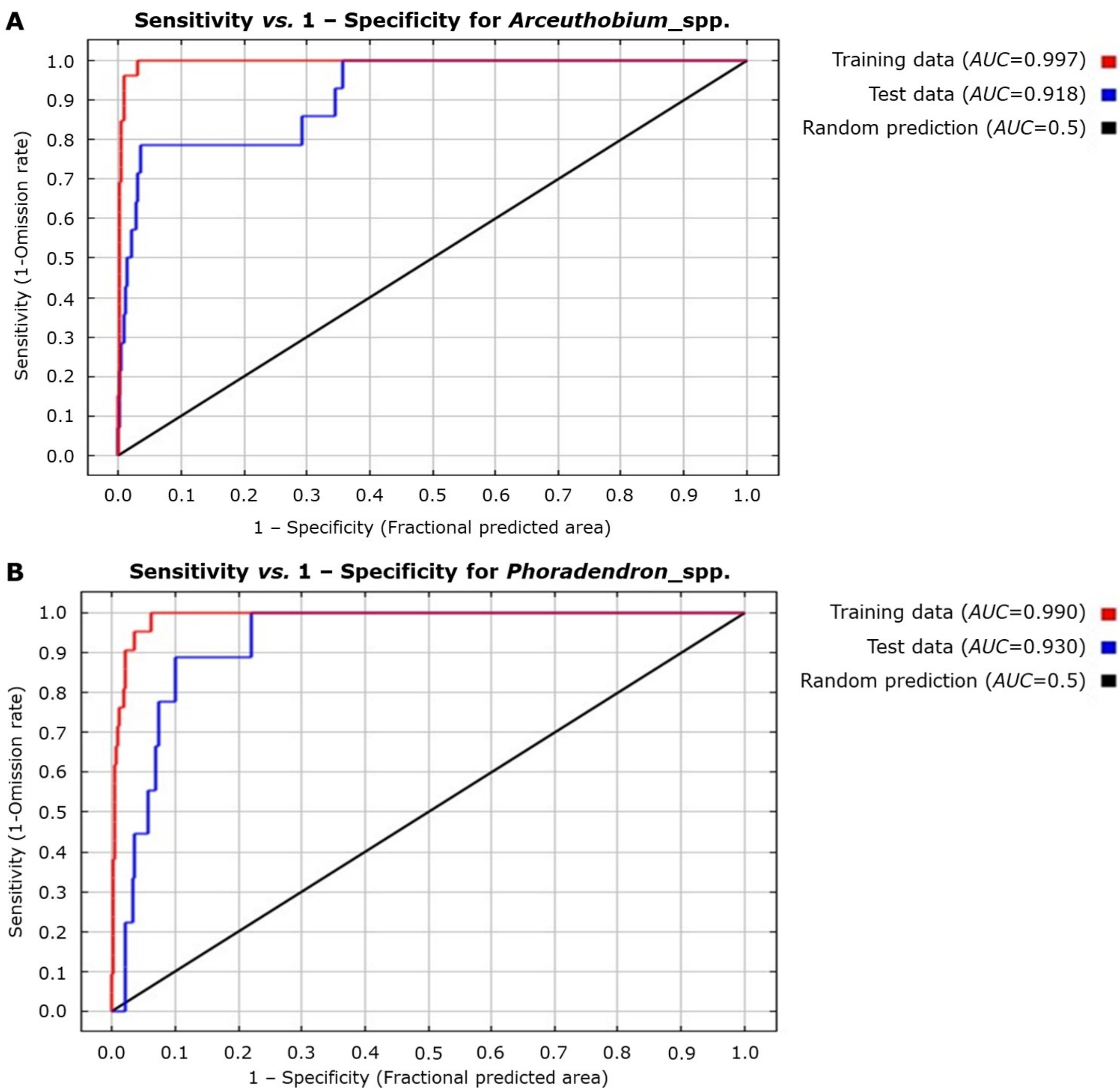
Table 4. Probability area by species (ha) in the State of *Durango*, Mexico.

Probability	***Arceuthobium* M. Bieb. (ha)**	**% relative**	***Phoradendron* Nutt. (ha)**	**% relative**
Low	736 673.43	82.72	1 499 309.92	89.87
Medium	108 350.83	12.16	120 560.06	7.23
High	45 605.16	5.12	48 512.17	2.91
Total	890 629.42	100	1 668 382.15	100

Forest management in the state of *Durango* should prioritize monitoring in the 48 512 ha and 45 605 ha of high probability identified, since they represent the nuclei of potential infection that could compromise forest health and timber production in the face of climate change scenarios that favor water stress in the hosts (Endara-Agramont et al., 2022).

A total of 94 117.33 hectares have been identified as high-probability areas (combining both genera). These areas should not be viewed merely as numbers, but as epicenters of phytosanitary pressure. The specialized literature indicates that in these zones, the intensity of the infection tends to reduce the increase in diameter and height of the hosts, affecting timber productivity and carbon sequestration (Mathiasen et al., 2008).

According to the statistical analysis of the records obtained from the Conafor (2023), the *AUC* values for each model were optimal since, as mentioned by Pérez-Miranda et al. (2019), models with *AUC* values of 0.75 are useful for predicting species distribution; in that sense, *AUC* values greater than 0.9, obtained in this work, specify that the models are highly described by the bioclimatic variables, for *Arceuthobium* spp. the value was 0.91 and for *Phoradenron* spp. it was 0.9 (Figure 3). According to the *ROC* curve, the resulting models are better than a random model, showing a minimum range of omission and commission errors (less than 25 %), since the training and test lines were kept as close together as possible (Chávez et al., 2025).



A = *Arceuthobium* spp.; B = *Phorandendron* spp.

Figure 3. Area under the curve.

Due to the above, it is observed that the state of *Durango* has temperate forests that allow the establishment of hemiparasitic plants such as mistletoe, influenced mainly by the temperatures and rainfall of each region. Furthermore, the presence of mistletoe and the mortality it causes have significant ecological and economic effects in severely infested forests and recreational areas (Mathiasen et al., 2008). Therefore, other external factors observed in the field that facilitate the spread of the disease and increase its severity over time must be considered, coinciding with Queijeiro-Bolaños et al. (2014). These factors include the presence of forest fires, excessive logging, proximity of trees to roads, or other types of disturbance.

Conclusions

Oaks in the state of *Durango* are severely affected by dwarf mistletoe and true mistletoe at different rates. Temperature (*BIO6*) and precipitation (*BIO19*) variables directly influence mistletoe dispersal. Due to the high suitability predicted by the model, true mistletoe (*Phoradendron* spp., 48 512.07 ha) has the largest suitability area, while dwarf mistletoe (*Arceuthobium* spp., 45 605.16 ha) has a smaller extent.

The bioclimatic profile and potential distribution maps of the different hemiparasitic plants not only facilitate locating the hypothetical occurrence framework, but could also be a tool for establishing management plans and reducing populations. In *Durango*, mistletoe dispersal is not random. While dwarf mistletoe is a specialist in forest structure, true mistletoe is a microclimate strategist. This means that forest management in *Durango* must be differentiated: *Arceuthobium* control requires sanitation thinning, while *Phoradendron* monitoring should prioritize sunny, humid slope areas. Based on the conclusions, the research generated serves as an essential predictive tool; it allows a shift from reactive to preventive management, prioritizing sanitation and monitoring actions in the areas of greatest vulnerability detected.

Acknowledgments

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Conflicts of interest

The authors declare that they have no actual or potential conflicts of interest.

Contribution by author

Mónica Yamzín Flores-Villegas: formal analysis, methodology, writing-revision and editing; Maria Berenice González Maldonado: manuscript review. All authors participated in the conception of the research and approval of the final version of the manuscript.

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