



DOI: [10.29298/rmcf.v17i93.1594](https://doi.org/10.29298/rmcf.v17i93.1594)

Research article

Potential distribution of *Pinus cembroides* Zucc. under scenarios from the Coupled Model Intercomparison Project in Mexico

Distribución potencial de *Pinus cembroides* Zucc. ante escenarios del Proyecto de Intercomparación de Modelos Acoplados en México

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Fecha de recepción/Reception date: 20 de agosto de 2025.

Fecha de aceptación/Acceptance date: 9 de diciembre de 2025.

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Abstract

Pinus cembroides is a piñon conifer resistant to dry conditions and is widely distributed in arid and semi-arid areas of Mexico, making it ideal for assessing the impacts of climate change on conifer forests. The impacts of climate change on the potential distribution of *Pinus cembroides* in Mexico was assessed, considering two climatic scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6): SSP2-4.5 (projected increase of 2.1 to 3.5 °C in mean temperature by the end of the twenty-first century) and SSP5-8.5 (projected increase of 3.3 to 5.7 °C). Modeling was based on the maximum entropy algorithm (MaxEnt), using 1 696 records of *P. cembroides* and 19 bioclimatic variables from CHELSA v2.1. The variables with the highest contributions were the temperature of the driest quarter (60.9 %) and the wettest quarter (28.9 %). Under the current climate conditions, only 6.3 % of mountainous regions in the *Sierra Madre Oriental* and *Sierra Madre Occidental* exhibited high suitability. Future changes in distribution were projected using a CMIP6 Multi-Model Ensemble (MME) in four periods: near-term (2021-2040), mid-term (2041-2060), far-term (2061-2080), and end of XXI century (2081-2100). In both scenarios, the potential distribution is projected to contract to ~10 % of its current extent by the end of the 21st century, limited to higher and wetter areas of low to medium suitability in *Sierra de Juárez* and *Sierra Madre Oriental*.

Keywords: Climate change, CHELSA, CMIP6, species distribution, MaxEnt, distribution models.

Resumen

Pinus cembroides es una conífera piñonera resistente a condiciones secas y está ampliamente distribuida en zonas áridas y semiáridas de México, por lo que es ideal para evaluar los impactos del cambio climático en los bosques de coníferas. Se evaluaron los impactos de ese fenómeno sobre la distribución potencial de *P. cembroides* en México, a partir de dos escenarios climáticos de la Fase 6 del Proyecto de Intercomparación de Modelos Acoplados (CMIP6): SSP2-4.5 (incremento proyectado de 2.1 a 3.5 °C en la temperatura media hacia finales del siglo XXI) y SSP5-8.5 (incremento proyectado de 3.3 a 5.7 °C). La modelación se realizó con el algoritmo de máxima entropía (*MaxEnt*), empleando 1 696 registros de *P. cembroides* y 19 variables bioclimáticas de *CHELSA* v2.1. Las variables con mayor contribución fueron la temperatura del aire en el trimestre más seco (60.9 %) y en el trimestre más húmedo (28.9 %). Bajo las condiciones climáticas actuales, solo 6.3 % de las regiones montañosas de la Sierra Madre Oriental y la Sierra Madre Occidental mostraron alta idoneidad. Los cambios en la distribución futura se proyectaron mediante un Ensamble Multi-Modelo (EMM) del CMIP6 en el corto plazo (2021-2040), mediano plazo (2041-2060), largo plazo (2061-2080) y finales del siglo XXI (2081-2100). En ambos escenarios, la distribución potencial disminuye hasta ~10 % del área actual a finales del siglo XXI, limitada a zonas más elevadas y húmedas de baja a media idoneidad en la Sierra de Juárez y la Sierra Madre Oriental.

Palabras clave: Cambio climático, *CHELSA*, CMIP6, distribución de especies, *MaxEnt*, modelos de distribución.

Introduction

Since the 1970s, significant alterations in global precipitation and temperature patterns associated with climate change have been recorded (Intergovernmental Panel on Climate Change [IPCC], 2023a; Trenberth, 2011). The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) projects that, without mitigation measures, the global average temperature will increase between 1.2 and 2.0 °C by 2050 and between 2.0 and 4.0 °C by the end of the 21st century (IPCC, 2023b). In Northern Mexico, the temperature has increased by 0.3 °C per decade over the last thirty years (Cavazos et al., 2020), and under high-emission scenarios, an increase of more than 4.5 °C is projected in the coming decades (Almazroui et al., 2021).

Forest ecosystems are highly vulnerable to climate change (Hansen & Phillips, 2015). Their response can manifest in three ways: (1) Adaptation to the new conditions within their current distribution, (2) Local extinction, or (3) Altitudinal or latitudinal displacement toward more favorable environments (Sáenz-Romero et al., 2017).

The analysis of these impacts has been carried out using species distribution models (SDMs), which integrate presence records with current and projected bioclimatic variables (Pearson et al., 2007). These models allow the identification of climatically suitable areas and the quantification of factors that limit distribution, constituting a key tool for forest conservation and management (Geng et al., 2022). Among the available algorithms, the maximum entropy algorithm (MaxEnt) has been widely used in the study of coniferous forests in Mexico (Manzanilla-Quijada & Treviño-Garza, 2024).

Mexico is home to nearly half of the species of the *Pinus* L. genus (Martínez-Sifuentes et al., 2020). Most are restricted to mountainous regions, which increases their vulnerability to climate change (Gómez-Pineda et al., 2020). Projections based on Representative Concentration Pathways (RCPs) scenarios from CMIP5 (Coupled Model Intercomparison Project Phase 5) indicate a contraction of temperate forests, particularly at their xeric limits (Sáenz-Romero et al., 2015).

More recently, these scenarios have been complemented by Shared Socioeconomic Pathways (SSPs) from CMIP6, which integrate socioeconomic development narratives with different levels of radiative forcing (Eyring et al., 2016). Of the five proposed scenarios, SSP2-4.5 represents an intermediate path with a radiative forcing of 4.5 W m² and a projected increase of 2.1 to 3.5 °C by the end of the 21st century, while SSP5-8.5 corresponds to a development based on fossil fuels and high Greenhouse Gas (GHG) emissions, with a forcing of 8.5 W m² and an increase of 3.3 to 5.7 °C (Eyring et al., 2016; O'Neill et al., 2016).

Pinus cembroides Zucc. is the most widely distributed pinyon pine in Mexico (Constante-García et al., 2009). It is found in transition zones between xerophytic formations of the Mexican Plateau, as well as in the *Sierra Madre Oriental*, *Sierra Madre Occidental* and the Trans-Mexican Volcanic Belt (Carlón-Allende et al., 2018). It is characterized by its adaptability and resistance to prolonged droughts and extreme temperatures.

This study evaluates the impact of climate change on the potential distribution of *P. cembroides* using the MaxEnt maximum entropy algorithm and CHELSA v2.1 (Karger

et al., 2017) data for the current climate and future projections from CMIP6. The specific objectives were: (1) To identify the climatic variables that determine its distribution, (2) To estimate changes in its potential distribution under two climate change scenarios, and (3) To locate suitable areas for its conservation in the coming decades.

Materials and Methods

The study area corresponds to the geographic distribution of *P. cembroides* in Mexico, from semi-arid zones in the North to subtropical regions in the Central and Southern parts of the country (García & Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio], 1998). *P. cembroides* populations are located between 1 350 and 3 500 masl, where temperatures range from 7 to 40 °C and annual rainfall varies from 360 to 800 mm (Constante-García et al., 2009).

Occurrence data were obtained from the National Forest and Soil Inventory (Infys) of the National Forest Commission (Comisión Nacional Forestal [Conafor], 2018) for the period 2009-2014 and the National Biodiversity Information System (SNIB) of *Conabio* (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio], 2020). A spatial autocorrelation analysis was applied, and only one presence data point was considered per 1 km² cell, eliminating duplicate records.

Nineteen bioclimatic variables from CHELSA v2.1 (CHELSA, 2025; Karger et al., 2017) were used for the 30-year reference climate period of 1981–2010 (current climate) and the future periods 2021–2040, 2041–2060, 2061–2080, and 2081–2100, considering the SSP2-4.5 and SSP5-8.5 scenarios, at a spatial resolution of 1 km². The data were downloaded using the Python 3.8 package *chelsa_cmip6_1.0* (Karger et al., 2023). CHELSA v2.1 (Karger et al., 2017) shows a lower correlation with topography and a more accurate representation of precipitation and temperature variables in

mountainous regions compared to WorldClim v2.1 (Bobrowski et al., 2021). To reduce multicollinearity between variables, a variance inflation factor (VIF) analysis was applied, establishing as an exclusion criterion a value greater than 10 (Dormann et al., 2013), so that highly correlated variables were discarded.

The selected bioclimatic variables were: diurnal temperature range (*Bio 2*), isothermality (*Bio 3*), temperature of the wettest quarter (*Bio 8*), of the driest quarter (*Bio 9*), annual precipitation (*Bio 12*), of the driest month (*Bio 14*), of the warmest quarter (*Bio 18*), and of the coldest quarter (*Bio 19*).

The potential distribution of *Pinus cembroides* was modeled using MaxEnt v3.4.4 software (Phillips et al., 2006). Previous studies have demonstrated that MaxEnt offers statistically reliable predictive capacity compared to other algorithms (Araújo & New, 2007). Seventy-five percent of the presence records were used to train the model, with the remaining 25 % reserved for validation (Merow et al., 2013; Phillips et al., 2006). The MaxEnt logistic output, which generates species suitability values (Phillips & Dudík, 2008) was used, with a maximum of 500 iterations and 10 000 background data points. A combination of linear, quadratic, and product classes was used with a convergence limit of 0.00001. Based on these values, the following classification thresholds were established: unsuitable (<0.1), low suitability (0.1-0.3), medium suitability (0.3-0.6), and high suitability (>0.6) (Zhong et al., 2023). To reduce extrapolation, the extrapolate and clamping functions were disabled (Elith et al., 2011).

The relative importance of each bioclimatic variable was determined using the Jackknife test (Phillips et al., 2006). Model performance was evaluated using the area under the curve (AUC) receiver operating characteristic (ROC) curve, considering the following classification ranges: insufficient (0.5-0.6), poor (0.6-0.7), good (0.8-0.9), and excellent (0.9-1.0) (Aguirre-Gutiérrez & Duivenvoorden, 2010). Values close to 1 indicate a greater correspondence between the selected bioclimatic variables and the potential distribution of the species (Phillips & Dudík, 2008).

The individual use of general circulation models (GCMs) increases the uncertainty of SDM projections due to biases in temperature and precipitation (Stewart et al., 2022).

Therefore, it is recommended to use ensembles of different GCMs to obtain more robust results (Thuiller et al., 2019). A Multi-Model Ensemble (MME) was generated from the GCMs that best represented current climate variability. Specifically, 25 GCMs from CMIP6 (Earth System Grid Federation [ESGF], 2025) were compared with monthly CRU data (Harris et al., 2014) for the period 1995-2014. The metrics considered included Pattern correlation coefficient (*PCC*), Centered mean squared error (*CRMSE*), Mean absolute error (*MAE*), bias, Taylor Skill Index (*TSS*), and Normalized standard deviation (*NSTD*). GCMs with *PCC* and *TSS* values close to 1, and *CRMSE*, *MAE*, *NSTD*, and bias values close to 0, were selected (Colorado-Ruiz et al., 2018). This model selection strengthens confidence in the validity of future projections (Knutti et al., 2017). The selected models were used to generate bioclimatic layers for each scenario across the four analyzed periods.

The distribution projections obtained for the different scenarios were compared using the bioclimatic variables derived from the MME. To assess the differences between the current and projected surface areas, the relative percentage change (*%CR*) was calculated using Equation 1 (Gutiérrez-García et al., 2015). Finally, stable or conserved areas, areas of gain, and areas of loss were identified using QGIS software version 3.16 (QGIS, 2020).

$$\%CR = \frac{Si - So}{So} \times 100 \quad (1)$$

Where:

Si = Future area in each scenario

So = Total area

Results and Discussion

A total of 1 696 records of *P. cembroides* were obtained nationwide. The model based on the MaxEnt algorithm showed high predictive capacity, with an *AUC* value of 0.894 (Aguirre-Gutiérrez & Duivenvoorden, 2010). This result supports the reliability of the model for predicting the potential distribution of *P. cembroides*. MaxEnt is one of the most widely used algorithms in conifer studies in Mexico (Manzanilla-Quiñones et al., 2019) because it only requires presence data and offers statistically reliable predictive capacity compared to other individual algorithms and ensemble-based methods. However, it should be considered that projections are vulnerable to biases that can lead to statistical overestimation (Araújo & New, 2007).

The bioclimatic variables *Bio 9* and *Bio 8* explained 60.9 % and 28.9 % of the variability, respectively (Table 1).

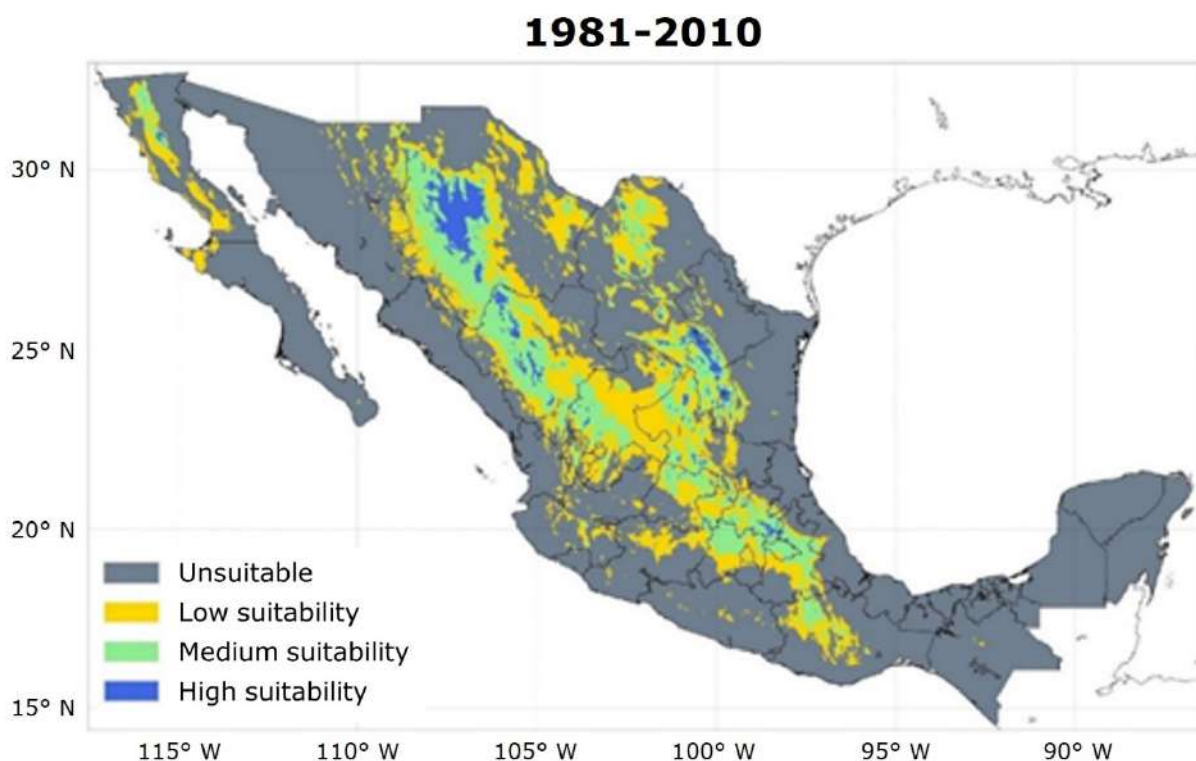
Table 1. Relative contribution (%) of the variables used in the spatial distribution of *Pinus cembroides* Zucc.

Variable	Description	Contribution (%)
<i>Bio 9</i>	Temperature of the driest quarter	60.9
<i>Bio 8</i>	Temperature of the wettest quarter	28.9
<i>Bio 12</i>	Annual precipitation	3.4
<i>Bio 2</i>	Diurnal temperature range	3.0
<i>Bio 3</i>	Isothermality	2.1
<i>Bio 18</i>	Precipitation of the warmest quarter	1.6
<i>Bio 14</i>	Precipitation of the driest month	0.1

Bioclimatic variables: Temperature (°C), Precipitation (mm)

These results are consistent with studies that indicate a greater influence of thermal variables compared to rainfall variables in species of the genus *Pinus*, using WorldClim v2.1 (Gómez-Pineda *et al.*, 2020; Martínez-Sánchez *et al.*, 2023). Although some studies based on this same system have discarded the variables *Bio 8*, *Bio 9*, *Bio 18*, and *Bio 19* due to discontinuities in precipitation distribution (Escobar *et al.*, 2014), this study decided to retain them, since CHELSA v2.1 describes the influence of topography on precipitation in greater detail (Karger *et al.*, 2017). Furthermore, the use of these indicators allows for a more accurate representation of interannual variability and ecological limitations in areas with seasonal climatic fluctuations (Booth, 2022). In general, high temperatures are considered to predict the distribution of geographically widespread species such as *P. cembroides* (Manzanilla-Quijada & Treviño-Garza, 2024).

The current distribution of *P. cembroides* includes the *Sierra Madre Oriental*, the *Sierra Madre Occidental* and the Trans-Mexican Volcanic Belt (Figure 1). 3.17×10^5 km² (55.8 %), 2.15×10^5 km² (37.8 %) and 3.60×10^4 km² (6.3 %) were estimated in the low, medium and high suitability categories, respectively.



Unsuitable (<0.1), low suitability ($0.1-0.3$), medium suitability ($0.3-0.6$), high suitability (>0.6).

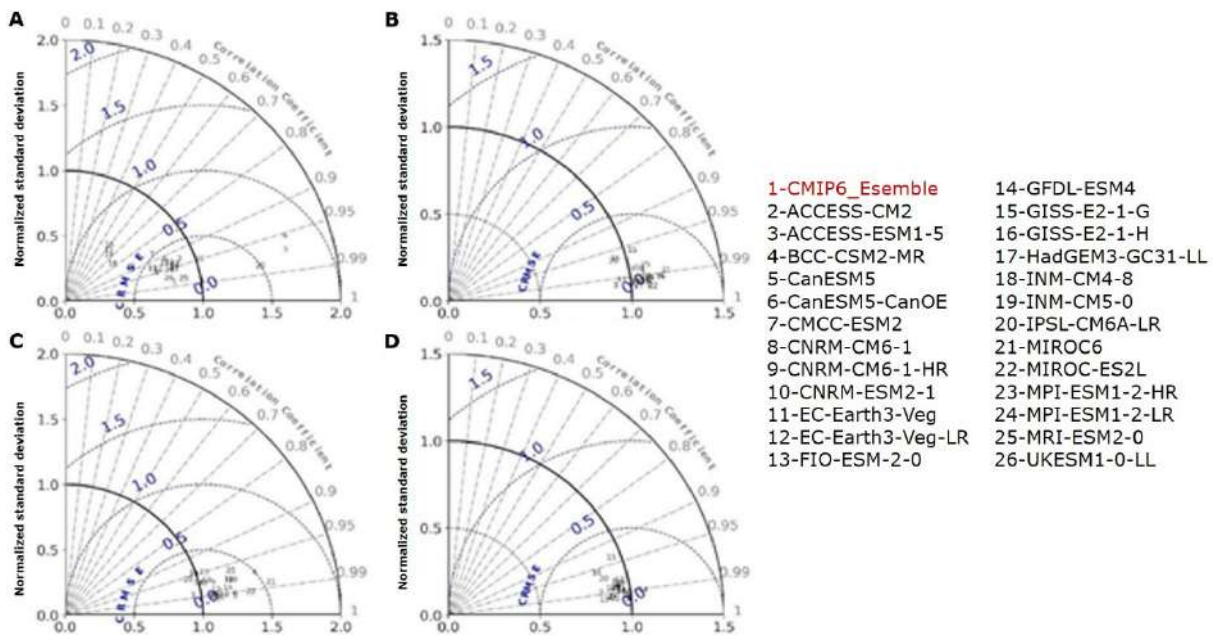
Figure 1. Potential distribution of *Pinus cembroides* Zucc. during the period 1981-2010.

Areas classified as having low suitability were concentrated primarily in much of the *Sierra Madre Oriental*, the *Sierra Madre Occidental* and the Trans-Mexican Volcanic Belt, as well as in the *Sierra de San Pedro Mártir*, the *Sierra de Juárez* and the Mexican Plateau (states of *Querétaro*, *Guanajuato*, *San Luis Potosí* and *Zacatecas*). Areas of medium suitability were distributed in isolated strips of the *Sierra Madre Occidental* (states of *Chihuahua* and *Durango*) and the *Sierra Madre Oriental* (state of *Nuevo León*). In contrast, regions with high suitability were restricted to specific sectors of *Chihuahua*, *Durango*, *Coahuila*, *Nuevo León*, *San Luis Potosí* and *Puebla*.

In general, the geographic distribution of the areas modeled as suitable is consistent with that reported in previous studies (Martínez-Sánchez et al., 2023; Téllez-Valdés et al., 2019). Furthermore, the potential projection exceeds the current geographic

range, a common behavior in species distribution models (SDMs) based exclusively on bioclimatic variables (Soberón & Peterson, 2005).

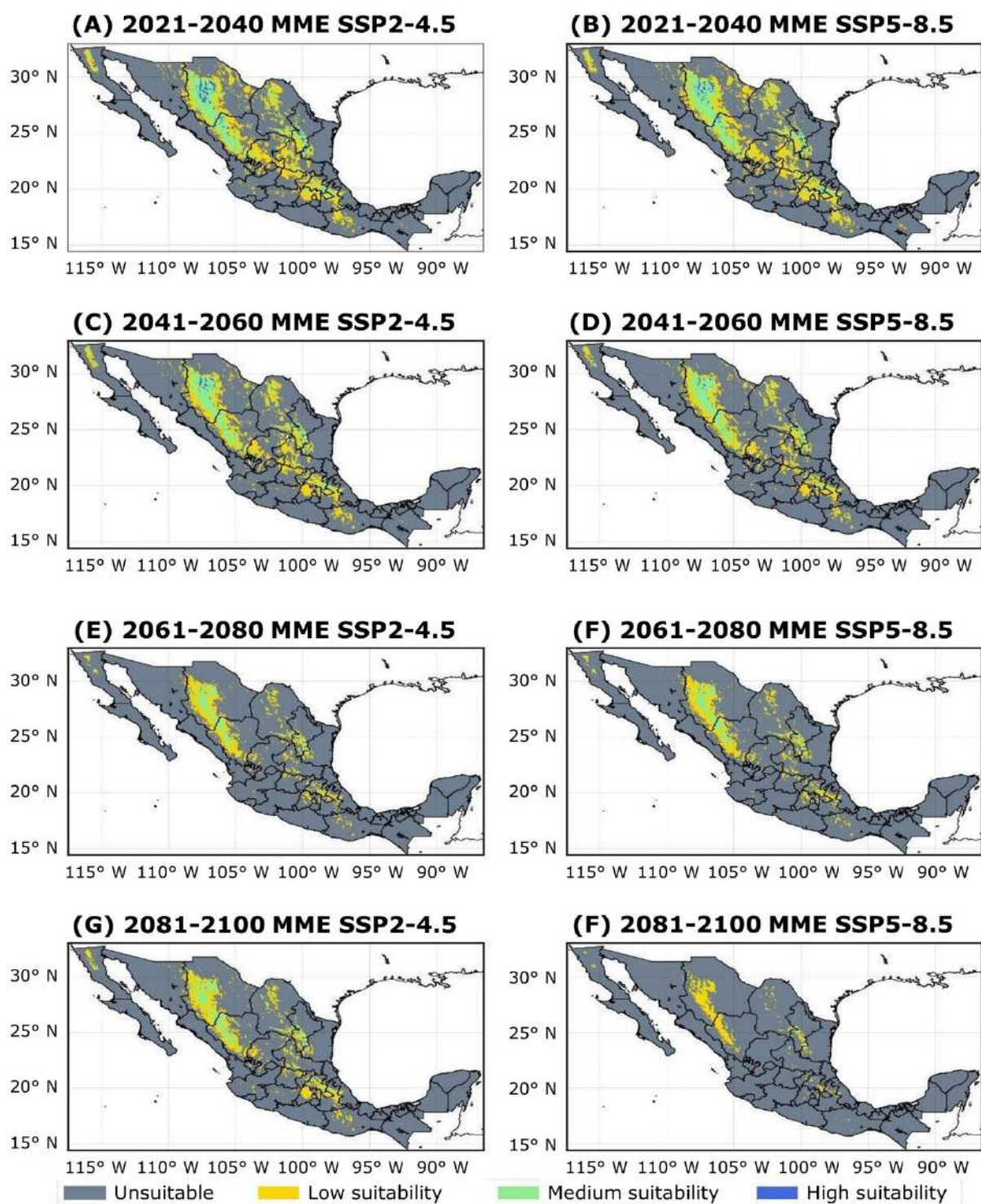
Based on Taylor diagrams (Figure 2), the selected GCMs for the MME were ACCESS-CM2, EC-Earth3-Veg, FIO-ESM-2-0, HadGEM-GC31-LL, MPI-ESM1-2-HR, and UKESM1-0-LL. These models showed greater correlation and less bias in simulating the regional historical climate, and were therefore considered appropriate for averaging their projections within the MME (Almazroui *et al.*, 2021).



A = Precipitation (*Pr*); B = Mean temperature (*Tas*); C = Maximum temperature (*Tasmax*); D = Minimum temperature (*Tasmin*).

Figure 2. Taylor diagrams for the period 1995 to 2014.

Figure 3 shows the variations in the suitability areas for *P. cembroides* under the SSP2-4.5 and SSP5-8.5 scenarios. In both cases, the model projects a progressive decrease in the areas with low, medium, and high suitability throughout all the analyzed periods.



A, C, E and G = SSP2-4.5 scenarios; B, D, F and H = SSP5-8.5 scenarios.

Figure 3. Potential distribution of *Pinus cembroides* Zucc. in the short (2021-2040), medium (2041-2060), long (2061-2080) and very long term (2081-2100) according to the Multi-Model Ensemble (MME).

During the reference period (1981-2010), the ideal area was 5.68×10^5 km². Under the SSP2-4.5 scenario, a reduction to 3.6×10^5 km² is projected in 2021-2040, 2.9×10^5 km² in 2041-2060, 2.5×10^5 km² in 2061-2080 and 2.0×10^5 km² in 2081-2100. In the SSP5-8.5 scenario, the decrease is more pronounced, with values of 3.6×10^5 km², 2.3×10^5 km², 1.5×10^5 km² and 0.5×10^5 km² in the periods 2021-2040, 2041-2060, 2061-2080 and 2081-2100, respectively. The suitability areas are summarized in Table 2.

Table 2. Predicted area ($\times 10^5$ km²) of suitability regions for *Pinus cembroides* Zucc. during the study periods according to the Multi-Model Ensemble (MME).

Suitability	1981-2010	2021-2040	2041-2060	2061-2080	2081-2100
		SSP2-4.5 SSP5-8.5	SSP2-4.5 SSP5-8.5	SSP2-4.5 SSP5-8.5	SSP2-4.5 SSP5-8.5
Low (0.1-0.3)	3.2	2.4	1.9	1.7	1.5
		2.3	1.6	1.2	0.5
Medium (0.3-0.6)	2.1	1.2	0.9	0.7	0.4
		1.2	0.7	0.3	0.02
High (>0.6)	0.4	0.08	0.03	0.02	<0.1
		0.06	0.01	<0.1	<0.1

In all cases, areas of low suitability are the most extensive, but also those that suffer the greatest reduction, while areas of high suitability are currently very small and practically disappear under both scenarios. Most of the currently suitable areas will be lost in the main mountain ranges (*Sierra Madre Oriental*, *Sierra Madre Occidental* and Trans-Mexican Volcanic Belt). In the most extreme scenario, SSP5-8.5, for 2081–2100 (Figure 4H), a reduction of nearly 90 % of the potential distribution is projected.

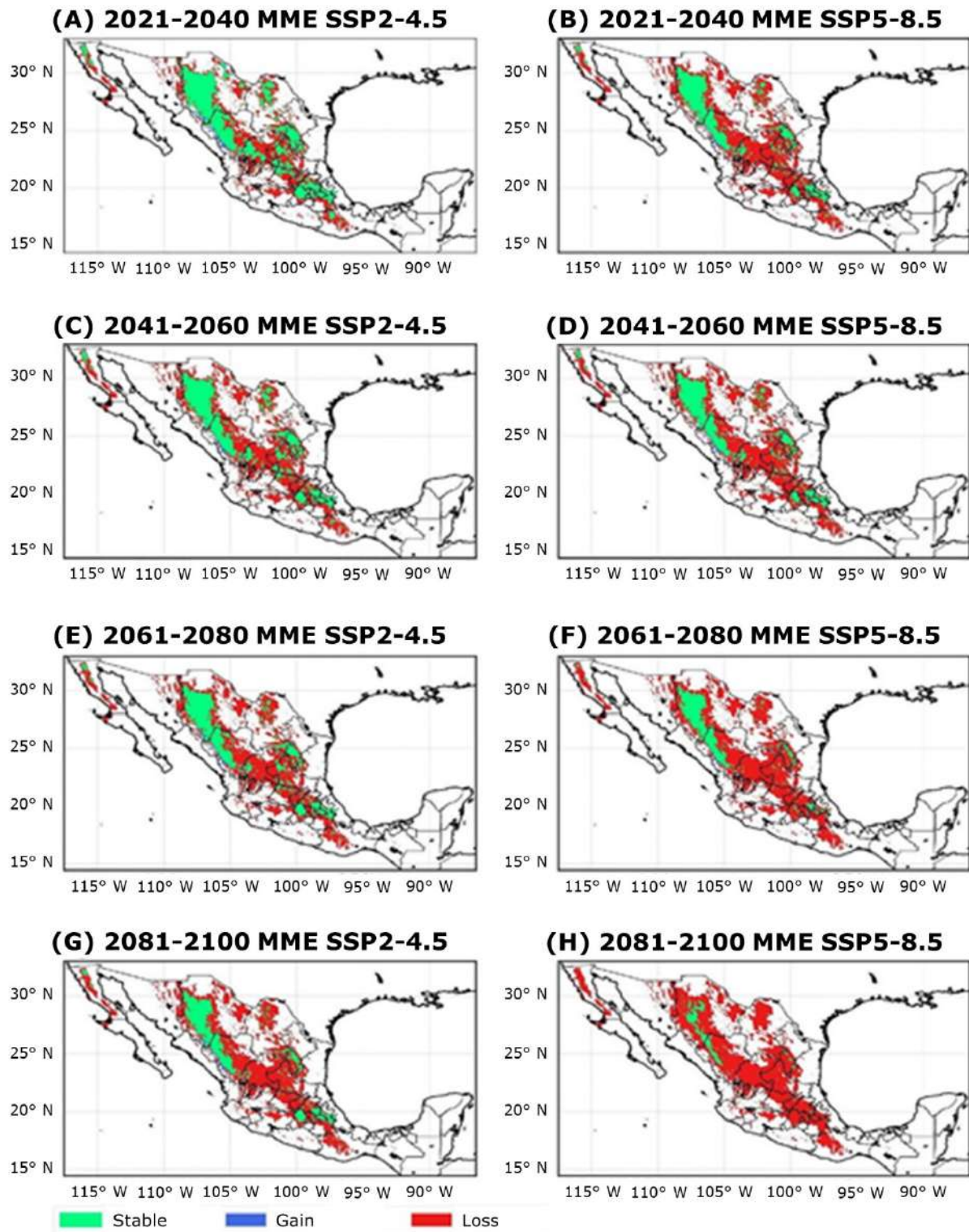


Figure 4. Changes in the potential distribution of *Pinus cembroides* Zucc. according to the Multi-Model Ensemble (MME).

During 2021-2040, *P. cembroides* would maintain part of its distribution in *Chihuahua* and *Nuevo León* under both scenarios (Figures 4A and 4B). The emergence of new suitable areas in state of *Baja California* (*Sierra de Juárez*) and *Durango* is also projected for 2021-2040 and 2041-2060 (Figures 4A and 4C). These areas would tend to shift to higher elevations between 2081 and 2100 and could disappear under SSP5-8.5 (Figure 4H).

The areas of land gain represent <5 % of the total surface area, indicating a very limited expansion potential. In contrast, stable areas comprise between 40 % and 64 % for most of the period, suggesting their persistence for several decades; however, under SSP2-4.5, their proportion drops below 50 % from 2041 to 2060 onward (Table 3).

Table 3. Changes (%) in the distribution area of *Pinus cembroides* Zucc. in the short term (2021-2040), medium term (2041-2060), long term (2061-2080), and very long term (2081-2100) under the SSP2-4.5 and SSP5-8.5 scenarios according to the Multi-Model Ensemble (MME).

Period	SSP2-4.5			SSP5-8.5		
	P	S	G	P	S	G
2021-2040	-36.5	63.5	+1.2	-37.1	62.9	+1.2
2041-2060	-50.3	49.6	+0.5	-59.2	40.7	+0.5
2061-2080	-56.0	43.9	+0.7	-73.6	26.4	+0.3
2081-2100	-65.3	34.7	+0.7	-90.3	9.7	+0.1

P = Loss; S = Stable; G = Gain.

The CMIP6 scenarios project a more severe contraction of *P. cembroides* habitat compared to equivalent estimates under CMIP5 (Gómez-Díaz *et al.*, 2011), particularly in the SSP5-8.5 scenario. This latter scenario anticipates a 4.0-4.5 °C increase in the regional mean temperature by 2081-2100 (Almazroui *et al.*, 2021), which would intensify the *Bio 8* and *Bio 9* bioclimatic variables in Northern and Central Mexico. Consequently, increased water stress for the species is projected, associated with

greater moisture deficits and evapotranspiration, which would negatively affect its growth and adaptive capacity (Manzanilla-Quijada & Treviño-Garza, 2024).

However, stable areas are projected to persist in the *Sierra Madre Oriental* and *Sierra Madre Occidental*, while new areas of limited suitability are expected to emerge in *Baja California*, *Coahuila*, *Nuevo León* and *Puebla*. These patterns align with studies based on CMIP5 (Romero-Sánchez et al., 2017), suggesting the presence of potential climate refuges for the species despite the adverse impacts of climate change.

The centroid of current climate suitability for *P. cembroides* (Figure 5), located around 25.2° N and 103.8° W, shows a consistent Northwestward shift trend throughout the 21st century in both scenarios. Under SSP2-4.5, the projected shift is ~40–50 km by the end of the century (2081-2100), while under SSP5-8.5 it reaches 70-80 km. Even by mid-century, a significant shift under SSP5-8.5 (~40 km in 2041-2060) is already evident compared to that projected under SSP2-4.5 (~20 km). This pattern coincides with the loss of suitable areas in Southern and lower-altitude regions, and with the persistence of climate refuges at higher latitudes and elevations.

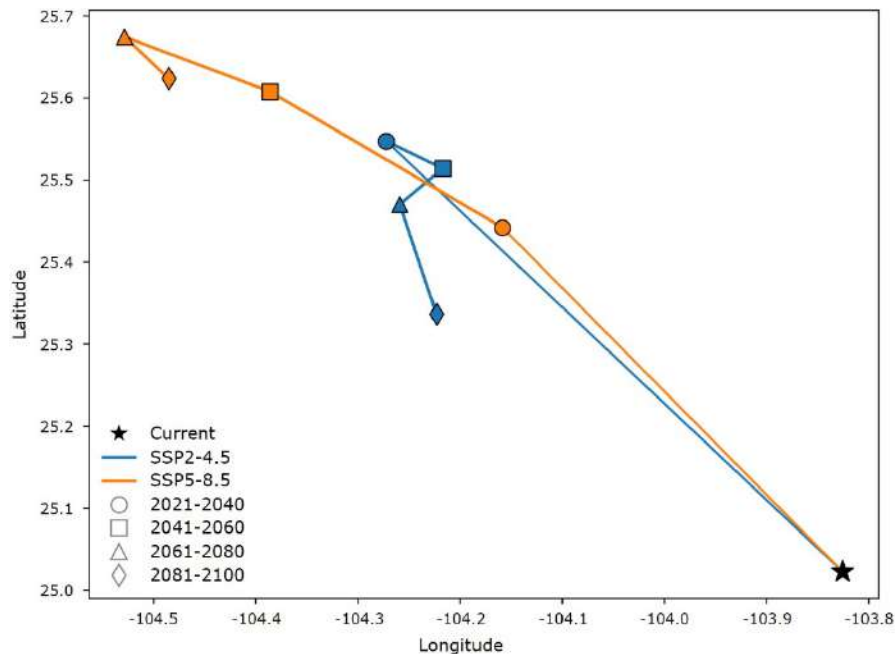


Figure 5. Centroid of the distribution of *Pinus cembroides* Zucc. under future climate conditions.

Implications for conservation

Species migration is a natural process that occurs gradually over multiple generations (Klisz *et al.*, 2023). However, the speed of climate change in recent decades exceeds the natural dispersal and adaptation capacity of many species and ecosystems. When environmental conditions change faster than species can adjust, the persistence of *P. cembroides* and other species with similar ecological traits is compromised (Aitken *et al.*, 2008).

In this context, assisted migration (AM) has emerged as a management strategy to facilitate the establishment of populations in habitats with more favorable future climatic conditions (Bower *et al.*, 2024; Palik *et al.*, 2022). In the case of *P. cembroides*, moving genotypes to more northerly or higher-elevation regions could anticipate the loss of local populations and promote the colonization of areas identified by models as climate refuges. The effectiveness of AM depends on rigorous protocols for selecting genetic material (*e. g.*, origins from warmer and drier environments), establishment trials, and adaptive monitoring that allows for adjusting densities, silvicultural treatments, and genetic mixtures based on performance (Palik *et al.*, 2022). At the same time, it is a priority to protect locations that could serve as natural refuges—particularly on the summits of the *Sierra Madre Occidental* and *Oriental*, where persistent suitability is projected—since these areas could concentrate the remaining genetic diversity of the species toward the end of the century (Haire *et al.*, 2022).

In addition to *in-situ* protection, maintaining and restoring ecological connectivity between current and future habitat fragments is crucial to reducing demographic and genetic costs during migrations. Establishing biological corridors that link remnant populations with projected refuge areas would facilitate the natural migration of *P. cembroides* along altitudinal and latitudinal gradients, increasing its chances of persistence and maintaining gene flow between subpopulations (Cantú-Garza, 2015).

These connectivity measures tend to generate co-benefits for co-occurring species, promoting the ecological integrity of the landscape in the face of climate change (Mawdsley et al., 2009).

Protected Natural Areas (PNAs) are critical nodes for sustaining these processes. In addition to conserving key habitats, they can function as “bridges” across environmental gradients and facilitate movement toward climatically more favorable zones (Chacón-Prieto et al., 2021). However, their future effectiveness may be limited if climatic niches shift outside their boundaries (Aguirre-Gutiérrez & Duivenvoorden, 2010). Therefore, it is strategic to incorporate climate projections into systematic conservation planning, create new protected natural areas (PNAs) or expand existing ones in areas identified as refuges, and strengthen connectivity through altitudinal and latitudinal corridors that link remaining populations with projected refuges (Mawdsley et al., 2009). These actions would also benefit numerous co-occurring species, contributing to the ecological integrity of the landscape.

From a forest management perspective, our results guide policies and restoration programs focused on priority sites. Identifying areas of potential loss and future refuges allows for directing reforestation and adaptive management toward higher elevations, which would become relevant as the last strongholds of *P. cembroides*. In these sites, restoration with seedlings of native drought-tolerant species and the incorporation of genotypes from arid zone populations could increase resilience to warmer and drier conditions (Palik et al., 2022). These measures can be integrated with national instruments—such as the National Ecological Restoration Strategy, National Forest Commission adaptation programs, and payment schemes for environmental services (Conafor, 2020)—always under rigorous protocols for the selection of genetic material, subsequent monitoring, and risk assessment (for example, alteration of recipient communities or low survival rates due to edaphic or biotic limitations not represented in the models).

Conclusions

The MaxEnt model, combined with high-resolution climate data from CHELSA v2.1 and a Multi-Model Ensemble (MME) from CMIP6, indicates a significant reduction in the distribution area under the SSP2-4.5 and SSP5-8.5 scenarios throughout the 21st century, with a more severe contraction under SSP5-8.5. In the latter scenario, it is estimated that by the end of the century only about 10 % of the currently suitable areas will remain, restricted mainly to mountainous regions. The temperatures of the driest (*Bio 9*) and wettest (*Bio 8*) quarters were identified as the main climatic factors limiting the species' distribution in Mexico.

The methodological approach employed helps reduce uncertainty in the projections and facilitates the identification of ecological corridors and potential climate refuges. This information is a key input for designing adaptation strategies—including assisted migration—and for implementing conservation and forest management plans focused on building the resilience of *P. cembroides* to climate change in Mexico.

Implementing these measures requires rigorous protocols for genetic selection and ecological assessment, as well as coordination among the scientific community, government authorities, and local stakeholders. Furthermore, associated risks must be considered, such as the disruption of host communities or the low viability of transplanted populations in the face of edaphic or biotic limitations not accounted for in climate models.

Acknowledgments

The authors wish to express their gratitude to the National Council for Humanities, Sciences and Technologies (*Conahcyt*) for the first author's scholarship. To the National Academy of Research and Development for providing its facilities for this research work.

Conflict of Interest

The authors declare no conflict of interest. Eduardo Alanís Rodríguez states that he did not participate in the editorial process of the manuscript.

Contribution by author

Julio Nemorio Martínez-Sánchez, Homero Alejandro Gárate-Escamilla, and Gerardo Cuéllar-Rodríguez: information search, potential distribution modeling, data review, writing of the manuscript; Tereza Cavazos: climate databases, manuscript review; Wibke Himmelsbach, Eduardo Alanís Rodríguez and José Israel Yerena Yamallel: manuscript review.

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