

Spatial modeling of the ecological niche of *Pinus greggii* Engelm (Pinaceae): A species conservation proposal in Mexico

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Abstract

Background

Studies in Mexico have shown that the genus Pine has always been under evolutionary changes, however currently they have accelerated as a result of human activities. *Pinus greggii* is a species restricted by particular environmental conditions of the Sierra Madre Occidental, which is of socio-economic importance in terms of wood production and provides environmental services to the ecosystem. Species distribution models are a relevant geospatial tool in decision making, and notable applications exist such as identifying areas of distribution and zones susceptible to climate change. The objectives of this study were: 1) model and quantify the current distribution, and possible future distribution under four scenarios of climate change; 2) identify the most relevant environmental variables that drive changes in distribution; and 3) to propose adequate zones for the species' conservation in Mexico.

Methods

438 records of *Pinus greggii* from several national and international databases were obtained, and were cleaned up to get rid of duplicates and overestimations in the models. Climatic, edaphic, and topographic variables were used and were generated 100 distribution models for current and future scenarios with Maxent software.

Results

The model one under replicated of crossvalidation had the best statistic, with an area under the curve of 0.88 and 0.93 for model training and validation, respectively, a partial ROC of 1.94, and a significant Z test ($p < 0.01$). The current estimated area of *Pinus greggii* in Mexico was 617,706.04 ha and the most important environmental variables for current distribution were the annual mean temperature, mean temperature of coldest quarter, and slope. For the 2041–2060 models, annual mean temperature, precipitation of coldest quarter, and slope were most important. The future models (2041–2060) predict a decrease in suitable habitat for the species from 48,403.85 (7.8%; HadGEM2-ES RCP 8.5 model) to 134,680.17 ha (21.8%; CNRM-CM5 RCP 4.5).

Conclusions

The spatial modeling of current and future conditions of the ecological niche of *Pinus greggii* in this study allows the proposal of two zones for conservation purpose and in situ restoration for the species in northeastern (Nuevo Leon) and central (Hidalgo) Mexico.

Background

Natural forest habitats exhibit wide biological diversity where conifer communities are dominated by the genus *Pinus* and provide ecological, economic, and social benefits. In ecological terms, they provide a diversity of environmental services such as hydrological cycle regulation, water production, carbon capture, promotion of biodiversity, and scenic beauty (CONAFOR 2009). Many *Pinus* species are exploited for commercial purposes and represent the most important source of wood, pulp, firewood, and resin, among other products (Sánchez-González 2008).

Mexico has the second largest number of *Pinus* species worldwide (Gernandt and Pérez-de la Rosa 2014); estimated at just greater than 52 of 111 species (almost 50%; Perry 1991). The majority of *Pinus* species in the country are restricted to very specific and contrasting geographic and environmental limits. *Pinus caribaea* var. *hondurensis* occurs at sea level, while *Pinus hartwegii* is found at 4,000 m, which constitutes the upper timberline (Woodward 1987; Farjon and Styles 1997; Gernandt and Pérez-de la Rosa 2014). Their distribution is determined by the climatic and edaphic conditions that dominate the site where they grow (Dawson and Spannagle 2009; Cruz-Cárdenas et al. 2016).

Scientific evidence from Mexico indicates the genera *Pinus* was always exposed throughout its evolutionary life to climatic changes; however, these changes have been accelerated due to anthropogenic activities, which caused the rhythm of these changes to increase (Thuiller et al. 2011; Intergovernmental Panel on Climate Change [IPCC] 2014). Future projections foresee a mean annual temperature increase of 2 °C by 2050 that will threaten global biodiversity (Tebaldi et al. 2006; IPCC 2019). According to climate models, the current biodiversity of *Pinus* spp. will experience three alternatives: tolerate the climatic alterations; become locally or regionally extinct; and/or undergo changes in current distribution (Sáenz-Romero et al. 2015; Cruz-Cárdenas et al. 2016). The effects of climate change in forest communities will result in a major adaptation process, which will lead to a modification of their current distribution and may lead to partial or total extinction of some species in the *Pinus* genera. (Davis and Shaw 2001).

Pinus greggii (Engelm), is one of the conifers restricted by the environmental conditions of the Sierra Madre Oriental. This species is socio-economically important in terms of firewood, fence posts, soil restoration, and the resin is used to produce turpentine (Muñoz et al. 2012). In Mexican plantations, the species has been evaluated with respect to soil conservation, reforestation, and atmospheric carbon capture (López and Valencia 2001; Pacheco et al. 2007). In plantations, *P. greggii* shows it is well adapted to several ecological conditions, particularly in semiarid conditions (López and Muñoz 1991) and degraded soils (López-Peralta and Sánchez-Cabrera 1996). In favorable conditions, its height and radius show high growth rates (Salazar et al. 1999). Plantations of *P. greggii* have also been established in other countries such as Argentina, Venezuela, South Africa, and Zimbabwe (Dvorak and Donahue 1992).

The knowledge of the ecological niche of *P. greggii* allows environmental managers to distinguish different environmental patterns that contribute to establishment and distribution of species—important information for conservation activities and management of genetic resources (Hernández-Ruiz et al. 2016). Scientific tools exist that allow environmental managers to predict the distribution of species (Elith et al. 2006); these are cartographic representations

wherein the species capacity occupies a geographic space according to a set of variables in conjunction with continuous or categorical character of the region's climatology, edaphology, and topography (Guisan and Zimmermann 2000).

MaxEnt is used to predict the current and future spatial distribution (ecological niche) of Pinaceae in Mexico (Cruz-Cárdenas et al. 2016; García-Aranda et al. 2018; Manzanilla-Quñones et al. 2019a), employing only prescient records (Phillips et al. 2006). MaxEnt is one of the most-used spatial distribution algorithms and is considered to be the best method of estimating at spatial level in relation to the suitability of species (Ortega-Huerta and Peterson 2008; Kumar and Stohlgren 2009). Global circulation models are used to simulate future climate behavior (Delgado and Suárez, 2009; Fernández-Eguiarte et al. 2015), and are therefore a good alternative to estimating and evaluating climate changes and how they will affect future species distribution (Peterson et al. 2011; García-Aranda et al. 2018; Manzanilla-Quñones et al. 2019a).

The outputs of these models (ecological niche and global circulation) processed in a Geographic Information System (GIS) allow generation of suitability maps of the relation between species' habitat (probabilistic) and different horizons of projected time. The results of these estimations are useful, especially to inform management programs focused on conservation and restoration of ecosystems in Mexico (Islas-Báez et al. 2015; Sáenz-Romero et al. 2012; 2015).

Although it is known that a real threat exists due to the negative effect of climate change on the future of the majority of species in the Pinaceae family, the prognosis for species (such as *P. greggii*) that inhabit the arid and semiarid climates, could be more encouraging, which would imply the current and future environmental conditions will be similar. Thus, most areas of current distribution of the species could persist or be preserved through time (niche conservatism theory) (Soberón and Miller 2009; Peterson 2011).

In this study, we analyzed geographic and environmental records (climatic, topographic, and edaphic) of *P. greggii* to help us to delimit, estimate, and identify the most relevant environmental variables in current and future distributions, as well as to propose conservation areas within the species' natural distribution in Mexico. In response to these objectives, the following specific goals were formulated: 1) delimit and estimate the area of distribution of the *P. greggii*; 2) identify the most relevant variables in the current and future (2041–2060) distribution; and 3) propose conservation areas for *P. greggii* to thrive within its current natural area of distribution in Mexico.

Methods

Study area

The present study includes the physiographic provinces of the Sierra Madre Oriental and a portion of the Neovolcanic Transversal Belt, specifically in the subprovince Plains and Sierras of Queretaro and Hidalgo, and Lagoons and Volcanoes of Anahuac (Fig. 1), and between the longitudinal coordinates of 97°0'0"–105°0'0" and latitudinal coordinates of 18°0'00"–30°0'00" (Instituto Nacional de Estadística y Geografía [INEGI] 2018). The geographic region of the provinces and subprovinces were considered to be the spatial area of modeling M, which is the geographic and environmental space where the presence of a species has been registered and is delimited according to the biological knowledge of it and its dispersal capacity (Soberón and Peterson 2005) for *P. greggii*. The highest elevation point corresponds to the Pico de Orizaba (5,610 masl), while the lowest is at sea level on the coast of Veracruz (Instituto Nacional de Estadística y Geografía [INEGI] 1998). The precipitation ranges from 154 to 3,866 mm, with an average of 685.09 mm and a mean annual temperatures range from – 2 °C to 28 °C (Fick and Hijman 2017).

Geographic Records

In this study four different sources of records about *P. greggii* were used, three of which are from a database and are included in official pages for their free download: 262 records were retrieved from the Global Biodiversity Information Facility (GBIF) which is an international organization whose purpose is to accumulate and provide scientific data (GBIF 2018) <http://www.gbif.org/occurrence/download/0053032-160910150852091>; 40 records of were retrieved from the database of the National Herbarium of the Universidad Nacional Autonoma de Mexico (MEXU 2019) <http://www.ib.unam.mx/botanica/herbario>; 63 records were retrieved from the Global Network of Biodiversity Information by CONABIO that contain different national and international collections (REMIB 2019); and 73 records were generated through dendrochronological expeditions made by personnel of the National Dendrochronological Laboratory of the INIFAP CENID-RASPA in 2018–2019.

In total, 438 records were obtained, and then cleaned up via the Niche ToolBox platform of the National Commission for the Knowledge and use of Biodiversity (Osorio-Olvera et al. 2019) to eliminate double records and spatial separations of less than 1 km of lineal distance between records. This step helped to avoid the autocorrelation spatial effect and a subestimation of the distribution models (Peterson and Nakazawa 2008; Monterrubio-Rico et al. 2016).

Current And Future Climatic Variables

Current climatic information was obtained from the 19 bioclimatic layers (Table 1) from the WorldClim database ver. 2.0 (Fick et al. 2017), which contain mean climatic global information from 1970 to 2000 with a spatial resolution of 30 seconds (~ 1 km²). For future distribution analysis, the Global Circulation Models (GCMs) CNRM-CM5 and HadGEM2-ES were chosen and are two of the more recently used GCMs in Mexico (Manzanilla-Quñones and Aguirre-Calderón 2017; Manzanilla et al. 2018; Manzanilla-Quñones et al. 2019a). They were generated from the Project of Regional Models CMIP-5 (Coupled Model

Intercomparison Project Phase 5 2013) of the IPCC. The bioclimatic layers of these models were downloaded with two radiative forcings of 4.5 (constant trajectories of CO₂) and 8.5 (high trajectories of CO₂) for 2041–2060 (Table 1), with a spatial resolution of 30 seconds (~ 1 km²).

In Table 1, the 19 current and future bioclimatic layers downloaded from WorlClim ver. 2.0 are presented.

Table 1
Current and future bioclimatic data downloaded from WorldClim.

Variable description (Unit of measure)	Code
Annual mean temperature (°C)	BIO1
Mean of monthly diurnal temperature range (°C)	BIO2
Isothermality	BIO3
Temperature seasonality (standard deviation × 100; °C)	BIO4
Maximum temperature of warmest month (°C)	BIO5
Minimum temperature of coldest month (°C)	BIO6
Annual temperature range (°C)	BIO7
Mean temperature of wettest quarter (°C)	BIO8
Mean temperature of driest quarter (°C)	BIO9
Mean temperature of warmest quarter (°C)	BIO10
Mean temperature of coldest quarter (°C)	BIO11
Annual precipitation (mm)	BIO12
Precipitation of wettest month (mm)	BIO13
Precipitation of driest month (mm)	BIO14
Precipitation seasonality (Coefficient of variation; %)	BIO15
Precipitation of wettest quarter (mm)	BIO16
Precipitation of driest quarter (mm)	BIO17
Precipitation of warmest quarter (mm)	BIO18
Precipitation of coldest quarter (mm)	BIO19

Topographic And Edaphic Variables

Topographic information was obtained from a digital elevation model with a 30 m spatial resolution downloaded from the Mexican Continuous Elevation ver. 3.0 (Instituto Nacional de Estadística y Geografía [INEGI] 2013), which was generated with ASCII layers; Digital Elevation Model (DEM) and slope (SLO) with 30 seconds (~ 1 km²) of spatial resolution; the last one was generated through the DEM with Arcmap 10.3 software (Esri 2014).

Edaphic information was downloaded from the SoilGrids database (https://soilgrids.org/#!/layer=ORCDRC_M_sl2_250m&vector=1), with a spatial resolution of 250 m (Batjes et al. 2017). This continuous edaphic information was developed in 2016 from the Global Soil Information Facilities (GSIF), which can be thought of as a spatial integration of a soil cartographic system at the global level (Hengl et al. 2014; 2017). SoilGrids was generated as a variable model for the prediction of the physical and chemical characteristics of the soil on site. In Mexico, INEGI provided series II soils profiles field data that served as input for the models. Continuous variables such as coarse fragment volumetrics, bulk density, absolute depth, pH, cation exchange capacity, and soil organic carbon content were extracted and adapted to an ASCII standard format with a spatial resolution of 30 seconds (~ 1 km²).

Variable Selection

For variable selection, a minimum convex polygon was generated according to the presence records of *P. greggii* (Fitz-Maurice et al. 2013). Later, 10,000 points of background were added and the climatic, topographic and edaphic information of each point was extracted. Environmental variables with correlation greater than $r > 0.7$ ($p < 0.01$) were eliminated to avoid the multicollinearity effect between variables (Hawkins et al. 2003; Merow et al. 2013). The selected environmental variables were transformed at the same spatial resolution of 30 seconds (~ 1 km²) according the spatial area of modeling M (study area) with the Arcmap ver 10.3 software (Esri 2014).

Current Distribution Modeling

The MaxEnt ver. 3.4.1 algorithm was used to model current distribution (Phillips et al. 2006). This algorithm was chosen because it is one of the most-used methods in the field study of potential distribution and generates accurate geographic predictions from only presence records (Elith et al. 2006; Ortega-Huerta and Peterson 2008). Seventy-five percent of records were used to train the model and 25% to validate it. The BIO1, BIO7, BIO11, BIO15, BIO17, BIO19, DEM, SLO, and pH variables are in ASCII format (Table 2).

The modeling criterion comprise internal replication by cross-validation, 1,000 iterations, logistic output, 100 replicates, and a convergence threshold of 0.00001 (Phillips et al. 2006; Phillips and Dudik 2008; Dambach and Rödder 2011). The Extrapolate and Do clamping options were deactivated, to avoid overestimation in the modeling prediction (Elith et al. 2011).

Table 2
Environmental variables used in modeling the current distribution of *P. greggii* in Mexico.

Variable Code	Variable description (unit of measurement)
BIO1	Annual mean temperature (°C)
BIO7	Annual temperature range (°C)
BIO11	Mean temperature of coldest quarter (°C)
BIO15	Precipitation seasonality (Coefficient of variation; %)
BIO17	Precipitation of driest quarter (mm)
BIO19	Precipitation of coldest quarter (mm)
DEM	Digital model elevation (m)
SLO	Slope (%)
pH	Hydrogen potential (0–14)

Model calibration was evaluated through the standardized coefficient of the Akaike information criterion (AICc), which provides model information, such as Feature type and the Regularization multiplier (Warren et al. 2011). The lowest value parameters of the AICc were selected for to generate the most accurate results. The calibration was made using the ENMeval library (Muscarella et al. 2014) in the R ver. 3.5.3 software (R Core Team 2015).

Modeling Under Future Scenarios

For the generation of model distribution under climate change scenarios, the calibration parameters and the model with the best statistical adjustment were transferred to the MaxEnt ver. 3.4.1 software (Morrone and Escalante, 2016). The estimated area (ha) of current and future distribution of *P. greggii* were obtained from the reclassification of the continuous values of both temporal projections (current and future) in three categories of suitability or habitat probability with equal intervals (low, medium, and high) with the reclass tool of the Arcmap 10.3 software (Esri 2014). The values of the high category were used as threshold cut, to transform the continuous models to binary (apt or non-apt) for every period (Manzanilla-Quiñones et al. 2019a). The conservation areas (that could be used for *in situ* conservation and restoration zones for *P. greggii*) were identified using the Intersect tool of Arcmap ver. 10.3 (Esri 2014), which was based on the simulation of the current and future environmental conditions.

Model Validation

The distribution models were evaluated through the statistical test of area under the curve (AUC) of the Receptor Operation Characteristics (ROC) analysis, the results of which oscillate between 0 and 1. Values from 0.7 to 0.9 classify the model setting is good, and above 0.9 as excellent (Peterson et al. 2011). However, the utility of this analysis is strongly questioned in the algorithm development that uses only presence records because this test requires true absences, and for this reason, omission and commission errors are weighted evenly (Lobo et al. 2007). It was necessary to perform a ROC partial test in the Niche ToolBox platform from the CONABIO (Osorio-Olvera et al. 2019) to counter the AUC deficiencies (Peterson et al. 2008). The suggestions of Peterson et al. (2008) were followed by using 1,000 replicates by bootstrapping between ASCII files of every period and the records of presence of the species, and establishing a 5% omission error (Osorio-Olvera et al. 2019).

The ROC partial test generated values from 1 to 2, where a mean ratio value of 1.0 is equal to a random model (Garza-López et al. 2016; Lobo et al. 2007; Peterson et al. 2008). A Z test between the proportions of the AUC of partial ROC was performed to determine if the models were statistically valid. The best model of each period was selected according to the highest value of the partial ROC, a lower standard error, and a statistically significant Z ($p < 0.01$). At the end, the model outputs selected for every period were visualized with a distribution map in the Arcmap ver. 10.3 software (Esri 2014).

Relevant environmental variables

The contribution of environmental variables in the current and future distribution were evaluated with the Jackknife test, which allowed us to identify and quantify the percent of contribution or relevancy of each variable in the growth and development of *P. greggii* during the current and future periods in the study area (Phillips et al. 2006).

Results

Modeling of the current distribution

The results of the 100 replicates of the AUC were from 0.879 to 0.886 for training and from 0.797 to 0.93 for validation, which indicated the development of the models was good. For *P. greggii* in Mexico, the best model resulted in a partial ROC value of 1.90 (Table 3), an AUC of 0.881, and 0.930 for training and validation.

The results estimated the potential current distribution of *P. greggii* in an area of 617,706.04 ha (Fig. 2) within the study area.

The majority of the current estimated area of *P. greggii* is located in the states of Nuevo Leon (260,028.94 ha, 42.1%) and Hidalgo (70,762.13 ha, 11.4%).

Modeling Under Scenarios Of Climatic Change

The AUC values obtained from the ROC test for the CNRM-CM5 RCP 4.5 model ranged from 0.901 to 0.909 for the training and from 0.809 to 0.953 for validation, while the values for the RCP 8.5 projection were from 0.885 to 0.894 for training and from 0.778 to 0.942 for validation.

The results of the HadGEM2-ES RCP 4.5 were from 0.877 to 0.888 for training and from 0.781 to 0.932 for validation, while for the values for the RCP 8.5 model were from 0.874 to 0.881 for training and from 0.785 to 0.936 for validation; these results allowed us to classify the models of the future distribution as very good.

Table 3
Performance of the models under climate change scenarios.

Global Circulation Model	Partial ROC mean ratio	Standard error	Z test
CNRM-CM5 (RCP 4.5)	1.92	0.060	p < 0.01
CNRM-CM5 (RCP 8.5)	1.90	0.060	p < 0.01
HadGEM2-ES (RCP 4.5)	1.90	0.059	p < 0.01
HadGEM2-ES (RCP 8.5)	1.89	0.059	p < 0.01

Relevant Variables In The Current And Future Distribution

The relevant variables in the current distribution were BIO1, BIO11, SLO, BIO19 and BIO7, which contributed 81.2% of the model's variability (Fig. 3). The relevant variables for the 2041–2060 CNRM-CM5 RCP 4.5 model were BIO1, SLO, BIO19, BIO15 and BIO11, and the relevant variables for the RCP 8.5 model were BIO1, SLO, BIO15, BIO19 and BIO11, with contributions of 83.4% and 87.9% respectively (Fig. 4).

Variables most relevant to the HadGEM2-ES model for 2041–2060 were BIO1, SLO, BIO11, BIO15 and BIO19, according to the RCP 4.5, and for the RCP 8.5 were BIO1, BIO11, SLO, BIO7 and BIO17, with contributions of 81.5% and 85.9% respectively (Fig. 5).

Current and future area of *P. greggii* in Mexico

Table 3 presents the estimated current and future area of *P. greggii* under four climate change scenarios during 2041–2060 in the province of Sierra Madre Oriental and the subprovinces Plains, Sierras of Queretaro and Hidalgo, and Lagoons and Volcanoes of Anahuac inside the Neovolcanic Transversal Belt.

Table 3
Potential Current and future area of *P. greggii* in Mexico.

Model	Area (ha)	Percent (%)
Current	617,706.04	100
CNRM-CM5 (RCP 4.5)	483,025.87	-21.8*
CNRM-CM5 (RCP 8.5)	508,004.15	-17.7*
HadGEM2-ES (RCP 4.5)	548,374.45	-11.2*
HadGEM2-ES (RCP 8.5)	569,302.19	-7.8*
* Percentage reduction concerning the current area.		

The results of the CNRM-CM5 (RCP 4.5) foresee a raise of 0.7 °C in mean annual temperature, which will reduce the species' ecological niche by 21.8% (relative to current area). The CNRM-CM5 (RCP 8.5) estimates a rise of 1.1 °C in mean annual temperature and an ecological niche reduction of 17.75%. Both scenarios estimate reductions in the natural distribution of the species between 2041 and 2060.

The results of the HadGEM2-ES (RCP 4.5) model calculated a rise of 1.5 °C in the mean annual temperature, resulting in a reduction of the ecological niche of 11.2%. The HadGEM2-ES (RCP 8.5) model indicates a reduction of the ecological niche of 7.5% relative to the current area, with an estimated 2.1 °C increase of the mean annual temperature.

The results of the four climate change scenarios predict a range from slight reduction (HadGEM2-ES RCP 8.5; 7.8%) to more extensive reduction (CNRM-CM5 RCP 4.5; 21.8%) in the ecological niche of *P. greggii* for 2041–2060. According to these models, the rise of the mean annual temperature is the principal variable responsible for the reduction in suitable ecological niche for *P. greggii* within their natural future distribution.

Conservation Of The Ecological Niche

The estimated area for the ecological niche conservation of *P. greggii* for 2041–2060 in Mexico, according to the CNRM-CM5RCP 4.5 was 392,923.28 ha, and with RCP 8.5 was 366,697.07 ha.. Areas of 467,108.76 and 464,252.59 ha were estimated according to the HadGEM2-ES RCP 4.5 and 8.5, respectively for 2041–2060 (Fig. 6). The interpretation of these results pointed to the HadGEM2-ES RCP 4.5, as the model with the largest area of ecological niche conservation in 2041–2060, with a 75.6% increase relative to the current estimated area. The persistence of these geographical areas could be used as suitable areas for conservation and *in situ* restoration activities of the species.

The majority of the ecological niche conservation areas of *P. greggii* are located in the states of Nuevo Leon (223,589.71 ha) and Hidalgo (46,341.99 ha). According to the results of the current and future model HadGEM2-ES RCP 4.5), two suitable areas for conservation and restoration activities of the species are proposed: the first is located in the north, in the state of Nuevo Leon; the second is located in the center of the country, in the state of Hidalgo (Fig. 7).

Discussion

Special modeling

The current and future distribution models developed in MaxEnt in the present study show a good performance in the AUC test (0.88) for the training data and (0.93) for validation, and an excellent adjustment in the partial ROC with results of 1.85 to 1.94 and significant values of Z ($p < 0.01$). Peterson et al. (2011) report AUC values between 0.7 and 0.9 and the performance of the model is considered good, and close values to two of partial ROC are adequate without random effects (Peterson and Nakazawa 2008; Garza-López et al. 2016).

The present study involved 250 records of the *P. greggii* species, where the quantity and quality of the records enhanced the model performance.

Stockwell and Peterson (2002) showed an increase in precision and suggested a minimum of 50 records to develop the species distribution analysis. Aceves-Rangel et al. (2018) developed a potential distribution analysis of *Pinus* species, but used only 33 records of *P. greggii* which resulted in an AUC of 0.95, although this AUC is greater than the one obtained in the present study, the high AUC may have been due to fewer records, the lack of debugging and calibration analysis, and a location in the state of Chiapas, being the *P. greggii* an endemic species of the Sierra Madre Oriental and the eastern section of the Neovolcanic Transversal Belt (Ramírez-Herrera et al. 2005).

A potential current area of 617,706.04 ha of *P. greggii* was identified in this study, in contrast to a study that was done by Aceves-Rangel et al. (2018) that determined a potential current area of only 550,300 ha. The difference between both estimations was 67,406.04 ha, although it should be noted that the previous study did not include edaphic variables, which are relevant in potential distribution studies (Cruz-Cárdenas et al. 2016; Manzanilla-Quñones et al. 2019a).

Relevant Environmental Variables

The most important variable for this study was the BI01 (mean annual temperature), coinciding with diverse studies related to the *Pinus* habitat, which have shown that this variable plays an important role for at least ten different species (Aceves-Rangel et al. 2018).

The high dependence shows the significance of the effect that temperature has in the establishment and growth of conifer species (Wang et al. 2016), which has been corroborated by the association of drought index and the rise of the temperature in arid zones (Vicente-Serrano et al. 2010; Ma et al. 2014).

One aspect to consider is that an increase in temperature generates an accelerated development of the species, but with reduction in their growth (Gennaretti et al. 2014). This behavior is attributed to elevated temperatures promoting an increase in evapotranspiration and, consequently, a metabolic alteration that impacts the assimilation of photosynthates (Girardin et al. 2012). Temperature is an important component in global climate change and has presented modulations in their variability (Medhaug et al. 2017), especially in northern Mexico where the climatic models forecast significant increases (IPCC 2014).

Studies like Gutiérrez and Trejo (2014); Martínez-Méndez (2016); Manzanilla-Quñones (2019a) have found that an increase in temperature caused by climatic change will lead to a decrease in the area of *Abies*, *Quercus*, and *Pinus* genera.

In the study by Aceves-Rangel et al. (2018), the variable BIO11 (mean temperature of coldest quarter) was found to be important for *P. arizonica*, which is ecologically associated with *P. greggii* and found in similar climate conditions (López-Peralta and Sánchez-Cabrera 1996).

García-Aranda et al. (2018) found the variable BIO11 plays an important role in the distribution of *P. nelsonii* in northwestern Mexico, a species associated with *P. greggii* in the Sierra Madre Oriental and the Neovolcanic Transversal Belt. The mean value of the BIO11 variable was 4.3 °C in the present study and is very similar to the mean value found for *P. nelsonii* of 4.6 °C – an adequate temperature for the growth and development of *P. greggii*.

The SLO for García-Aranda et al. (2018) found that this topographic variable presented great relevance in three *Pinus* species with distribution restricted to northeastern Mexico (*P. cembroides*, *P. culminicola*, and *P. nelsonii*), contributing to the model with 21.1% significance; close to that found in this study of *P. greggii* with 18.3% of contribution to the current distribution model.

The SLO is a significant variable for the establishment of tree species located on steep soils. Muñoz et al. (2012) mention that the *P. greggii* is present on slopes with up to a 5% grade; the mean slope value found in this study is 8%.

The BIO19 variable (precipitation of coldest quarter) was considered an important variable for at least seven *Abies* species in Mexico (Martínez-Méndez et al. 2016). According to the study of Aceves-Rangel et al. (2018) BIO19 was relevant for *P. lumholtzii* at a national level with 8.2% as the lowest value, in comparison to the 12.8% found for *P. greggii*. In this analysis, the mean BIO19 was 427 mm, however *P. greggii* is adapted to zones with low precipitation ranging from 293 to 747 mm (Ramírez-Herrera et al. 2005).

The annual oscillation of the temperature (BIO7) for the current distribution of *P. greggii* in the present study had a mean value of 25.4 °C, which, according to the study zone, is a suitable temperature in the ideal annual range for the species development. This variable is relevant in other studies as well: Hernández et al. (2018) found that BIO7 had an importance factor of 12% for distribution of *Cedrela odorata* in Mexico, slightly less than our 15.5% of the total in the present study of *P. greggii*; Martínez-Méndez et al. (2016) considered BIO7 a useful and relevant variable in the distribution of four species of *Abies* at a national level, which demonstrates BIO7 to be a relevant environmental characteristic for tree species in Mexico.

Future Scenarios

Diverse studies about climate change scenarios have been generated in Mexico for Pinaceae, the majority of which belong to temperate and cold climates. These studies agree with the theory of a significant reduction in the distribution areas of the Pinaceae for 2050 (Sáenz-Romero et al. 2012; 2015; Cruz-Cárdenas et al. 2016; Manzanilla-Quifiones et al. 2019a). However, this type of study has not been widely applied to *Pinus* species that grow in the arid and semiarid regions of the country.

According to the increases of temperature forecast by the CNRM-CM5 and HadGEM2-ES models with two radiative forcings (RCP 4.5 and 8.5) for 2041–2060, the ecological niche will decrease between 7.8% and 21.8% within the endemic zone of *P. greggii*, but with a tendency to modify their distribution with consideration for the climatic change scenarios between RCP 4.5 and RCP 8.5 as are mentioned by Gavilán (2008).

In the modeling study of pinyon pines under climate change scenarios in Mexico by Pérez et al. (2019), they found that *P. culminicola*, *P. johannis*, and *P. pinceana* will show a decrease in area in relation to the current area, with a greater area presented in RCP 8.5 relative to RCP 4.5. This situation is similar to that of *P. greggii* with respect to a scenario with constant trajectories of CO₂ concentration and other with increases in concentrations on the atmosphere, because all four species are from similar environmental conditions located at the bottom of the mountains of arid and semiarid climates (Perry 1991; Farjon and Styles 1997).

In the analysis of future distribution based on the statistical model of scale reduction for *P. arizonica* and *P. cembroides* (species similar to *P. greggii*), Romero-Sánchez et al. (2017) found there would be an increase in area of 52.29% and 45.95% by 2050, respectively (in comparison to the current area in Sierra de Zapalín, Coahuila). While the study of Romero-Sánchez et al. (2017) was regionalized, the tendency of increasing in area of forest species in arid climates foresees favorable effects on species such as *P. greggii*, *P. arizonica* and *P. cembroides* under climate change effects considering the area of a one forcing to other, suggesting that although effects of global climate change may be negative, the analysis at local level may be beneficial for some species.

Conservation Areas Of Niche

Studies conducted on conservation of ecological niche mention that species with the tendency to conserve their niche either adapt to climatic changes through time or move to colonize new geographical areas with characteristics similar to those of their original ecological niche of (Martínez-Meyer and Peterson 2006; Peterson 2011).

The study of niche conservation based exclusively in the ecological niche modeling provide the advantage of the comparison method of environmental values of the locations where the species can be found, with estimated values through an environmental probabilistic index for the species. This index provides detailed relevant information about the niche components because it applies the niche theory as a multidimensional hypervolume proposed by Hutchinson (1957) and is complemented with the geographical analysis part by Soberón and Peterson (2005), in which some or most of its environmental components are preserved (McComarck et al. 2010) allowing one species to persist at a different temporal scales (Martínez-Meyer 2006; Peterson 2011). However, these types of studies are very scarce for the Mexican conifers and it is just beginning to be studied in the country.

Martínez-Méndez et al. (2016) mention (without testing the hypothesis) that the ecological niche (as determined for Mexico) of the genus *Abies* has remained stable over time. Manzanilla-Quiñones et al. (2019a) tested this hypothesis in *Abies religiosa* [Kuth] Schltld & Cham, finding that the ecological niche of *A. religiosa* has remained stable or has been preserved since 6,000 years ago in the high and humid parts of the Neovolcanic Transversal Belt. The results obtained by our study through the conservation model HadGEM2-ES RCP 4.5 estimate 75.6% of the conservation niche. These results indicate a smaller conservation niche area in comparison to the study of Manzanilla-Quiñones et al. (2019a) for *A. religiosa*, which is due to a reduction in the amount of moisture and an increase in the temperature in the ecological niche of *P. greggii*.

According to the analysis of the interaction of the relevant variables in the current and future distribution, it was possible to delimit two conservation niche zones suitable for the generation of conservation and restoration activities of *P. greggii* inside their natural distribution in Mexico.

Aguirre and Duivenvoorden (2010), in their study about the potential modeling of 56 *Pinus* species in Mexico mentioned as a conservation proposal that one of most important zones to establish new protection areas for this genus is the Sierra Madre Sur where several currently modeled species exist, as well as few areas that are under regulatory protection. However, this conservation proposal was focused on *Pinus* species in a more temperate climate, which differed from the arid to semiarid of *P. greggii*.

Manzanilla et al. (2019b) proposed two zones of conservation and seed production for *P. pseudostrubus* and *P. montezumae*. Although they have different environmental requirements than *P. greggii*, the proposed zones of conservation and seed production are similar, with two delimited zones in both our study and Manzanilla et al. (2019b).

Most of the studies on this subject have been made on Pinaceae of temperate-cold climates, therefore, the findings of our study are relevant because it allows us to define and propose two important areas for the conservation and restoration of *P. greggii* in Mexico.

Finally, according the objectives of this study, it was possible to delimit and estimate the current natural distribution of *P. greggii* in Mexico and the most relevant environmental variables were also analyzed. From this data we were able to determine the presence of this important ecological and economic species in Mexico, and from the niche conservation analysis between the current and future distributions, it was possible to propose conservation areas, which do not compromise the development and growth of the species because they would be under similar current–future environmental conditions.

Conclusions

The analysis in this study allowed us to delimit and estimate the natural geographic distribution of *P. greggii* and the occupied area for the species in the Sierra Madre Oriental and Neovolcanic Transversal Belt in Mexico. The delimitation and estimation of the species distribution under four scenarios of climate change from 2041 to 2060 was also developed; an area of study where few studies with species of arid and semiarid climates exist.

The most important variable that determined the suitable of the current and future ecological niche of *P. greggii* in Mexico was the mean annual temperature, which is a variable that is expected to increase in the future due to climate change. In this study, a decrease in area of *P. greggii* is expected according to the four projected scenarios (two with constant concentrations and two others with increased in greenhouse gas emissions). This projected decrease in area is in relation to the current area, however according to the present study, comparatively between modeled scenarios (RCP 4.5 to RCP 8.5), there will be a slight increase, which will favor the species in the future.

The area most affected by climate change would be the states of Hidalgo and Puebla, according to the four projected scenarios for *P. greggii* during the period of 2041–2060. It should be noted that the change in environmental conditions under the effects of climate change probably will limit the growth and development of tree species, but would not imply a local or regional extinction.

The niche conservation analysis of *P. greggii* allowed us to identify areas under similar environmental conditions that may become ideal for the subsistence of *P. greggii* in Mexico in the future. These areas are divided into north (Nuevo Leon) and center (Hidalgo) and could be used for conservation, restoration, and forest propagation purposes *in situ*.

Declarations

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Author's contributions

ARMS designed the study, analysis, and wrote the paper. JVD refinement and provided a thorough review of the paper. UMQ participated in the spatial analysis and style of the paper. JLBL and JAHH provided a thorough review and edit of the paper. JEA and AHVP participated in the study design and conceptualization and study.

All the authors read and approved the final manuscript

Founding

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Availability of data and materials

The datasets generated and/or analyzed during the current study are available in the GBIF repository, www.gbif.org

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Figures

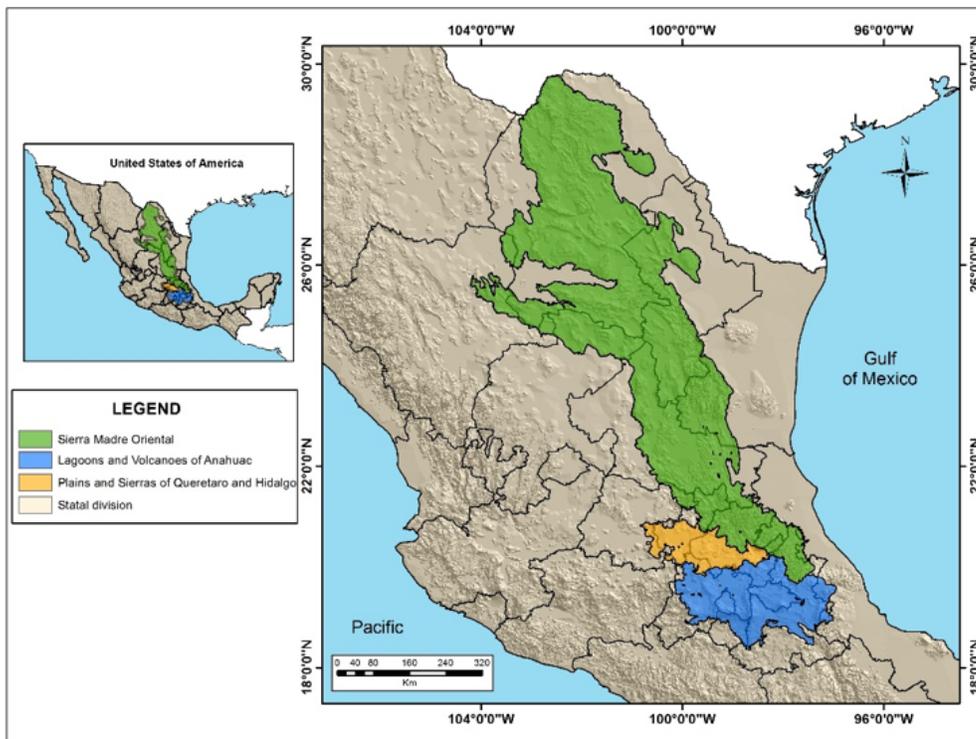


Figure 1

Geographical location of the study area.

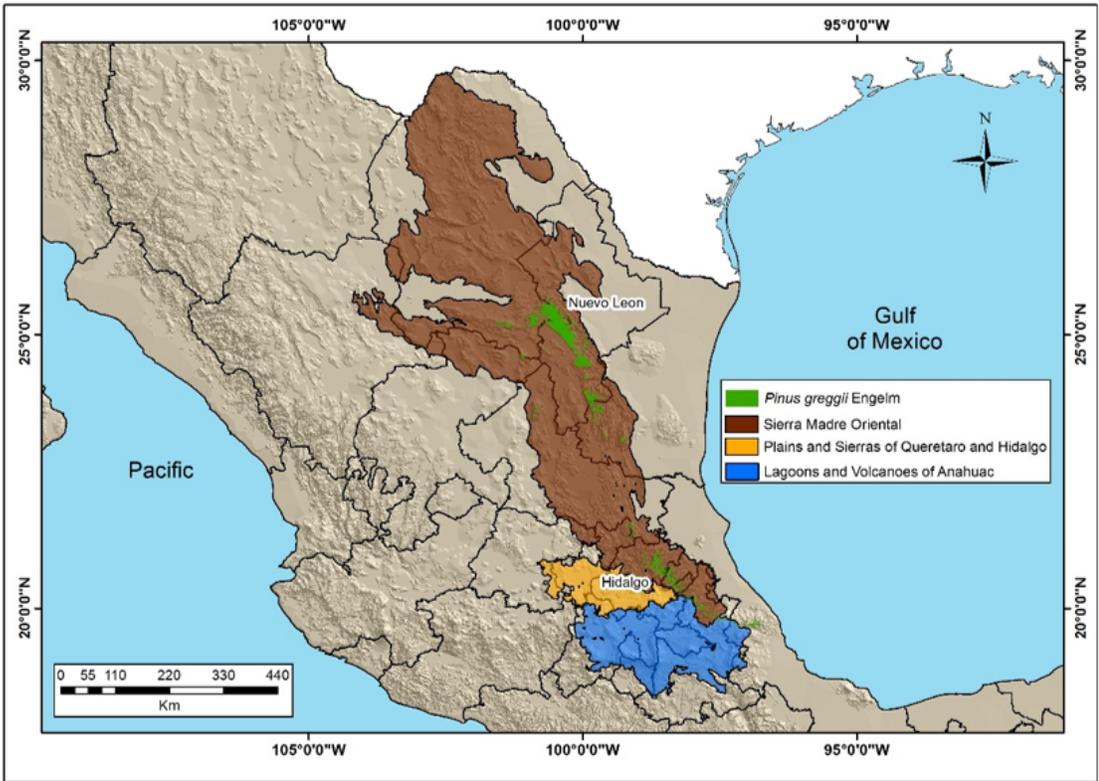


Figure 2

Potential current distribution model of *P. greggii* in the study area.

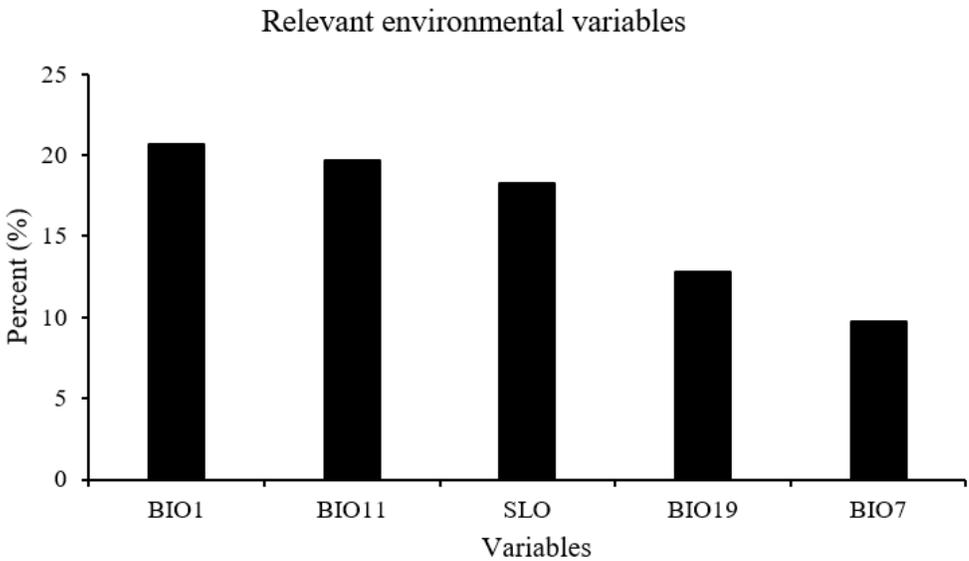


Figure 3

Relevant environmental variables of the current distribution models.

Relevant environmental variables

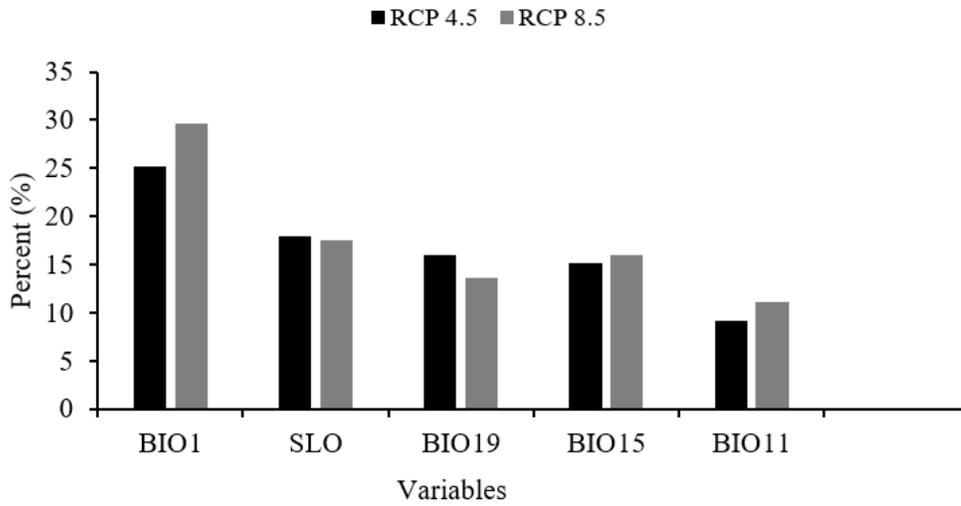


Figure 4

Relevant environmental variables of the CNRM-CM5 RCP 4.5 and 8.5 models.

Relevant environmental variables

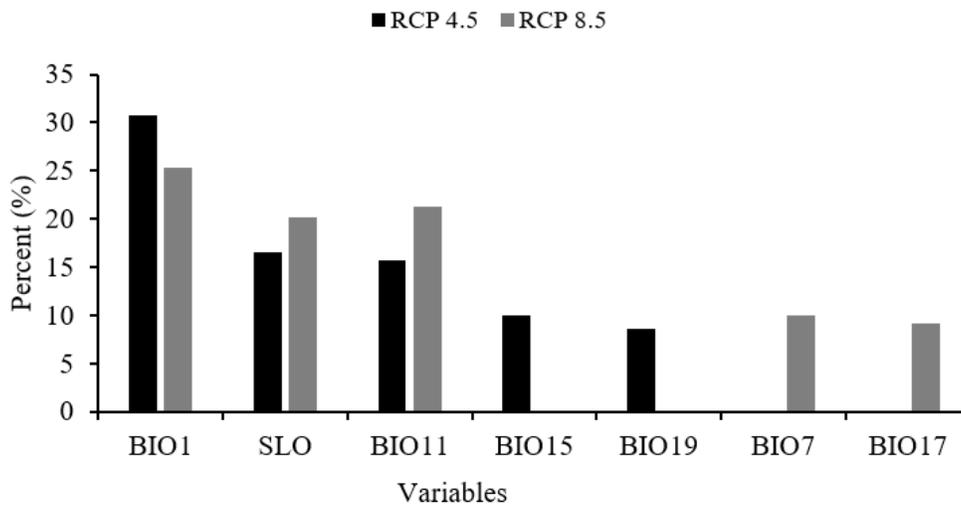


Figure 5

Relevant environmental variables of the HadGEM2-ES RCP 4.5 and 8.5 models.

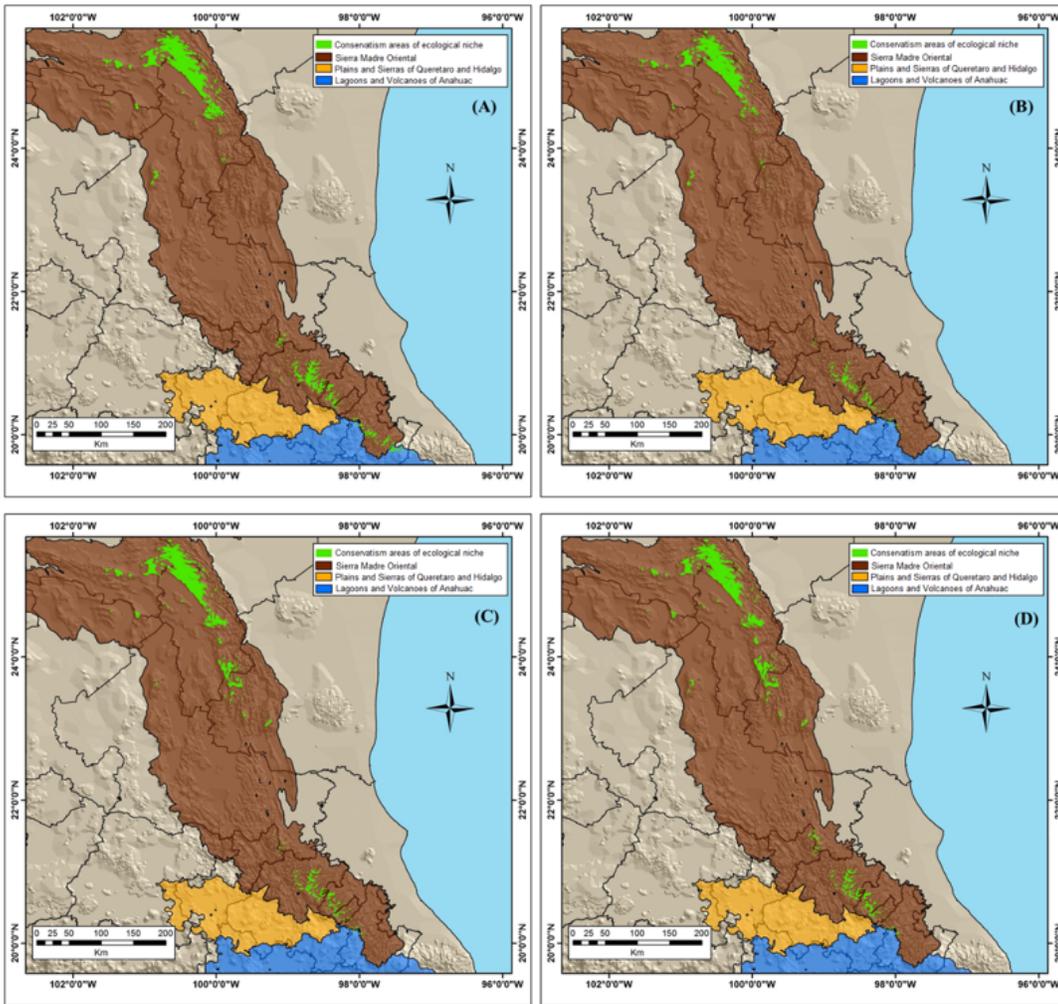


Figure 6
 Conservation areas of ecological niche of *P. greggii* in the study area under climatic change scenario models (A) CNRM-CM5 RCP 4.5, (B) CNRM-CM RCP 8.5, (C) HadGEM2-ES RCP 4.5, and (D) HadGEM2-ES RCP 8.5 for 2041–2060.

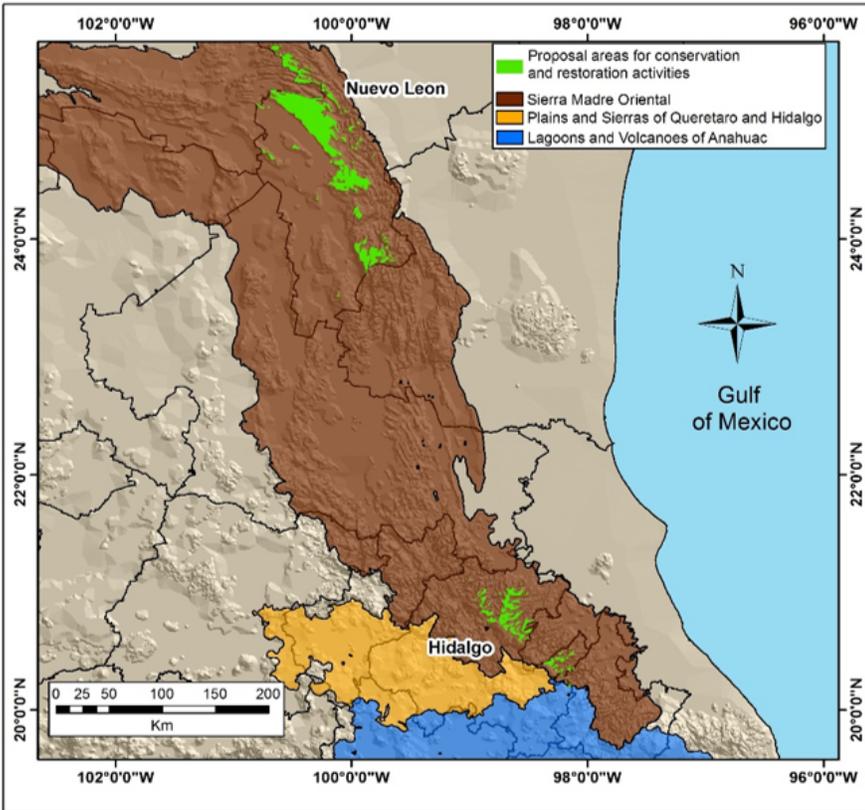


Figure 7

Proposal of suitable areas for conservation and restoration activities of *P. greggii* in the study area.