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Different Criteria for Evaluation of the Conservation Status of *Ceratozamia Miqueliana* (Zamiaceae)

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Abstract

Ceratozamia miqueliana is a cycad (Zamiaceae) species endemic to southeastern Mexico. It is currently listed on the International Union for Conservation of Nature (IUCN) Red List as "Critically Endangered" and under Mexican law as "Endangered". The objective was to complement the evaluation of *C. miqueliana* based on criterion B of the IUCN, and the method proposed by the Mexican Norm. This information is in turn reinforced with the potential distribution model. We collected data from different herbaria and field visits and obtained the EOO and AOO using GIS and the GeoCat portal, the distribution of the species was modeled using the Maxent program. According to the IUCN guidelines (Geographic distribution, Criterion B) and Mexican law, the species could be considered Endangered and Subject to Special Protection, respectively. The comparison of AOO and EOO obtained by GIS and the GeoCat portal show that both methodologies used coincide in assigning the same categories based on geographic criteria. The integration of the potential distribution helps to identify the environmental factors that influence its habitat, in addition to identifying the ideal sites for its conservation. Is necessary to carry out evaluations of microendemic species such as *Ceratozamia miqueliana* from different approaches (populations, geographic aspects and habitat evaluation) to obtain more precise results. *C. miqueliana* must be protected by national and international laws.

Keywords

cycads, endangered species, endemic, IUCN, maxent, potential distribution

The cycads are a group of seeding plants that have existed on Earth for approximately 270 million years (Norstog & Nicholls, 1997; Zheng et al., 2017). Their morphoecophysiological characteristics have enabled them to survive to the present day (Brenner et al., 2003), despite the considerable climatic and environmental changes the planet has undergone over that time period (Zheng et al., 2017). The global distribution of most of the species is limited to the tropics and subtropics (Fragnière et al., 2015), with 358 species currently recognized worldwide, distributed among 10 genera and three families (Calonje et al., 2013–2020). In Mexico, 54 species from three genera of the family Zamiaceae are represented: *Ceratozamia* (25 species), *Dioon* (13) and *Zamia* (16). Of these, 48 (88.9%) are

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endemic to the country (Nicolalde-Morejón et al., 2014; Vovides et al., 2004).

More than 60% of cycad species worldwide are threatened (Fragnière et al., 2015). In Mexico, species of this taxonomic group are mainly at risk because of the diminution of their habitat caused by expansion of livestock production and agricultural activities, as well as increased urbanization and illegal commercial extraction (Pérez-Farrera et al., 2006). This situation has led the international biodiversity conservation bodies (IUCN: International Union for Conservation of Nature and the Convention on International Trade in Endangered Species - CITES -), as well as Mexican law (NOM-059-SEMARNAT-2010), to consider these organisms under different degrees of threat. In southeastern Mexico, one of the cycad species affected by habitat fragmentation is *Ceratozamia miqueliana*. Under Mexican national law, this species is listed in the category "Endangered" (D) and is also on the IUCN Red List in the category "Critically Endangered" (CR). Both of these categories represent the maximum degree of risk assigned according to different criteria. In the case of the IUCN, this classification was established following the criterion A (Population size reduction); however, under the guidelines of criterion B (Geographic distribution), there is no precise data pertaining to area of occupancy (AOO) and extent of occurrence (EOO), which would be required in order to conduct a more accurate evaluation of the conservation status (IUCN, 2019).

Ceratozamia miqueliana (Figure 1) is endemic to Mexico and found in the states of Chiapas, Tabasco and Veracruz (Vázquez-Torres et al., 2010; Vovides et al., 2003). To date, knowledge of the cycads in Mexico has allowed an initial approximation of the conservation status of the species; however, there is still a requirement for detailed analysis that considers both the current and potential distribution of the species, the current size of the vegetation fragments in which they develop and the number of individuals in each population, as well as the variables that affect the occurrence of ideal conditions for their establishment.

In this study, we therefore use species distribution modeling as a method by which to analyze the abiotic variables that influence the distribution of *C. miqueliana*. The use of species distribution models has undergone considerable development (e.g., Araújo et al., 2005; Araújo & Williams, 2000; Ortega-Andrade et al., 2016) and has had implications for conservation (Araújo et al., 2002; Krömer et al., 2013; Vergara-Rodríguez et al., 2017), research into evolutionary processes (Gómez et al., 2016; Pérez et al., 2014), potential species distribution (Armenta-Montero et al., 2015; Contreras-Medina et al., 2010) and, modeling with respect to climatic change (Alfonso-Corrado et al., 2017; Prieto-Torres et al., 2016). In this study, we model the potential distribution of *C. miqueliana*, understood as the area in which the abiotic and biotic conditions are favorable for this species, as an additional approach to learn about its distribution in order to complement the information regarding its conservation status (Soberón & Nakamura, 2009).

The present study serves to complement the information available regarding the risk status of this species based on the geographic information of the IUCN criterion B and the environmental factors that influence the existing populations. The main goals of the study are: (1) to model the potential distribution of *C. miqueliana*, which increases the knowledge of the current distribution and habitat suitability and can be useful for possible future management and conservation plans; and (2) re-assess the conservation status of this species using the methods of the IUCN and Mexican law (MER, for its Spanish acronym).

Methods

Study Area

The distribution of *C. miqueliana* is limited to southeastern Mexico, in the states of Chiapas, Tabasco and Veracruz, where it inhabits tropical high evergreen and mixed deciduous forests from 0 to 1000 m asl (Martínez-Domínguez et al., 2017; Vovides et al., 2010). However, it is also found in tropical montane cloud forest, as well as in transition zones between tropical forest and oak forest at elevations exceeding 600 m asl (Castillo-Campos et al., 2011; Carvajal-Hernández et al., 2018). At elevations below 500 m asl in the zone of occurrence of the species, the warm humid climate predominates, with temperatures that range from 22 to 26 °C and some isolated sites presenting average temperatures that exceed 27 °C, with extreme maximum temperatures above 30 °C and minimum temperatures below 15 °C, and a mean annual precipitation of 1500 mm (Soto-Esparza & Giddings, 2011). In the high zone of distribution of the species, a mean annual temperature of 20.6° C and mean annual precipitation of 3638 mm are recorded.

Database and Field Sampling

The following herbariums were visited in order to identify the collection points of the species to determine their range of distribution: Institute of Ecology, Xalapa (XAL), Veracruz; Faculty of Biology, Universidad Veracruzana (XALU); National Herbarium (MEXU) of the Institute of Biology, UNAM; University of Sciences and Arts of Chiapas (HEM) and the Autonomous Juárez University of Tabasco (UJAT). We decided to carry out a review of the herbariums in order to confirm the correct identification of the species

Figure 1. (A) Adult plant of *Ceratozamia miqueliana*; (B) seedlings; (C) female cone; (D) male cone (author's photographs).

and collection data. Information from online databases was not used, since it could not be corroborated.

Based on the information obtained from the herbariums, with the knowledge of people of the local communities and previous experience of botanic explorations in the zone of distribution, the species was identified at ten sites, each in different municipalities of the three states in which the species is reported. With the exception of the locality of Las Choapas, Veracruz, the localities were all fully explored in order to corroborate the presence of the species since the collections were more than 15 years old in some cases. For example, the IUCN information for the species mentions that the Malpaso locality in Chiapas has practically disappeared, and the herbarium record of that location (from 1991) was collected in a place where it is not currently found. However, we were able to corroborate the presence of some individuals in contiguous localities (less than 5 km away).

Given that the focus of this study is to complement the knowledge regarding the geographic distribution of *C. miqueliana*, individuals were quantified in each locality but separation into age categories was not conducted within the sampling units, as would be required for a demographic study. The fieldwork was conducted in the period November 2016 to October 2017.

Conservation Status

Classification of the conservation status is based on the categories and criteria proposed in the directives of the IUCN Red List at regional level (IUCN 2019, v. 14): Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT) and Least Concern (LC). Application of these criteria was supported by land use information (Instituto Nacional de Estadística y Geografía, 2016), the software ArcGIS Version 10.2.2 of Esri® and field observations. For each species, the area of the habitat currently occupied by the taxon (AOO) and the spatial distribution of the areas currently occupied by the taxon (EOO) (IUCN, 2019, v. 14) were estimated using the software ArcGIS Version 10.2.2 of Esri®, according to the methodology established by the IUCN (2019, v. 14).

The AOO was determined using a 2 x 2 km grid placed over the area records of the species, with application of the formula recommended by the IUCN (AOO = no. of occupied cells x area of an individual cell). For the EOO, the minimum convex polygon was constructed with the Minimum bounding geometry tool with elimination of a discontinuity that added marine space. For this, the area of distribution expressed in km^2 was compared with criterion B (Geographic distribution), which considers the number of collection sites and the trends of diminution or severe fragmentation of the relevant habitat in order to assign a risk status to each species (IUCN 2019, v. 14). Moreover, based on the registration points, the open source tool Kew's GeoCat portal (http://geocat.kew.org/) was used to perform a rapid analysis for the IUCN Red List, focused on the EOO and AOO (Bachman et al., 2011).

In addition to the criteria established by the IUCN, evaluation was also conducted based on that established under Mexican law, specifically Mexican Official Norm 059-SEMARNAT-2010, in its Normative Annex II (Method to Assess the Risk of Extinction of Wild species in Mexico -MER-). This evaluation consisted of a matrix of assignation of values (scores) based on the analysis of four criteria: i) geographic distribution; ii) habitat characteristics; iii) biological vulnerability and iv) impact of human activities. The values assigned under each criterion correspond to parameters established in the evaluation format, where the species is only cataloged according to the information previously obtained through the visit to each of the localities of the species (to answer the questionnaire of the criteria of geographical distribution and habitat characteristics). Furthermore, through literature review and specialist consultation, the criteria of biological vulnerability and impact of human activities were addressed. This method even contemplates the absence of information for some factors (e.g. demographic or genetic information) (see Appendix 2 for more details) (Secretaría de Medio Ambiente y Recursos Naturales, 2010). Categorization was based on the sum of the resulting scores of the values assigned to each one of the criteria (ordered from highest to lowest threat): Endangered ($\geq$2 points), Threatened ($>$ 1.7 and $<$2) and Subject to special protection ($<$1.7).

Species Distribution Modelling

As information complementary to the evaluation of conservation status, a species distribution model was constructed. In order to determine the dispersal area of our species, we used the BAM model by Soberón and Peterson (2005), which indicates the relationship between biotic (B), abiotic factors (A) and the mobility of the species within a geographical area (M). For M, the ecoregions map (Olson et al., 2001), determined by the records of the species, was used. The area M was found to occupy two ecoregions: Sierra de Los Tuxtlas and the Petén-Veracruz moist forests.

The species presence data were analyzed on the platform ArcGis Version 10.2.2 of Esri®, identifying the points of collection and recording of individuals in the field. All points that were in an area of less than $\sim$1 km^2 (to adjust to the pixel size of the environmental variables) were selected, producing a total of 14 points, which were then integrated into the model. The cartography and variables employed were as follows: i) Global tree cover data (Hansen et al., 2013); ii) Soil map of the world (FAO-UNESCO, 2007); and iii) 20 environmental variables of WorldClim v.1.4 (Hijmans et al., 2005). These climatic databases present a resolution of $\sim$1 km^2. The package R v. 3.5.1 (R Core Team, 2018) was subsequently used to perform a test of colinearity with the variables in order to eliminate those that were most correlated (Dormann et al., 2013). In addition, corroboration with the previous knowledge of the authors regarding this group of plants was used to determine the variables of greatest importance (only 14) to the species (Appendix 1). These variables were transformed to the ASCII format with the software ArcGIS Version 10.2.2 of Esri®.

In order to determine the potential distribution of *C. miqueliana*, the program Maxent v.3.4.1 was used. This program performs species modeling based on a statistical approximation known as maximum entropy, which allows predictions to be made using incomplete information from presence data (Phillips et al., 2006). Zones that present the set of environmental conditions necessary for the potential establishment of *C. miqueliana* were estimated. The model ran with 500 interactions and the extrapolation and clamping options were deactivated, selecting 30% of the points for validation of the model. The Jackknife test for studies with small samples of $<$20 specimens (Pearson et al., 2006; Shcheglovitova & Anderson, 2013) was applied in order to indicate the variables that best explained the presence of *C. miqueliana*. After various tests in Maxent, the model that best fitted the distribution of the species observed in the field was selected.

The model was validated considering the Area Under the Curve (AUC) of the analysis of the Receiver Operating Characteristic (ROC), considering the AUC value to be between 0.5 and 1.0, in which values close to 1.0 denote good discrimination, i.e., greater probability of occurrence (Fielding & Bell, 1997). Validation was also performed with the test of partial ROC curves (Peterson et al., 2008) with values $>$1. This consists of measuring that observed against that expected, with the help of the program Tool for Partial-ROC (Narayani, 2008), with 50% of the independent evaluation points in bootstrap, 1,000 replicates and an error of omission below 5% (1-omission threshold $>$ 0.95).

Results

According to the guidelines established by the IUCN and the results of the AOO, EOO and the three conditions of criterion B (Table 1), *C. miqueliana* should be considered as endangered (EN) B2ab(iii, iv) at global level.

A total of 1,013 *C. miqueliana* individuals were counted in 10 localities (Table 2). Of the sites in which the species was found, four are within Protected Natural Areas under different categories of protection. The sites that offer the greatest area of habitat for the species correspond, in descending order, to the localities of Villa de Guadalupe in Tabasco, Malpaso in Chiapas

Table 1. Area of Occupancy (AOO) and Extent of Occurrence (EOO) With Two Different Methods for the Species *C. miqueliana*.

	IUCN (Arcgis)	GeoCat	Conditions
AOO	EN (121 Km^2)	EN (76 Km^2)	a) Number of locations: 10
EOO	VU (6,950 Km^2)	VU (7,064.878 Km^2)	b) Continuing decline observed: iii) quality of habitat; and iv) number or locations
Threatened category	EN	EN	EN

Table 2. Forest Areas That Are Still Maintained in the Different Localities Where the *C. miqueliana* Species Was Registered.

Localities (altitudinal range m asl)	Vegetation type	Surrounding vegetation	Ha	Habitat	Individuals
Villa de Guadalupe (29)	TRF, TMCF	P	5,156	Primary and secondary tree and shrub vegetation	29
Malpaso (590–660)	TRF	P	2,181	Secondary tree and shrub vegetation	19
San Martín Pajapan volcano (300–800)	TRF, OF	P	1,428	Primary vegetation	220
Moloacán (90)	TRF	P	1,161	Secondary shrub vegetation	25
Rancho el Milagro (100)	TRF	P	816	Primary and secondary tree vegetation	n/d
Amayaga (500–600)	TRF	P	605	Primary and secondary tree vegetation	49
Cerro El Vigía (800)	TRF	AGR, P	348	Secondary tree and shrub vegetation	127
Predio Benjamín (80–100)	TRF	P, HS	258	Secondary shrub vegetation	333
Jaguaroundi ecological park (35)	TRF	P, HS	172	Primary and secondary shrub vegetation	124
Majahual (170)	P	P, AGR	0	0% of primary or secondary vegetation	107
Total Ha			12,126		

Except Villa de Guadalupe (Tabasco) and Malpaso (Chiapas), the rest of the localities are in the state of Veracruz. AGR: Agriculture; HS: Human settlement; P: Pasture; OF: Oak forest; TMCF: Tropical montane cloud forest; TRF: Tropical rain forest. Source: Instituto Nacional de Estadística y Geografía, 2016.

and the San Martín Pajapan volcano in Veracruz (Table 2). It was also observed that these sites are close to zones where the influence of industrial activity is greater, for which reason the habitat of *C. miqueliana* is reduced in area. Moreover, in most of the zones in which the species is found, the vegetation has deteriorated or is secondary, derived from tropical high evergreen forest.

According to the IUCN and GeoCat methodology (Figure 2), were established in the same categories for the species, AOO in EN and EOO in VU. Comparisons of the results obtained in this study with the information available in the IUCN fact sheet pertaining to the species indicate differences in some of the evaluation criteria (Table 3). On the other hand, with respect to the categorization based on the guidelines of Mexican law, the sum of the evaluated criteria is 1.65 and, according to NOM-059, values greater than or equal to 1.5 and less than 1.7 correspond to species considered to be under special protection (Pr), as is the case of *C. miqueliana* (Appendix 2).

With respect to the potential distribution of the species (Figure 3), the model indicated an area of approximately 2567.14 km^2 (>80%). This area represents the ideal habitat occupied by the species, mainly in the core zones of Los Tuxtlas Biosphere Reserve (San Martín Tuxtla volcano, Sierra de Santa Marta, San Martín Pajapan volcano), the region of Coatzacoalcos in Veracruz and the west and east of the state of Tabasco (Figure 3). The environmental variables that best explain the probability of occurrence of the species are: soil (68%), forest (26%), elevation (3%), precipitation in the driest month (2%) and mean temperature in the warmest quarter (1%), based on Jackknife. The AUC and partial ROC values were 0.97 and 1.40, respectively. This indicates that the actual and potential distribution values are very similar and the model therefore presents an adequate level of confidence, since the probability of error is less than 1%.

Discussion

Conservation Status

The evaluation indicated that, according to criterion B of geographic distribution of the IUCN and given its increase in AOO/EOO and number of localities, the species could be considered as Endangered (EN) rather than

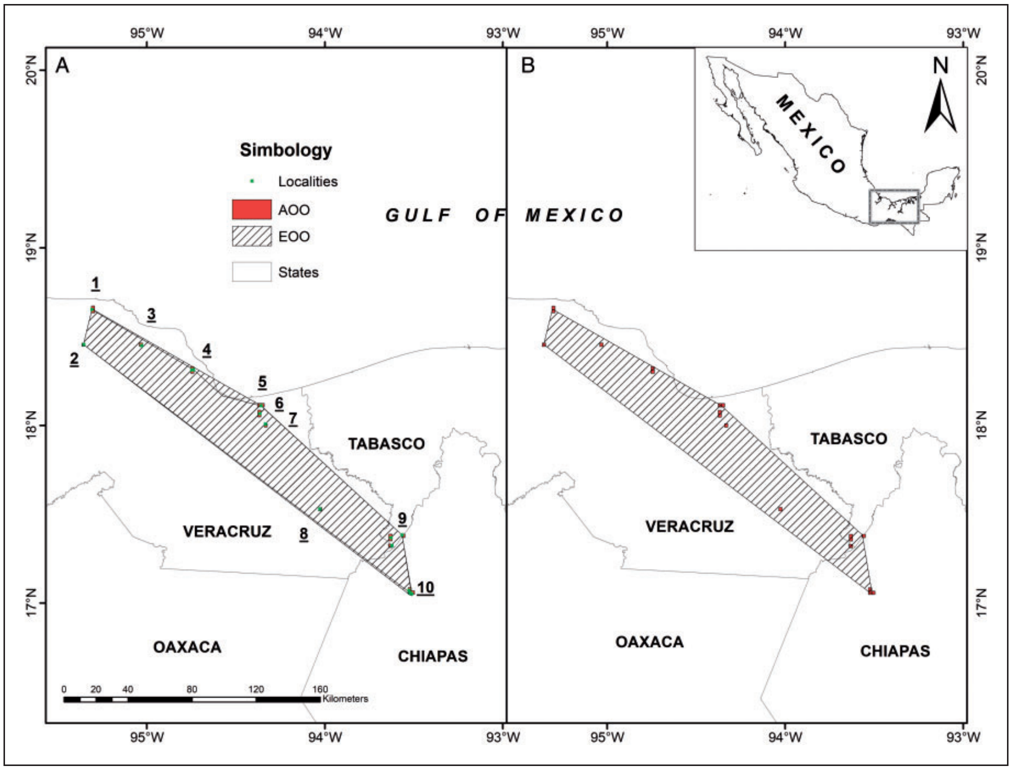

Figure 2. Area of occupancy (AOO) and Extent of occurrence (EOO) with two different methods for the species *C. miqueliana*. (A) Methodology established by IUCN through GIS; (B) Analysis through the GeoCat portal.

Table 3. Comparison Between the Data Available on the IUCN Fact Sheet for *Ceratozamia miqueliana* (Vovides et al., 2010) and the Results Obtained in the Present Study.

Criteria	IUCN (Vovides et al., 2010)	Present study
Area of occupancy (AOO)	Unknown $>$ 10 km^2	121 km^2
Extent of occurrence (EOO)	6,925 km^2	6,950 km^2
Number of localities	2–5	10
Elevational range (m asl)	60–800	30–1,000
Number of individuals	600-800	+ 1,000
Status	Critically endangered (CR) A2acd	Endangered (EN) B2ab(iii, iv)

Critically Endangered (CR). According to the criteria of NOM-059, however, it could be considered in the lower risk category of Subject to Special Protection (Pr), rather than Endangered (D).

For this species in particular, there are some localities in which the conditions necessary for its permanence prevail; e.g., those found within protected natural areas, such as the populations of Amayaga and Pajapan, or in the private conservation zones such as the Jaguaroundi ecological park and Predio Benjamín, Veracruz. This serves to increase the possibilities for permanence. These latter zones are destined for conservation, and Predio Benjamín in particular is a site declared as a private conservation area with a management plan dedicated to the propagation and conservation of *C. miqueliana*.

The comparison of AOO and EOO obtained by GIS (ArcGis) and the GeoCat portal shows that both evaluations assigned the Endangered (EN) category according to the AOO, and the Vulnerable (VU) category when the EOO results were considered. For this reason, according to the IUCN, the category that should be assigned in cases like this is that of the highest risk (EN). With this, it is corroborated that the two methodologies used coincided in terms of assigning the same categories based on geographic criteria.

In Jaguaroundi and Predio Benjamín, the population is formed both by individuals that originate in the

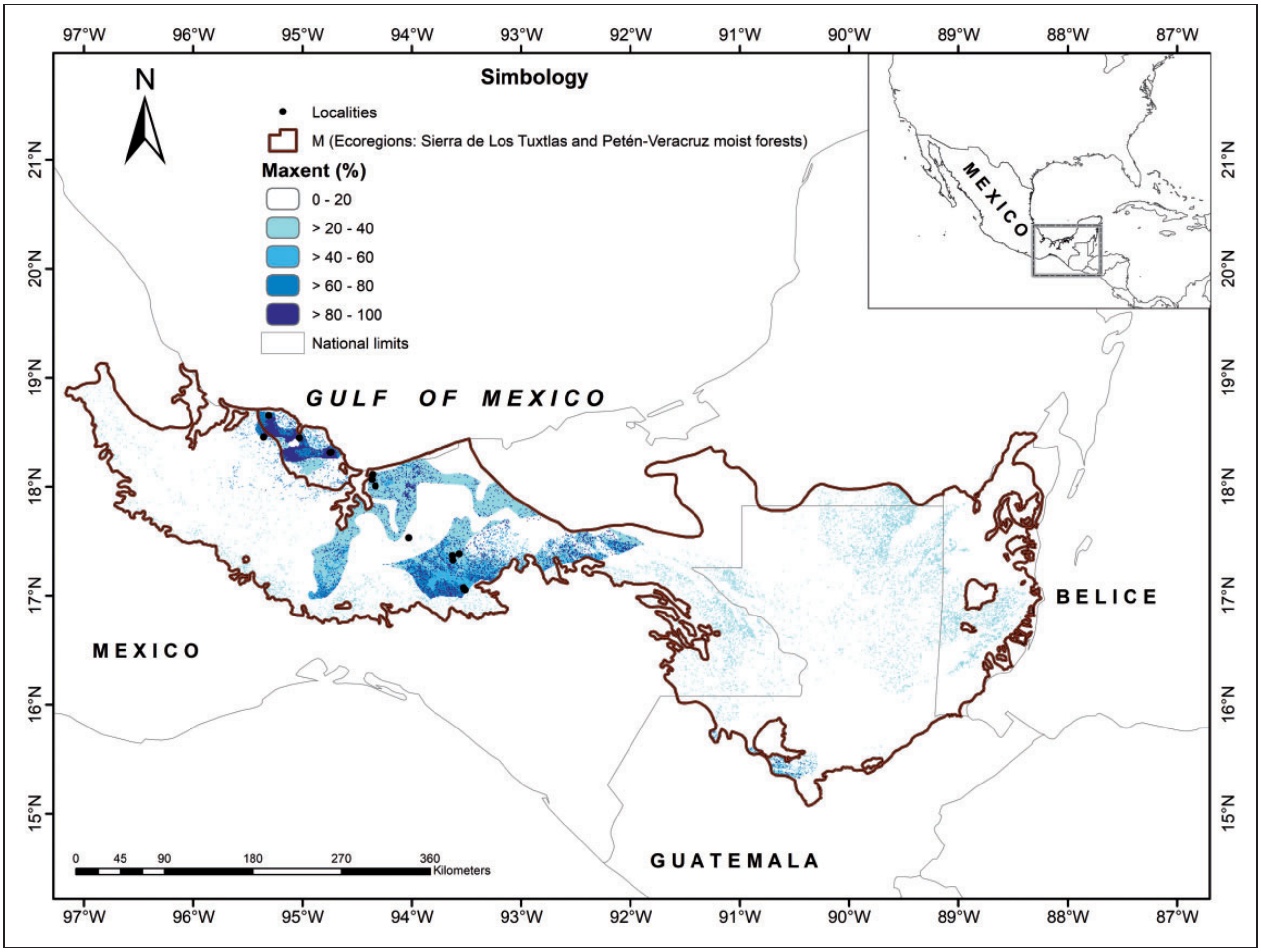

Figure 3. Actual and potential distribution of *Ceratozamia miqueliana* according to the model of maximum entropy (Maxent). The tones in dark blue represent a higher probability of suitable habitat. The localities in which the species was recorded are: 1. Laguna de Majahual; 2. El Vigía; 3. Amayaga; 4. San Martín Pajapan volcano; 5. Jaguaroundi; 6. Predio Benjamin; 7. Moloacán; 8. El Milagro; 9. Villa de Guadalupe; 10. Malpaso.

locality and by others that were relocated into the zone due to land use changes in their zone of origin. This relocation was conducted seven years ago and the individuals were taken from a nearby site (4 and 3 km in distance, for Jaguaroundi park and Predio Benjamín, respectively). In the case of Predio Benjamín, seedlings were also introduced (six years ago) as a result of reproduction from seeds and, according to the data provided by the site administration, there are currently around 1,000 individuals present. Although cycads are plants of slow growth (Dehgan, 1983), the protection and ongoing surveillance of the site suggests the permanence of the species in the zone.

The information provided in this study does not coincide with that included in the IUCN fact sheet (Vovides et al., 2010), since they involve different evaluation methods (Table 3). For example, the data provided in the Red List establishes that the EOO of the species is 6,950 km^2, which should, according to the guidelines based on geographic distribution (criterion B), lead to its categorization as Vulnerable (VU). However, it is in fact placed in the category of Critically Endangered (CR) under criterion A (population size reduction), for which reason it is considered that evaluation of the conservation status of the species is a theme that requires exploration in greater detail, based on field corroboration and the information available in collections. The difference between the results of this study and the information presented in the IUCN could be due to the fact that this study included twice the number of reported locations, which acts to increase the AOO and EOO, as well as the altitudinal range and the number of individuals. The increase in information for the species in this study illustrates the importance of updating and corroborating data in the field in order to obtain more accurate results. In addition, population data and geographic data are necessary.

The results of this study suggest a different risk category. Information has been published that demonstrates that species of various taxonomic groups of plants that are not protected under any scheme are, in reality, suffering problems at a regional or even global level. For example, many species of Araceae, grammitidoid ferns, or of the genera *Peperomia* and *Phlegmarirurus* are classed as Endangered due to the reduction and deterioration of their habitat, for which reason these should be groups considered in some category of risk for certain regions (Armenta-Montero et al., 2015; Jimeno-Sevilla et al., 2018; Krömer et al., 2013; Krömer et al., 2019; Vergara-Rodríguez et al., 2017).

Of the ten localities sampled, there are some populations that have deteriorated considerably due to habitat degradation and the low quantity of individuals. This is the case in Malpaso in Chiapas, as well as Moloacán and Las Choapas in Veracruz (Vovides et al., 2010), for which reason the populations in both sites are at risk. However, according to the analysis of the associated vegetal coverage, these sites present forest coverages of greater than 800 ha, and should therefore be ideal for realizing plans of habitat conservation associated with programs of reproduction, considering the high *ex situ* reproduction success of many cycad species (Pérez-Farrera & Vovides, 1997). In the case of Malpaso, Chiapas, it was confirmed that a small population is located at another geographical point close to the town reported in the herbarium specimens, and it is therefore possible that more individuals could be found in these areas covered with vegetation, although field explorations would be required to corroborate this.

On the other hand, the population of Pajapan is within the core zone of the Los Tuxtlas Biosphere Reserve, with individuals represented from 300 to 800 m asl. In the case of the population of Villa de Guadalupe in Tabasco, in this study, the presence of individuals at 1,000 m asl was considered on the north facing slope of the site. However, there are records of the species in the same site, but with an eastern aspect (a location not visited in the present study), with the presence of individuals reported from 400 m asl (Martínez-Domínguez et al., 2017). For this reason, the number of specimens in that site could be even greater.

The locality of Laguna de Majahual, Veracruz, presents a population with a great number of adult individuals in a reproductive state and with evident recruitment. The analysis indicated that this is the zone with least forest coverage, since the plants are in a reduced fragment of tropical forest surrounded by livestock grazing pastures.

This study recorded the presence of the species in other vegetation types and localities that differed from those mentioned in the literature (Martínez-Domínguez et al., 2017; Vovides & Nicolalde-Morejón, 2010), such as the transition between tropical and oak forest in the locality of San Martín Pajapan, as well as the only fragment of humid montane forest in the state of Tabasco (Carvajal-Hernández et al., 2018). In principle, the increase in the number of recorded localities generates knowledge of a greater number of individuals than has been estimated to date, which is beneficial for the species. Furthermore, a greater number of localities acts to reinforce the analysis and the relationship with the different environmental variables. Moreover, the increase in the sites reported and vegetation types where species inhabit could indicate a greater adaptation to the heterogeneity of the microclimate, substrates or topography, which determines the biodiversity and thus the complexity of the interactions that the species maintain with the biotic and abiotic factors (Stein et al., 2014). However, studies that specifically address this aspect are necessary.

The geographic study confirmed that, given its endemism to a specific region of southeastern Mexico, *C. miqueliana* must remain protected within some risk category in order to ensure its permanence (Secretaría de Medio Ambiente y Recursos Naturales, 2010; Vovides et al., 2010). However, the two evaluations based on the criteria established by the IUCN and NOM-059 coincided in the result of a lower risk category, although it must be considered that the IUCN evaluation that proposed *C. miqueliana* as a critically endangered species is based only on elements of the population, which is why the results are different. A specific evaluation of demographic aspects of this species, including the new localities mentioned in this study, would be necessary. Furthermore, in the IUCN information, no details of the population (age categories, density, etc.) are given, in order to have a more in-depth comparison.

Potential Distribution Modeling

Although the potential distribution model is not essential for assessing the conservation status of species, according to the IUCN (2019), it can be used complementarily to establish the area of habitat occupied by the taxon, as well as the factors required by the populations. This partially coincides with most of the potential distribution areas assigned by Rojas-Soto et al. (2014). For example, the Los Tuxtlas Biosphere Reserve and the boundaries between Chiapas, Tabasco and Veracruz are prominent as the sites with the greatest habitat suitability for *C. miqueliana*.

The results of the Maxent model indicate that *C. miqueliana* requires specific environmental conditions, such as those of the soil (in this case, an acrisol), which was also found to be one of the most important variables in terms of conservation of this group of plants. Soil is the most important variable for some cycads, such as *Encephalartos latifrons* (Swart et al., 2018), *Dioon sonorense* (Álvarez-Yépiz et al., 2011), *Macrozamia macdonnellii* (Preece et al., 2007) and *Macrozamia lucida*, a species for which the soil is the most important variable in terms of abundance (Kaye et al., 2016). The presence of high concentrations of potassium characterizes the acrisol soil type, which is associated with humid tropical zones with tropical rain forest (TRF) vegetation that facilitates a greater retention of moisture on the leaves of the plants (Food and Agriculture Organization, 2008).

Another important variable for the results of the modeling was the presence of forest cover. The TRF originally dominated the area of distribution of this species, however, this vegetation type is now present only in fragments, occasionally isolated due to land use change for agricultural, livestock production and industrial activities (Ellis et al., 2011), these being the main threats found for *C. miqueliana* (Vovides & Nicolalde-Morejón, 2010). Activity related to the petroleum industry affects only the populations near the Coatzacoalcos region (Benjamin, Jaguaroundi, Moloacan); however, companies in the area are legally obliged to allocate spaces to conserve species of flora and fauna, including *C. miqueliana*. The first two of the aforementioned towns are areas destined for conservation, while the third is a private area in which the landowner pursues conservationist policies.

The interaction of factors such as soil type and the presence of tropical rain forest are therefore the most determinant variables in the distribution model. Elevation is an important factor, with most of the individuals found between 50 and 600 m asl, and it should be noted that humidity and temperature during dry or hot days are also important, although to a lesser extent ($< 3\%$). Humidity is the factor most related to the presence of the plant. A similar result was reported by Kaye et al. (2016) for *Macrozamia lucida*, a species that inhabits Australia; while maximum temperature has been reported as such for *Macrozamia macdonnellii* (Preece et al., 2007).

Modeling of the potential distribution of the species provides important information, since it serves to identify areas that maintain an ideal habitat for its establishment. For example, there are areas in Coatzacoalcos and in Los Tuxtlas biosphere reserve that could be considered for future programs of conservation of the species that could include habitat preservation, propagation or even reintroduction or enrichment of a population in the areas indicated as suitable by the model.

The distribution analysis of the species modeling is also useful to determine priority areas for conservation and specific zones for reintroduction (Engler et al., 2004) or even to indicate potential biological corridors in areas where the model suggests the presence of the species. Non-documented knowledge has been collated through the accounts of local people regarding populations of *C. miqueliana* that were disappearing at the time of the land use change. This is the case in the locality of Texalapan in the municipality of San Andrés Tuxtla and, according to old collections, in some specific points between the Sierra de Santa Marta and the San Martín Pajapan volcano in the Los Tuxtlas Biosphere Reserve. At these sites, the proposal of possible plans for the reintroduction of individuals could be feasible.

Implications for Conservation

Understanding the relationship between organisms and their environment is a crucial part of addressing the problem of environmental change and its consequences for biodiversity conservation (Schwenk et al., 2009). In this sense, directing strategies towards the conservation of threatened species is no easy challenge. However, investigations such as the present study serve to further our knowledge of the conservation status of a given biological group. It was corroborated that different results can be obtained with different evaluation criteria, and it is therefore necessary to carry out evaluations of microendemic species such as *C. miqueliana* using different approaches (populations, geographic aspects and habitat evaluation) to obtain more precise results. *Ceratozamia miqueliana* must be protected under both national and international law. For this reason, it is necessary to develop new conservation programs as well as monitor those that are already established (e.g., in Jaguaroundi ecological park or Predio Benjamín) in order to ensure the future permanence of the species.

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Appendices

Appendix 1. Environmental Variables Used in the Model That Were Not Correlated for *Ceratozamia Miqueliana*

Key	Variable
bio4	Temperature seasonality (sd*100)
bio5	Max temperature of warmest month
bio7	Temperature annual range (bio5-bio6)
bio10	Mean temperature of warmest quarter
bio12	Annual precipitation
bio13	Precipitation of wettest month
bio14	Precipitation of driest month
bio15	Precipitation seasonality
bio16	Precipitation of wettest quarter
bio18	Precipitation of warmest quarter
bio19	Precipitation of coldest quarter
Alt	Elevation
soil	Type of soil
forest	Tree canopy cover

Appendix 2. Index of Evaluation of the Risk Status of *Ceratozamia Miqueliana* According to the Criteria Established in the Mexican Environmental Protection Law, Specifically the Normative Annex II of the NOM-059-SEMARNAT-2010

Criteria	Condition of the species	Value assigned
Criterion A. Characteristics of geographic distribution		
1) Extent of the distribution	Area of distribution occupies more than 1 km^2 but <1% of the Mexican national territory	3
2) Number of localities	9–25	1
Number of biogeographic provinces (CONABIO, 1997) in which the taxon is found	1	3
Representativity of the distribution of the taxon in the Mexican national territory	Peripheral or extralimital distribution	1
Total value of criterion A = 8/11 = 0.72		
Criterion B. Characteristics of habitat		
In how many vegetation types is the taxon presented?	2	2
Does the taxon have a specialized habitat?	No	0
Is the permanence of the population dependent on a primary habitat?	No	0
Does the permanence of the population require particular perturbation regimes or is it associated with transitory stages in the succession?	No	0
Amplitude of the elevational interval occupied by the taxon.	500 m- <1000 m	1
Total value of criterion B = 3/9 = 0.33		
Criterion C. Intrinsic biological vulnerability		
Total number of individuals	501–5,000	2
Recruitment (where there is no information available, assign a value of 0)	There are observations of recruitment in some populations = 2	2
Demographic attributes (where there is no information available, assign a value of 0)		0
Quantity of genetic variation (estimated indirectly through other characteristics)	High	0
Level of differentiation among populations (estimated indirectly through other characteristics)	High	1
Does the taxon require a "nurse plant" for establishment?	No	0
Does the taxon require a specific host or phorophyte (in the case of holoparasites or hemiparasites and epiphytes or hemiepiphytes, respectively)?	No	0
Does the taxon require a specific pollinator?	Yes	1
Does the taxon have a specific disperser?	No	0
Does the taxon present obligate myrmecophily?	No	0
Does the taxon present strict dependency on mycorrhizae?	Yes (in this case, the cyanophyceae algae)	1
Does the taxon suffer an important affectation by predators or pathogens (including very intense competition with allochthonous or invasive species)?	No	0
Total value of criterion C = 7/23 = 0.30		
Criterion D. Impact of human activity		
How does anthropic alteration of the habitat affect the taxon?	There is no effect or the effect is unknown	0
What is the level of impact of human activities on the habitat of the taxon (impact = fragmentation, modification, destruction, urbanization, grazing or contamination of the habitat and refers to both the intensity and extent)?	The impact is strong in some or moderate in all of the populations	2

(continued)

Continued

Criteria	Condition of the species	Value assigned
Is there any evidence (measurements, models or predictions) to indicate deterioration in the quality or extent of the habitat as an effect of global changes (e.g., sensitivity to climatic change) or is a drastic change foreseen in the land use?	No	0
What is the impact of the use on the taxon?	The impact of the use is strong in some or moderate in all of the populations	2
Is the taxon cultivated or propagated *ex situ*?	Yes	-1
Total value of criterion D = 3/10 = 0.30		
Total value considering all criteria: 1.65		
a) Greater or equal to 1.5 and less than 1.7.		
According this evaluation , *Ceratozamia miqueliana* must be considered a species Subject to Special Protection (Pr) and not as it is classified at present (Endangered of Extinction).		