Revista Mexicana de Ciencias Forestales Vol. 16 (87)
Enero - Febrero (2025)

DOI: 10.29298/rmcf.v16i87.1510
Research article

Modelado espacial de *Guazuma ulmifolia* Lam. ante el cambio climático en México

Spatial modeling of *Guazuma ulmifolia* Lam. in the face of climate change in Mexico

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Fecha de recepción/Reception date: 8 de agosto de 2024.
Fecha de aceptación/Acceptance date: 7 de noviembre de 2024.

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Abstract

Guazuma ulmifolia grows in tropical and warm-humid areas of Latin America. It has good forage qualities and is fast-growing; it offers palatable leaves, good nutritional quality for livestock and the ability to produce forage and fruits during the dry season. The objective of this study was to model the areas with probable environmental suitability and the possible modifications due to climate change for *Guazuma ulmifolia* in Mexico. Using MaxEnt, and based on 25 bioclimatic variables and images of altitude, slope and soil texture, the distribution of the species was modeled for 1961-2010 (reference climatology) and for 2041-2060 (2050). The climatic data for the first period were obtained from the Agroclimatic Information System (Siamexca), and for the future scenario (2050) an ensemble model was used, derived from eleven general circulation models from WorldClim. The results showed that the variables that contribute most to the environmental suitability of the species are the extreme minimum temperature, the precipitation of the warmest quarter, the thermal oscillation and the maximum temperature of summer; the best areas are located in the *Yucatan* Peninsula, the Isthmus of *Tehuantepec*, coastal areas of the Pacific Ocean from *Chiapas* state to the South of *Sonora* state and coastal areas of the Gulf of Mexico, from *Tabasco* state to the South of *Tamaulipas* state. Climate change will promote a dynamic expansion of areas with high environmental suitability that in the current scenario are of medium environmental suitability, mainly in Central and Northern Mexico.

Key words: Environmental suitability, ecological descriptors, *Guazuma ulmifolia* Lam., MaxEnt, distribution models, Siamexca.

Resumen

Guazuma ulmifolia crece en las zonas tropicales y cálido-húmedas de América Latina. Posee buenas cualidades forrajeras y es de rápido crecimiento; ofrece hojas palatables, buena calidad nutricional para el ganado y capacidad para producir forraje y frutos durante la época seca. El objetivo del presente estudio fue modelar las áreas con probabilidad de aptitud ambiental y las posibles modificaciones por efecto del cambio climático para

Guazuma ulmifolia en México*.* Con el uso de *MaxEnt*, y con base en 25 variables bioclimáticas y las imágenes de altitud, pendiente y textura de suelo, se modeló la distribución de la especie para 1961-2010 (climatología de referencia) y para 2041-2060 (2050). Los datos climáticos para el primer periodo se obtuvieron del Sistema de Información Agroclimática (Siamexca), y para el escenario futuro (2050) se trabajó con un modelo ensamble, derivado de 11 modelos de circulación general de *WorldClim*. Los resultados mostraron que las variables que más contribuyeron a la idoneidad ambiental de la especie fueron la temperatura mínima extrema, la precipitación del cuatrimestre más cálido, la oscilación térmica y la temperatura máxima de verano; las mejores áreas se localizaron en la Península de Yucatán, Istmo de Tehuantepec, zonas costeras del Pacífico desde Chiapas hasta el sur de Sonora y zonas costeras del Golfo de México, desde Tabasco hasta el sur de Tamaulipas. El cambio climático propiciará una dinámica de expansión de áreas con aptitud ambiental alta que en el escenario actual son de aptitud ambiental media, principalmente en el centro y norte de México.

Palabras clave: Aptitud ambiental, descriptores ecológicos, *Guazuma ulmifolia* Lam., *MaxEnt*, modelos de distribución, Siamexca.

Introduction

In Mexico there is a great wealth of species for agricultural and livestock use; *Guazuma ulmifolia* Lam., known by the common names of *guácimo*, *guazamo*, *caulote*, *pixoy*, *guácimo de ternero*, *majagua de toro*, *yaco* and *granadillo*, is a tree that commonly grows in tropical and warm-humid areas of Latin America. It is included in the group of secondary species and young open forests, since it has the potential to adapt to humid, dry and compacted soils or with a sandy texture (Casanova-Lugo et al., 2014; Gerber et al., 2020; Manríquez-Mendoza et al., 2011). It is present in Mexico, *Cuba*, *Guatemala, Honduras, Ecuador, Bolivia*, Brazil, Barbuda, *Argentina, Bahamas, Barbados, Colombia*, Dominican Republic, Grenada, *Haití, Jamaica, Nicaragua, Costa Rica, Panamá, Paraguay, Perú, Puerto Rico*, Saint Vincent and the Grenadines, *Trinidad y Tobago* and the Virgin Islands (Araujo et al., 2020; Kumar & Gurunani, 2019). The species is native to the Caribbean and tropical America (Food and Agriculture Organization of the United Nations [FAO], 2022; Matulevich & García, 2016).

Fast growing (Gerber et al., 2020; Mayren-Mendoza et al., 2018), with palatable leaves of good nutritional quality for livestock and great capacity to produce forage, *Guazuma ulmifolia* preserves said material as well as the fruits during the dry season (Casanova-Lugo et al., 2014; Manríquez-Mendoza et al., 2011; Rojas-Hernández et al., 2015). *Guácimo* trees are used on farms as living fences, in pastures they provide shade for animals, fruits for wildlife, valuable nectar for honey production, good quality firewood, fruits, leaves, bark, roots and flowers with medicinal properties and multiple restorative effects (Jiménez et al., 2019; Matulevich & García, 2016).

Climate is one of the factors that delimit the distribution of plants; each species has a tolerance range to various environmental factors and to certain conditions of temperature, humidity and light to germinate, grow, flower and fruit (Gutiérrez & Trejo, 2014). Currently, climate change is causing regional and global environmental variations in temperature and precipitation (Ramírez-Magil et al., 2020). These changes affect the phenology and distribution of plants due to their specific light and humidity requirements for their development and survival (Parmesan, 2006; Ramírez-Magil et al., 2020). To perceive the impacts of the environment on species, there are a variety of models that incorporate bioclimatic variables based on data from the sites where the species are present and it is assumed that, for some of them, climate and soil moisture are some of the most important factors in their distribution (Hof, 2010; Ramírez-Magil et al., 2020). These models are valuable tools that, together with geographic information systems (GIS), allow modeling the current and future distribution of various species (Navarro-Martínez et al., 2018).

Different algorithms are used for this purpose (Velázquez-Hernández et al., 2023). MaxEnt, by only needing data from georeferenced accessions, offers advantages over other programs. It can also use continuous or categorized data, its algorithms are efficient and guarantee the optimal distribution of the probability of maximum entropy (Quesada-Quirós et al., 2017). Thus, the objective of the present study was to model the areas with probability of environmental suitability and the possible modifications due to the effect of climate change for *Guazuma ulmifolia* in Mexico using Maximum Entropy and based on bioclimatic variables, altitude, soil texture and slope.

Materials and Methods

Biological databases

A database of 4 910 sampling sites from the National Forest and Soil Inventory (Infys) of the National Forestry Commission (Comisión Nacional Forestal [Conafor], 2018) was used; this database was purged, duplicate coordinates and records without a location were discarded. The records were located in the geographic space and the location of the points was checked to ensure that they were consistent with their historical distribution recognized at a regional level (Monterrubio-Rico et al., 2016).

Climate databases and geographic information system

Precipitation and temperature data from the periods 1961-2010 (reference climatology) and 2041-2060 (with two representative trajectories of greenhouse gas concentrations rcp4.5 and rcp8.5) were used. The climatic data for the reference climatology were obtained from the Agroclimatic Information System for Mexico and

Central America (Siamexca) (Ruiz-Corral et al., 2018); and for the 2050 scenario, an ensemble model was used based on the median value of 11 general circulation models from the WorldClim Global Climate Data portal (United States Geological Survey [USGS], 2017) and raster and ascii images were used at 30 arc seconds.

These models are included in the climate modeling developed by the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Ruiz-Corral et al., 2016). Additional variables were derived from the basic climate variables (Table 1) to perform the MaxEnt analysis of the distribution models.

Table 1. Variables used to model the current and potential environmental suitability of *Guazuma ulmifolia* Lam. in Mexico.

Environmental variables	
Maximum mean annual T	Minimum *T* of the coldest month
Maximum *T* of the wettest period	Annual cumulative *P*
Maximum *T* of the driest period	*P* of the wettest period
Maximum *T* of the warmest quarter	Cumulative *P* of the driest period
Mean annual *T*	*P* of the driest month
Mean *T* of the wettest period	*P* of the wettest month
Mean *T* of the driest period	*P* of the wettest quarter
Mean *T* of the warmest month	*P* of the driest quarter
Mean *T* of the coldest month	*P* of the warmest quarter
Mean *T* of the warmest quarter	*P* of the coldest quarter
Mean *T* of the coldest quarter	Thermal oscillation (°C)
Mean annual minimum *T*	Soil slope (%)
Minimum *T* of the wettest period	Soil texture (type)
Minimum *T* of the driest period	Altitude (masl)

T = Temperature (°C); *P* = Precipitation (mm)

The implementation of these parameters and the generation of the respective raster images was done with the Idrisi Selva system (Eastman, 2012). The climatic and edaphic variables for the analysis of this study are those that have been normally used for the territorial potential of plant species (Moreno et al., 2011).

Selection of variables

To select the variables, data was extracted from the raster images using the ArcMap software version 10.8 (Environmental Systems Research Institute [ESRI], 2013) with the SDM Toolbox tool. With the data extracted from the 28 variables of the presence points, a data matrix was built in Microsoft Excel. Prior to the execution of the statistical analyses, the Shapiro-Wilk test was applied to verify the normality of the data, and no normality was detected ($P<0.05$) for any variable.

To select a set of variables that contribute more to the models and to eliminate multicollinearity, a Spearman correlation was performed with a correlation threshold value of $r>0.9$ (Hebbar et al., 2022). Of the variables with collinearity, the one considered to be most relevant to the existence of the species was chosen. To perform the correlation analyses, the data from the Variable Matrix were used; this statistical analysis was carried out with programs developed in the R software version 4.05 (R Core Team, 2023) and with the normalized data.

Ecological niche modeling

The selection of candidate covariates, prior to obtaining the model, is a crucial process, therefore it is necessary to perform a correlation analysis between covariates to eliminate autocorrelation (Elith et al., 2011), and thus avoid instability and eliminate the possibility of obtaining an over-adjusted or over-parameterized model (Cobos *et al.,* 2019).

Modeling was performed with MaxEnt and the Kuenm package in R (Cobos et al., 2019; R Core Team, 2023), which automates the processes to obtain the Ecological Niche Model (ENM). Kuenm_ceval creates candidate models with occurrence data and environmental predictors. This function adjusts the performance of the models through statistical significance with the cal eval function, in addition to the relative quality of the model; the evaluation is done using the Akaike Information Criterion (*AIC*) (Cobos et al., 2019). It also allows the evaluation of numerous regularization multiplying factors (RM), class combinations (FC), different groups of environmental predictors, and creates the allowable omission rate (OR). For each parameter configuration, a model is created based on the complete set of occurrences and another based only on training data.

For the present investigation, models were tested in a sequential order with six types of classes (FC) with all possible combinations of L, LQ, H, LQH, LQHP, LQHPT (where L=Linear, Q=Quadratic, H=Hinge, P=Product, T=Threshold), and regularization multiplier (RM) values from 0.1 to 10 in intervals of 0.1; a maximum omission rate of 5 % was established and it was run at 25 k replicates of each configuration with 500 interactions (Camacho-Portocarrero et al., 2021; Cobos et al., 2019; Velázquez-Hernández et al., 2023). The occurrence sites of *G. ulmifolia* and the images in ascii format for four selected variables were used in the elaboration of ENM with the Kuenm package in R.

In this study, final models for *G. ulmifolia* were developed using the complete set of occurrences and the selected parameterizations. To obtain robust models, five replicas with logistic outputs were generated and these models were transferred to the current and future scenarios; and this is how the final models evaluated and without risk of extrapolation were created.

Final models, evaluation and extrapolation risk

Partial *ROC* curve analysis with omission rates (*E*=5 %) was used for the final evaluation of the model. The final models and their evaluations were carried out using the kuenm mod and kuenm feval functions (Cobos et al., 2019). The mean of all replicates in all parameters was used to consolidate the species results. To identify the risks of extrapolation in model transfers, a *MOP* analysis was performed using the kuenm_mmop function.

Finally, maps were obtained to represent the areas with medium-low environmental suitability (probability ≤0.50) and high environmental suitability (probability >0.50) of the species. To represent the current and potential distribution area, the threshold of the Balance Training Omission, Predicted Area and Threshold Value was used.

Results and Discussion

Selection of variables

Through Spearman correlation analysis, it was possible to eliminate collinearity between variables (Hebbar et al., 2022), so that of the 28 original variables, only 9 remained and were used in subsequent analyses.

Modeling the potential distribution of *G. ulmifolia*

Through ecological niche modeling, the Kuenm package allowed the number of environmental variables to be optimized to only four due to their greater contribution to the presence and distribution of G. *ulmifolia*. The results of the Jacknife statistical test were used to check the certainty and participation of each variable individually, which has as its main function to run each model with each variable alone to measure the contribution of the particular variable (Quesada-Quirós et al., 2017). The prediction shows that the environmental variables (Table 2) that most influence the environmental suitability and potential distribution of *G. ulmifolia* are the extreme minimum temperature (69.3 %), the precipitation of the warmest quarter (28.8 %), the thermal oscillation (1.4 %) and the maximum summer temperature (0.5 %).

Table 2. Selection of environmental variables (%) without adjustment problems to model the current and potential environmental suitability of *Guazuma ulmifolia* Lam. in Mexico.

Environmental variables	Contribution	Permutation

Minimum *T* of the coldest month	69.3	69.8
P of the warmest quarter	28.8	21.5
Annual thermal oscillation	1.4	4.9
Maximum *T* from May to October	0.5	3.8

T = Temperature (°C); *P* = Precipitation (mm).

372 candidate models were obtained with the Kuenm package in R (Figure 1); all models were significant, that is, the models matched the most frequently occurring data test by random association of points and a given area prediction; however, only one model met the Akaike criterion (*AIC*=0) and a maximum omission rate of 5 %; the selected model presented an area under the curve (*AUC*) value of 0.88, usually *AUC* values of 0.7 to 0.9 have a useful application in the model (Quesada-Quirós et al., 2017).

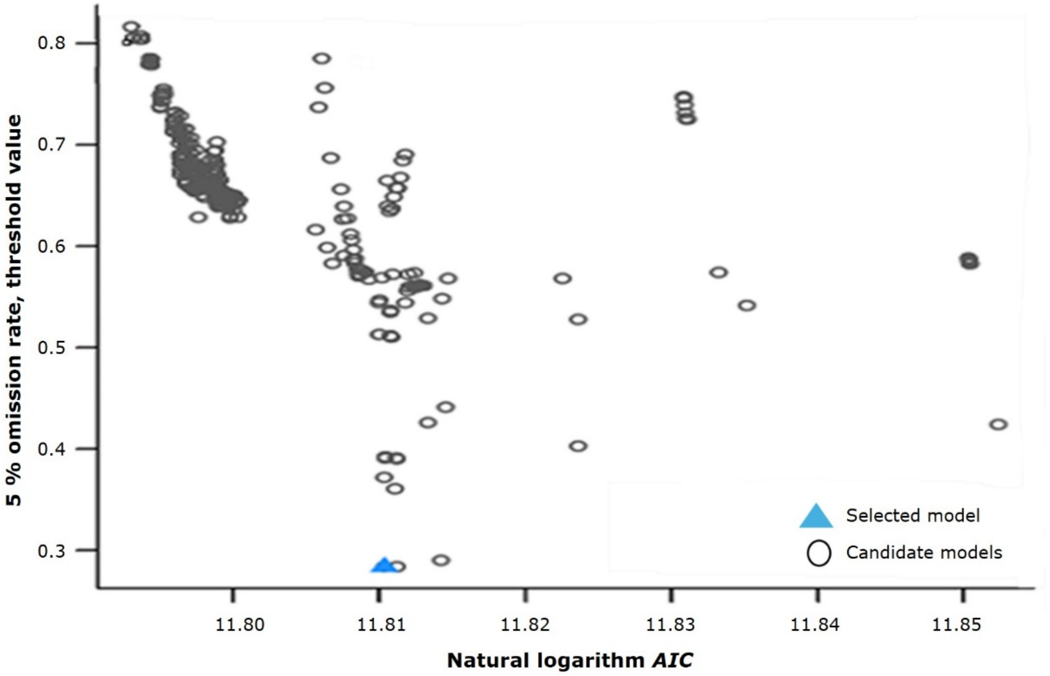


Figure 1. Models obtained and evaluated by the Kuenm package *for Guazuma ulmifolia* Lam. in Mexico

The Kuenm package in R implemented with MaxEnt established that 10 was the appropriate regularization multiplier to represent the species' distribution area. The quality of the model was evaluated with the AUC value of the ROC curve and the Akaike Information Criterion.

Ecological descriptors

Table 3 shows a wide range of temperature and precipitation in the species distribution; it has been pointed out that environmental and historical determinants of species richness patterns, such as global potential evapotranspiration, number of wet days per year, and topographic and habitat heterogeneity, are the most important predictors of vascular plant species richness (López-Mata et al., 2012).

Table 3. Ecological descriptors of environmental variables that contribute to the geographic distribution of *Guazuma ulmifolia* Lam. in Mexico.

Environmental variable	Minimum value	Maximum value	Mean	Standard deviation
Minimum temperature of the coldest month	0.5	21.5	13.4	3.6
Precipitation of the warmest four-month period	362	2 398	893	287
Maximum temperature of the wettest period	20.3	37	32.4	1.9
Thermal oscillation (°C)	8.7	19.3	14.2	2

Temperature (°C); Precipitation (mm).

The extreme minimum temperature and accumulated rainfall during the warmest four-month period are the variables that contributed most to the geographic distribution of G*. ulmifolia* in Mexico (Table 3). Some accessions located in Northern Mexico, specifically in the mountain ranges of the states of *Chihuahua* and *Durango* (Figure 2), thrive at an extreme minimum temperature of 0.5 °C; other accessions located in Southern *Sonora* thrive at an extreme maximum temperature of up to 37 °C; these temperature ranges coincide with those indicated by FAO (2022), which indicates that *G. ulmifolia* develops in areas with temperatures from 10 to 36 °C, which coincides with what was indicated by Martínez and Sánchez (2016), who refer that the optimal germination temperature range is 25 to 35 °C.

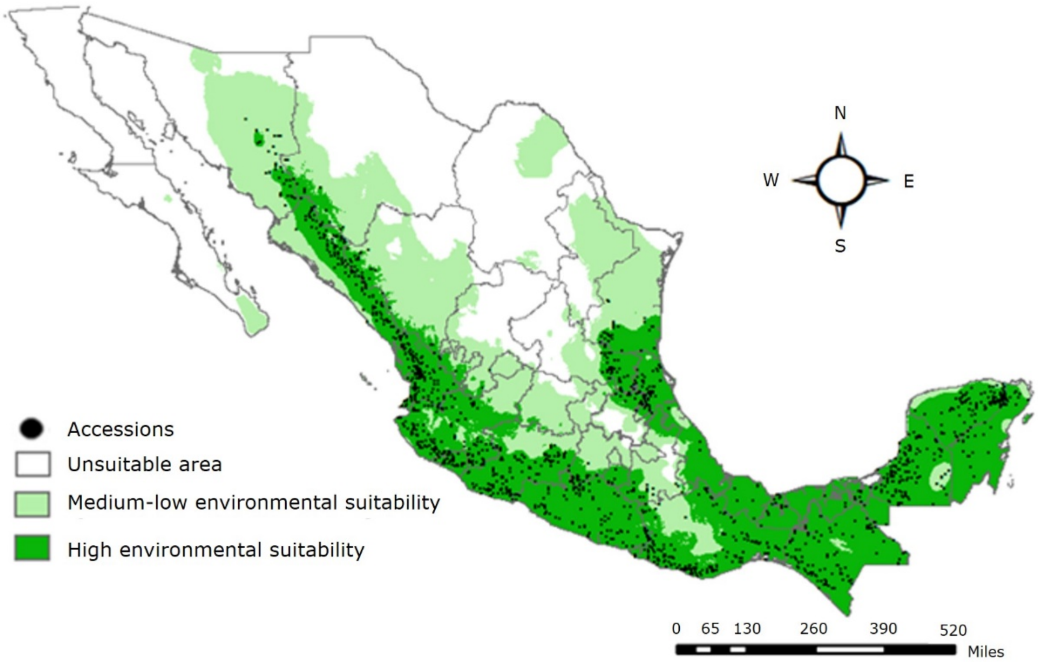


Figure 2. Environmental suitability area of *Guazuma ulmifolia* Lam. for the 1961-2010 period in Mexico.

The precipitation of the warmest four-month period (June to September) is also one of the variables that contributes most to explaining the geographic distribution of the species (Table 3). According to the rainfall values, *G. ulmifolia* is distributed between 362 and 2 398 mm, which coincides with Manríquez-Mendoza et al. (2011), who specify that in the Central part of the state of *Veracruz*, the species has evolved in regions where rainfall is seasonal and very marked, with dry periods of up to eight months.

Araujo et al. (2019) report that the species is distributed from 600 to 1,500 mm, but can also develop well in areas with annual rainfall of 2,500 mm. FAO (2022) establishes that the species develops in areas where the annual rainfall is at least 500 mm. Villa-Herrera et al. (2009) describe that the species develops widely in the humid and sub-humid areas of tropical forests in Mexico.

Modeling of current environmental suitability for *G. ulmifolia*

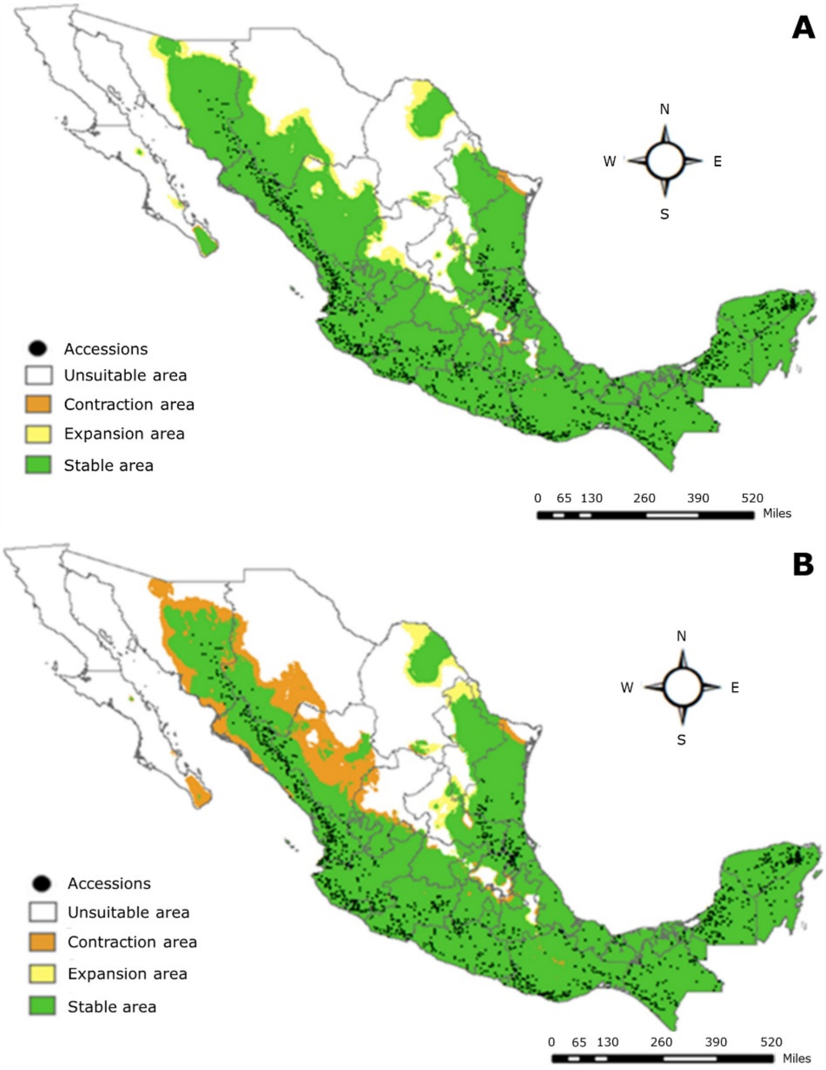
According to the results, the area with probability of environmental suitability (Figure 2) has an extension of 1 284 224 km^2, and is located in the coastal areas of the Pacific from the states of *Sonora* to *Chiapas*, the Transversal Volcanic Axis, the *Yucatán* Peninsula, the Isthmus of *Tehuantepec* and the coastal areas of the Gulf of Mexico, from the state of *Tabasco* to Southern state of *Tamaulipas*. This information is in accordance with that established by Casanova-Lugo et al. (2014), who mention that *G. ulmifolia* grows naturally in Southern Mexico, in large areas of humid and subhumid tropical and subtropical forests; likewise, near the Gulf of Mexico coast, from *Tamaulipas* to the *Yucatán* Peninsula and on the Pacific Ocean coast, in open areas with several types of vegetation: coastal, thorny scrub, semi-evergreen and deciduous forest, grassland, oak forests, mangrove, ruderal and tall evergreen forest; the species is a secondary growth and is considered an indicator of disturbed areas.

Villa-Herrera et al. (2009) state that it is a native species of America and adapts to altitudes ranging from 0 to 1 500 m; in addition, it is mentioned that it is a very abundant tree species that grows wild in the state of *Veracruz*. Due to its great adaptation to edaphoclimatic conditions and adverse management, it is a potential resource to be included in silvopastoral systems with the purpose of producing fodder for livestock feed. Manríquez-Mendoza et al. (2011) mention that, in Mexico, this species has been evaluated in forage banks, agrosilvopastoral systems, in coastal plains, mountain ranges, mountains and highlands of *Veracruz* and *Chiapas*.

The areas with medium environmental suitability are located in a large part of the states of *Sonora*, Southern *Chihuahua*, a large part of *Durango*, Southern *Zacatecas*, *Aguascalientes*, *Guanajuato*, part of *Michoacán* and *Jalisco*, as well as some areas of Northern *Coahuila*, *Nuevo León* and *Tamaulipas*.

Modeling environmental suitability under climate change

The maps in Figure 3 show that a large part of the surface area will remain environmentally stable due to the effect of climate change, but the model also predicts a dynamic of contraction and expansion in both climate scenarios (Table 4). Thus, the expansion areas will be favored by 2 % in the optimistic scenario (rcp4.5); the surfaces that in the current climate have medium environmental suitability will become in the future (2050) places with high environmental suitability. The model also predicts that there will be a contraction of areas with environmental suitability in the pessimistic scenario (rcp8.5); the area that in the current condition has medium environmental suitability will contract by up to 14 %.



A = Scenario 2050 with rcp4.5; B = Scenario 2050 with rcp8.5.

Figure 3. Areas with stable environmental suitability, expansion and contraction, for the 2050 scenario for *Guazuma ulmifolia* Lam. in Mexico.

Table 4. Areas with expansion, contraction and stable environmental suitability (km^2) for *Guazuma ulmifolia* Lam. with the reference climate and with two climate change scenarios in Mexico.

Climate scenario	ES Areas	Expansion	Contraction	Stable
1961-2010	1 284 224.3			
2050 rcp4.5	1 309 245.1	30 868.9	5 848.1	1 278 376.1
2050 rcp8.5	1 106 026.4	4 096.7	182 294.6	1 101 929.6

ES = Environmental suitability.

This effect is in line with what was established by Gutiérrez and Trejo (2014) and Parmesan (2006), who mention that with the effect of climate change, ecosystems will suffer alterations in the distribution and abundance of species or in the direct disappearance of some populations. The authors also mention that species would tend to modify their distribution towards latitudes and altitudes different from those found today; particularly, this effect will be more severe for species located in geographically confined ecosystems, such as mountains, since they will be more sensitive to changes in climatic conditions. Benton et al. (2022) cite that angiosperms have a great propensity to adapt and evolve, since their physiology and anatomy allow them to capture energy and Carbon faster than other plants, which helps drive their high species richness today.

The surface area with environmental suitability that is predicted for the future scenarios will completely cover the states of *Aguascalientes*, *Guerrero*, *Oaxaca*, *Jalisco*, *Nayarit* and *Sinaloa*, and a large part of *Guanajuato*, *Durango*, *Tamaulipas*, *Nuevo León*, *Coahuila*, *Chihuahua*, *Sonora*, *Zacatecas*, *Querétaro*, *San Luis Potosí*, State of Mexico, *Morelos* and *Puebla*. It is important to note that some areas that expanded with the optimistic scenario will contract in the pessimistic scenario; the latter will be located in a large part of the states of *Sonora*, *Chihuahua* and *Durango* and a small part in *Sinaloa*, *Zacatecas* and *Tamaulipas*.

Conclusions

The areas with environmental suitability for *Guazuma ulmifolia* in Mexico are located mainly in the coastal areas of the Gulf of Mexico and the Pacific Ocean, the Transversal Volcanic Axis, the Isthmus of *Tehuantepec* and the *Yucatán* Peninsula.

The effects of climate change on *G. ulmifolia* in Mexico, predicted for the year 2050, represent an alteration in the areas with environmental suitability. Areas that in the current scenario are of medium environmental suitability will become areas of high environmental suitability in the future under the optimistic scenario.

The alterations will be located mainly in the Transversal Volcanic Axis, the *Sierra Madre Occidental* and the *Sierra Madre Oriental*.

The MaxEnt prediction reflects that rainfall in the warmest four-month period of the year (June to September), the maximum temperature of the wettest period, the extreme minimum temperature and the thermal oscillation are the variables that contribute the highest percentage to explain the environmental suitability of *G. ulmifolia* in Mexico.

G. ulmifolia is a species that adapts to a wide range of conditions, both in terms of precipitation and temperature, which gives it adaptive advantages in environments with climatic variation.

Acknowledgements

The authors thank National Forestry Commission (Conafor) for providing field information on the species under study.

Conflict of interest

The authors declare that they have no conflicts of interest or personal relationships that could have influenced the work presented in this article.

Contribution by author

Noé Durán Puga: research planning, manuscript planning, analysis execution, review of writings throughout the process and corrections requested by the reviewers; Diego Raymundo González Eguiarte: research planning, manuscript planning, review of writings throughout the process; José Ángel Martínez Sifuentes: contribution in the execution of analysis, review of the manuscript in the initial stages; Miguel Prado López: review of the manuscript in its initial stages and participation in its planning.

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