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PREDICTING THE POTENTIAL SUITABLE HABITAT FOR CHINA'S ENDANGERED PLANT *CYCAS SEXSEMINIFERA* BASED ON THE MAXENT MODEL

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Abstract

A fundamental concept in ecology and conservation is understanding the association between the environmental conditions of plant and their geographical distribution. MaxEnt modeling and ArcGIS were used to estimate the potential habitat of China's endangered species, *Cycas sexseminifera*, using 41 verified distribution records and eight specific environmental factors. The significant factors influencing the possible distribution of *C. sexseminifera* were assessed and evaluated using the jackknife statistical method in combination with percentage contribution and permutation importance. The possible range of the species was determined using the response curves of critical bioclimatic factors. The simulation accuracy of the generated MaxEnt model was validated to be excellent (AUC = 0.997). The provinces of Guangxi, Yunnan, Guangdong, Sichuan, Hainan, Fujian, and Taiwan contain most of the current core potential distribution areas, indicating a significant inter-regional difference. The distribution area of *C. sexseminifera* was most significantly influenced by the annual mean temperature (Bio1), precipitation of the driest month (Bio14), and minimum temperature of the coldest month (Bio6). The results could provide scientific direction to enhance the management and preservation of this vanishing species.

Key words: *Cycas sexseminifera*; Climate change; MaxEnt model; Species distribution model (SDM); Bioclimatic factor

Introduction

Climate change is a decisive factor affecting the plants' vegetation type and spatial distribution pattern, especially the frequent occurrence of extremely high temperatures and droughts (Dyderski *et al.*, 2018; He *et al.*, 2023). It represents a direct threat to plant survival. It induces changes in related environmental factors, thereby exposing species to the risk of extinction, disrupting regional biodiversity and ecological security patterns and reducing ecosystem functions (Thapa *et al.*, 2018). Therefore, these organisms must adapt to novel conditions or shift their geographic distributions (Thapa *et al.*, 2018; Feeley *et al.*, 2020).

Climate change mainly regulates various physiological processes of plants by altering the energy and water provided by temperature and rainfall (Graham *et al.*, 2019). Intense climate change in a short period may shift the range of natural species, especially those with weak adaptability, poor dispersal ability, limited geographical location, and/or endemic species, which are on the brink of extinction due to their inability to adapt to unusual climate conditions (Cuena-Lombraña *et al.*, 2018; Kouhi & Erfanian, 2020). Moreover, the spatial and temporal variations in climate change may significantly impact plant recruitment, physiological processes, soil characteristics, plant diseases, plant interactions between ecosystems, functional structures, and characteristics of forest ecosystems (Hebbar *et al.*, 2022). Therefore, evaluating the influence of climate change on the range of habitats for endangered species and identifying the primary environmental factors may minimize the possible threat of extreme conditions to endangered species' habitats, which is crucial for the preparation and storage of germplasm resources for endangered species, in the context of increasing global warming (Nguyen *et al.*, 2021; Lippmann *et al.*, 2019).

Species distribution modeling, such as MaxEnt, Garp, Bioclim, and Climex assesses the present and possible suitable distribution regions of a given species by integrating information from known distribution samples and environmental factor data (Soilhi *et al.*, 2021; Khan *et al.*, 2022). The impact of multiple environmental factors in restricting the spatial distribution of species can be elucidated via the development of the model, which enables the assessment of changes in suitable habitats globally in response to present and future climatic predictions (Choi & Lee, 2022). The MaxEnt model is the most widely used in species distribution modeling. It predicts species distribution using the maximum entropy method and species incidence data to estimate the probability of species occurrence in unknown areas (Boral & Moktan, 2021). The MaxEnt model combines latitude and longitude data of known species distribution regions to assess habitat suitability by integrating interactions among variables, including height, soil, and vegetation type (Wang *et al.*, 2023). Further, it has the advantages of supporting multiple variables, short computing time, simple operation, stable computing results, and small sample size requirements (Asanok *et al.*, 2020; Tang *et al.*, 2021). Despite its limited geographic information and restricted distribution range, it is widely employed in predicting distribution habitats of endangered species (Huang *et al.*, 2020).

Cycas sexseminifera F. N. Wei is classified as one of the world's oldest extant seed plants. It survived under environmental variations, climate fluctuations, and intense tectonic activity. However, due to severe habitat destruction and long-term large-scale poaching, the population of *C. sexseminifera* is sharply decreased. Recently, the wild population of *C. sexseminifera* occurs sporadically throughout the crevices of low altitude limestone mountains in of Guangxi, Southwestern China. There are not many male and female plants of *C. sexseminifera* at flowering age in each population (only 2 to 3 plants), and only a few plants can bloom and bear seeds every year, resulting in a low fruiting rate (Zheng *et al*., 2017). Therefore, it has been classified as a first-level protected species and is listed among *National Key Protected Wild Plants* in China. Presently, studies on this species are limited, particularly about its habitat-forming factors and geographical distribution.

A distribution and habitat assessment of *C. sexseminifera* was carried out using Maxent modeling and ArcGIS, combined with high-resolution environmental data for present and potential climate scenarios, and abundance records of the species. The main objectives of the present study were as follows: (1) to identify the primary determinants that spatial distributions of *C. sexseminifera* in China; (2) to determine whether environmental variables are associated with a potentially suitable distribution pattern; and (3) predict the habitat suitability of *C. sexseminifera* in light of current climatic scenarios. The results can enhance our understanding of the species distribution patterns and ecological adaptation of *C. sexseminifera* to climate change. The findings can also provide a theoretical foundation and guidance for the sustainable development usage and conservation of *C. sexseminifera*.

Material and Methods

Data collection on species occurrence: Records of *C. sexseminifera* were collected from various sources, including the Global Biodiversity Information Facility (https://www.gbif.org), National Specimen Information Infrastructure (http://www.n-sii.org.cn), Chinese Virtual Herbarium (http://www.cvh.ac.cn), Plant Photo Bank of China (http://www.Plantphotophoto.cn), China National Knowledge Infrastructure (https://www.cnki.net), and field survey data from the forestry management department. Sample points were chosen based on their accurate Latin names and precise latitude and longitude locations, and inaccurate geocoded data or duplicate information was removed. There were 41 authentic occurrence records of *C. sexseminifera* included in this study.

The precise geographic distribution point longitude and latitude values were acquired from ArcGIS (10.8). After this, the whole point data was uploaded into Excel database and transferred to CSV format based on the specifications of the MaxEnt model (Fig. 1).

Selecting environmental variables: The species distribution models used 19 bioclimatic variables derived from the WorldClim database (http://www.worldcli-m.org) with a spatial resolution of 30 arc seconds (~ 1 km) for the current period (Table 1). All variables' percent and permutation impact on the preliminary model results were evaluated via the jackknife test to identify the most critical ecological components for modeling. A Pearson Correlation Coefficient (r) test was used to assess multicollinearity. Variables with correlation coefficients (r) less than 0.8 were considered for retention, whereas those with low contributions and high correlations correlation (r≥0.80) were excluded (Chi *et al*., 2023). After excluding some variables and analyzing the contribution percentage (%) of all bioclimatic variables compared to the baseline model, 8 out of 19 were selected as evaluator variables for constructing the MaxEnt model for *C. sexseminifera* regional distribution in this study.

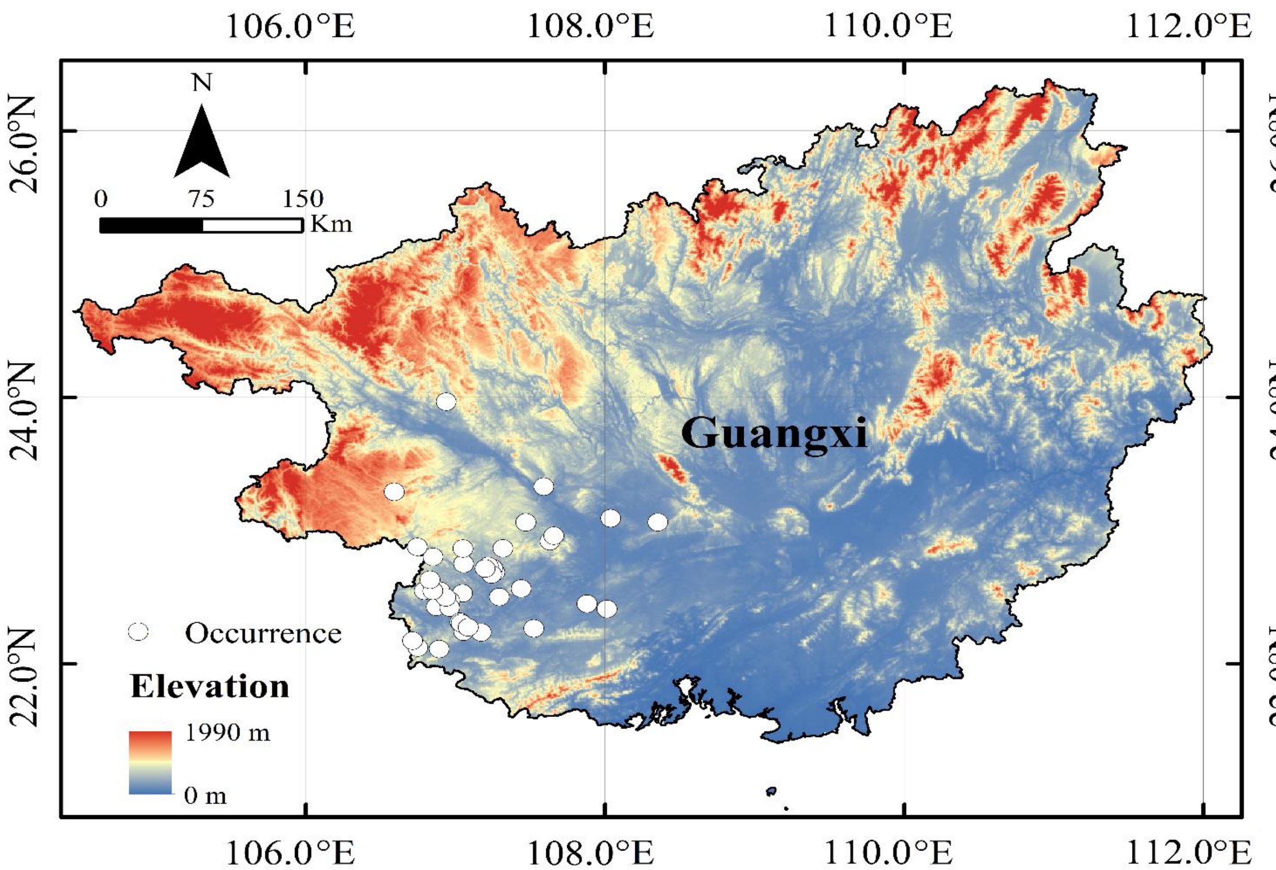

Fig. 1. The images depict the original area of distribution (white circles) of *Cycas sexseminifera* in the Guangxi provinces of southwestern China.

Table 1. The environmental variables included during the model development. A total of 8 variables selected for the MaxEnt modeling study were denoted by their codes in bold font.

Code	Environmental variables	Unit
Bio1	Annual mean temperature	℃
Bio2	Mean diurnal range (mean of monthly (maximum temp-minimum temp))	℃
Bio3	Isothermality (Bio2/Bio7) (*100)	-
Bio4	Temperature seasonality (standard deviation*100)	℃
Bio5	Maximum temperature of the warmest month	℃
Bio6	Minimum temperature of the coldest month	℃
Bio7	Temperature annual range (Bio5-Bio6)	℃
Bio8	Mean temperature of the wettest quarter	℃
Bio9	Mean temperature of the driest quarter	℃
Bio10	Mean temperature of the warmest quarter	℃
Bio11	Mean temperature of the coldest quarter	℃
Bio12	Annual precipitation	mm
Bio13	Precipitation of the wettest month	mm
Bio14	Precipitation of the driest month	mm
Bio15	Precipitation seasonality (coefficient of variation)	-
Bio16	Precipitation of the wettest quarte	mm
Bio17	Precipitation of the driest quarter	mm
Bio18	Precipitation of the warmest quarter	mm
Bio19	Precipitation of the coldest quarter	mm

Model simulation: The models were developed and assessed using *C. sexseminifera* occurrence data and 8 environmental variables entered the Maxent software for modeling species niches and distributions (Version 3.4.0, http://www.cs. princeton.edu/wschapire /Maxent/). The relative significance of different environmental variables was determined using the Jackknife method, which involved calculating the area under the curve (AUC) gains for training, testing, and three scenarios (no, one and all variables) (Wu *et al*., 2021). The accuracy of the simulation results was then evaluated via the AUC in conjunction with the receiver operating characteristic curve (ROC), which served as an analytical method for the model accuracy test. The AUC value varied between 0.5 and 1. A higher value signified a more pronounced independence of the geographic distribution of the simulation object from the random distribution. Therefore, a strong association was observed between the simulation outcome and the environmental variables; thus, a higher AUC value corresponded to a more accurate model (Wang *et al*., 2023; Wei *et al*., 2018). Excellent (0.9 to 1.0), good (0.8 to 0.9), fair (0.7 to 0.8), poor (0.6 to 0.7), and fail (0.5 to 0.6) are the performance classifications applied to the AUC statistic (Sarma *et al*., 2022).

The ASCII file from MaxEnt was loaded into ArcGIS 10.8 and turned to raster format via the Arc Toolbox conversion tool. It was then used to classify and graphically represent the distribution region of *C. sexseminifera* within a 0-1 range (Zhang *et al*., 2021). The potential habitat suitability for *C. sexseminifera* was divided into 4 groups: poor (<0.2), fair (0.2 to 0.4), good (0.4 to 0.6), and excellent (>0.6).

Results

Model performance evaluation: The observed omission rates in the model were comparable to the predicted omission rates in the training data, indicating that the data were accurately adjusted. Both the test and training data were also unique (Fig. 2a). The reconstructed MaxEnt model yielded an AUC value of "excellent" (mean=0.997, Fig. 2b), significantly exceeding the AUC value of the randomly predicted model (0.5). This suggested that the predictions were more accurate and could effectively represent the distribution areas of *C. sexseminifera* under current climate scenarios.

Critical environmental factors and results validation for modeling: The impact of different environmental factors was evaluated on the MaxEnt prediction model. The results showed that Bio1 and Bio14 were the two most influential variables, contributing 39.1% and 25.1%, respectively (Table 2). The permutation critical analysis revealed that Bio6 had the most significant impact on the habitat model, representing 48.9% of the contribution (Table 2). The primary bioclimatic variables that significantly influenced the MaxEnt prediction model were Bio1, Bio14, and Bio6.

The estimation of the contribution of each bioclimatic variable to the distribution of *C. sexseminifera* was carried out using the jackknife test. This estimation was based on the performance of the MaxEnt prediction model for the suitable habitats of *C. sexseminifera* worldwide. The highest gains in AUC, test, and regularized training were observed for Bio6 and Bio1, as shown in the test with only variable results (Fig. 3). This indicates that these bioclimatic variables are crucial for understanding the distribution of *C. sexseminifera*; the longer the bar, higher the significance of the bioclimatic variable for the species distribution. Collectively, the findings from the jackknife analysis suggested that Bio1 and Bio6 were the primary bioclimatic factors influencing the distribution of *C. sexseminifera*.

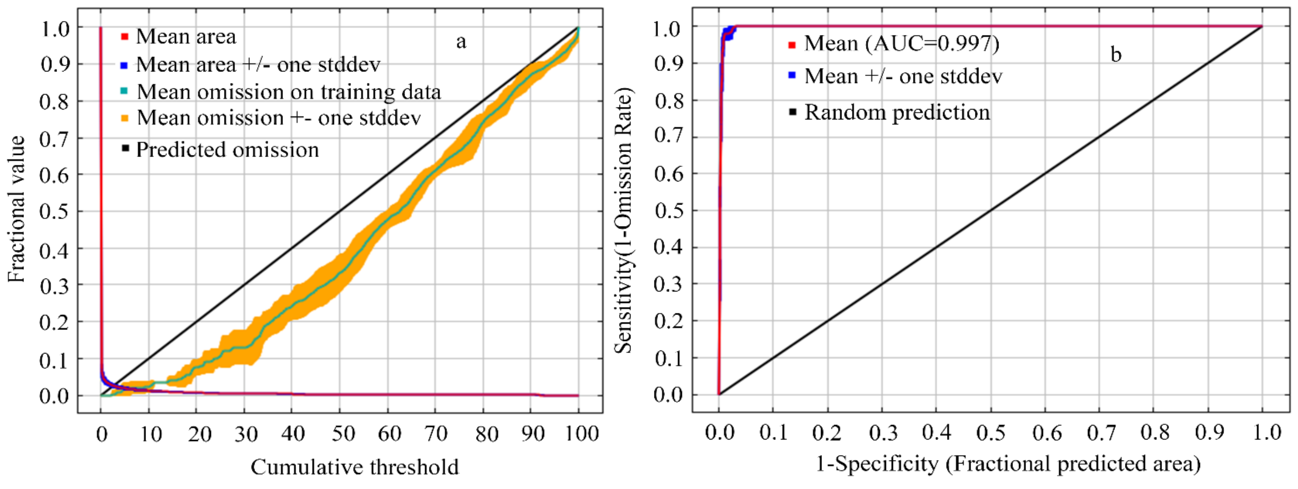

Fig. 2. Evaluation of the model predicting *C. sexseminifera* distribution using (a) omission rate and (b) ROC curve.

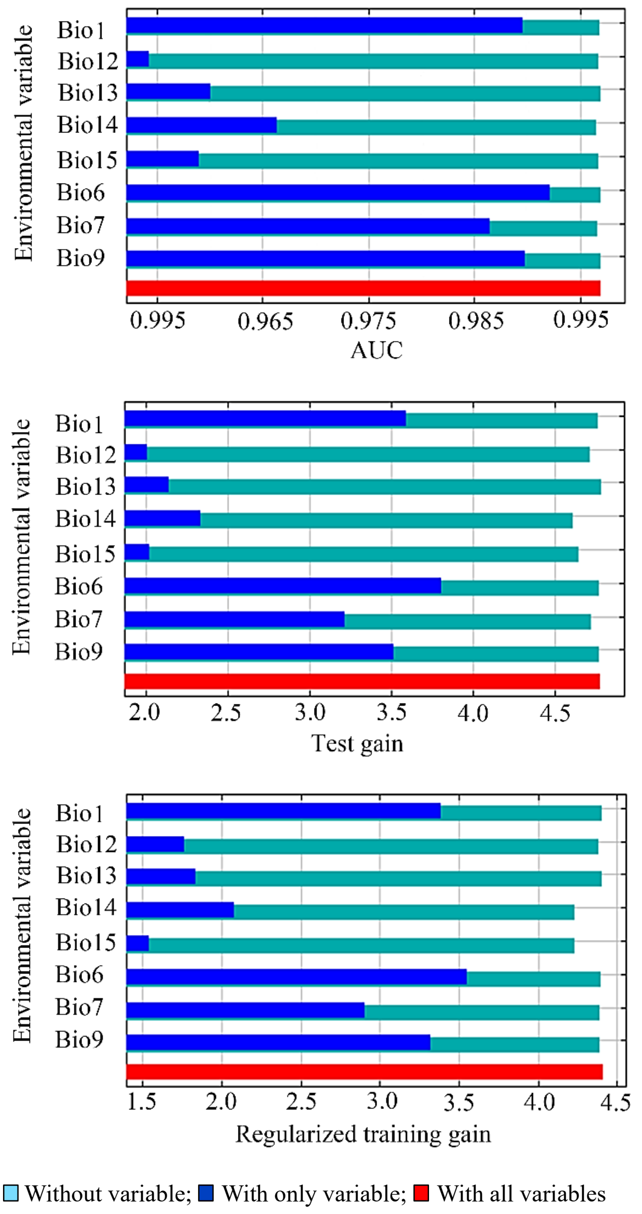

Fig. 3. Comparative predictive value of the 8 environmental variables in MaxEnt models, based on the jackknife test of regularized training gain, test gain, and AUC.

The MaxEnt response curves, which depicted the link between environmental variables and species' existence, showed that environmental stresses affect the incidence of target species (Fig. 4). The response curves for three bioclimatic variables revealed the optimal value range for their corresponding parameters. Among these, the minimum temperature range for the coldest month (Bio 6) was 6 to 10°C. At these temperatures, the possibility of *C. sexseminifera* prevalence increased from 6 to 10°C and reduced from 10 to 14°C. The possible presence of *C. sexseminifera* rose from 18 to 22°C and dropped from 22 to 25°C within the optimum Bio1. Figure 4 displays that the probability of *C. sexseminifera* presence decreased from 21 to 28 mm, corresponding to the optimal precipitation range during the driest month (Bio14).

Estimating the optimal habitats for *C. sexseminifera* in China: Considering current climate conditions, the MaxEnt prediction model was employed to predict the possible habitats suitable for *C. sexseminifera*. The findings indicated that the regions most suited to the present climate were Guangxi, Yunnan, Guangdong, Sichuan, Hainan, Fujian, and Taiwan (Fig. 5). The total suitable area was 134.761×10^4 km^2, occupying 14.038% of the whole area of China (960×10^4 km^2). The respective regions suitability habitats were classified as poor (129.220×10^4 km^2), fair (3.063×10^4 km^2), good (1.736×10^4 km^2), and excellent (0.742×10^4 km^2) were measured (Table 3). The ideal suitable habitats were located in Guangxi, Taiwan, Fujian and Yunnan with areas of 0.615×10^4 km^2, 0.106×10^4 km^2, 0.019×10^4 km^2 and 0.002×10^4 km^2 (Table 3). However, there were no distribution records in the studies of Yunnan, Guangdong, Sichuan, Hainan, Fujian, and Taiwan. The current possible distribution size of *C. sexseminifera* is substantially larger than its actual presence in China, suggesting that this vulnerable plant will increase its biogeographic range to cover the potential region.

Discussion

The present study was the first to use MaxEnt modeling to assess the suitability of *C. sexseminifera* in China and determined the key environmental variables influencing habitat suitability. The modeled suitability habitat of *C. sexseminifera* in China was performed with an AUC 0.997 (Fig. 2), indicating highly accurate model performance. Other studies have suggested that AUC values over 0.75 could be useful and suitable for assessing the efficiency of a niche model (Gebrewahid *et al*., 2020). The results also demonstrated that the MaxEnt model could study the link between changes in the habitat and climate of *C. sexseminifera* and provide guidance for field investigations and the protection of endangered species.

Environmental conditions are intricately linked to the spatial distribution of plants, with temperature being a significant determinant of the regional-scale geographical distribution of plants (Cotrina-Sánchez *et al*., 2021; Boogar *et al*., 2019). The percentage contribution result in the Maxent model indicated that Bio6 and Bio1 were the most influential temperature variables on the geographic distribution of *C. sexseminifera* (Table 2; Fig. 3). The formation and distribution of organic matter are also influenced by temperature, photosynthesis, respiration, and transpiration, all plant metabolic processes (Moore *et al*., 2021). Low temperatures can impede the hydrolysis and transportation of starch stored within the chloroplasts, thus reducing the rate of photosynthesis (Khalil *et al*., 2021; Ikkonen *et al*., 2018). This is due to the sensitivity of many aspects of photosynthetic metabolism to temperature. In contrast, as the temperature rises, the rate of photosynthetic activity increases until it reaches a thermal optimum, at which point enzyme inactivation reduces both electron transfer rate and chlorophyll content (Prasad and Djanaguiraman, 2011). Moreover, premature freezing injuries to plants occur due to the minimum temperature decrease during the coldest month. Furthermore, plants at the distribution limit may die due to prolonged low temperatures (Harsch *et al*., 2016).

Table 2. The percentage contribution and permutation importance levels of the 8 environmental variables in the MaxEnt models, organized by their contribution percentage.

Code	Bioclimatic variable	Percent contribution	Permutation importance
Bio1	Annual mean temperature	39.1	8.6
Bio14	Precipitation of the driest month	25.1	11.5
Bio15	Precipitation seasonality	15.4	10.5
Bio6	Minimum temperature of the coldest month	10.1	48.9
Bio12	Annual precipitation	6.0	2.6
Bio9	Mean temperature of the driest quarter	2.7	0.8
Bio7	Temperature annual range	1.6	16.5
Bio13	Precipitation of the wettest month	0.1	0.8

Table 3. Predicted suitable areas for *C. sexseminifera* under the climate in various provinces or autonomous regions (10^4 km^2). The ratio represents the calculated total area as a percentage of the overall land area of the province or autonomous region.

Province or autonomous region	Predicted suitable area ratio			
	Poor	Fair	Good	Excellent
Guangxi	17.342	1.691	1.389	0.615
Taiwan	3.050	0.128	0.076	0.106
Fujian	10.970	0.141	0.116	0.019
Yunnan	33.762	0.427	0.071	0.002
Guangdong	15.398	0.500	0.083	0.000
Hainan	2.964	0.148	0.000	0.000
Sichuan	45.734	0.028	0.000	0.000

Based on the findings, precipitation during the driest month (Bio14) was identified as the primary determinant influencing the possible distribution of *C. sexseminifera*. This outcome can be attributed to *C. sexseminifera*'s prolonged adaptation to the specific environmental conditions of the area. The available distribution data indicates that the endangered plant is predominantly observed in karst environments characterized by inadequate surface disposal and sporadic small soil pockets interspersed among numerous rock outcrops. A significant quantity of soil water is evaporated during bright, heated summer days (Wang *et al*., 2023). Therefore, adequate precipitation during the driest season can substantially increase the moisture content of the soil, enabling it to sustain normal physiology and transpiration while fostering an optimal environment for the development and maturation of fruits (Gebrewahid *et al*., 2020). However, an overabundance of water in the soil may disturb the delicate water balance that plants necessitate, impeding their morphology and metabolism, restricting their development, and potentially halting their survival (Zhang *et al*., 2021).

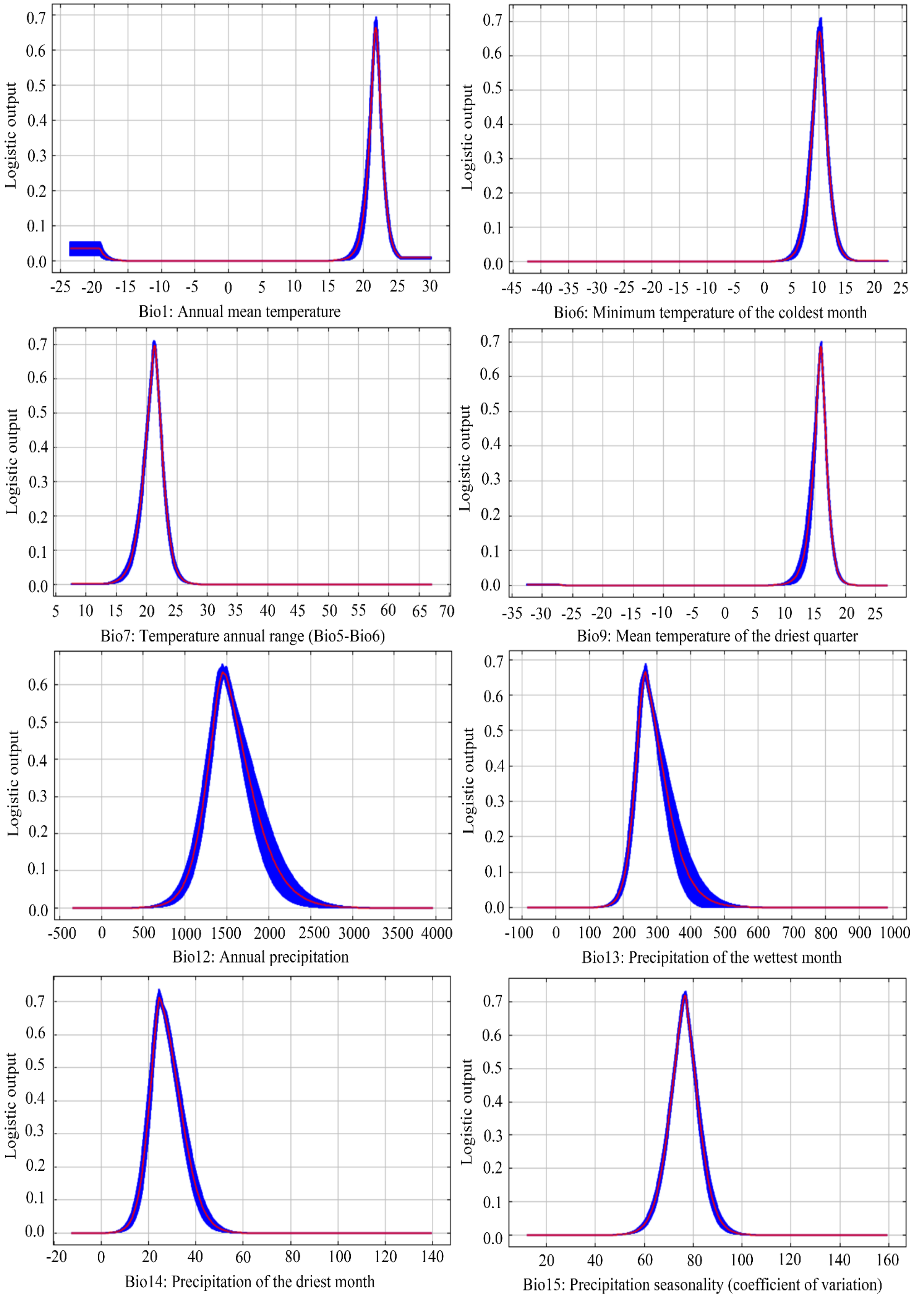

Fig. 4. Curves representing the environmental variables' responses to distribution probability.

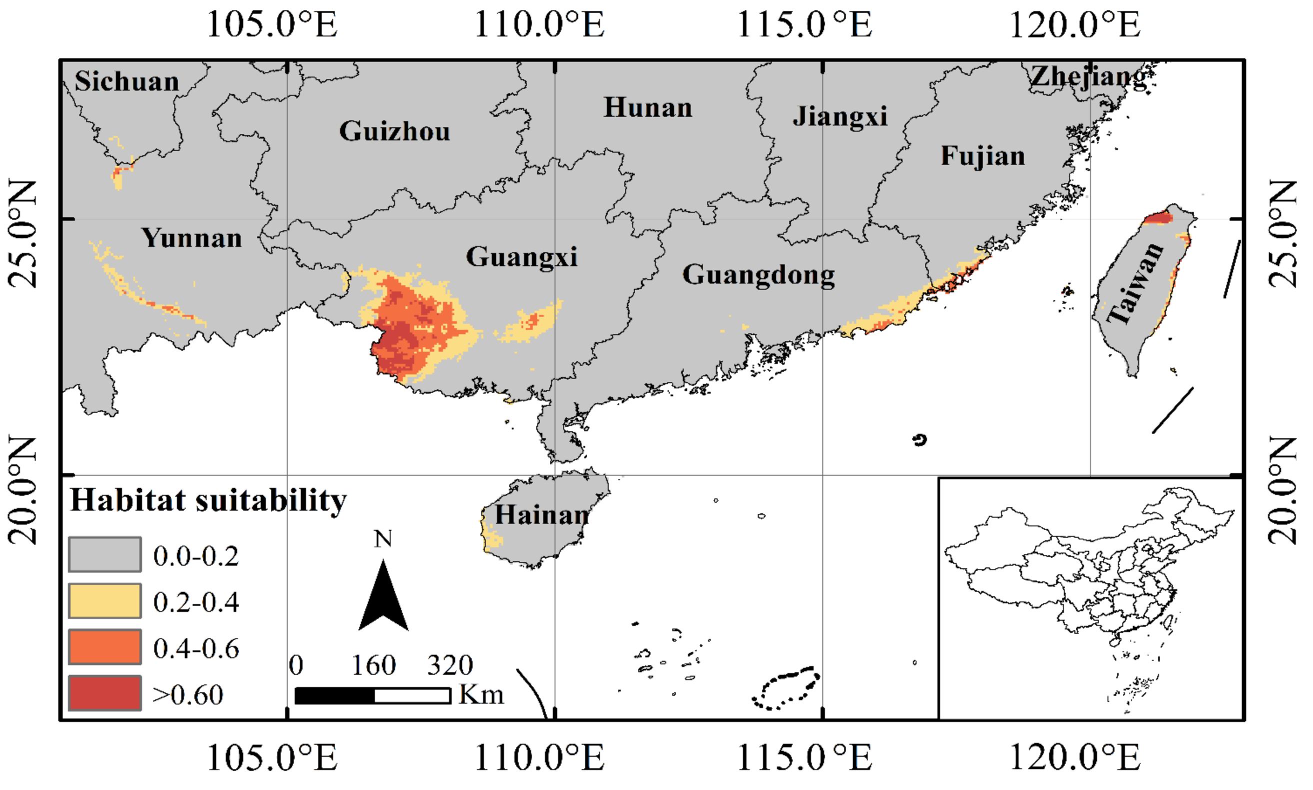

Fig. 5. The distribution range of *C. sexseminifera* predicted via MaxEnt modeling.

A comprehensive understanding of the appropriate habitat for *C. sexseminifera* is essential for collecting germplasm resources, conserving genetic diversity, and enhancing genetic progress. The simulation findings indicated that the optimal habitat area for *C. sexseminifera* was 0.742×10^4 km^2 (Table 3), predominantly found in Guangxi, Yunnan, Taiwan, and Fujian provinces. This suggests a restricted geographical distribution range for its population. This also indicates the potential for concentrating on exploration, collecting resources, investigation, and conservation efforts in these areas, as *C. sexseminifera* tends to be widely distributed in the main germplasm regions and might show significant genetic variation. The possible distribution area of *C. sexseminifera* is expected to grow and extend in China beyond its current range (Fig. 1; Fig. 5). The difference in the spatial distribution of species data points on different scales may explain the difference between actual and potential ranges. The model relies on niche-based presence data, leading to predictions of the species' fundamental niche instead of the realized niche, causing overestimating the results (Zhou *et al.*, 2023). Moreover, predicting species distribution needs to consider their physiological limitations, population dispersal ability, topographical isolation, responses to external environmental influences, triggers changes, and competition within ecological communities, potentially resulting in an interval between species' actual geographic distribution and climate change (Wang *et al.*, 2023).

Conservation efforts for rare species can be strengthened by enriching the distribution of species information, increasing the number of surveys, and providing detailed habitat characteristic data (Rhoden *et al.*, 2017). The findings show that the natural distribution range of *C. sexseminifera* is relatively limited. Future fluctuations in the essential environmental factors for this species could potentially impact the distribution area and population size of this threatened species. However, this phenomenon of changing the range of species' spatial distribution is intricate. It can be impacted by various factors, including but not limited to species interactions, regional microclimate, topography, soil quality, and human activities (Sannigrahi *et al.*, 2020).

Thus, specific steps can be implemented to maintain and broaden the distribution range of *C. sexseminifera*. For example, conducting fundamental biological research, mapping the potential range of pollinators and seed dispersers, setting up different small protected areas in vulnerable regions, continue to monitor the distribution dynamics of *C. sexseminifera* under climate change, reinforce field investigations and protection efforts in its core distribution areas, protecting current fruit-bearing trees to enhance seed production and explore ways to enhance its reproductive capacity, collecting complete and precise data to optimize the conservation of this threatened species in various climate change scenarios.

Conclusion

The MaxEnt niche model and ArcGIS accurately identified possible distribution areas of *C. sexseminifera* in China. All variables Bio6, Bio1, and Bio14 were identified as critical environmental factors predicting the current distribution and appropriate habitats of *C. sexseminifera* from the 8 variables used in the MaxEnt model. The plant grows in ideal conditions in the provinces of Guangxi, Yunnan, Taiwan, and Fujian in China. The area has a minimum temperature of 6 to 10°C in the coldest month, an annual average temperature of 21 to 22°C, and a precipitation of 21 to 28 mm in the driest month. The results enable us to identify specific conditions necessary for the species' best growth and offer a scientific foundation for enhancing the preservation and management of this vulnerable plant.

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