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Posted Date: 4 September 2023

doi: 10.20944/preprints202309.0149.v1

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Ecogeography of *Dioscorea remotiflora* Kunth Reveals Its Potential in Regions Already Affected by Climate Change

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Abstract: *Dioscorea remotiflora*, a perennial climbing herbaceous plant wild and native to México, bears tubers of important ethnobotanical and nutritional value. However, the information for its production and use is precarious. The objective of this research was to characterize the adaptation habitats of *D. remotiflora* in order to determine its ecological descriptors and current distribution, as well as to model its potential distribution. A comprehensive database encompassing 481 geo-referenced accessions was assembled. Using the Agroclimatic Information System for México and Central America (SIAMEXCA), 42 environmental variables were formulated. The MaxEnt model within the Kuenm R-package was employed to predict the species distribution. The findings reveal a greater presence of *D. remotiflora* in harsh environments, characterized by arid to semi-arid conditions, poor soils, and hot climates with long dry periods. The plant's nutritional and medicinal attributes, combined with its ecological adaptability, suggest its viability within evolving regional cropping systems under the influence of climate change. Niche modeling revealed that seven key variables determine the geographical distribution of *D. remotiflora*: precipitation of the warmest quarter, precipitation of the driest month, minimum temperature of the coldest month, November-April solar radiation, annual mean relative humidity, annual moisture availability index, and May-October mean temperature. Favorable regions for *D. remotiflora* coincide with its current presence sites, while other suitable areas, such as the Yucatan Peninsula, Northeast region, and Gulf of México, offer potential expansion opportunities for the species distribution. The characterization obtained for *D. remotiflora*, together with the description of its edaphic and climatic adaptation habitats, will enable an efficient design of strategies for its use and conservation in the near future.

Keywords: *Dioscorea remotiflora*; mexican endemic species; niche modeling; ecological descriptors; climatic adaptation

1. Introduction

Dioscorea remotiflora is a monocotyledonous, perennial, and climbing plant, with heart-shaped leaves, dioecious flowers, and seeds in axillary clusters. It belongs to the *Dioscoreaceae* family [1] and is one of the native species of México from the genus *Dioscorea* [2,3]; currently, it is considered an endemic species [4]. Although *D. remotiflora* is not a cultivated plant, its roots, tubers, and rhizomes are collected since prehistoric times to be used as food [5], they contain 85% carbohydrates, 7.35% proteins, 3.76% lipids, and 3.68% minerals (K, Fe, Na, and Mg), therefore, it is used as a healthy snack or even as a gourmet dish [6,7]. The tubers contain secondary metabolites such as steroids, saponins,

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and diosgenin, though in low concentration [7], thus, they are not used for the extraction of diosgenin. Currently, *D. remotiflora* is considered an underutilized species; being a factor that contributes to this, the lack of research on this species; Up to now, the reports regarding the description of the ecology, climatic adaptation, and potential distribution of *D. remotiflora* are bare and insufficient; this hinders the design of strategies for its conservation and optimal use [8,9]. Therefore, the objective of this research was to use the occurrence data of *D. remotiflora*, in its natural distribution areas, to conduct an eco-geographical analysis in order to elucidate the contribution of several ecological descriptors in determine its current distribution, identify its adaptation patterns, and develop optimal Maxent models of potential geographic distribution, through the use of the Kuenm R-package, which automates the creation, calibration, and evaluation of ecological niche models [10].

Plant growth and distribution are the results of the species' response to the environmental complex that prevails in the occurrence sites [11,12], where aspects of climate, soil, vegetation, and others concur. As a species moves from its center of origin to other geographic regions, it finds it necessary to adapt to different environmental conditions. Whether the adaptation process is successful, then the species will have colonized new territories, extending its distribution, and thus, its adaptation environmental scope, which usually triggers the increase of its tolerance to abiotic and biotic stress [13]; this aspect may not be manifested uniformly in all the eco-geographic populations of the species [14], and, moreover, the novel traits may be the result of the action of genetic or epigenetic adaptation processes [15,16] with the possibility of simultaneous and complementary action of both mechanisms [16].

D. remotiflora is distributed mainly in the central, southern, and western regions of México [17], generally in dry deciduous tropical forests [18,19], which indicates its adaptive capacity to diverse environments [20]. This is why characterizing the ecogeography of a plant species considering their all accessions and populations is a key aspect.

With the presence of climate change in agricultural areas, and the increasing environmental stress for crops, food production must face the challenge with productive plant species that are resistant to drought and heat (main types of abiotic stress in México; [21]. However, in various regions of México, the crop pattern is reduced due to a short growing season with a low availability of rainwater [22]. In these cases, it is necessary to explore new crop species, for which a characterization study is required such as the one addressed in the present investigation for *D. remotiflora*.

2. Results

2.1. Selection of environmental variables

The Spearman correlation analysis enabled to reduce from 42 to 20 environmental variables to be used in further analysis [23,24]. Furthermore, preliminary tests with MaxEnt revealed that of the 20 variables, seven are the most relevant in determining the distribution of *D. remotiflora*.

2.2. Current distribution, climatic adaptation and ecological descriptors

Figure 1 shows the current distribution of *D. remotiflora* in the agroclimatic regions of México, as shown, this species is found predominantly in the areas near the Mexican Pacific coast, mainly in the central and southern portions. A greater presence of *D. remotiflora* is observed in the agroclimatic regions: Humid-subhumid semi-warm (98 accessions), Dry-subhumid semi-warm (88 accessions), Humid-subhumid warm (67 accessions, and Dry-subhumid warm (66 accessions). However, *D. remotiflora* is present in 15 of the 29 agroclimatic regions of México (Table 3), which enables this species to develop in thermal zones from semi-cold to very warm and in hydric zones from semi-arid to humid.

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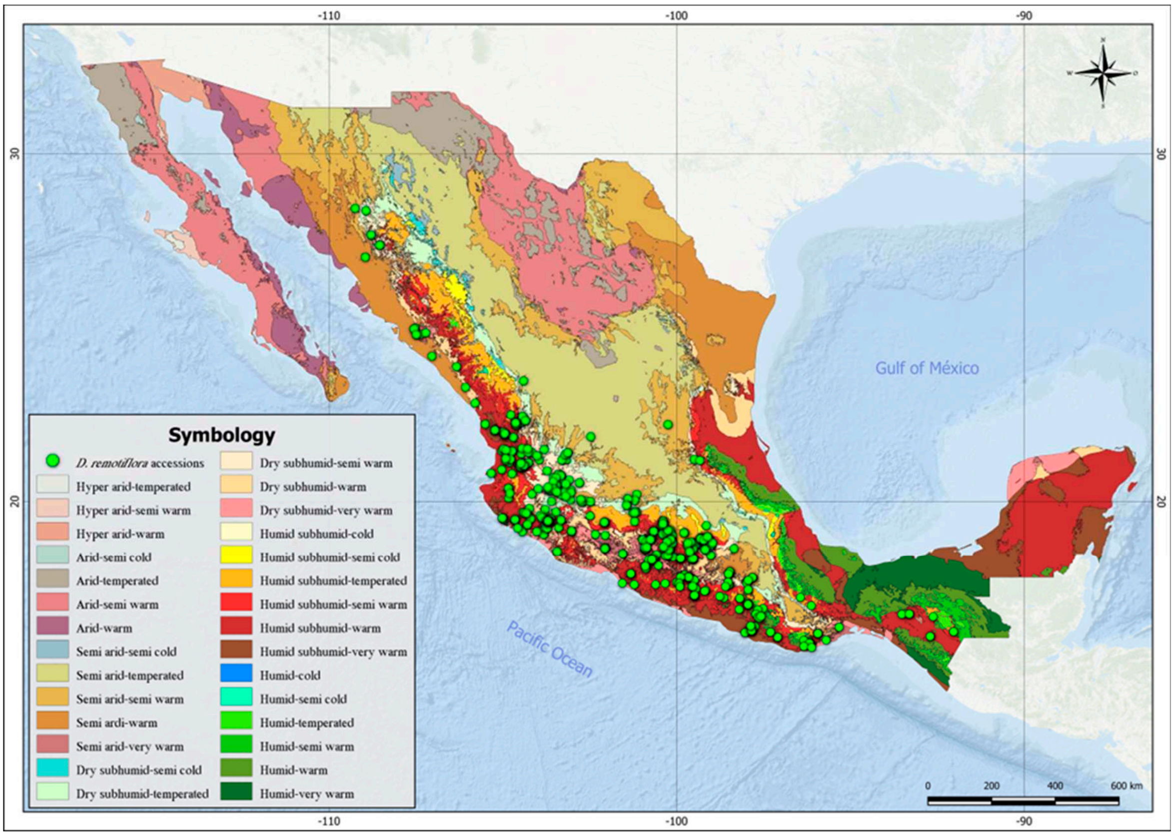

Figure 1. The current distribution of *D. remotiflora* in the agroclimatic regions of México.

Table 3. Annual mean temperature and annual moisture availability index intervals for 17 agroclimatic regions with the presence of *D. remotiflora* in México.

Agroclimatic Region	Annual moisture availability index	Annual mean temperature (°C)	Total Accessions
Semiarid very warm	0.2 - 0.5	>26	17
Semiarid warm	0.2 - 0.5	22 - 26	22
Semiarid semi-warm	0.2 - 0.5	18 a 22	14
Semiarid temperate	0.2 - 0.5	12 a 18	3
Dry-subhumid very warm	0.5 - 0.65	> 26	20
Dry-subhumid warm	0.5 - 0.65	22 – 26	**66**
Dry-subhumid semi-warm	0.5 - 0.65	18 – 22	**88**
Dry-subhumid temperate	0.5 - 0.65	12 – 18	7

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Humid-subhumid very warm	0.5 - 0.65	>26	19
Humid-subhumid warm	0.65 - 1.0	22 - 26	**67**
Humid-subhumid semi-warm	0.65 - 1.0	18 – 22	**98**
Humid-subhumid temperate	0.65 - 1.0	12 - 18	11
Humid very warm	>1.0	>26	2
Humid warm	>1.0	22 - 26	26
Humid semi-warm	>1.0	18 - 22	12
Humid temperate	>1.0	12 - 18	6
Humid semi-cold	>1.0	5 - 12	3

Table 4 shows the FAO soil units and the textural classes in which *D. remotiflora* is distributed. As can be seen, most of the occurrence sites of this species are distributed in the following soil types: Lithosol (144 accessions), Calcaric Regosol (98 accessions), Eutric Regosol (99 accessions) and Haplic Faozem (45 accessions).

Table 4. Soil units and soil texture classes with the presence of *D. remotiflora*.

FAO Soil Unit	Soil Texture	Total Accessions
Lithosol	Coarse	108
Regosol calcaric	Coarse	57
Regosol eutric	Coarse	209
Faozem haplic	Coarse	34
Vertisol cromic	Fine	39
Solonchak ortic	Fine	22
Fluvisol eutric	Medium	10
Fluvisol calcaric	Coarse	1

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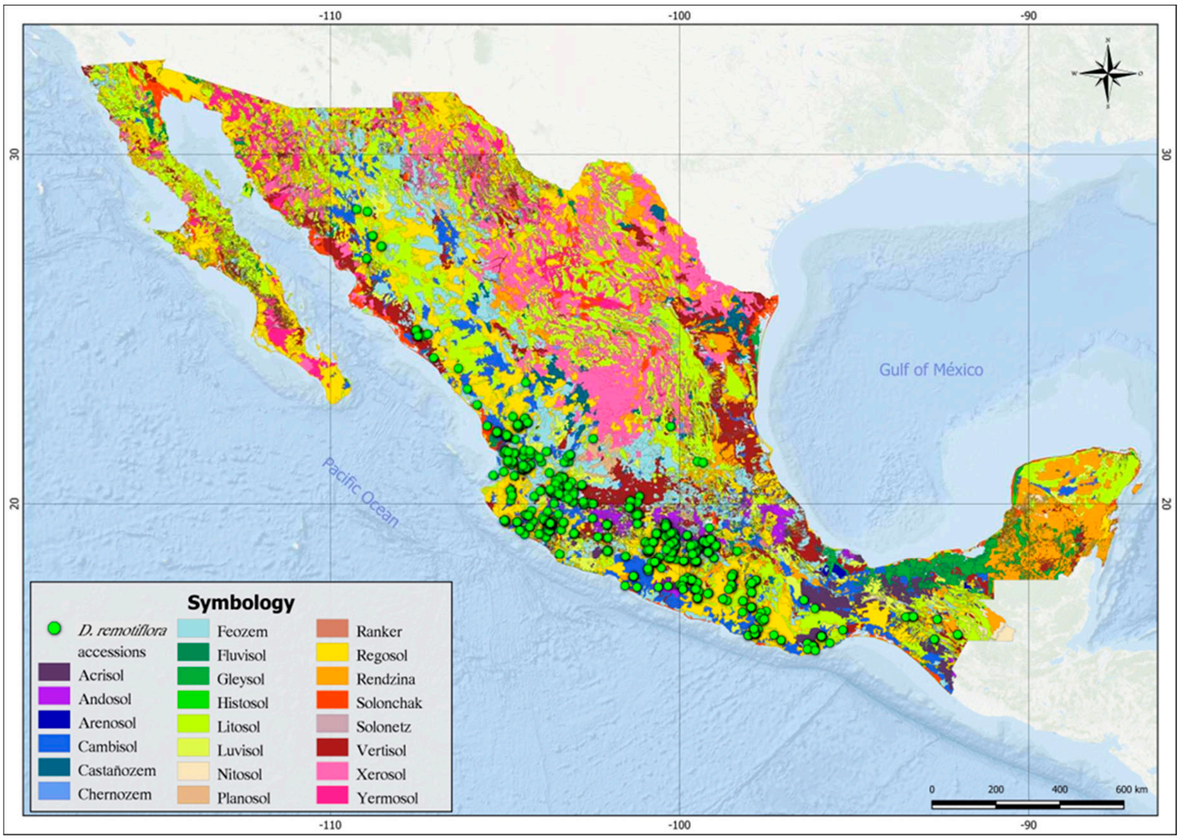

Figure 2. Current distribution of *D. remotiflora* in soil units of México.

Table 5 shows the ecological descriptors of *D. remotiflora*, which contain the environmental adaptation ranges (RAA) of the species (minimum and maximum values of environmental variables that allow the presence of *D. remotiflora*, and the optimal environmental range (RAO), which makes possible the higher frequency of occurrence sites of this plant. According to the information in Table 5, *D. remotiflora* is distributed in environments with an annual moisture availability index (MAI) ranging from 0.27 to 2.32, with an optimal range of 0.40 to 0.99, which corresponds to an RAA and RAO of an annual precipitation interval of 444 to 2886 and 700 to 1299 mm, respectively. This plant prefers areas where precipitation in the wettest quarter ranges from 400 to 884 mm, although it tolerates conditions from 240 to 1204 mm. This species can tolerate a long season (November-April) with low precipitation, even with an accumulation of only 23 mm in those six months (Table 5). The optimum growing season goes from 120 to 150 days, although it grows in regions with a growing season as long as 120-190 days.

Altitudinally, *D. remotiflora* is present from 6 to 4295 masl, but most of the presence sites occur between 200 and 800 masl. This encourages this species to develop in areas with an average annual temperature between 14.7 and 28.5°C, with an optimum of 19 to 27°C, an extreme monthly average maximum temperature of 41.2°C (Maximum maximorum temperature) and an extreme monthly average minimum temperature of 1.7°C (Minimum minimorum temperature). Both in the seasonal periods May-October and November-April, the interval in which the greatest number of accessions occurs is from 19 to 26°C, very similar to the optimum average annual temperature. Regarding soil properties, *D. remotiflora* is present in coarse, medium and fine textured soils, but prefers its presence is more abundant in coarse-textured soils, the number of occurrence sites decreases markedly in medium and fine-textured soils, indicating a clear preference of the species for soils with excellent drainage.

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Table 5. Ecological descriptors for *D. remotiflora*.

Environmental variables	Min	Max	Optimum
1.Precipitation of the warmest quarter (mm)	240	1,204	400-884
2.Precipitation of the driest month (mm)	1	73	1-7
3.Annual mean precipitation (mm)	444	2,886	700-1299
4.May-October mean precipitation (mm)	344	1,943	700-1199
5.November-April mean precipitation	23	863	30-100
6.Annual moisture availability index	0.27	2.32	0.40-0.99
7.November-April availability index	0.026	1.83	0.030-1,300
8.May-October availability index	0.005	1.47	0.009-1.4
9.Maximum maximorum temperature (°C)	24.61	41.17	29-37
10.Minimum minimorum temperature (°C)	1.7	18.2	5-15
11.Annual mean temperature (°C)	14.66	28.51	19-27
12.May-October mean temperature	9.13	29.88	19-26
13.November-April mean temperature	7.95	27.83	19-26
14.Annual thermal oscillation (°C)	10.42	19.54	13.16
15.Annual temperature range (°C)	1.54	14.52	3-7
16.Soil texture	Arenoso	Fina	Media
17.May-October mean photoperiod (h)	12.5	12.9	12.6-12.9
18.November-April mean photoperiod (h)	10.97	11.47	11.10-11.39
19.Growing season			120-190
20.Altitude (mm)	6	4,295	200-1800

Min= Minimum value; Max= Maximum value; Optimum= Optimal range.

2.3. Modeling distribution niches of D. remotiflora

Due to Maxent not being exempt from the effects of collinearity and the fact that these can intervene in the estimation of the factors, as well as inferring the uncertainties when the models are transferred spatially and temporally [25], and with the purpose of obtaining an accurate model with a reduced number of variables, eliminating the possibility of obtaining an over-fit or over-parameterized model[10]; the Kuenm R-package allowed, through ecological niche modeling, optimizing the number of environmental variables, leaving only 7, due to their greater contribution to the presence and distribution of *D. remotiflora*. The results of the Jackknife statistical test of factorial importance reported that the most determining environmental variables in the presence and distribution of *D. remotiflora* are: precipitation of the warmest quarter (42.4%), mean precipitation of the driest month (17.5%), minimum temperature of the coldest month (15%), November-April mean solar radiation (10%), annual mean relative humidity (8.5%), annual moisture availability index (5.7%), and May-October mean temperature (0.9%) (Table 6).

Table 6. Contribution of seven environmental variables to depict the presence and distribution of *D. remotiflora.*

Environmental variables	Contribution (%)	Permutation importance (%)
Precipitation of the warmest quarter (mm)	42.4	49
Pprecipitation of the driest month (mm)	17.5	2.8
Minimum temperature of the coldest month (°C)	15	31
November-April mean solar radiation (w/m²)	10	0.8
Annual mean relative humidity (%)	8.5	3.6
Annual moisture availability index	5.7	7.4
May-October mean temperature (°C)	0.9	5.3

Based on the results obtained through the Jackknife test, three sets of cases were analyzed: "only with variable", "without variable" and "with all variables" [26], thus revealing the effects of environmental variables in the appropriate range of *D. remotiflora* (Figure 3). Among these environmental variables, it was found that solar radiation from November to April was the most relevant, with a regularized training gain greater than 0.8. In addition, other variables of significant importance were identified, such as the precipitation of the warmest quarter, the annual humidity index, relative humidity, the minimum temperature of the coldest month, the precipitation of the driest month, and the average temperature from May to October. In all these cases, the regularized training gains exceeded 0.6.

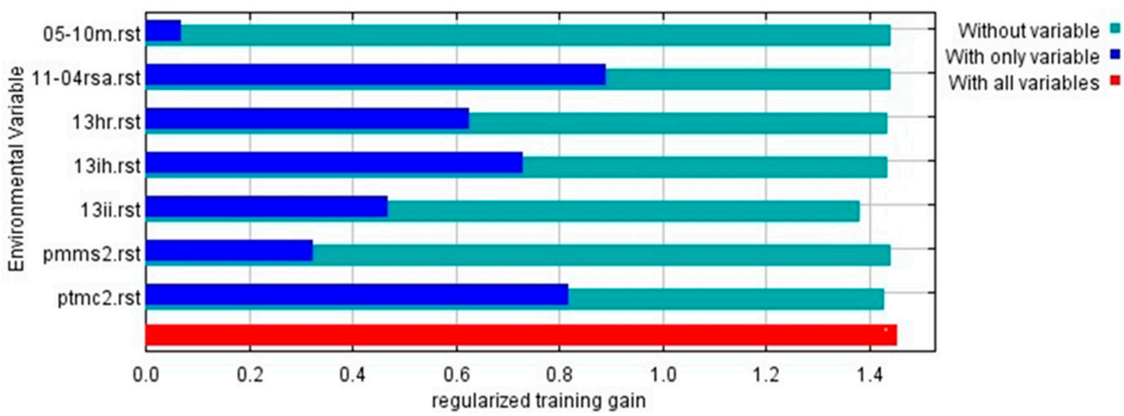

Figure 3. Results of jackknife test of the relative importance of predictor environmental variables in MaxEnt model for *D. remotiflora* in México.

Kuenm R-package enabled to obtain 372 models (Figure 4), all of them significant, however, only two models positively met the Akaike criterion (AIC=0) and a maximum omission rate of 5%. The

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Kuenm R-package implemented with MaxEnt determined that 3.0 was the optimum regularization multiplier. The model finally selected to depict the distribution of *D. remotiflora* was judged excellent since the AUC of the ROC curve accounted for 0.935.

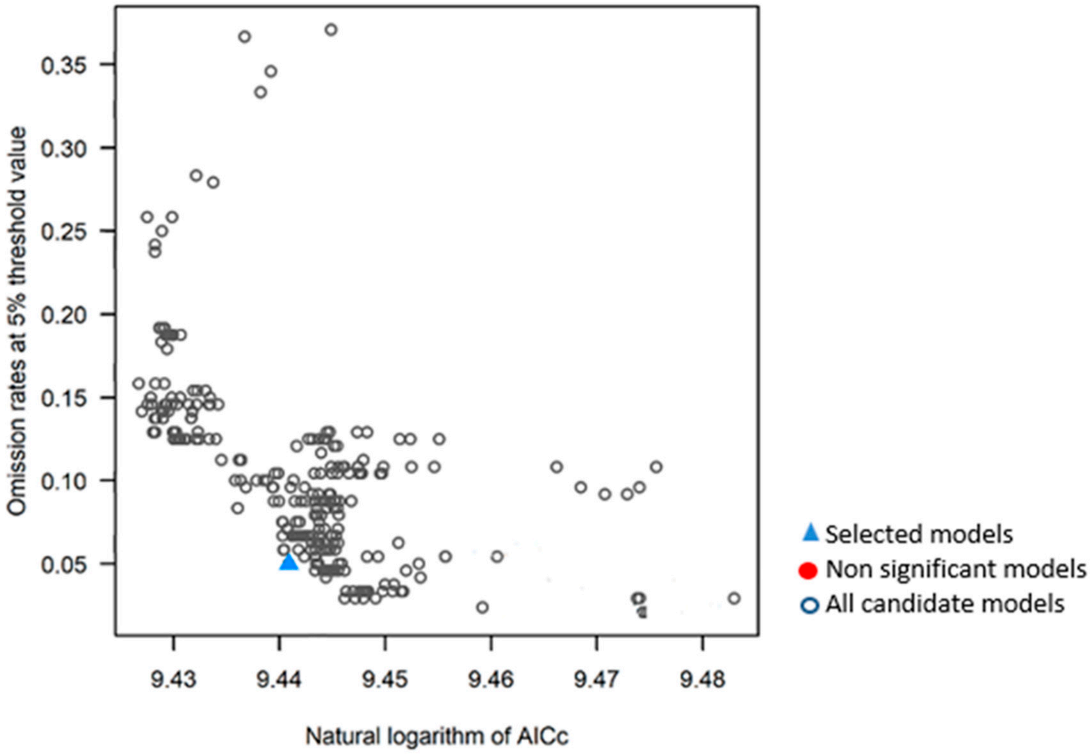

Figure 4. Models obtained and evaluated by Kuenm R-Package for *D. remotiflora.*

Figure 5 shows the current and potential distribution of *D. remotiflora* based on thresholding the environmental suitability with the "Balance training omission, predicted area, and threshold value" criterion. The map in Figure 4 shows four types of areas: areas not suitable (white color), areas with low environmental suitability (light green), areas with medium suitability (dark green), and areas highly suitable for *D. remotiflora* presence (dark grey), which matches the largest number of occurrence sites. The total potential distribution area for *D. remotiflora* accounted 428,747.68 km^2, distributed as follows: The areas with low suitability account for 150,547.104 Km2 and are located in Sonora, north Sinaloa, Guanajuato, Querétaro, México State, coasts of Guerrero, center Oaxaca, Chiapas, Campeche, San Luis Potosí, south Tamaulipas, and Veracruz. The areas with medium suitability cover 127,817,096 km2 and locate in southern Sonora, southern Chihuahua, northern Sinaloa, the coasts of Nayarit, Jalisco, Michoacán, Guerrero, Oaxaca, and Chiapas. The highly suitable areas resulted in 150,383.48 km2 (dark gray), and are located in Sinaloa, Nayarit, Jalisco, Colima, Michoacán, Morelos, little portions of Puebla and Tamaulipas, northern Guerrero, and the coasts of Oaxaca. As can be seen in Figure 4, there are potential areas in regions where the presence of *D. remotiflora* has not yet been reported, which indicates territories that could be the target of future exploration of new populations. This is the case of the Peninsula of Yucatán, center Veracruz, southeastern San Luis Potosí, southern Tamaulipas, Guanajuato, northeastern Jalisco, northern Sinaloa, northern Hidalgo, and western México state.

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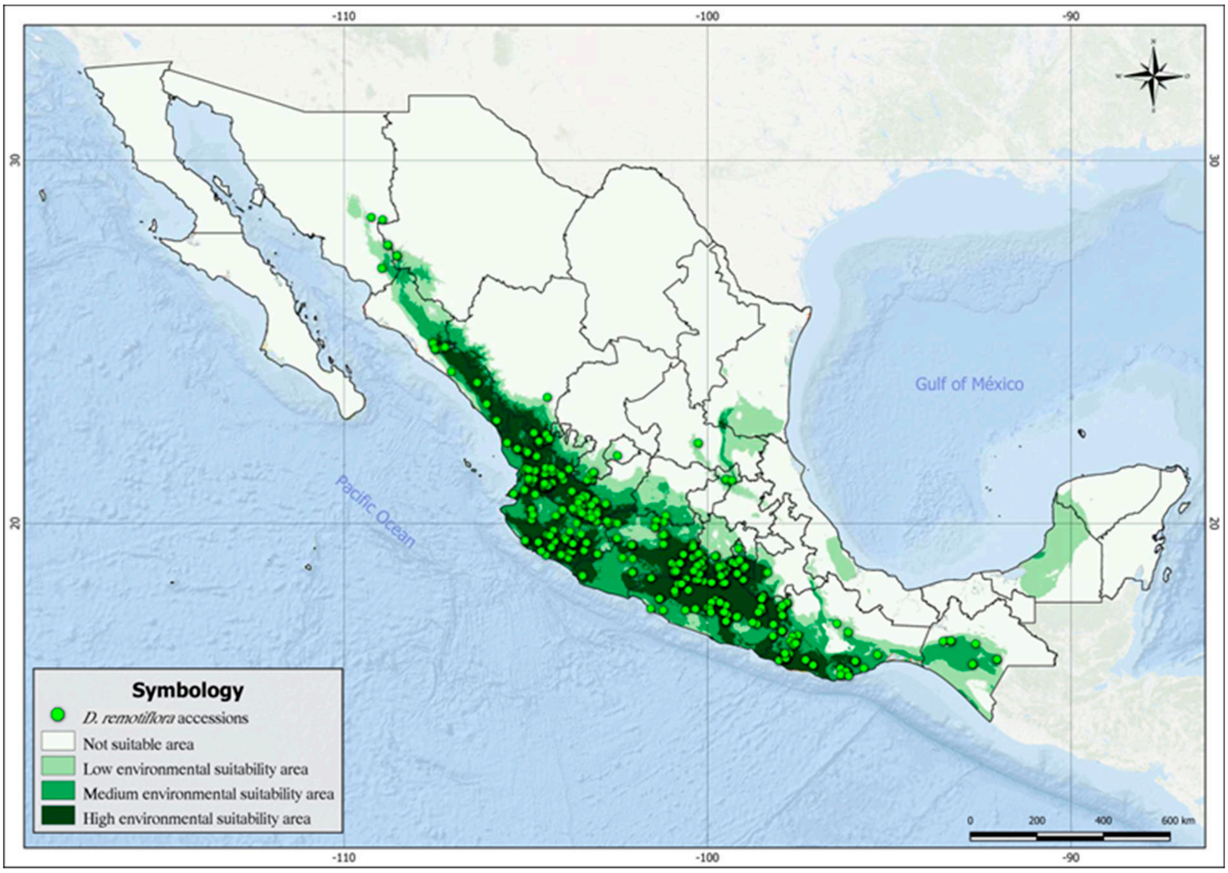

Figure 5. Areas with environmental suitability for *D. remotiflora* in México.

3. Discussion

3.1. Current distribution, climate adaptation and ecological descriptors

Most of the *D. remotiflora* occurrence sites are concentrated amongst the dry-subhumid and humid-subhumid agroclimatic regions with the warm and semiwarm variants, with an annual mean temperature between 19 and 27°C and an annual moisture availability index (MAI) between 0.4 and 0.99 (Table 4). These results agree with the ones reported by [2] who indicate that *D. remotiflora* is distributed in areas with semi-warm, warm and sub-humid climates, ranging from the northern portion to the central region of México. However, an interesting aspect is the climatic extremes in which *D. remotiflora* can adapt, meaning that even when most of the occurrence sites of this species are located between 700 and 1299 mm of annual rainfall, there are populations that subsist with 444 mm per year, and on the other extreme, other populations do it in sites with 2886 mm of precipitation per year. When combined with annual potential evapotranspiration data, these precipitation values translate into MAI values from 0.27 to 2.32, which according to arid zones scheme from UNEP (Middleton & Thomas, 1997; adapted by Ruiz et al., 2004); match with semiarid to very wet lands. Regarding this, [28] mentions that some species of *Dioscorea* adapt to dry periods and can survive under conditions of water deficit better than many other species and crops. This seems to be the case of *D. remotiflora*, according to the ecological indicators obtained. The presence of populations of *D. remotiflora* in extremely humid sites (2886 annual mm and MAI > 2) could be explained in sites with excellent soil drainage or to consider those data as an indicator of the ability of this species to colonize habitats typically unsuitable for its development [18].

Regarding the variable precipitation of the warmest quarter, which was the most significant for the presence of *D. remotiflora* in the MaxEnt modelling, Table 4 indicates a range of 240 to 1,204 mm, with an optimal range of 400-884 mm. Considering then that *D. remotiflora* is present in sites with a minimum annual rainfall of 444 mm, and that, from those millimeters at least 240 must occur in the warmest quarter [29](Avalo and García, 2021), we can conclude that this plant has the ability to adapt and develop in environments with an irregular distribution of precipitation, which may also represent a comparative advantage of *D. remotiflora* in relation to other species. This also leads to conclude that *D. remotiflora* is a species that adapts more to moderate to low humidity conditions, thus, the very humid orarid environments are not conducive to high productivity of this species. The results obtained also coincide with previous reports related to the adaptation of the genus *Dioscorea* to tropical and subtropical zones, with tolerance of some species to conditions of water deficit [28,30].

The environmental characterization of the presence sites of *D. remotiflora* shows that there is a greater number of accessions of this plant in Lithosol, calcaric Regosol and eutric Regosol soils, which do not offer the best conditions for the development of vegetation and crops [31]. According to [32], Leptosols (Litosols and Rendzinas) represent 28.3% of the Mexican territory and are characterized by very thin, stony and poorly developed soils, that can contain a large amount of calcareous material, which immobilizes mineral nutrients. They are common in mountainous areas and on shallow limestone plains. Their agricultural potential is limited by their shallow depth and high compaction, which makes them difficult to work on. On the other hand, Regosols are considered very young soils that develop on unconsolidated material, light in color and poor in organic matter. They are common in arid, semi-arid (including the dry tropics) and montaneous regions, they can be found associated to Leptosols and with rock or tepetate outcrops. From the above, it can be deduced that *D. remotiflora* has a great adaptive capacity to poor soils, with non-optimal agroclimatic conditions for the rest of the species, which may be an attribute that makes this species an alternative for cultivation in regions where climate change is deteriorating the environmental conditions of agricultural production systems [33].

Regarding soil texture, according to Table 4, *D. remotiflora* prefers coarse-textured soils, typical of Lithosol and Regosol soils, which do not store a large amount of water. Unlike other species of the *Dioscorea* genus, *D. remotiflora* is susceptible to tuber putrescence [18], therefore it requires well-drained soils. The presence of *D. remotiflora* detected in medium-textured soils is related to the occurrence of lower annual precipitation levels (735.6 mm on average) than those of sites with coarse-textured soils (1034 mm on average), which ensures that even in soils that store more moisture, it is possible for this species to adapt, as long as the volumes of precipitation are not high; this compensatory effect has been previously reported for diverse crop species [34].

According to table 4, *D. remotiflora* can tolerate an extreme monthly average minimum temperature of 1.7°C and, on the other hand, it can survive an extreme monthly average maximum temperature of 41.7°C, with annual thermal oscillations ranging from 10 to 20° C and with an optimal annual thermal range of 13 to 16°C, fact that shows the wide range of thermal conditions in which this plant can survive, and this includes temperature regimes that are classified as very extreme [35]. Other species of the genus *Dioscorea* have shown tolerance to extreme thermal environments, such as *D. divaricata*, which can tolerate temperatures as low as -18°C. The occurrence of these extreme minimum temperatures, however, causes delayed full maturity and reached until 3 to 4 years after [36].

On the other hand, extreme temperatures are generally considered a source of dormancy in postharvest tubers and seeds [37]. [28] mentions that the dormancy of the tubers of the *Dioscorea* species lasts 120 days, which limits their agricultural production; this indicates an aspect that should be worked on in the immediate future to make *D. remotiflora* a more promising agricultural species. [37] report that tuberization is induced by environmental cues such as short days, low temperatures, and higher soil moisture content.

Another important aspect in the development of this species is photoperiod since it intervenes in the formation and growth of leaves and tubers; there are differences among *Dioscorea* species in relation to their response to photoperiod. In the case of *D. remotiflora*, in the long-day season, which is from May to October, foliar growth is favored, and in short days, the growth and swelling of the tuber are stimulated, promoting the production and storage of starches [38]. In Table 4, it can be observed that the optimal range of photoperiod for exhibiting adequate leaf growth is from 12.6 to 12.9 h, and for good tuber development the optimal range is from 11.10 to 11.39 h.

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3.2. Modeling of distribution niches of *D. remotiflora*

The Kuenm R-package implemented with MaxEnt, allowed to obtain an optimal niche model to appropriately depict the *D. remotiflora* distribution in México; based on the requirements of statistical significance, the optimal regularization multiplier, the feature classes, and the omission rate established, the analysis process with Kuenm produced two possible models (Figure 4). One of them was selected, which can be considered a good decision since it fulfills the requirements established [39], and the AUC of the ROC curve accounted for a value greater than 0.93 [40]. The AUC value is an important tool to assess model performance, the higher the AUC value (closer to 1) the better the model performance is [41,42]. The Jackknife test identified the most determining variables for the presence of *D. remotiflora*, the precipitation of the warmest quarter, precipitation of the driest month, minimum temperature of the coldest month, November-April solar radiation, annual mean relative humidity, annual moisture availability index, May-October mean temperature. However, the Jackknife test indicates that the most important variable is solar radiation from November to April (Figure 3). These results agree with what was reported by [43], who mentions that the production of diosgenin, corticosteroids, carbohydrates, and other compounds produced by these species are subject to solar radiation. On the other hand, these results agree with those reported by Viruel et al. (2014) who pointed out that the environmental variables of major influence for the presence of *Dioscorea humilis* are the precipitation of the wettest quarter, the precipitation of the warmest quarter, and the precipitation of the coldest quarter. On the other hand, [43] report that for 10 species of the *Dioscorea* genus, the variables that are most important and intervene in the production of secondary metabolites are annual precipitation and average annual radiation.

The capabilities observed in the present research by *D. remotiflora*, to develop in adverse environments, could be explained through the ability to adjust its metabolism and modify its morphological characteristics, such as the size and thickness of the leaf, allowing it to adapt to extreme conditions, where other species fail to thrive [44,45].

The current distribution of *D. remotiflora* obtained in the present research (Figure 4), agrees with that reported by [46], who mentions that this species is distributed in Chiapas, Chihuahua, Colima, Durango, Guanajuato, Jalisco, Oaxaca, Guerrero, Michoacán, Guerrero, Nayarit, Puebla, Tamaulipas, Tabasco, and Zacatecas; which represents areas along the foot of the Sierra Madre Occidental, the Sierra Madre del Sur and its confluence with the Transversal Neovolcanic Axis, where coniferous and oak forests are found, these two, are home to herbaceous and forest communities with presence of endemism [47]. However, the distribution, diversity, and structure of populations are strongly influenced by historical, geographical, and climatic events [48], which also trigger speciation processes [49,50]. These arguments explain the number of species of the genus *Dioscorea* and the differences between them in terms of environmental ranges. On the other hand, the areas of high environmental suitability are located on the Mexican Pacific coast; this location suggests that optimal conditions of agroclimatic variables exist in these areas for the development of this plant. In contrast, in the areas of medium and low environmental suitability, it is possible that the species is adapting to agroclimatic ranges that go from very arid to very humid, moving to the central part of México. These areas, therefore, have the potential to establish crops of the species. However, it is important to note that the classification of environmental suitability areas may be modified by the effects of climate change [51], thus, a complementary research regarding potential distribution áreas under climate change scenarios would be required.

3.3. *D. remotiflora* cultivation prospects

Currently, *D. remotiflora* is a plant that is exploited for human consumption, but basically through the collection of tubers in its natural habitat (Figure 5). However, it presents favorable characteristics to integrate into regional crop patterns, given its comparative advantages regarding other plant species, such as its adaptation and production in poor, shallow, and infertile soils, as well as its tolerance to drought, since it does not have a high water requirement for its development. Besides, some characteristics inherent to the species should be taken into account before considering it, as a cultivation option, such as the fact that sexual propagation is not considered a viable alternative up to now, due to the fact that the seeds it produces are attacked by pests, damaging 60 to 80% of them; thus, the health of the seeds should be ensured through pest control or opting for asexual propagation through the sprouting of tubers. However, the tubers have a prolonged dormancy of up to 120 days, which is a limitation to program their propagation. This leads to the need of exploring some of the available techniques to reduce the duration of dormancy and accelerate the germination process.

4. Materials and Methods

4.1. Occurrence data

1,030 geo-referenced accessions from herbaria, floristic inventories, scientific articles and databases were identified, later on, they were reviewed to eliminate repeated records, records with poor geographic coordinates, and those out of the study area [52]. These strategies were used to avoid considering accessions that correspond to introductions outside the natural areas of distribution [53]. Finally, 480 records were selected (Table 1).

Table 1. Occurrence data sources for *D. remotiflora*.

Institution/source	Institution/Department	Accessions
Universidad Nacional Autónoma de México (UNAM).	Instituto de Biología	169
Instituto de Ecología (INECOL).	Xalapa Veracruz	30
Universidad Autónoma de Querétaro (UAQ).	Facultad de Ciencias Naturales	3
Instituto Nacional de Estadística y Geografía (INEGI).	Departamento de Botánica	2
Universidad Autónoma de Aguascalientes (UAA).	Centro de Ciencias Básicas	2
Universidad Autónoma de Veracruz (UPAV) (CIB).	Instituto de Investigaciones Biológicas	1
Universidad Autónoma de San Luis Potosí (UASLP).	Instituto de Investigación de Zonas Desérticas	3
Colegio de la Frontera Sur (ECO SUR).	Herbario San Cristóbal	3
Universidad de Guadalajara (CUCBA, CUC SUR).	Herbario IBUG, Herbario ZEA	6
Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán.	Herbario Facultad de Biología Universidad Michoacana de San Nicolás de Hidalgo	6

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Artículos científicos/Inventarios florísticos de los estados de Oaxaca, Chiapas, Veracruz, Tabasco, Guerrero, Puebla, Jstor Plant Science.		20
Universidad Autónoma de Nuevo León (UNL).	Facultad de Ciencias Biológicas	1
La Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO).	Herbario digital de CONABIO	3
Trópicos.org.		3
Red de Herbarios del Noroeste de México.		13
GBIF		215
Total		480

4.2. Climatic data

Monthly, quarterly, seasonal, and annual rasters of precipitation, temperature, solar radiation and relative humidity were used to determine potential distribution areas of *D. remotiflora*. These climatic data were obtained from the Agroclimatic Information System for México-Central America (SIAMEXCA) [21]. The raster images have a resolution of 30″ of arc and correspond to the period 1961-2010. From the SIAMEXCA rasters, other additional variables were generated adding a total of 42 environmental variables (Table 2).

Table 2. Environmental variables considered in this research.

Variable	Description	Temporal scale
BIO01	(Annual mean temperature)	Annual
BIO02	Mean diurnal range	Variation
BIO03	Isothermality	Variation
BIO04	Temperature seasonality	Variation
BIO05	(Maximum temperature of the warmest month)	Month
BIO06	(Minimum temperature of the coldest month)	Month

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BIO07	Temperature annual range	Annual
BIO08	(Mean temperature of the wettest quarter)	Quarter
BIO09	(Mean temperature of the driest quarter)	Quarter
BIO10	(Mean temperature of the warmest quarter)	Quarter
BIO11	(Mean temperature of the coldest quarter)	Quarter
BIO12	Annual precipitation	Annual
BIO13	Precipitation of the wettest month	Month
BIO14	Precipitation of the driest month	Month
BIO15	Precipitation seasonality	Variation
BIO16	Precipitation of the wettest quarter	Quarter
BIO17	Precipitation of the driest quarter	Quarter
BIO18	Precipitation of the warmest quarter	Quarter
BIO19	Precipitation of the coldest quarter	Quarter
N-AMT	November-April mean temperature	Seasonal
M-OMT	May-October mean temperature	Seasonal
M-OXT	Maximum temperature May-October	Seasonal
N-AXT	November-April maximum temperature	Seasonal
AXT	Annual maximum temperature	Annual
M-OIT	May-October minimum temperature	Seasonal
N-AIT	November-April minimum temperature	Seasonal
AIT	Annual minimum temperature	Annual
ATO	Annual thermal oscillation	Annual
M-OP	May-October precipitation	Seasonal
N-AP	November-April Precipitation	Seasonal
M-OPH	May-October photoperiod	Seasonal
N-APH	November-April photoperiod	Seasonal
AMI	Annual moisture index	Annual
M-OMI	May-October mean moisture index	Seasonal
N-AMI	November-April mean moisture index	Seasonal

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ASR	Annual mean solar radiation	Annual
M-OSR	May-October mean solar radiation	Seasonal
N-ASR	November-April solar radiation	Seasonal
ARH	Annual relative humidity	Annual
M-ORH	May-October relative humidity	Seasonal
N-ARH	November-April relative humidity	Seasonal
GSL	Growing season length	Seasonal

BIO = Bioclimatic variable.

4.3. Environmental characterization of the occurrence sites

Based on the geographic coordinates of the *D. remotiflora* occurrence sites, an environmental characterization of these sites was carried out using the 42 variables mentioned in Table 2. For this, data extraction procedures were done, out from the raster images, using the ArcMap software version 10.8 [54]. With data extracted from the 42 variables, an environmental data matrix (EDM) was built in Microsoft Excel.

4.4. Selection of environmental variables

Prior to the execution of the statistical analysis, the Shapiro-Wilk test was applied to verify the data normality, not finding normality ($P<0.05$) for any of the data series within the 42 environmental variables included in the EDM.

Diverse studies have shown that multicollinearity is a problem that can cause high correlations among independent variables, a fact that can lead to unreliable and unstable estimations of the regression coefficients [55]. For determining the presence of multicollinearity, a Spearman correlation coefficient $r > 0.9$ was established as a threshold value [39]. In this way, the correlated variables with an $r <0.9$ coefficient were selected, and among the variables with collinearity, the one considered the most relevant for the presence of the species was selected. Data from the EDM were used to perform the correlation analyses; this statistical analysis was carried out with programs developed in the R software version 4.05 [56] and with normalized data. The result of these analyses reported 20 useful variables, later Preliminary analyses were carried out in MaxEnt individually and in conjunction with the Kuenm R-package in order to use the Jackknife test to select the most relevant variables in the distribution of *D. remotiflora* and thus carry out the final modeling of the ecological niche.

4.5. Characterization of the adaptive capacity of D. remotiflora.

Based on the geographic location of the *D. remotiflora* occurrence sites, the agroclimatic regions, soil units, and vegetation types where the species is currently distributed were characterized. For this purpose, the map of agroclimatic regions of México and Central America was used [13], as well as the soil units map and the vegetation types map for México [57]. This made possible the elaboration of a list of the edapho-climatic conditions to which *D. remotiflora* currently adapts and its preference for certain hábitats [58.

In addition, the ecological descriptors for *D. remotiflora* were determined by using the EDM information, but only taking into account the 20 environmental variables that were selected after the correlation-colinearity analysis. The ecological descriptors were established in terms of environmental ranges for *D. remotiflora* adaptation, and optimal environmental ranges for *D. remotiflora* presence, which corresponded to the highest frequency of occurrence sites.

4.6. Ecological niche modeling

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Ecological niche modeling was done by using Maxent model, which uses the principle of maximum entropy with species presence and environmental data to create a correlative model that relates the ecological requirements of a species with the regional environmental availabilities to predict the relative habitat suitability, also it allows deriving specific descriptors for enriching the ecological characterization of the territories [59–61]. We used the Kuenm R-package [10,56,62] to automate and optimize the Ecological Niche Modeling (ENM) process. Kuenm's Kuenm_ceval function creates preliminary models [63] with occurrence data and environmental predictors, and also evaluates the efficiency of these models through their statistical significance with the cal_eval function, in addition, the relative quality of the model is evaluated by using the Akaike Information Criterion (AIC), corrected for small sample sizes (AICc) [10]. Kuenm also enables to assess diverse regularization muliplier (RM) factors, combinations of feature classes (FC) and different groups of environmental predictors, as well as to establish the allowable omission rate (OR). For each parameter setting, two models are created: one based on the complete set of occurrences, and the other based only on the training data. For this research, models were tested using a sequential order of the FC (L, LQ, H, LQH, LQHP, LQHPT) and RM values of 0.1 to 5 with 0.1 increases, a maximum omission rate of 5%, and run 50 k-fold replicates of each configuration; 500 iterations were used [64]. The *D. remotiflora* occurrence sites and the ASCII files for the 20 variables selected after correlation-collinearity analysis were used as inputs in the ENM process with Kuenm R-package.

5. Conclusions

D. remotiflora is an endemic species from México, whose tubers are collected in their natural habitat for human consumption. *D. remotiflora* is mostly adapted to semi-warm to warm environments and to semi-arid to sub-humid climates with a long dry season. However, the whole range of environmental adaptation of *D. remotiflora* also includes extremely humid, temperate, and very warm habitats, which indicates a high adaptive capacity of this species. In addition, *D. remotiflora* has a greater presence in regions where very thin, stony, poorly developed, and low-fertility soils predominate. All these characteristics make *D. remotiflora* a species with comparative advantages to develop in edapho-climatic environments that are adverse for most crop species. However, the greater presence of *D. remotiflora* occurrence sites indicates optimal environmental conditions, under which the development and productivity of the species would be expected to be maximum. In this way, populations of *D. remotiflora* proliferate in soils of coarse texture, in low to midlands, with annual precipitation of 700 to 1300 mm, and annual mean temperature of 19 to 27°C.

D. remotiflora is currently distributed in the western portion of México, along regions bordering the Mexican Pacific, which hints at its center of geographic origin. Niche modeling identified precipitation of the warmest quarter, precipitation of the driest month, mean minimum temperature of the coldest month, November-April mean solar radiation, Annual mean relative humidity, Annual moisture availability index, and May-October mean temperature as the variables with the greatest contribution to explain the presence of *D. remotiflora*. Furthermore, the Kuenm R package enabled the selection of a niche model that optimized the depiction of the potential distribution areas for this species. Thus, potential areas with high environmental suitability for *D. remotiflora* were located in the Mexican States where this species is already present, and potential areas with low to mid environmental suitability were identified in regions with the current presence of *D. remotiflora* as well as regions where it has not yet been reported, as in the Yucatan Peninsula, Northeast region, and the Gulf of México.

The cultivation perspectives of *D. remotiflora* are favorable considering its capacity to adapt to harsh environments, and that its nutritional and medicinal properties are valuable, however, the prolonged dormancy of its tubers is one of the intrinsic aspects of this plant that limits its offer as a cultivation option.

The information generated in this research will make it possible to learn more about the distribution, adaptation, and ecology of this species, which can also contribute to the design of conservation strategies for *D. remotiflora* and to the planning and selection of potential areas for its cultivation.

Currently, plant genetic resources worldwide are facing the pressure of overexploitation and environmental change, resulting in habitat fragmentation and biodiversity threats. To ensure the permanence of these natural resources, it is essential to maintain or increase the resilience of these systems against these pressures (Ten Broeke et al., 2019; Gülçin, 2021). Therefore, an efficient conservation management model must be adopted to address these changes and adequately preserve this plant genetic resources.

References

1. Hussein, I; Mengs, B; Matiwos, T Effect of Plant Growth Regulators on in Vitro Propagation of Yam Landraces (*Dioscorea* Species) Using Nodal Segments. *Journal of Biology Agriculture and Healthcare* **2018**. *8*, 13-23. https://core.ac.uk/ download/pdf/234662712.pdf.
2. Rodríguez, RR; Téllez, VO Las *Dioscoreas* (Dioscoreaceae) del Estado de Morelos, México. *Anales del Instituto de Biología. Serie Botánica* **1992**, *63*, 67-99. https://www.redalyc.org/pdf/400/40063104.pdf.
3. Castañeda, NJJ; Santacruz, RF; de Jesús SGJ; Parra, JR; De la Cruz, LL; Barba, R Shading and Container Effects on the Weight of the *Dioscorea sparsiflora* Tuber. *Agronomy Journal* **2017**, *109*, 33-38. https://doi.org/10.2134/agronj2015.0452.
4. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO). https://enciclovida.mx/especies/192190-dioscorea-remotiflora: (Consulted September 9 2022).
5. Obidiegwu, JE; Akpabio, EM The geography of yam cultivation in southern Nigeria: Exploring its social meanings and cultural functions. *Journal of Ethnic Foods* **2017**, *4*, 28-35. https://doi.org/10.1016/j.jef.2017.02.004.
6. Akissoé, N; Hounhouigan, J; Mestres, C; Nago, M How blanching and drying affect the color and functional characteristics of yam (*Dioscorea cayenensis-rotundata*) flour. *Food Chemistry* **2003**, *82*, 257-264. https://doi.org/10.1016/S0308-8146(02)00546-0.
7. Montañez, SJL; Venegas, GJ; Bernardno, NA; González, CL; Yañez, FJ Chemical Characterization and Nutritional Evaluation of Mountain's yam (*Dioscorea remotiflora* Kunth). *Tubers* **2014,** *5*, 153-160. https//doi: 10.15515/abr.0976-4585.5.2.153160.
8. Bernabe, AA; Santacruz, RF; Cruz, SF Effect of plant growth regulators on plant regeneration of *Dioscorea remotiflora* (Kunth) through nodal explants. *Plant Growth Regulation* **2012,** *68*, 293-301. https://doi 10.1007/s10725-012-9717-z.
9. Obidiegwu, JE; Lyons, JB; Chilaka, CA The *Dioscorea* Genus (Yam) An Appraisal of Nutritional and Therapeutic Potentials. Foods 2020, *9*, 1304. https://doi:10.3390/foods9091304.
10. Cobos, ME; Peterson, AT; Osorio, OL; Jiménez GD; An exhaustive analysis of heuristic methods for variable selection in ecological niche modeling and species distribution modeling. *Ecological Informatics* **2019**, *53*, 100983. https://doi.org/10.1016/ j.ecoinf.2019.100983.
11. Chandra, A; Naithani, HB; Verma, PK; Saxena, J; & Prajapati, S. Plant diversity assessment of selected forest sites of Gaya district of Bihar, India. *Journal of Applied and Natural Science* **2021**, *13*, 424-432. https://doi 10.22092/WMEJ.2017.115733.
12. Ghorbani, A; Bahrami, B The influence environmental factors on the distribution of plant species in the southeast rangelands of Sabalan. *Watershed Management Research Journal* **2017**, *30*, 15-29. https://doi 10.22092/WMEJ.2017.115733
13. Sánchez, GJDJ; Ruiz, CJA; García, GM; Ojeda, GR; Larios, LDLC; Holland, JB; García, RGE Ecogeography of teosinte. *PLoS One* **2018,** *13*, e0192676. https://doi 10.1371/journal.pone.0192676.
14. Aburto-Cansino, GN; Ruiz-Corral, JA; Sánchez González, JDJ; & González Eguiarte, DR Temperaturas cardinales de desarrollo del teocintle (Zea spp.). *Revista mexicana de ciencias agrícolas* **2018** 9, 1269-1281. https://doi.org/10.29312/remexca.v9i6.1587.
15. Grativol, C; Silva HA; and Gomes, FP. Genetic and epigenetic regulation of stress responses in natural plant populations. *Biochimica et Biophysica Acta* (BBA) - Gene Regulatory Mechanisms **2012,** *1819*, 176-185. https://doi.org/10.1016/j.bbagrm.2011.08.010.
16. Ashapkin, VV; Kutueva, LI; Aleksandrushkina, NI; & Vanyushin, BF Epigenetic mechanisms of plant adaptation to biotic and abiotic stresses. *International journal of molecular sciences* **2020,** *21*, 7457. http://doi:10.3390/ijms21207457.
17. Sosa, V; Nova, J Linajes de angiospermas endémicas en México: zonas de alto endemismo para la conservación. *Acta Botánica Mexicana* **2012**, *100*, 293-315. https://abm.ojs.inecol.mx/index.php/abm/article/view/38.
18. Santacruz, RF; Casas, SJF; Pérez, PR; Rodríguez, GE; Torres, MMI; Castillo, HC; Iturbe SI; Conservación, manejo y aprovechamiento del camote de cerro (*Dioscorea* spp.) en el estado de Jalisco, México. *Avances de la Investigación Científica en el CUCBA*. XVI: **2005**, 179-183. http://www.floradejalisco.cucba.udg.mx /sites/default/files/publicaciones1/avances/avances_2005/Agronomia/SantacruzRuvalcabaFernando/SantacruzRuvalcabaFernando.pdf.

19. Miranda, AG; Soto, JLM; Ruiz, IG. Parcial caracterización de nuevos almidones obtenidos del tubérculo de camote del cerro (*Dioscorea* spp). *Revista Iberoamericana de Tecnología Postcosecha* **2008**, *9*, 81-88. https://www.redalyc.org /pdf/813/81311226011.pdf.
20. González, VME El ñame (*Dioscorea* spp.) Características, usos y valor medicinal. Aspectos de importancia en el desarrollo de su cultivo. *Cultivos Tropicales* **2012.** *33*, 05-15. http://scielo.sld.cu/scielo.php?pid=S0258-59362012000400001& script=sci_ arttext&tlng=en.
21. Ruiz, CJA; Medina, GG; García, RGE Sistema de información agroclimática para México-Centroamérica. *Revista Mexicana de Ciencias Agrícolas* **2018**, *9*, 1-10. https://doi:10.29312/remexca. v9i1.843.
22. Barrera-Sánchez, CF; Ruiz-Corral, JA; Zarazúa-Villaseñor, P; Lépiz-Ildefonso, R; & González-Eguiarte, DR Cambio climático y distribución potencial de frijol lima en Mesoamérica y Aridoamérica. Revista Mexicana Ciencias Agrícolas **2020** 11, 1361-1375. https://doi.org/10.29312/remexca.v11i6.2412.
23. Dormann, CF; McPherson, JM; Araujo, MB; Bivand, R; Bolliger, J; Carl, G Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. *Ecography* **2007**, *30*, 609–628. https://doi. org/10.1111/j.2007.0906-7590.05171.x.
24. Peterson, AT; Nakazawa, Y Environmental data sets matter in ecological niche modelling: an example with Solenopsis invicta and Solenopsis richteri. *Global Ecology and Biogeography* **2008,** *17*, 135–144. https://doi. org/10.1111/j.1466-8238.200700347.
25. Feng, X., Park, DS; Liang, Y; Pandey, R; Papeş, M Collinearity in ecological niche modeling: Confusions and challenges. *Ecology and evolution* **2019**, *9*, 10365-10376. https://doi.org/10.1002/ece3.5555.
26. [26] Xu, Y; Zhu, R; Gao, L; Huang, D; Fan, Y; Liu, C; Chen, J. Predicting the current and future distributions of *Pennisetum alopecuroides* (L.) in China under climate change based on the MaxEnt model. *Plos one* **2023,** e0281254. https://doi.org/10.1371/journal.pone.0281254.
27. UNEP (United Nations Environmental Program). World Atlas of Desertification 2 ed.; Middleton N. and Thomas D. S. G: London, UK,1997. pp 1-182.
28. Rodríguez, W Botánica, domesticación y fisiología del cultivo de ñame (*Dioscorea alata*). *Agronomía Mesoamericana* **2000**, *11*, 133-152 https://www.redalyc.org/pdf/437/ 43711221.pdf.
29. Avalo, DMR; García, MB Producción y diversificación sostenible del cultivo de ñame (*Dioscorea* spp.) en condiciones de sequía agrícola en el municipio de Jiguaní. *Agrisost* **2021**, *27*, 1-7. https://revistas.reduc.edu.cu/index.php/agrisost/article/view/ e10333-1.
30. Velázquez, HJM; Durán, PN; Ruiz, CJA; González, EDR; Santacruz, RF; Gallegos, RA. Distribución geográfica y usos de especies del género *Dioscorea. E-cucba* **2022**, *19*, 141-150. https://doi.org/10.32870/ecucba.vi19.273.
31. Mueller, L; Schindler, U; Mirschel, W; Shepherd, TG; Ball, BC; Helming, K; Rogasik, J; Eulenstein, F; Wiggering, H Assessing the productivity function of soils. *A review. Sustainable Agriculture* **2010**, *30*, 601 - 614 https://doi.org/10.1007/978-94-007-0394-0_33.
32. INEGI Suelos. Instituto Nacional de Estadística y Geografía. D. F México 2007. pp 36 https://apps1. semarnat.gob.mx:8443/dgeia/informe_12/pdf/Cap3_suelos.pdf.
33. López, FAJ; Hernández, CD Cambio climático y agricultura: una revisión de la literatura con énfasis en América Latina. *El trimestre económico*. **2016**, *83*, 459-496. http://dx.doi.org/10.20430/ete.v831332.231.
34. Ruiz, CJA.; Medina, GG. González, AIJ. Flores, LHE. Ramírez, OG. Ortiz, TC. Byerly, MKF. Requerimientos agroecológicos de cultivos, 3ª ed.; INIFAP-Prometeo Editores: Jalisco, México, 2013; pp. 564. https://www.researchgate.net/publication/343047223_REQUERIMIENTOS_AGROECOLOGICOS_DE_CULTIVOS_2da_Edicion.
35. García, E. *Modificaciones al Sistema de Clasificación Climática de Köppen (Para adaptarlo a las condiciones de la República Mexicana)*, 5ª Edición.; Instituto de Geografía-UNAM: Ciudad de México, México, 2004; pp. 90. http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/book/83.
36. Thompson, AK; Oduro, I. Yams: Botany, Production and Uses, 1ªed.; CABI: Boston, USA, 2021; pp. 296 https://doi.org/10.1079/ 9781789249279.0000.
37. Patricio, VEG; Rodrigo, ARJ; Isaías, MAR; Cristina, LVI; del Pilar, PMN; Santiago, EVJ; Inhibición de la brotación del tubérculo de papa: una revisión de los métodos empleados Inhibition of potato tuber sprouting: a review of the methods employed. *Journal of the Selva Andina Biosphere* **2018**, *6*, 55-64. http://scielo.org.bo/pdf/jsab/v6n2/v6n2_a04.pdf.
38. Coursey, D. *Yams: Dioscorea spp*, 2nd Edition.; In: Wiley: London, UK, 1967; pp. 70-74. https://agris.fao.org/ agrissearch/search.do?recordID=US201303063121.
39. Yang, J; Huang, Y; Jiang, X; Chen, H; Liu, M; Wang, R Potential geographical distribution of the endangered plant Isoetes under human activities using MaxEnt and GARP. *Global Ecology and Conservation* **2022**, e02186. https://doi.org/10.1016/j.gecco. 2022.e02186.
40. Abdelaal, M; Fois, M; Fenu, G., Bacchetta, G Using MaxEnt modeling to predict the potential distribution of the endemic plant Rosa arabica Crép. in Egypt. *Ecological informatics* **2019**, *50*, 68-75. https://doi.org/10.1016/j.ecoinf.2019.01.003.

41. Muscarella, R; Galante, PJ; Soley, GM; Boria, RA; Kass, JM; Uriarte, M; Anderson, RP ENMeval: an R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in Ecology and Evolution* **2014**, *5*, 1198-1205. https://doi.org/10.1111/2041-210X.12261.
42. Fois, MA; Cuena, LG; Fenu, G Bacchetta Using species distribution models at local scale to guide the search of poorly known species: review, methodological issues and future directions. *Ecol. Model.* **2018**, 124-132. https://doi.org/10.1016/j.ecolmodel. 2018.07.018.
43. Shen, L; Xu, J; Luo, L; Hu, H; Meng, X; Li, X.; Chen, S Predicting the potential global distribution of diosgenin-contained *Dioscorea* species. *Chinese medicine* **2018**, 13:58. https:// doi.org/10.1186/s13020-018-0215-8 1-10.
44. Yin, DS; Chen, F; Chen, Z; Guan WF Morpho- anatomical and physiological responses of two *Dendranthema* species to waterlogging. *Environmental and Experimental Botany*. **2010**, 68, 122-130. https://doi.org/10.1016/j.envexpbot.2009.11.008.
45. Jiménez, JDLC; Moreno, LP; Magnitskiy, S Respuesta de las plantas a estrés por inundación. Una revisión. *Revista Colombiana de Ciencias Hortícolas* **2012**, 6:1, 96-109. https://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S2011-21732012000 100010.
46. Jiménez, JDLC; Moreno, LP; Magnitskiy, S Respuesta de las plantas a estrés por inundación. Una revisión. *Revista Colombiana de Ciencias Hortícolas* **2012**, 6:1, 96-109. https://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S2011-21732012000 100010.
47. Medina, GC; Giménez, deJ; Velázquez, MA Las comunidades vegetales del bosque de coníferas altimontano en el macizo del Tancítaro, Michoacán, México. *Acta botánica mexicana* **2020**, p.127. https://doi.org/10.21829/abm127.2020.1584.
48. Schaal, BA; Hayworth, DA; Olsen, KM; Rauscher, JT; Smith, WA Phylogeographic studies in plants: problems and perspectives. *Molecular Ecology* **1998**, 465–474. https://www.researchgate.net/profile/Kenneth-Olsen-4/publication/227339 790_Phylogeographic_studies_in_plants_Problems_and_prospects/links/5dfd016da6fdcc2837318eee/Phylogeographic-studies-in-plants-Problems-and-prospects.pdf.
49. Dillon, MO; Tu, T; Xie, L; Quipuscoa, SV; Wen, J Biogeographic diversification in Nolana (*Solanaceae*), a ubiquitous member of the Atacama and Peruvian Deserts along the western coast of South America. *Journal of Systematics and Evolution*. **2009**, *47*, 457–476. https://doi.org/10.1111/j.1759-6831.2009.00040.x.
50. Schmidt, JR; Sytsma, KJ Phylogenetics of Puya (*Bromeliaceae*): placement, major lineages, and evolution of Chilean species. *American Journal of Botany* **2010**, *97*, 337–356. https://doi.org/10.3732/ajb.0900107.
51. Gao, X; Liu, J; Huang, Z The impact of climate change on the distribution of rare and endangered tree Firmiana kwangsiensis using the Maxent modeling. *Ecology and Evolution* **2022**, *12*, e9165. https://doi.org/10.1002/ece3.9165.
52. Zhao, Y; Deng, X; Xiang, W; Chen, L; Ouyang, S Predicting potential suitable habitats of Chinese fir under current and future climatic scenarios based on Maxent model. *Ecological Informatics*. **2021**, *64*, 101393. https://doi.org/10.1016/j.ecoinf.2021. 101393.
53. {53] Ramírez, OG; Peralta, IE; Rodríguez, GE; Sahagún, CJ; Chávez, SJL; Medina, HTC; Rodríguez, PJE Edaphoclimatic Descriptors of Wild Tomato Species (*Solanum* Sect. Lycopersicon) and Closely Related Species (*Solanum* Sect. Juglandifolia and Sect. L*ycopersicoides*) in South America. *Frontiers in genetics* **2021**, 12. https://doi.org/10.3389/fgene.2021.748979.
54. Environmental Systems Research Institute (ESRI) ArcGIS Desktop: Release 10. Environmental Systems Research Institute. Redlands, CA, USA. 2010, 1 p5. https://earthobservations.org/about_geo.shtml.
55. O'brien, RM Caution Regarding Rules of Thumb for Variance Inflation Factors. *Qual Quant* **2007,** *41*, 673–690. https://doi.org/10.1007/s11135-006-9018-6.
56. Core, T.R. R.A., Language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.Austria. (Versión 4.2.1). 2021. https://www.R-project.org/.
57. INEGI., 2017. Conjunto de datos vectoriales de edafología serie 4, escala 1:250,000. Aguascalientes: Instituto Nacional de Estadística y Geografía. https://www. inegi.org.mx/temas/edafologia/.
58. Thouverai, E; Marcantonio, M; Lenoir, J; Galfré, M; Marchetto, E; Bacaro, G; Rocchini, D Integrals of life: Tracking ecosystem spatial heterogeneity from space through the area under the curve of the parametric Rao's Q index. *Ecological Complexity* **2023**, *52*, 101029. https://doi.org/10.1016/j.ecocom.2023.101029 .
59. Phillips, SJ; Anderson, RP; Schapire, RE Maximum entropy modeling of species geographic distributions. *Ecological Modelling* **2006**, *190,* 231-259. https://doi: 10.1016/j.ecolmodel.2005.03.026.
60. Elith, J., Phillips, SJ; Hastie, T; Dudík, M; Chee, YE; Yates, CJA Statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* **2011,** *171,* 43-57. https://doi 10.1111/j.1472-4642.2010.00725.x.
61. Warren, DL; Seifert, SN Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecological applications* **2011**, *21*, 335-342. https://doi.org/10.1890/10-1171.1.

 doi:10.20944/preprints202309.0149.v1

62. Mazzolari, AC; Millán, EN; Bringa, EM; Vázquez, DP Modeling habitat suitability and spread dynamics of two invasive rose species in protected areas of Mendoza, Argentina. *Ecological Complexity* **2020**, *44*, 100868. https://doi.org/10.1016/j.ecocom.2020.100868.
63. Gull E; Fareen, A; Mahmood, T; Bodlah, I; Rashid, A; Khalid, A; Mahmood, S. Modeling potential distribution of newly recorded ant, Brachyponera nigrita using Maxent under climate change in Pothwar region, Pakistan. *PLoS One* **2022**, *17*, e0262451. https://doi.org/10.1371/journal.pone.0262451.
64. Cao, Y; DeWalt, RE; Robinson, JL; Tweddale, T; Hinz, L; Pessino, M Using Maxent to model the historic distributions of stonefly species in Illinois streams: The effects of regularization and threshold selections. *Ecological Modelling* **2013**, *259*, 30-39. https://dx.doi.org/10.1016/j.ecolmodel.2013.03.012.