EDAPHOCLIMATIC DIVERSITY AND ECOLOGICAL DESCRIPTORS OF *Guadua* BAMBOO SPECIES (*Poaceae: Bambusoideae*) IN MEXICO

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ABSTRACT

Conservation and sustainable use require the description of the environments where species develop. The objectives of this research were:1) determine edaphoclimatic diversity patterns and ecological descriptors associated with geographic distribution of species of *Guadua* and, 2) identify the climatic variables of greatest importance for distribution and environmental similarity between seven Mexican bamboo species. Using 192 accessions and an environmental information system composed of 40 edaphoclimatic variables in raster format with spatial resolution of 1 km^2, diversity patterns of distribution areas of each specie were identified, as well as ecological descriptors through the use of Geographic Information Systems tools. Influence of edaphoclimatic variables on the geographical distribution was determined by multivariate techniques using Principal Component Analysis and Cluster Analysis. In distribution areas of accessions considered, seven climatic types were identified, predominantly tropical, monsoon (Am) and tropical, Savannah (Aw) and 12 soil units, predominantly vertisol. Principal component analysis determined that eight variables were the most important to determine the geographic distribution of these accessions. In addition, cluster analysis identified six groups of species according to their similarity. Information about edaphoclimatic conditions and the environmental breadth of the distribution of seven Mexican native bamboo species was provided.

Keywords: Multivariate analysis, ecological descriptors, edaphoclimatic diversity, native bamboo species, Guaduinae.

1. INTRODUCTION

Bamboo is part of the first "Kit" of tools of humanity [1]. The use of bamboo in Mexico has pre-Hispanic antecedents, used by various ethnic groups such as: Totonacas, Huastecos, Aztecas, Teotihuacanos and Maya-Chontales [2]. *Bambusoideae* subfamily is the third most diverse of the *Poaceae* family with more than 1,680 species described worldwide [3, 4, 5]. Neotropical woody bamboos are classified into three subtribes, one of them is *Guaduinae*, with 60 species [5, 6, 7, 8, 9].

The geographical limits of this subtribe extend from Mexico to Argentina and the West Indies [7, 9].

Ruiz-Sanchez et al. (2015) [8] registered 50 native species of woody bamboo and four herbaceous bamboo, which 33 are endemic to Mexico. On the other hand, Dávila et al. (2018) [10] cited 62 species of woody and herbaceous bamboo, and 32 are reported as endemic to Mexico. Finally, Ruiz-Sanchez et al. (2020) [11] reported 51 species of native woody bamboo [12]. To the list of 52 native species of woody bamboo, four more were added, one of them from the genus *Rhipidocladum*, another from the genus *Otatea* and two more from *Chusquea* genus [13, 14, 15]. The most recent list includes 56 species of woody bamboo, with 39 of them endemic to Mexico. The *Guaduinae* subtribe is the most important culturally and economically for Mexico.

Guadua is the most important genus of bamboos in America, endemic to this continent and composed of 33 species. The *Guadua* genus in America, present in a great variety of habitats, is the most commercially used, mainly in construction, due to its hardness and the arrangement of its fibers, and it is considered the structural bamboo by excellence. In addition, *Guadua* species are the largest and the leafiest of the American bamboos [16].

Species of *Guadua* in Mexico are distributed in the following biogeographic regions: Veracruzana, Lowlands of the Pacific, Tamaulipas, High areas of Chiapas, Sierra Madre Oriental and Sierra Madre del Sur [11]. The seven native Mexican species of *Guadua* considered in this research are: *G. aculeata* Rupr. ex Fourn., *G. amplexifolia* J. Presl., *G. inermis* Rupr. ex Fourn., *G. longifolia* (E. Fourn.) R.W. Pohl, *G. paniculata* Munro, G. tuxtlensis Londoño & Ruiz-Sanchez and *G. velutina* Londoño & L.G. Clark [11, 12].

Ecogeographic studies of plant genetic resources allow to identify the adaptive ranges of the species and most relevant environmental variables that define their distribution [17]. Its main applications are related to the collection, conservation, characterization, documentation and use of plant genetic resources [18, 19, 20, 21, 17, 22]. Additionally, with the use of ecological descriptors derived from geographic location of germplasm and environmental maps obtained through GIS tools [23, 21, 24], it is possible to predict the environmental conditions of the accession sites [25, 21].

The objectives of this research were determining the edaphoclimatic diversity patterns and ecological descriptors associated with the geographic distribution of seven native bamboo species of *Guadua* genus, and identify the most important climatic variables for distribution and environmental similarity between Mexican *Guadua* species.

2. MATERIALS AND METHODS

2.1. Accession database

For the present study, a database was built with information from georeferenced accessions of seven native bamboo species (*G. aculeata, G. inermis, G. amplexifolia, G. longifolia, G. paniculata, G. tuxtlensis and G. velutina*) with information from national [26] and international [27] inventories as well as scientific articles [11].

All records were reviewed in order to eliminate atypical data such as records with little geographic precision, repeated data, and accessions outside the study area, which were eliminated, thus forming a database with 192 collections distributed in Mexico (Figure 1).
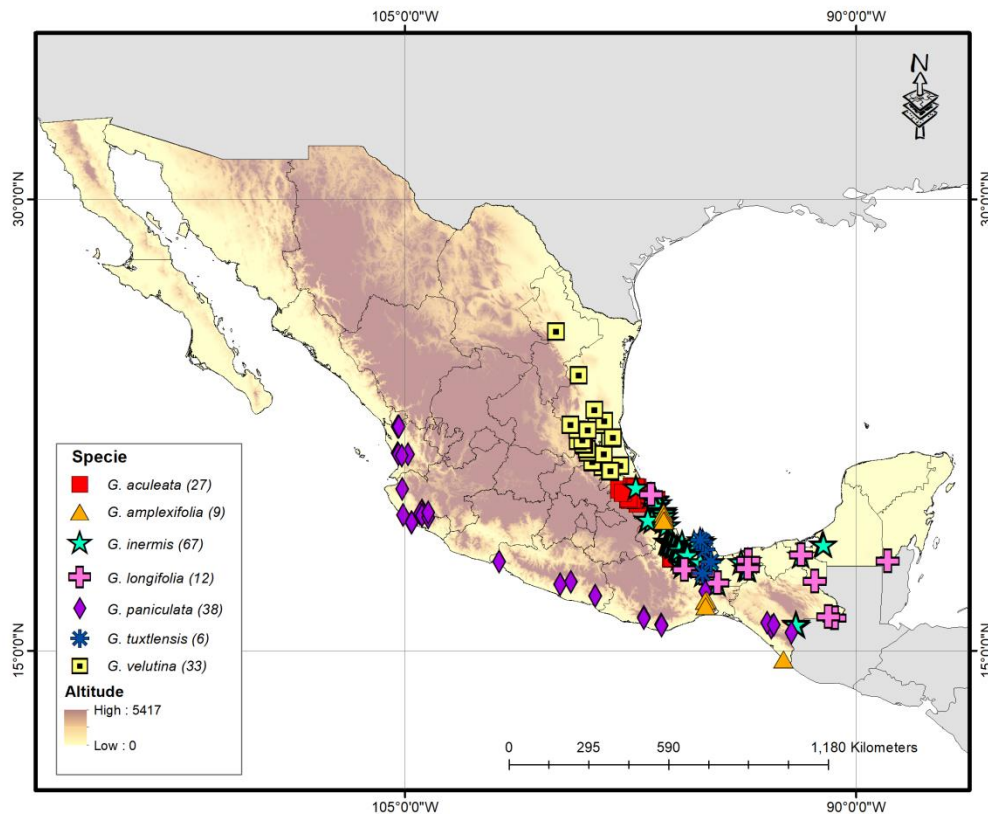
Figure 1: Geographic distribution of seven accessions of *Guadua* species in Mexico.

2.2. Edaphoclimatic information system

The environmental information system was built with 21 climatic variables and 19 edaphic variables. Nineteen of the climatic variables correspond to the bioclimatic variables of WorldClim version 2.1 corresponding to the climatic period 1970-2000 with spatial resolution of ~ 1 km² [28]: annual mean temperature (BIO1, °C), mean diurnal range (BIO2, °C), isothermality (BIO3, BIO2/BIO7*100), temperature seasonality (BIO4, standard deviation*100), max temperature of the warmest month (BIO5, °C), min temperature of coldest month (BIO6, °C), temperature annual range (BIO7, BIO5-BIO6), mean temperature of wettest quarter (BIO8, °C), mean temperature of driest quarter (BIO9, °C), mean temperature of warmest quarter (BIO10, °C), mean temperature mean of coldest quarter (BIO11, °C), annual precipitation (BIO12, mm), precipitation of wettest month (BIO13, mm), precipitation of driest month (BIO14, mm), precipitation seasonality (BIO15, coefficient of variation), precipitation of wettest quarter (BIO16, mm), precipitation of driest quarter (BIO17, mm), precipitation of warmest quarter (BIO18, mm) and precipitation of coldest quarter (BIO19, mm).

Altitude (ALT, masl) of the site of each accession was determined from an elevation model in raster format with spatial resolution ~ 1 km² [28]. Finally, annual evapotranspiration (ET, mm)

was calculated from the monthly values in raster format with the same spatial resolution as the rest of the variables [29].

Edaphic variables used were percentage of gravel (GR, %), sand (SA, %), silt (SI, %) and clay (CL, %), bulk density (BD, kg / dm^3), organic carbon (CO, %), pH, base saturation (BS, %), TEB (cmol / kg), calcium carbonate (CACO$_3$, %), calcium sulfate (CASO4, %), salinity (SAL, dS / m) and sodium (SOD, %). These variables were obtained from the world database in raster format called Harmonized World Soil Database version 1.1 with spatial resolution of ~ 1 km^2, developed in 2009 by the Food and Agriculture Organization of the United Nations (FAO), International Institute for Applied Systems Analysis (IIASA), International Soil Information and Reference Center (ISRIC- World Soil Information), Institute of Soil Sciences- Chinese Academy of Sciences (ISS-CAS) and the Common Center for European Commission Research [30].

2.3. Ecological descriptors

Ecological descriptors of each variable for each bamboo species, was calculated using the methodology proposed by Ruiz-Corral et al. (2008) [21]. For this, the vectors with the geographical coordinates of each accession were used to obtain the point values of each variable through the use of GIS tools. The information was concentrated in a spreadsheet, where the extreme values (minimum and maximum), and mean value of each variable for each species were subsequently determined [24, 22].

2.4. Edaphoclimatic diversity

The diversity of climate and soil types were determined through a vector made with the database of accessions of bamboo species and environmental variables with the use of GIS tools. For this, the point value of each climatic type and soil unit was extracted for each accession, where the frequencies of each category by species were subsequently identified. Climatic types of accessions sites were defined from the world climatic classification with the Köppen-Geiger system with spatial resolution of ~ 1 km^2 proposed by Beck et al. (2018) [31]: Af (Tropical, rainforest), Am (Tropical, monsoon), Aw (Tropical, Savannah), BWh (Arid, deser, hot), BWk (Arid, desert, cold), BSh (Arid, steppe, hot), BSk (Arid, steppe, cold), Csa (Temperate, dry summer, hot summer), Csb (Temperate, dry summer, warm summer), Csc (Temperate, dry and cold summer), Cwa (Temperate, dry winter, hot summer), Cwb (Temperate,dry winter, warm summer) Cwc (Temperate, dry winter, cold summer), Cfa (Temperate, no dry season, hot summer), Cfb (Temperate, no dry season, warm summer), Cfc (Temperate, no dry season, cold summer), Dsa (Cold, dry summer, hot summer), Dsb (Cold, dry summer, warm summer), Dsc (Cold, dry summer, cold summer), Dsd (Cold, dry summer, very cold Winter), Dwa (Cold, dry winter, hot summer), Dwb (Cold, dry winter, warm summer), Dwc (Cold, dry winter, cold summer), Dwd (Cold, dry winter, very cold winter), Dfa (Cold, no dry season, hot summer), Dfb (Cold, no dry season, warm summer), Dfc (Cold, no dry season, cold summer), Dfd (Cold, no dry season, very cold Winter), ET (Polar, tundra) and EF (Polar, Frost).

Soil units were obtained from the Harmonized World Soil database (2009) [30]: Acrisol (AC), Alisol (AL), Andosol (AN), Arenosol (AR), Anthrosol (AT), Chernozem (CH), Calcisol (CL), Cambisol (CM), Fluvisol (FL), Ferralsol (FR), Gleysol (GL), Greysem (GR), Gypsisol (GY), Histosol (HS), Kastanozem (KS), Leptosol (LP), Luvisol (LV), Lixisol (LX), Nitosol (NT),

Podzoluvisol (PD), Phaezem (PH), Planosol (PL), Plinthosol (PT), Podzol (PZ), Regosol (RG), Solonchak (SC), Solonetz (SN), Vertisol (VR).

2.5. Statistical analysis

Multicollinearity between variables of the environmental system was calculated through Pearson's correlation between pairs of variables, eliminating those with absolute coefficients > 0.95. With the selected variables, a principal component analysis (PCA) was performed in Rstudio [32]. The selected variables were integrated into three groups referring to temperature, precipitation and those related to physicochemical soil factors (Table 1). The calculation of eigenvalues, eigenvectors and contribution of the variables of principal components were obtained with the FactoMineR [33] and factoextra [34] packages.

Table 1. Classification of edaphoclimatic variables used in multivariate analysis.

Group	Variables
I – Temperature	BIO1, BIO3, BIO4, BIO5, BIO6, BIO7, BIO11 and Altitude
II – Precipitation	BIO12, BIO13, BIO15, BIO18, BIO19, ET
III – Soil	Gravel, sand, silt, clay, BD, OC, pH, CEC, BS, CACO$_3$, Salinity

Cluster analysis (CA) was performed with Euclidean distances and Ward's method of least variance to identify environmentally similar accessions. To verify if there is a tendency to clustering, Hopkins (H) statistic was calculated with clustertend [35], where values ≤ 0.5 indicate a high tendency to clustering. The best algorithm for grouping (hierarchical and non-hierarchical methods) was calculated with clValid [36]. For the selection of the optimal number of groups, the NbClust package was used with the majority rule [37]. Finally, analysis of variance and Tukey mean comparisons were performed for the groups of species generated.

3. RESULTS

3.1. Ecological descriptors and edaphoclimatic diversity

The result of the ecological descriptors is shown in Table 2. For this, the mean annual temperature, annual precipitation, annual evapotranspiration and altitude were selected as the most important variables for the distribution of the species under study.

Table 2. Ecological descriptors by bamboo species. ALT= altitude, BIO1= annual mean temperature, BIO12= annual precipitation and ET= annual evapotranspiration. Max= maximum, Min= minimum, Med= average.

| SPECIE	ALT			BIO1			BIO12			ET		
	Max.	Min.	Med.	Max.	Min.	Med.	Max.	Min.	Med.	Max.	Min.	Med.
G. aculeata	906	12	326	26.0	20.8	22.9	2719	1312	1889	1477	990	1261
G. amplexifolia	213	8	77	28.1	24.9	25.8	1438	1012	1140	1111	744	917
G. inermis	995	0	137	26.7	20.4	25.1	3656	1080	1616	1533	890	1126
G. longifolia	237	5	97	26.6	24.4	25.6	3656	1399	2303	1533	1166	1374
G. paniculata	1733	38	536	26.9	16.9	24.2	2479	910	1502	1260	632	1008
G. tuxtlensis	347	16	142	25.7	24.4	25.1	2453	1818	2040	1347	1202	1297
G. velutina	1016	2	238	25.3	21.1	23.8	2023	746	1434	1421	614	1088

Figure 2 shows the distribution of four variables used for general ecological descriptors of seven bamboo species. In the figure, it is possible to identify areas of overlap between variables and species due to their geographical distribution. About altitudinal range of bamboo species, *G. paniculata* is the species that reaches higher altitudes, and *G. amplexifolia* is the species that is distributed at the lowest altitude above sea level
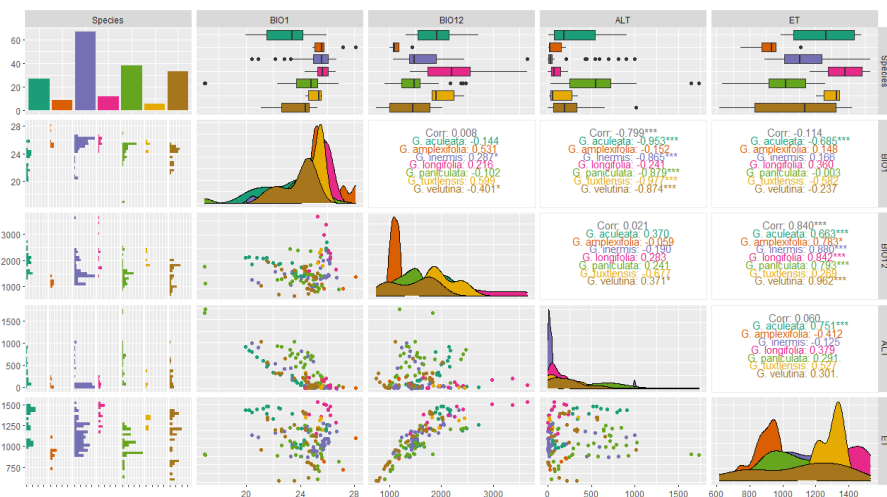
Figure 2: Boxplots, histograms, density plots, scatter plots and correlations of the mean annual temperature (BIO1), altitude (ALT), annual precipitation (BIO12) and annual evapotranspiration (ET) of seven bamboo species. * = p <0.05, ** = p <0.01, *** = p <0.001.

Annual mean maximum temperature ranges between 25.3 (*G. velutina*) and 28.1 °C (*G. amplexifolia*), minimum annual temperature between 16.9 and 24.9 °C, and annual mean temperature between 22.9 and 25.8 °C. Regarding water requirements, *G. amplexifolia* is the species that requires the least annual precipitation (1,111 mm). Opposite case occurs in the distribution of *G. longifolia* species (2,303 mm of average annual precipitation and 1,374 mm of

average annual evapotranspiration). About annual evapotranspiration, *G. velutina* is the species with the lowest average annual evapotranspiration. Information about edaphoclimatic diversity of *Guadua* species is concentrated in Figure 3 where can be identify the proportion of each species respect to the climate type and soil unit in which each accession is distributed.
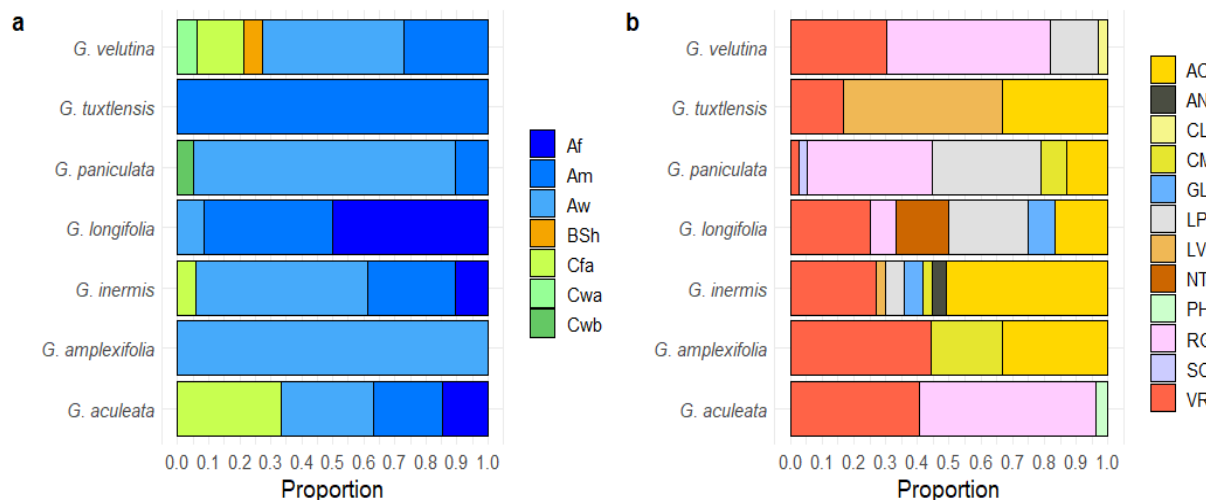
Figure 3: Climatic (a) and edaphic (b) diversity proportion of *Guadua* species. Climate type= Af (Tropical, rainforest), Am (Tropical, monsoon), Aw (Tropical, Savannah), BSh (Arid, steppe, hot), Cfa (Temperate, no dry season, hot summer, Cwa (Temperate, dry winter, hot summer) y Cwb (Temperate,dry winter, warm summer); Soil unit = AC (Acrisol), AN (Andosol), CL (Calcisol), CM (Cambisol), GL (Gleysol), LP (Leptosol), LV (Luvisol), NT (Nitosl), PH (Phaeozem), RG (Regosol), SC (Solonchak) and VR (Vertisol).

Edaphic diversity of *Guadua* species is greater (12 soil units) respect to the diversity of climates (7 climate types) present in the same species. Regarding climates, bamboo species are distributed in eight of the 30 climates proposed by Beck et al. (2018) [31]: Af, Am, Aw, BSh, Cfa, Cwa and Cwb. Of these climate types, climates Am and Aw are the ones that occur most frequently, while the climates Cwa and Cwb are only found in one species (*G. velutina* and *G. paniculata*, respectively). Climatic diversity within each species, *G. velutina* is the species with the greatest diversity of climates (5), while *G. tuxtlensis* and *G. amplexifolia* are only located in one climatic type: Am for *G. tuxtlensis* and Aw for *G. amplexifolia*. Vertisol, acrisol and regosol predominate in distribution areas of the seven bamboo species studied. The less frequent soils units are calcisol (*G. velutina*), andosol (*G. inermis*), nitosol (*G. longifolia*) and phaeozem (*G. aculeata*). Soil diversity among species, *G. tuxtlensis*, *G. amplexifolia* and *G. aculeata* are the species with the lowest soil diversity (3 units). On the contrary, *G. inermis* is the species with the greatest soil diversity.

Tables 3 and 4 show the ecological descriptors of the seven bamboo species, grouping them according to climate type and soil unit. In these tables, the average values associated with the soil units and climatic types where each species is distributed can be identified. An example of this is the combination of *G. paniculata* with Cwb climate, having the lowest annual temperature and

the highest altitude. The opposite case occurs in *G. amplexifolia* associated with the Aw climate, where the highest annual temperature occurs.

3.2. Statistical analysis

Multicollinearity between variables of the environmental system was eliminated through a correlation analysis, where all those variables with absolute coefficients > 0.95 were eliminated (BIO2, BIO8, BIO9, BIO10, BIO14, BIO16, BIO17, TEB, CASO4 and Sodicity) with a total of 25 edaphoclimatic variables to run the statistical analyses.

The PCA gave as result that it is possible to explain 81.6% of the total variation with only two principal components (PC). PC1 contributed 43.1% of variation and is composed of variables related to precipitation: annual evapotranspiration (ET), annual precipitation (BIO12), precipitation of the coldest four-month period (BIO19), seasonal precipitation (BIO15) and precipitation of the wettest month (BIO13). On the other hand, PC2 (35.5%) was made up of variables related to temperature: BIO1 (annual mean temperature), BIO5 (maximum temperature of the warmest month) and altitude (ALT). Figure 4 shows the biplot with the distribution of the variables used in the PCA and the distribution of the collections by species on the first two PCs.

Figure 4a shows the distribution of temperature, precipitation and soil variables. It is observed that most of the variables related to precipitation are located in both upper quadrants (except BIO15), temperature variables are located in the left quadrants (with the exception of altitude, BIO3 and BIO7, located in the lower right quadrant) and soil variables are distributed in all quadrants.

The distribution of the seven bamboo species studied with respect to principal components is shown in Figure 4b. In this figure, it can be seen that *G. paniculata* is the only species that showed a distribution pattern where there are no transition zones or overlap between the rest of the species. This information agrees with the geographic distribution of the *G. paniculata* accessions located mostly in the western part of Mexico.
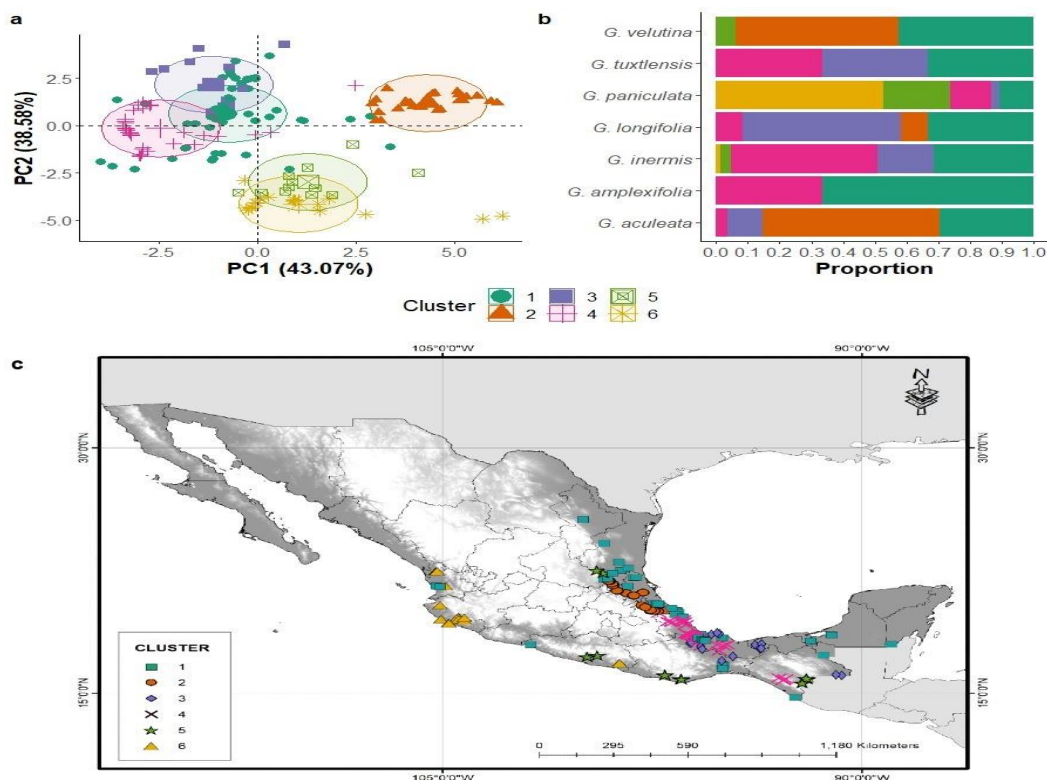
CA resulted in the formation of six clusters.
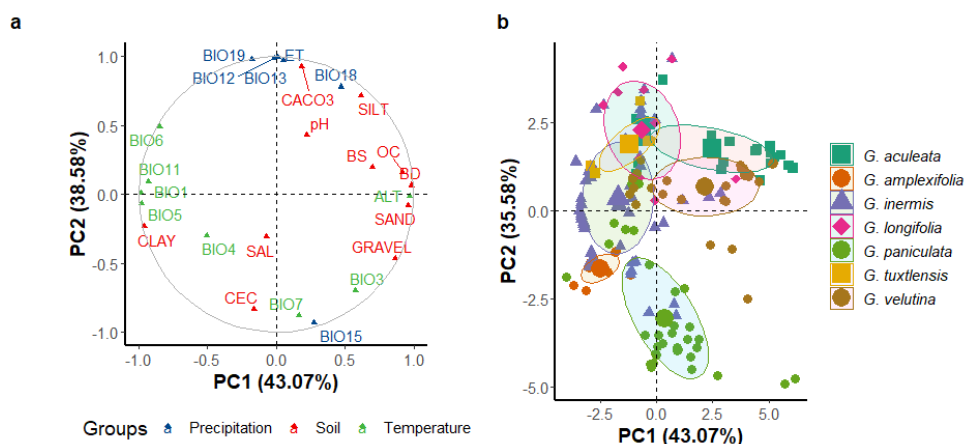
Figure 4: a) Biplot of precipitation, temperature and soil variables on the first two PC. b) Distribution of the accessions of seven bamboo species on the first two PC.

Figure 5 shows the distribution of each cluster, as well as the proportion of accessions of each species for the formation of these six groups.

Figure 5: Groups formed by CA from 25 edaphoclimatic variables with Euclidean distances and Ward's grouping method. a) Cluster distribution according to the first 2 CPs, b) Proportion of accessions in the contribution of each cluster, c) Geographic distribution of the clusters identified by the CA.

Table 5. Average values of eight edaphoclimatic variables and Tukey's mean comparison test for the six clusters identified with CA. BIO1= mean annual temperature (°C), ALT= altitude (m), BIO12= annual precipitation (mm), ET= annual evapotranspiration (mm), BD= bulk density (kg / dm³), pH, CEC= cation exchange capacity (cmol / kg), SB= percentage of bases (%).

Cluster	BIO1	ALT	BIO12	ET	BD	pH	CEC	SB
1	24.8 AB	114 C	1,374 C	1,030 BC	1.30 DE	7.5 B	27.1 B	97.7 A
2	22.8 C	352 B	1,843 B	1,321 A	1.56 B	8.0 A	18.0 CD	100.0 A
3	25.8 A	60 C	2,478 A	1,358 A	1.33 D	6.6 C	20.3 C	86.4 B
4	24.7 AB	211 BC	1,564 C	1,092 B	1.27 E	4.7 E	15.0 DE	44.0 C
5	24.0 BC	636 A	1,322 C	1,019 BC	1.39 C	7.7 AB	44.0 A	100.0 A
6	23.9 BC	592 A	1,391 C	952 C	1.65 A	6.0 D	13.1 E	75.1 B

Medians with the same letter within each column are not statistically different (p ≤ 0.05) according to the multiple comparisons and Tukey test.

Table 5 shows the average values of eight edaphoclimatic variables and Tukey mean comparison test for the clusters identified in the CA. Cluster 1 is composed of accessions of all species with a majority of Aw climate type, is distributed in the Gulf Coast region and Chiapas with some accessions in the Pacific region, characterized by mean annual temperature of 24.8 °C, altitude of 114 masl and 1,374 mm of annual precipitation with moderately basic soils (pH = 7.5).

Cluster 2 consists mainly of accessions of *G. aculeata*. The species in this group are mainly distributed in the Gulf Coast region. The species of this group are those with the lowest mean annual temperature (22.8 °C) and the highest soil pH value (8.0).

Species in cluster 3 are mainly distributed in the southern Gulf Coast region and the majority of *G. longifolia* accessions are found in this group. This group of species is characterized by presenting mean annual temperature of 25.8 °C, lower altitude distribution (60 m) and greater water availability (2,478 mm).

Cluster 4 is distributed in the Gulf Coast region, extending to Chiapas. *G. inermis* mostly integrates cluster 4. The species in cluster 4 are those that have edaphic characteristics with lower values such as strongly acidic soils (4.7), the lowest percentage of bases and bulk density.

Finally, cluster 5 and 6 are distributed in the Pacific coast region. Both and mainly made up of accessions of *G. paniculata*. This clusters are characterized by having accessions with the highest altitude distribution and in distribute in areas with little amount of annual precipitation.

4.DISCUSSION

Bamboo is a forest species with a large number of potential uses, such as construction, fibres, food and combustion, ornamental [38], and with great ecological importance as having a great capacity to capture carbon [39]. Therefore, there are many species of bamboo with a great diversity of climatic requirements for their growth, making it difficult to characterize optimal requirements for their establishment [40].

Variables considered in the general climatic descriptors reported in Table 2 (mean annual temperature, altitude, accumulated precipitation and annual evapotranspiration) are important to identify the patterns that determine the distribution of the studied bamboo species. Precipitation affects the distribution and growth limits of bamboo more than any other climatic component, with the exception of temperature. In India, 61% of bamboo species are located in areas with annual precipitation of 1,500 to 4,000 mm [41].

In addition to the high-water requirements, the availability of water during specific growth stages affects the productivity of bamboo [42].

Battisti et al. (2019) [40] identified as optimal values for the establishment of bamboo optimal mean annual temperature of 15.1 to 35.3 °C, minimum temperature of 12.0 °C and maximum temperature of 38.8 °C. The results obtained in the present investigation as ecological descriptors (Table 2) are within these ranges for all the seven species studied.

Regarding precipitation for bamboo cultivation and growing, Battisti et al. (2019) [40] determined a minimum value of 775 mm per year, a maximum of 1,320 mm and a wet period of 8 months per year. In this regard, the ecological descriptors on annual precipitation (Table 2), exceed the

values reported in the literature. This research also provides the annual evapotranspiration ranges, as an indicator of the cycle and water balance.

Despite the immense diversity of soils and the complex interactions between the physicochemical parameters and soil characteristics, it is difficult to relate bamboo growth to specific edaphic factors. Table 3 and 4 show the climate and soil descriptors related to the diversity of climate types and soil units of each bamboo species.

Table 3. Average values of edaphoclimatic variables according to climate types by bamboo species in Mexico. BIO1= annual mean temperature (°C), ALT= altitude (m), BIO12= annual precipitation (mm), ET= annual evapotranspiration (mm), BD= bulk density (kg / dm^3), pH, CEC= cation exchange capacity (cmol / kg), SB= percentage of bases (%). Climate types= Af (Tropical, rainforest), Am (Tropical, monsoon), Aw (Tropical, Savannah), BSh (Arid, steppe, hot), Cfa (Temperate, no dry season, hot summer), Cwa (Temperate, dry winter, hot summer) and Cwb (Temperate, dry winter, warm summer).

Species	Climate	BIO1	ALT	BIO12	ET	BD	pH	CEC	SB
G. aculeata	Af	23.1	260	1,897	1,382	1.4	8.0	20.7	100
	Am	24.7	88	2,102	1,212	1.4	7.6	21.3	100
	Aw	23.8	119	1,496	1,043	1.3	8.0	26.5	100
	Cfa	20.8	698	2,092	1,493	1.5	7.8	18.0	98.8
G. amplexifolia	Aw	25.8	76	1,140	917	1.3	6.1	18.1	79.4
G. inermis	Af	25.7	37	2,400	1,403	1.3	5.8	19.0	71.2
	Am	25.3	87	1,903	1,239	1.3	6.2	23.5	75.5
	Aw	25.3	92	1,352	1,013	1.3	5.8	20.9	68.2
	Cfa	20.5	971	1,309	1,140	1.2	4.7	15.0	43.0
G. longifolia	Af	25.5	93	2,718	1,492	1.2	6.7	20.0	81.3
	Am	25.6	99	1,985	1,349	1.3	6.9	24.8	88.6
	Aw	25.1	113	1,399	1,166	1.3	7.5	35.0	100
G. paniculata	Am	24.4	440	2,255	1,222	1.2	5.3	16.5	57.2
	Aw	24.6	475	1,407	986	1.5	6.4	22.3	86.2
	Cwb	16.9	1,690	1,514	922	1.5	6.0	11.0	100.0
G. tuxtlensis	Am	25.1	142	2,040	1,296	1.2	6.5	24.0	78.0
G. velutina	Am	23.8	229	1,768	1,343	1.5	8.0	18.0	100.0
	Aw	24.7	78	1,171	937	1.3	7.9	26.6	100.0
	BSh	22.9	278	768	614	1.3	8.2	18.0	100.0
	Cfa	21.8	475	1,949	1,285	1.5	8.0	18.0	100.0
	Cwa	21.9	838	1,282	1,054	1.3	7.6	32.0	100.0

Table 4. Average values of edaphoclimatic variables associated with soil units by bamboo species in Mexico. BIO1= annual mean temperature (° C), ALT= altitude (m), BIO12= annual precipitation (mm), ET= annual evapotranspiration (mm), BD= bulk density (kg / dm^3), pH, CEC= cation exchange capacity (cmol / kg), SB= percentage of bases (%). Climate types= Af (Tropical, rainforest), Am (Tropical, monsoon), Aw (Tropical, Savannah), BSh (Arid, steppe, hot), Cfa (Temperate, no dry season, hot summer), Cwa (Temperate, dry winter, hot summer) and Cwb (Temperate, dry winter, warm summer).

Species	Soil	BIO1	ALT	BIO12	ET	BD	pH	CEC	SB
G. aculeata	PH	20.5	799	1,896	1,413	1.3	6.4	18.0	90.0
	RG	22.0	451	1,936	1,349	1.6	8.0	18.0	100.0
	VR	24.4	112	1,825	1,126	1.3	7.8	26.8	100.0
G. amplexifolia	AC	25.1	21	1,117	959	1.3	4.7	15.0	43.0
	CM	27.6	18	1,227	928	1.4	6.4	17.0	93.0
	RG	25.5	148	1,115	882	1.4	7.2	21.0	100.0
G. inermis	AC	25.0	154	1,536	1,096	1.3	4.7	15.0	43.0
	AN	23.2	338	1,564	1,178	1.6	6.4	38.0	80.0
	CM	26.1	12	1,493	1,059	1.2	6.8	23.0	89.0
	GL	26.2	9	1,803	1,260	1.3	6.7	33.5	92.5
	LP	25.7	326	1,505	1,095	1.4	7.6	39.5	100.0
	LV	24.8	414	1,927	1,120	1.4	6.8	21.5	91.0
	VR	25.3	41	1,737	1,159	1.3	7.4	22.8	100.0
G. longifolia	AC	25.7	50	2,197	1,340	1.3	4.7	15.0	43.0
	GL	26.2	22	2,133	1,375	1.4	5.7	19.0	85.0
	LP	26.0	63	1,810	1,312	1.3	7.5	35.0	100.0
	NT	25.8	199	3,178	1,498	1.2	7.3	18.0	80.0
	RG	24.7	237	1,660	1,382	1.6	8.0	18.0	100.0
	VR	25.1	73	2,555	1,373	1.3	7.5	23.7	100.0
G. paniculata	AC	24.4	586	2,221	1,216	1.3	4.7	15.0	43.0
	CM	25.4	191	1,283	893	1.3	6.5	19.0	91.7
	LP	22.8	821	1,382	1,007	1.5	7.0	31.3	100.0
	RG	25.0	402	1,368	953	1.7	6.0	14.0	80.0
	SC	25.5	53	1,469	931	1.2	9.0	33.0	100.0
	VR	25.5	117	2,169	1,213	1.4	7.2	21.0	100.0
G. tuxtlensis	AC	25.5	57	1,904	1,215	1.3	4.7	15.0	43.0
	LV	24.8	237	2,030	1,344	1.3	7.5	31.0	94.0
	VR	25.4	30	2,344	1,316	1.4	7.2	21.0	100.0
G. velutina	CL	22.4	336	790	614	1.5	8.4	7.0	100.0
	LP	23.6	466	1,378	1,090	1.3	7.6	29.6	100.0
	RG	23.5	271	1,772	1,294	1.6	7.0	18.0	100.0
	VR	24.6	57	953	786	1.2	8.0	29.0	100.0

In general, it is recognized that bamboo grows in areas with "poor" soils [43], so it is used for the rehabilitation of degraded soils [44]. Among the physical factors of soil that influence the productivity of bamboo are the slope, texture, bulk density, moisture storage capacity and soil temperature [42].

Among chemical properties of soils, the availability of nutrients, pH and salinity are the most important properties that mark the productivity and growth of bamboo plantations. Compared to other crops, bamboo is less affected by acidic soils, making them suitable for cultivation on degraded lands in tropical and subtropical regions where soils are frequently flooded and therefore with low pH. Bamboos generally do not tolerate salty conditions in the soil [42].

There are no studies about the edaphoclimatic diversity of the sites where *Guadua* species studied are distributed. The closest approach is the work done by Ruiz-Sanchez et al. (2020) [11] about the diversity and endemism of native bamboos of Mexico. In this work the authors define diversity using physiographic provinces, biogeographic regions and political division, concluding that the greatest diversity of bamboos is located in the Mexican transition zone, followed by the neotropical region.

One of the species with less climatic and edaphic variability is *G. tuxtlensis*, a fact attributable to the geographic isolation in the area of Los Tuxtlas where it is located with an age of 16,000 to 1.92 million years [45]. This species is partially sympatric with *G. inermis* that grows in the coastal plain to the northwest of Los Tuxtlas region. *G. tuxtlensis* shares morphological characters with *G. aculeata and G. inermis* [46].

The present work successfully identified edaphic and climatic variables with the greatest association and importance for distribution of bamboo species under study (Figure 4 and 5). Multivariate analysis techniques are very useful to identify patterns between sets of variables. In this regard, there are few works where the benefits of these statistical techniques are used to bamboo species, or data with which the results obtained can be compared.

An example of a study using multivariate techniques is that carried out by Cifuentes and Mejía (2013) [47] with a multivariate characterization through the use of principal components with morphological variables. Another interesting example is the one carried out by Marulanda et al. (2002) [48] with the use of principal components and cluster analysis for data obtained with molecular markers.

There are several examples of research in other plant species where multivariate statistics are used to identify patterns of association between variables, such the one made for Ruíz-Corral et al. (2013) [49] in corn, Sánchez-González et al. (2018) [22] in teocinte, Ramírez-Ojeda et al. (2021) [50] on wild tomatoes, to name a few.

The findings of this work constitute a basis on the edaphic and climatic requirements of some of the native bamboo species distributed in Mexico. This information is of utmost importance for the identification of ecological characteristics and distribution environments in which the evaluated species can thrive optimally. The results can be used to identify potential areas of establishment of the species for commercial purposes.

In addition, this information can be used in order to generate strategies for the conservation and identification of material in danger of extinction due to climate change or with potential use as a source of germplasm for the development of new varieties of bamboo adapted to specific edaphoclimatic conditions.

This work is only a small part of the ecogeographic characterization of the Mexican native bamboo species. It is worth mentioning that it is extremely important to continue with the evaluation of the environments and ecological patterns that determine the distribution of the native species of bamboo in Mexico.

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