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Articles

Potential distribution of *Guadua* bamboo in Mexico, based on three arrays of environmental variables

Distribuição potencial do bambu *Guadua* no México, com base em três conjuntos de variáveis ambientais

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ABSTRACT

The environmental conditions of Mexico allow the presence of several species of bamboo, where commercial uses have diversified due to their rapid growth and characteristics. The Mexican Guaduas are specimens with exemplary structural characteristics, however, there is no cartographic information in Mexico that allows locating and sizing the areas where bamboo species are located or can be located, which restricts decision making for commercial forest plantations. Therefore, it is intended to determine the probability of occurrence of the 7 species of this genus of bamboo, based on the maximum entropy approach and three arrangements of 21 environmental variables, for which 478 presence records were used. All generated models defined a good fit with the training data, with an AUC value greater than 0.90. It was found that the niche distribution of Guadua mexicana species is mainly influenced by altitude (ELEV), so they are found in areas close to coastal regions. Likewise, in defining the distribution of this genus, annual precipitation (BIO12), evapotranspiration (ETP) and average annual temperature (BIO1) stood out. This was independent of the three arrangements of environmental variables that were tested.

Keywords: Maximum entropy; Omission/commission curves; Permutation importance

RESUMO

As condições ambientais do México permitem a presença de várias espécies de bambu, onde, devido ao seu rápido crescimento e características, os usos comerciais se diversificaram. As Guaduas mexicanas são exemplares com características estruturais exemplares, porém não há informações cartográficas no México que permitam localizar e dimensionar as áreas onde estão ou podem estar localizadas espécies de bambu, o que restringe a tomada de decisão para plantações florestais comerciais. Portanto, pretende-se determinar a probabilidade de ocorrência das 7 espécies deste gênero de bambu, com base na abordagem de máxima entropia e três arranjos de 21 variáveis ambientais, para as quais foram utilizados 478 registros de presença. Todos os modelos gerados definiram um bom ajuste com os dados de treinamento, com um valor de AUC maior que 0,90. Verificou-se que a distribuição de nicho das espécies mexicanas de Guadua é influenciada principalmente pela altitude (ELEV), por isso são encontradas em áreas próximas às regiões costeiras. Da mesma forma, a precipitação anual (BIO12) destacou-se na definição da distribuição deste gênero, assim como a evapotranspiração (ETP) e a temperatura média anual (BIO1). Isso foi independente dos três arranjos de variáveis ambientais que foram testados.

Palavras-chave: Entropia máxima; Curvas de salto/comissão; Importância da permutação

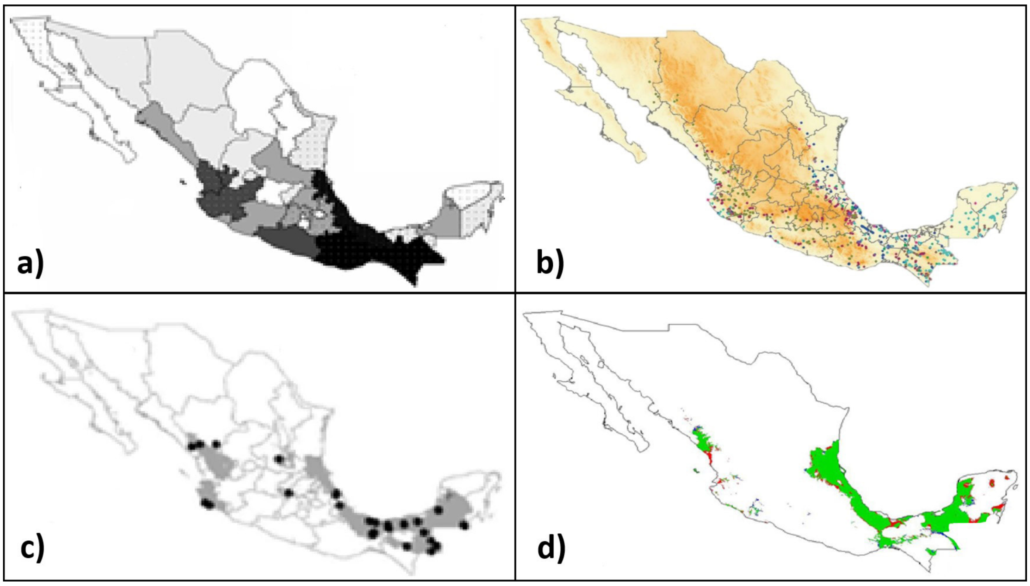
1 INTRODUCTION

Mexico's environmental conditions allow the presence of several species of bamboo, where, due to its rapid growth and characteristics, commercial uses have diversified (Ruiz-Sanchez, 2019), therefore it has sought to promote the areas with bamboo species to increase. Bamboo plays a very important role as an ancestral resource with a broad economic, social and cultural perspective, representing above all an alternative to meet the demand for affordable housing in Mexico (Echezuria, 2018). Bamboo is considered an excellent substitute for wood due to its structural qualities (Gupta; Kumar 2008; Xu; Liang; Chen; Li; Qin; Fuhrmann, 2020). Ecosystem services such as soil protection from erosion, nutrient recycling, habitat for flora and fauna, carbon storage and capture, water capture, protection of river causes, regulation of hydrological micro-basins and beauty are an example of which bamboo is an excellent option for mitigating global warming (Mishra; Giri; Panday; Kumar; Bisht, 2014; Añazco, 2015; Cruz-Armendariz; Ruiz-Sanchez; Reyes-Agüero, 2023).

For this, a series of commercial plantations have been developed, where the aim is to maximize their production. However, first, it is necessary to know, locate and dimension the agroecological requirements that favor the presence of bamboo species (Cervantes-Serna; Serna-Lagunes; Salazar; Pérez, 2018). In this way, the ecological niches can be georeferenced (Navarro-Martínez; Ellis; Hernández-Gómez; Romero-Montero; Sánchez-Sanchez, 2018) to define the potential distribution of bamboo (Palacios-Romero; Rodríguez; Hernandez; Jimenez; Tirado, 2016), which will allow locating the environmental conditions that most favor the development of commercial plantations. However, determining the location of potential areas for bamboo is complicated, because it is difficult to obtain specific information on the environmental conditions where bamboo species develop naturally, mainly because they occur in small areas (Londoño, 2006). Moreover, in Mexico there are few studies that allow locating and sizing its current and potential distribution, however it is known that wild bamboo is located in several states, such as Chiapas, Oaxaca, Veracruz and Jalisco (Ruiz-Sanchez; Muguía-Lino; Vargas; Rodríguez, 2020). This has limited the scale of mapping the distribution of bamboo species in Mexico (Figure 1), which has been defined from several perspectives: a) mapping the distribution of *Guadua inermis* through the modeling of the ecological niche (Figure 1d), based on 19 bioclimatic variables (Ruiz-Sanchez; Mendoza-Gonzalez; Rojas-Soto, 2018), using the MaxEnt algorithm (Phillips; Anderson; Schapire, 2006). The results indicate that the mean diurnal amplitude (Monthly mean (maximun temperature – minimum temperature) and the precipitation in the rainiest month represented the greatest contribution to model the distribution of *G. inermis*; b) punctual distribution (records of presence) of the bamboo species (Figure 1b and 1c); c) location of bamboo species on all states (Figure 1a), where the largest number of species appears in the states of Chiapas, Veracruz, Oaxaca and Jalisco. These limitations could be solved with information from other latitudes, however, in the countries where Mexican bamboo species are developed, there are no precise statistics on the areas covered with bamboo (Añazco; Rojas, 2015).

As a result, in Mexico there is no cartographic information that allows locating and dimensioning the areas where bamboo species grow, or can grow, which, restricts decision-making for the commercial forest plantations. Furthermore, there is no complete information on the ecological requirements of each species (Illoldi; Linaje; Sánchez-Cordero, 2002; Ortega-Huerta; Peterson, 2004), since their distribution, in the absence of competitors, is conditioned by their physiological performance, under certain conditions, environmental restrictions, which define its ecological niche (Begon; Townsed; Harper, 2005). Accordingly, by knowing the spatial distribution of the factors that define this niche (habitat), it is possible to define the potential distribution of bamboo species, which is based on the generation of geographic prediction models (Guisan; Zimmermann, 2000). These models can be structured under different approaches, such as: a) discriminant analysis (Spichiger; Calenge; Bise, 2005); b) classification trees analysis (Steen; Zorn; Seelbach; Schaeffer, 2011); c) bioclimatic context models (Feilhauer; He; Rocchini, 2012); d) linear regressions (Guisan; Edwards; Hastie, 2002); e) artificial intelligence (Stockwell; Peters, 1999); f) artificial neural networks (Park; Edwards; Hastie, 2001); and g) hierarchical Bayesian models (Best; Richardson; Thomson, 2005). However, these perspectives require the location of sites in areas with and without the presence of bamboo, which would differentiate the agroecological conditions that favor their location (Gutiérrez-Hernández; Senciales-González; Camacho-Olmedo; García, 2016). Nevertheless, the implementation of these sites is expensive and requires the participation of experts to guarantee the identification of the bamboo species. As an alternative, there is the maximum entropy approach (Phillips; Anderson; Schapire, 2006), which can generate accurate predictions (Elith; Graham; Anderson; Dudík; Ferrier; Guisan; Hijmans; Huettmann; Leathwick; Lehmann; Li; Lohmann; Loiselle; Manion; Moritz; Nakamura; Nakazawa; Overton; Peterson; Phillips; Richardson; Scachetti-Pereira; Schapire; Soberón; Williams; Wisz; Zimmermann, 2006) of the potential distribution of Mexican bamboo species (Ruiz-Sanchez; Mendoza-Gonzalez; Rojas-Soto, 2018). This approach is based on a better discrimination of the most significant variables for the species of interest, considering only records from sites where it has been detected (absence sites are not considered). Based on the maximum entropy approach, the objective of this study was to determine the probability of occurrence of seven species of native bamboo of the genus *Guadua*, in Mexico, supported on three selection criteria (arrangements) of environmental variables.

Figure 1 – Perspectives of the distribution of bamboo in Mexico



Source: Galicia and Ceccon (2009); Ruiz-Sanchez (2019); Ruiz-Sanchez; Mendoza-Gonzalez; Rojas-Soto (2018).

In where: a) Richness of native bamboo species (Galicia; Ceccon, 2009), darker color implies a greater number of species; b) Records of presence of bamboo species (Ruiz-Sanchez, 2019); c) Distribution of *Guadua longifolia* (Galicia; Ceccon, 2009); d) Potential distribution of *Guadua inermis* (Ruiz-Sanchez; Mendoza-Gonzalez; Rojas-Soto, 2018).

2 MATERIALS AND METHODS

To develop the mapping of the distribution of the bamboo species of the genus *Guadua*, based on the principle of maximum entropy, the corresponding potential distribution models were defined. For this, the MaxEnt V.3.4.2. algorithm was used, which predicts the distribution of species with reference to georeferenced sites, where there is evidence of the presence (records) of these species. The geographical location of these sites (of occurrence of the species) helps to determine the environmental conditions where the species of interest occur, which in turn establishes restrictions (limits) for the environmental variables (Cruz-Cárdenas; Villaseñor; López-Mata; Martínez-Meyel; Ortiz, 2014). Based on this, the estimation of the distribution of the species of interest is defined based on the areas that satisfy these environmental restrictions (limits). From the perspective of a geographic information system, the above is explained considering an image (set of pixels [cells]), where the approximation of an unknown probability distribution (π), of the presence of the species of interest, is estimated starting from the delimitation of a specific area (finite number of pixels [X]), within which a set of pixels is located where the presence of the species of interest has been registered. Based on this, the π distribution assigns a non-negative probability π (x) to each pixel x, where the total of these probabilities sum to 1. Thus, the approximation of π implies a probability distribution (π), for which the entropy representation of $\hat{\pi}$ (Shannon index) is defined as (Phillips; Anderson; Schapire, 2006), as following in Equation (1):

$$H(\hat{\pi}) = -\sum_{x \in X} \hat{\pi}(x) ln\hat{\pi}(x) \quad (1)$$

where: $H(\hat{\pi})$ = Entropy of $\hat{\pi}$; $\hat{\pi}$ = approximation of unknown probability; ln = natural logarithm; X = finite number of pixels (points); x = individual elements of X.

Maxent tends for the mean of each function, of each variable, to be close to the real mean of the variable at the points where there is a record (presence) of the species. Based on this, of the possible combinations of the functions, the one that minimizes the entropy function is used, leading to an optimal selection of variables, eliminating those that do not provide significant restrictions to the model. Thus, the probability function is expressed as follows (Felicísimo; Muñoz; Mateo; Villalba; Mateos, 2011), as following in Equation (2).

$$P(x) = e^{\lambda \cdot f\,(x)} / Z_{\lambda} \tag{1}$$

where: λ = vector of weighting coefficients; f = corresponding vector of functions; Z = normalization constant used to ensure that P(x) is unity.

Where it is important to consider that the P(x) values determined with this function should not be interpreted strictly in terms of probability, but rather, should be interpreted as values of relative suitability (Felicísimo; Muñoz; Mateo; Villalba; Mateos, 2011). Furthermore, although the values can be used directly, they are generally transformed by a logistic, cumulative or log-log function (Phillips; Anderson; Schapire, 2017), which adjusts the output values to a more understandable scale in the range between 0 (incompatible) and 1 (ideal) (Felicísimo; Muñoz; Mateo; Villalba; Mateos, 2011).

Estimating the spatial distribution of a species, can be done based on geographic prediction models, which require reference sites (presence records) to predict the presence (true positives) or absence (true negatives) of certain species (Fielding and Bell, 1997). As an advantage, the niche modeling process with the Maxent algorithm was based only on positive true records (presence) of the species of interest. Thus, in this study two databases were used: a) 192 records of the presence of 7 bamboo species in Mexico (Ramírez-Ojeda; Orozco; Barrera-Guzmán; Ruiz-Sanchez, 2021) from collections made in situ through taxonomic knowledge; and b) 286 records from CONABIO (2022) data obtained from the virtual repository. These records include the following *Guadua* species in Mexico (Figure 2): *Guadua aculeata* Rupr. ex E. Fourn (171); *Guadua amplexifolia* Presl. (55); *Guadua inermis* Rupr. ex E. Fourn (67); *Guadua longifolia* (E. Fourn.) R.W. Pohl (108); *Guadua paniculata* Munro (38); *Guadua tuxtlensis* Londoño & Ruiz-Sanchez (6); *Guadua velutina* Londoño & L.G. Clark (33).

Botanical description of woody bamboo species (Ramirez-Ojeda; Orozco-Gutiérrez; Ruiz-Sánchez; Flores-Garnica; Rubio-Camacho, 2023):

– *G. aculeata:* very spiny 12 to 20 m high by 12 to 18 cm in diameter, erect and apically arched, light green when young to dark green when mature, slightly pubescent when young covered by white trichomes, culms slightly asymmetrical, internodes 20 to 42 cm long, hollow, cylindrical with walls 3 to 4 cm thick, supra- and infranodal nodal bands of white trichomes, the upper one 0.4 to 0.6 cm thick and the lower one 1.2 to 1.5 cm thick.

– *G. amplexifolia*: thorny 4 to 8 m long by 3 to 8 cm in diameter, arched with tortuous, not straight culms, internodes 15 to 20 cm long, solid, symmetrical cylindrical, supra and infranodal nodal bands of white trichomes, asymmetrical, the upper one 1 cm thick and the lower one 1.5 cm thick;

– *G. inermis*: spineless or poorly developed, 4 to 10 m high, 2 to 8 cm in diameter, erect and apically arched, when young very pubescent green covered by white trichomes, very asymmetrical culms, internodes 11 to 23 cm long, solid, cylindrical with marked asymmetry and with a central sulcus, supra- and infranodal nodal bands of white trichomes, very asymmetrical, the upper one 0.5 to 1 cm thick and the lower one 1.3 to 2.5 cm thick;

– *G. paniculata*: thorny 5 to 10 m high by 3 to 5 cm in diameter, erect and apically arched, when young light green with pubescence, covered by white, asymmetrical trichomes, internodes 25 to 28 cm long, hollow, with very thick walls, cylindrical, asymmetrical with a central sulcus, very faint supranodal and infranodal nodal bands that tend to disappear at maturity, slightly asymmetrical, the upper one 0.5 thick and the lower one 0.8 cm thick;

– *G. tuxtlensis*: thorny 10 to 20 m high by 5 to 12 cm in diameter, erect and arched apically, whitish-green when young to grayish green when adult, pubescent when young covered by white trichomes, slightly asymmetrical culms internodes of 28 to 32 cm long, hollow, cylindrical with walls 2 to 4 cm thick, supra- and infranodal nodal bands of white trichomes, the upper one 0.8 to 1 cm thick and the lower one 1 to 1.2 cm thick.

– *G. velutina*: not very prickly, 5 to 15 m high by 5 to 12 cm in diameter, erect and arched apically, green, pubescent when young covered by white trichomes, internodes 18 to 20 cm, solid or hollow, when hollow the walls are very thick, supra- and infranodal nodal bands of white trichomes, the upper one 0.5 to 1 cm wide and the lower one 2 to 2.5 cm thick;

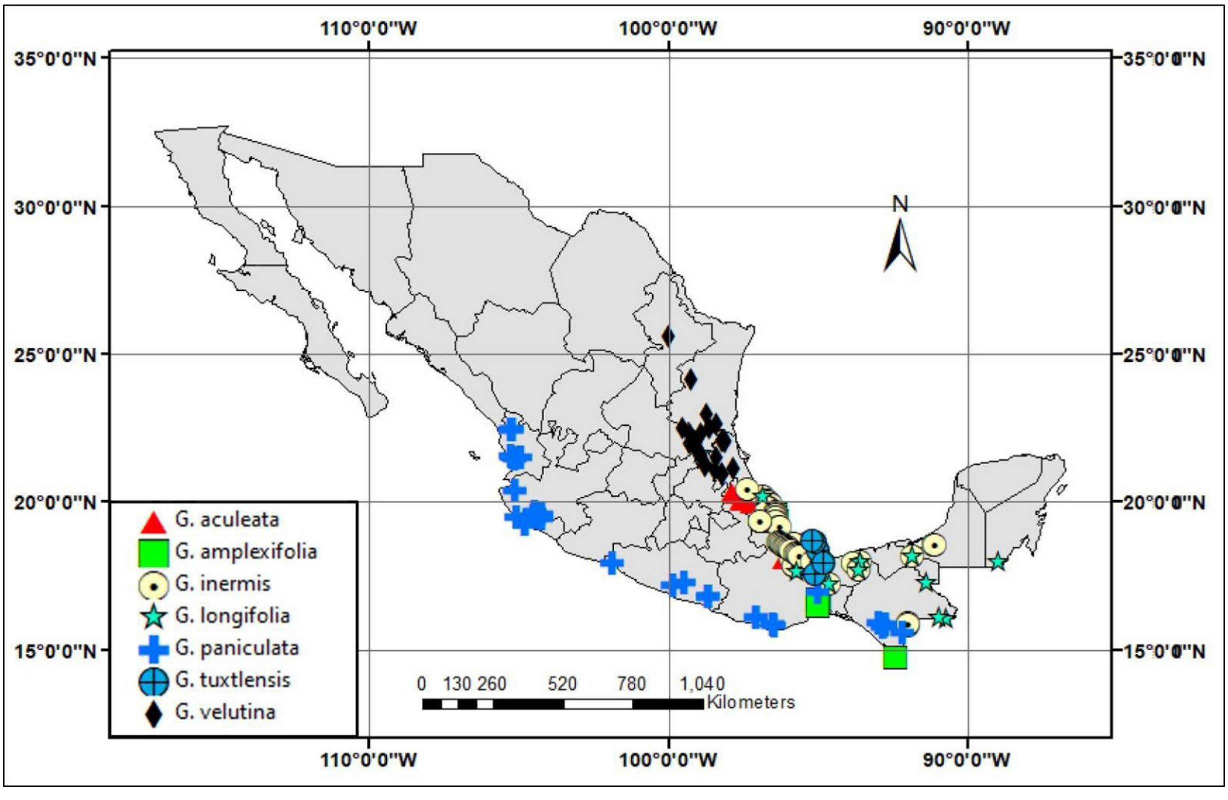
– *G. longifolia*: Bamboo 2-7(-10) m high by 2 to 6 cm in diameter, erect at the base and very arched on the rest of the culm, green and pubescent covered by white trichomes, very noticeable when young, internodes (12.5-)20 to 30(-32) cm long, hollow, cylindrical with thin to thick walls, without supra- and infranodal bands, with supranodal crests, the basal nodes develop a broad central spine, flanked by four smaller spines, develops one branch per node, flanked by some lateral branches, the branches develop hook-shaped thorns.

The modeling of the relative suitability (potential distribution) of the seven bamboo species was based on the following 21 environmental variables, which come from Worldclim Version 2.1 (1970-2000), with a spatial resolution of □1 km (Fick; Hijmans, 2017): Temperature annual mean (BIO1); Mean diurnal range (BIO2; Isothermality (BIO3); Temperature seasonality (BIO4); Maximum temperature of the warmest month; Minimum temperature of the coldest month (BIO6); Annual temperature range (BIO7); Average temperature of the wettest quarter (BIO8); Mean temperature of the driest quarter (BIO9); Mean temperature of the warmest quarter (BIO10); Mean temperature of the coldest quarter (BIO11); Annual Precipitation (BIO12); Precipitation of the rainiest month (BIO13); Precipitation of the driest month (BIO14); Precipitation Seasonality (Coefficient of Variation) (BIO15); Precipitation of the wettest quarter (BIO16); Precipitation of the Driest Quarter (BIO17); Precipitation of the warmest quarter (BIO18); Precipitation of the coldest quarter (BIO19); Altitude (ELEV); Annual evapotranspiration (ETP) (Trabuco; Zomer, 2017).For the generation of the distribution models of each of the *Guadua* species, the following three arrangements of the 21 available environmental variables: A) Four variables (ELEV, BIO1, BIO12 and ETP), derived from the work of Ramírez-Ojeda; Orozco; Barrera-Guzmán; Ruiz-

Sanchez. (2021), where first the multicollinearity between the environmental variables was calculated, eliminating those with R2 > 0.95, from these the best variables were selected, through principal component analysis.

The final selection was made through cluster analysis, with which environmentally similar accessions were identified; B) Analysis of maximum entropy taking into account the 21 environmental variables, where multicollinearity was compensated between the variables through the regularization method (Elith; Graham; Anderson; Dudík; Ferrier; Guisan; Hijmans; Huettmann; Leathwick; Lehmann; Li; Lohmann; Loiselle; Manion; Moritz; Nakamura; Nakazawa; Overton; Peterson; Phillips; Richardson; Scachetti-Pereira; Schapire; Soberón; Williams; Wisz; Zimmermann, 2006); C) Derived from the selection of environmental variables of option B), the maximum entropy analysis was performed again based on the four variables with the greatest permutation importance for each species.

Figure 2 – Distribution of reference sites (records of presence) of bamboo species, of the genus *Guadua* in Mexico, considering two databases



Source: Authors (2023)

The environmental variables served to establish the restrictions (maximum entropy [Phillips; Anderson; Schapire, 2006]) for the establishment of these species, for which, each variable corresponds to a weighting (restriction), referred to the conditions in each record (site of presence) georeferenced. For this, the most significant variables were defined to model the distribution of the *Guadua* species, for which the importance of the (random) permutation was taken as a criterion, which was determined considering the values of each environmental variable of the reference sites. (records of presence) and background data (absence) (Phillips, 2009). The models that defined a good fit with the data from the reference sites (records) were selected using the area under the curve (AUC) criterion (Phillips, 2009). Subsequently, for the selection of the models that best estimated the distribution of each of the bamboo species, the predictive capacity of them was evaluated, for which the analysis criterion of the omission/commission curves was considered. For this, the error of omission of the test data was plotted against the error of omission of the training data, where the predicted area can vary in relation to the choice of a cumulative threshold, tending to define that the omission of the test is adjustment to the omission of training (Phillips, 2009). In this way, the commission error is considered a false positive (over-prediction); that is, the species is predicted to exist, even though it is not present. While the omission is a false negative (under-prediction); that is to say that, although the species is present, it is predicted to be absent (Kigen; Patrick; Konje; Maingi, 2013).

3 RESULTS

Under the AUC criterion (Table 1), all the models generated defined a good fit with the data from the reference sites (presence records), since its value was greater than 0.90 (Araújo; Pearson; Thuiller; Erhard, 2005). However, of the 21 environmental variables used, only 16 were significant for estimating the distribution of *Guadua* species (Table 1), where the ELEV variable stands out, which was present in at least one model. The next most frequent variables in the generated models were BIO1, BIO12, ELEV and ETP.

Table 1 – Values of the area under the curve (AUC) and the permutation importance of each variable (values under each variable), according to the three arrangements analyzed

SPECIES	OPTION	AUC	VARIABLES			
G. aculeata	A	0.933	BIO1	BIO12	ELEV	ETP
			14.1	54.8	30.5	0.5
	B	0.954	BIO2	BIO4	BIO12	BIO13
			10.9	20.6	22.6	19.2
	C	0.942	BIO2	BIO4	BIO12	BIO13
			10.9	38.9	47.9	2.3
G.amplexifolia amplexifolia	A	0.899	BIO1	BIO12	ELEV	ETP
			1.4	82.4	15.8	0.4
	B	0.965	BIO7	BIO13	BIO14	BIO15
			16.8	22.4	27.9	10.5
	C	0.937	BIO7	BIO13	BIO14	BIO15
			45.8	27.2	16	11
G. inermis	A	0.964	BIO1	BIO12	ELEV	ETP
			3.9	68.2	26.5	1.4
	B	0.99	BIO7	BIO14	BIO6	ELEV
			18.6	14.5	16.6	33.4
	C	0.982	BIO7	BIO14	BIO16	ELEV
			35.6	15.7	31.7	17
G. longifolia	A	0.937	BIO1	BIO12	ELEV	ETP
			2.2	77.5	17.0	3.3
	B	0.962	BIO4	BIO16	BIO19	ELEV
			8.2	80.2	1.3	3.0
	C	0.952	BIO4	BIO16	BIO19	ELEV
			8.2	56.3	13.5	22.0
G. paniculata	A	0.964	BIO1	BIO12	ELEV	ETP
			1.4	79.5	9.4	9.6
	B	0.988	BIO4	BIO16	BIO17	ELEV
			53.3	4.2	6.0	21.8
	C	0.976	BIO4	BIO16	BIO17	ELEV
			13.4	48.0	23.8	14.7
G. tuxtlensis	A	0.963	BIO1	BIO12	ELEV	ETP
			0.0	0.0	9.3	90.7
	B	0.997	BIO3	BIO4	BIO5	BIO17
			47.3	36.5	4.4	3.7
	C	0.995	BIO3	BIO4	BIO6	BIO17
			25.1	60.4	14.3	0.2

To be continued ...

Table 1 – Conclusion

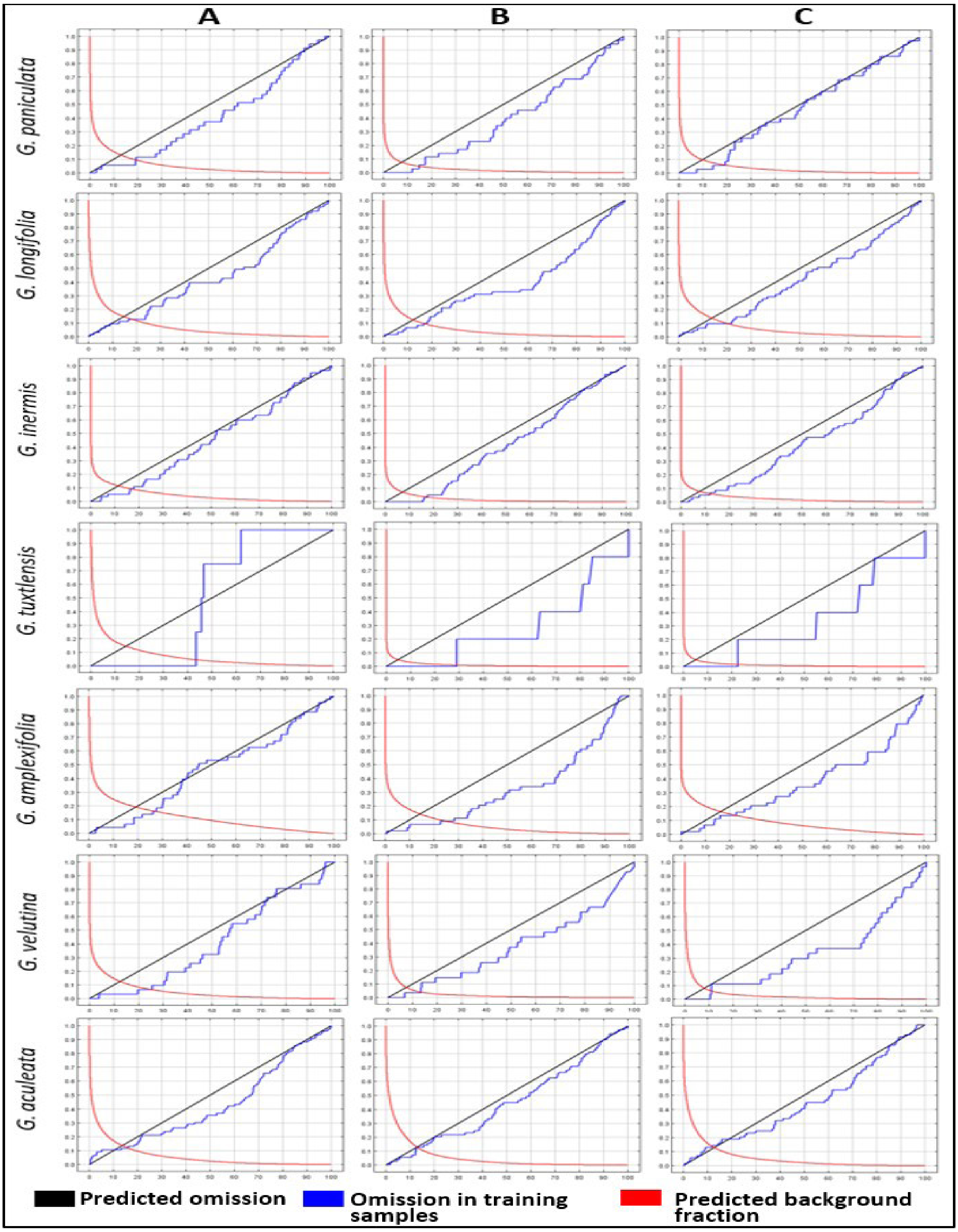
SPECIES	OPTION	AUC	VARIABLES			
	A	0.972	BIO1	BIO12	ELEV	ETP
			16.1	29.4	53.2	1.3
G. velutina	B	0.989	BIO3	BIO7	BIO15	BIO17
			38.2	18.0	9.1	11.3
	C	0.987	BIO3	BIO7	BIO15	BIO17
			47.9	16.5	6.7	29.0

Source: Authors (2023)

In where: A) Four variables ELEV, BIO1, BIO12 and ETP; B) With 21 environmental variables; C) Selection of environmental variables of option B).

The variables BIO2, BIO5, BIO6 and BIO19 were those that appeared in the fewest number of models. While the variables BIO8, BIO9, BIO10, BIO11 and BIO18 were not significant for the distribution of any of the species. In Figure 3, it can be seen that the test omission and the training omission, as well as the predicted area, vary with the selection of the cumulative threshold, therefore, for the selection of the model that best defined a good separation between the ideal zones distribution of the *Guadua* species and unsuitable areas, it was sought that the line of variation of the omission in the test training data, fit the line that represents the predicted omission rate (Phillips; Dudik, 2008). This indicated that the arrangements of variables that resulted in a better fit of models, for each of the *Guadua* species, were the following: *G. paniculata* (C); *G. longifolia* (C); *G. inermis* (A); *G. tuxtlensis* (C); *G. amplexifolia* (A); *G velutina* (A); *G. aculeata* (B). In the case of *G. tuxtlensis*, the adjustment between the training and predicted omission is defined in a “stepped” manner, which is the result of the low number of presence records with which we worked. Regarding *G. aculeata*, the three arrangements of variables presented similar adjustments; however, arrangement B was chosen since it tends to be more homogeneous throughout the cumulative threshold.

Figure 3 – Omission/commission curves of the potential distribution models of the Guadua species, for each arrangement of variables



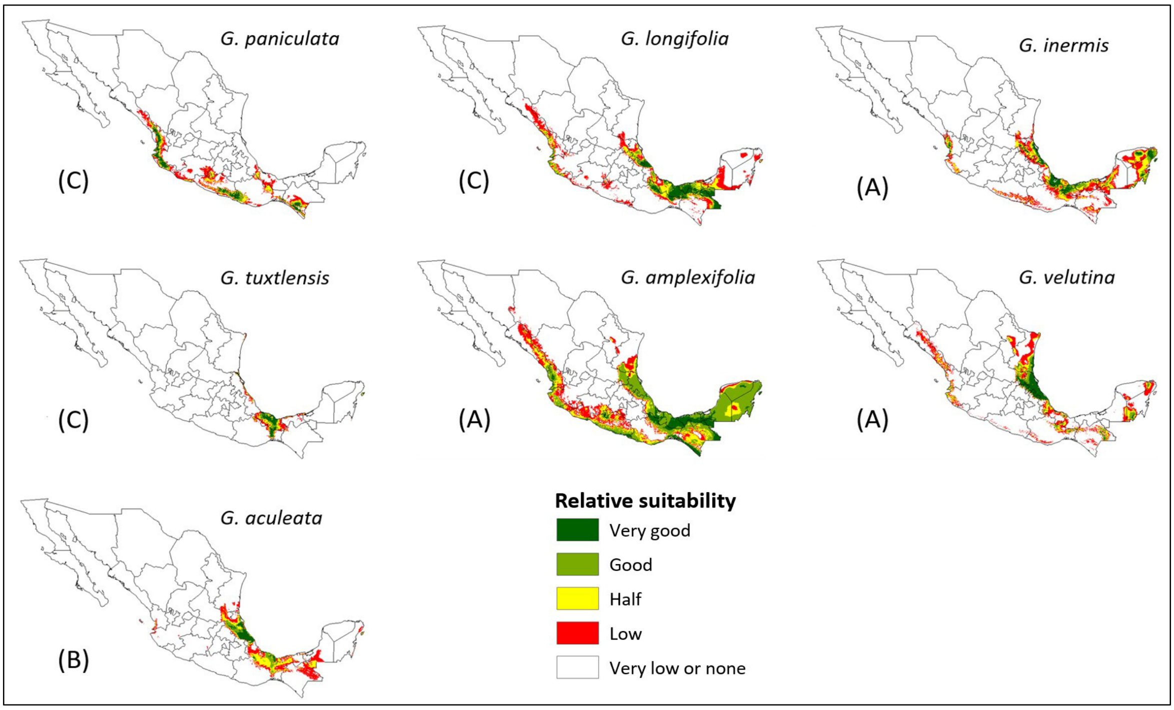
Source: Authors (2023)

In where: A) Only four variables ELEV, BIO1, BIO12, ETP; B) With 21 environmental variables; C) Selection of environmental variables of option B).

Figure 4 shows the maps resulting from the implementation of the probability models of the distribution potential of the *Guadua* species, where the generated output values were scaled (cloglog), with the purpose of defining the following probability classes: A) Very good (from 0.8 to 1); B) Good (from 0.6 to 0.8); C) Medium (from 0.4 to 0.6); D) Low (from 0.2 to 0.4); E) Very low or null (> 0.2). Based on this classification, the resulting potential distribution by species indicates that: *G. paniculata* is potentially distributed preferentially in the coastal areas of western Mexico, from Sinaloa to Chiapas; *G. longifolia* occurs mainly in the Gulf zone, covering the states of Veracruz, Tabasco, Campeche and slightly in the north of Chiapas and some areas of Yucatán. There are also areas, mainly, of low probability in the western part of the country (Sinaloa, Nayarit and Jalisco); *G. inermis* presents a potential distribution similar to that of *G. longifolia*, although to a lesser extent in terms of the very good class. This species also presented good potential in the states of Yucatán and Quintana Roo; *G. tuxtlensis* presented the most limited potential distribution, which results from the low number of records used and because this species has very specific environmental requirements as Orozco-Gutiérrez, Flores Garnica and Ramirez Ojeda, (2023); *G. amplexifolia* is the species that presented the greatest potential distribution, occurring in both the Gulf and Pacific areas of the country. Likewise, it presented the highest probability surface ("Very good" and "Good"); *G. velutina* potentially occurs in the northern Gulf Zone, between the states of Veracruz and Tamaulipas. Although it presents low potentials in the state of Sinaloa, Oaxaca, Chiapas and Quintana Roo; *G. aculeata* limits its potential distribution in the Gulf zone, mainly covering the states of Veracruz and Puebla. Although it is also potentially located north of the state of Oaxaca.

Potential surfaces for each species are presented in Table 2, which do not exclude land covers, such as urban areas, agriculture, water, etc. On the other hand, there are several states of the republic where no potential for the presence of *Guadua* species was indicated, such as Baja California Norte and Sur, Chihuahua, Durango, Coahuila, which are characterized by being states with dry climates. Likewise, it was not observed that there is potential for these species in several states of central Mexico, such as Tlaxcala, among others, where, due to the altitude, there are relatively low temperatures.

Figure 4 – Distribution of the probability of the potential of the *Guadua* species, generated based on the analysis of maximum entropy, according to the selected arrangement of variables



Source: Authors (2023)

In where: A) Only four variables ELEV, BIO1, BIO12 and ETP; B) With 21 environmental variables; C) Selection of environmental variables of option B).

Table 2 – Surfaces (km²) by potential class, for each of the bamboo species, where no specific soil cover is excluded

Class	*G. longiflora*	*G. inermis*	*G. amplexifolia*	*G. aculeata*	*G. paniculata*	*G. tuxtlensis*	*G. velutina*
Low	90,617	64,935	265,536	55,091	68,719	17,480	52,948
Medium	23,420	15,046	53,150	23,876	29,246	9,057	6,195
Good	40,138	20,792	130,195	19,479	10,288	5,085	9,841
Very good	58,023	27,997	119,829	33,655	26,127	14,978	30,849

Source: Authors (2023)

4 DISCUSSIONS

The models are better than a random estimate (Fielding and Bell, 1997). According to this, it is considered that the models accurately locate the occurrence of *Guadua* species. As a reference, when using the maximum entropy algorithm, Ávila, Villavicencio and Ruiz (2014) obtained AUC values of 0.959 and 0.958, when modeling the distribution of Pinus herrerae Martínez, based on climatic variables; while Miranda, Geada and Sotolongo (2017) defined an AUC of 0.959 when modeling *Pinus caribaea* Morelet var. caribaea Barrett and Golfari. In both cases the authors concluded that they obtained high precision in their results.

The selected variables match with the four variables selected by Ramírez-Ojeda Orozco, Barrera-Guzmán and Ruiz-Sanchez (2021) for the same *Guadua* species. The distribution of *G. inermis* is more consistent with the model proposed by Ruiz-Sanchez, Mendoza-Gonzalez and Rojas-Soto (2018), however, they also consider the states of Jalisco, Guerrero and Oaxaca as medium and low. On the contrary, in this model the state of Nayarit is not contemplated, where the proposed model in this work suggests a potential distribution between low and very good.

The species that presented a lower potential distribution was *G. tuxtlensis*, only being located with a very good distribution in the Tuxtlas region in Veracruz, as cited by Villaseñor (2016) and Dávila-Aranda, Mejia-Saulés, Soriano-Martínez, Herrera-Arrieta (2018) who found this species in Veracruz. On the other hand, *G. aculeata* also presented a low distribution, being located only in the plain of the gulf and in the southwest of the republic, especially in the states of Veracruz, Campeche, Chiapas, Oaxaca, Puebla, San Luis Potosí and Tabasco coinciding with some authors (Dávila-Aranda, 2006; Ramírez-Delgadillo; Vargas-Ponce; Arreola-Nava; Cedano-Maldonado; González-Tamayo; González-Villarreal; Harker; Hernández-López; Martínez-González; Pérez de la Rosa; Rodríguez-Contreras; Reynoso-Dueñas; Villarreal de Puga; Villaseñor, 2010; Mejía-Saulés y Dávila-Aranda, 2011; Dávila-Aranda; Mejia-Saulés; Soriano-

Martínez; Herrera-Arrieta, 2018). In the case of *G. paniculata*, distribution is observed in western Mexico, especially on the coast of the Chiapas, Colima, Guerrero, Jalisco, Nayarit, Michoacan, Oaxaca, Puebla, San Luis Potosí, Sinaloa states and extending to Veracruz (Dávila-Aranda, 2006; Ramírez-Delgadillo; Vargas-Ponce; Arreola-Nava; Cedano-Maldonado; González-Tamayo; González-Villarreal; Harker; Hernández-López; Martínez-González; Pérez de la Rosa; Rodríguez-Contreras; Reynoso-Dueñas; Villarreal de Puga; Villaseñor, 2010; Mejía-Saulés; Dávila-Aranda, 2011; Dávila-Aranda; Mejia-Saulés; Soriano-Martínez; Herrera-Arrieta, 2018). On the other hand, the species with the greatest potential distribution was *G. amplexifolia*, which is distributed in the states of Campeche; Chiapas; Hidalgo, Jalisco; Morelos; Oaxaca; San Luis Potosi; Sinaloa; Tabasco; Tamaulipas; Veracruz and Yucatán (Dávila-Aranda, 2006; Carnevali; Tapia; Duno de S.; Ramírez, 2010; Ortíz-Díaz, 2010; Dávila-Aranda; Pacheco; Mejia-Saulés, 2011; Mejía-Saulés and Dávila-Aranda, 2011; Villaseñor, 2016). However, the potential distribution of this species is much greater, as shown in figure 3. Above all, in the western region of Michoacán, Guerrero, Colima and Oaxaca; and to the Southeast in the state of Quintana Roo. In the case of *G. longifolia*, there are documented records showing a natural distribution of this species in the states of Campeche, Chiapas, Chihuahua, Durango, Guerrero, Jalisco, Morelos, Mexico city, Nayarit, Oaxaca, Puebla, Queretaro, Quintana Roo, San Luis Potosí, Sinaloa, Sonora, Tabasco and Veracruz (Dávila-Aranda, 2006; Ortíz-Díaz, 2010; Carnevali; Tapia; Duno de S.; Ramírez, 2010; Ramírez-Delgadillo; Vargas-Ponce; Arreola-Nava; Cedano-Maldonado; González-Tamayo; González-Villarreal; Harker; Hernández-López; Martínez-González; Pérez de la Rosa; Rodríguez-Contreras; Reynoso-Dueñas; Villarreal de Puga; Villaseñor, 2010; Mejía-Saulés and Dávila-Aranda, 2011; Dávila-Aranda; Pacheco; Mejia-Saulés, 2011; Espejo-Serna, 2012; Villaseñor, 2016; Vargas-Ponce; Ramírez; Arreola; Cedano; González; González; Harker; Hernández; Martínez; Pérez; Rodríguez; Reynoso; Villalpando; Villarreal; Villaseñor, 2017; Dávila-Aranda; Mejia-Saulés; Soriano-Martínez; Herrera-Arrieta, 2018). *G. velutina* shows distribution for the states of San Luis Potosí, Tabasco, Tamaulipas, Veracruz and in some regions of Oaxaca as cited by Dávila-Aranda*,* 2006; Dávila-Aranda; Pacheco; Mejia-Saulés, 2011; Mejía-Saulés and Dávila-Aranda, 2011; Villaseñor, 2016; Dávila-Aranda y Mejía-Saulés, 2018. However, it can be extended with a low probability in Sinaloa, the coast of Jalisco and Colima, Guerrero and Chiapas; as well as in the south of the country in some areas of the states of Yucatán and Quintana Roo.

5 CONCLUSIONS

The results suggest that the altitude variable (ELEV) was the one that mainly determined the potential distribution of the *Guadua* species, where the tendency is to be located at lower altitudes, so that the bamboo species get potentially located in areas close to the regions coastal. Similarly, annual precipitation (BIO12) stood out in the definition of the distribution of this genus, the same occurs with the variables evapotranspiration (ETP) and mean annual temperature (BIO1). This was independent of the three arrangements of environmental variables that were tested.

However, the arrangement that was defined based on the variables with the greatest influence (permutation importance) was the one that resulted in the best adjustments. It is important to highlight the marked difference that occurs in the potential distribution of the species in relation to the three arrangements of environmental variables. The influence on the results of the number of presence records is also clear, where the case of *G. tuxtlensis* stands out, whose spatial distribution was defined with only 6 records, so it is suggested to collect a larger number of records. Furthermore, it is considered that the distribution of the records of each of the species tends to be grouped.

Therefore, it is suggested that, in order to improve the precision of the results of each species, new records must be located throughout the area of potential distribution that have been defined in this work. In general, bamboo species are located in the Gulf of Mexico area and to a lesser extent in the Pacific region. On the other hand, northern regions (for example, Sonora, Chihuahua and Durango) and central regions (for example Mexico City and Tlaxcala) of the country were defined, where it was not determined that some species of *Guadua* could potentially be distributed. Finally, based on Phillips and DUDIK (2008), for an adequate interpretation of the results, the contribution of the selected environmental variables should not necessarily be understood as the cause of the distribution of the *Guadua* species, but to define a good separation between the suitable areas and unsuitable areas for the distribution of each species.

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