Pak. J. Bot., 56(5): DOI: http://dx.doi.org/10.30848/PJB2024-5(34)

PREDICTING SUITABLE HABITAT FOR CHINA'S ENDANGERED PLANT *CYCAS SEGMENTIFIDA* USING MAXENT UNDER CLIMATE CHANGE

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Abstract

The identification of both the extent and potential biogeographical distribution of a plant species is imperative for elucidating the crucial environmental factors that influence its habitat. In the present study, MaxEnt modeling was used for predicting the possible distribution range of China's endangered species, *Cycas segmentifida*, based on 8 selected environmental variables and 38 validated distribution records under current climatic conditions. The jackknife statistical method was employed with percentage contribution and permutation importance to elucidate pertinent factors limiting the potential *C. segmentifida* distribution. The Maxent model indicated better results than the random with an average AUC 0.994. According to species response curves, *C. segmentifida* preferred habitats with temperature seasonality of 420 to 640℃, and the warmest quarter's precipitation from 540 to 780 mm. Currently, the primary potential distribution areas include Guangxi, Guizhou, and Yunnan provinces in Southwest China, with the greatest effect on the *C. segmentifida* distribution area. The results of this research could offer scientific guidance to improve the conservation and management of this declining species.

Key words: *Cycas segmentifida*; Climate change; MaxEnt model; Species distribution model; Bioclimatic factor; Suitable area.

Introduction

Climatic change is the most significant threat to the protection and maintenance of global biodiversity (Fortunel *et al*., 2014; Dawson *et al*., 2011). The frequent occurrence of global warming and drought has changed the temperature and water content in the environment, and can lead to the shrinkage, degradation, or destruction of plant habitats, ultimately shifting the distribution range of natural species (Manish *et al*., 2016). Particularly those that are geographically limited and/or endemic and cannot adapt to altered climatic conditions and become endangered or even extinct (Knapp *et al*., 2008; Blach-Overgaard *et al*., 2010).

Climate change is the most crucial factor responsible for the habitat's physical geography and species distribution (Remya *et al*., 2015; Sarma *et al*., 2022). The changes in major climate factors, for example, extreme temperature, and annual average temperature and precipitation, may cause fragmentation and loss of habitats, increasing the likelihood of extinction in a variety of species (Bellard *et al*., 2012; Veloz *et al*., 2012). The occurrence of harmful and aberrant climate will change plants' regeneration, morphology, growth pattern, reproductive behavior, and natomy, resulting in increased contraction, fragmentation, and shifting of various plant species' geographical distribution patterns globally (Ferrarini *et al*., 2019; Liu *et al*., 2021). Moreover, climate change can alter the plant's spatial distribution, such as by inhibiting reproduction and elevating the mortality rate, thereby decreasing the population of globally endangered species (Duflot *et al*., 2018; Selwood *et al*., 2015). Moreover, further threats to the endangered plant species could jeopardize their survival because of straining beyond the threshold (Román-Palacios & Wiens, 2020).

The cumulative and substantial effects of climatic alterations have disturbed the ecosystem's operation and stability (Wasowicz *et al*., 2013; Mahmoodi *et al*., 2022). For instance, short-term drastic alterations could kill weakly adapted individuals with poor dissemination capability, narrowing species distribution, or local extinction (Kouhi & Erfanian, 2020). Consequently, identification of the association between species and environmental variables, as well as predicting how a species would respond to climatic change is essential for effectively protecting and restoring endangered species and species with narrow niches (Dubuis *et al*., 2011; Kaky & Gilbert, 2016). This information would help monitor and restore the decreasing populations, elucidate and abate anthropogenic effects, and improve resource management (Kaky *et al*., 2020).

Species distribution models (Bioclim, Garp, MaxEnt, and Climex) are employed for analyzing specie's potential geographic distribution and to predict changes in their distributions under different climate change scenarios based on rainfall, relative humidity, maximum and minimum temperatures, and other environmental factors (Urbina-Cardona *et al*., 2019; Çoban *et al*., 2020). Among these, MaxEnt is better than other models in predicting the distribution of endangered species as it can maintain the stability and reliability of its forecast precision even with a small sample size and uncleared correlation between environmental variables (Petitpierre *et al*., 2012). Mostly, there are only a few records of threatened species of distribution that are geographically close together; therefore, modeling their appropriate habitat distribution is difficult when using common modeling approaches as such data have limited information for identification of the link between the species and their habitat (Stalin & Swamy, 2015). MaxEnt only needs a current record of the species as input data and generates accurate spatial environmental suitability maps for species. Furthermore, it also elucidates the importance of environmental variables for species distribution (Kamyo & Asanok, 2020; Tuan *et al*., 2021). The MaxEnt model is widely utilized for predicting suitable regions for endangered species, priority evaluation for species conservation, the climatic environment suitability for a particular species (Koch *et al*., 2017), and the ecological niche similarities comparison between various species in environmental and geographic spatial alterations (Cotrina *et al*., 2021).

Cycas segmentifida (D.Y. Wang & C.Y. Deng) is among the oldest living seed plants in the world. It is primarily found in the valleys of the You River basin in northwestern Guangxi, eastern Yunnan, and southwestern Guizhou provinces in Southwest China (Feng *et al*., 2017). It has survived climate fluctuations, dramatic tectonic activities, and environmental variations (Zheng *et al*., 2017). However, its edible stem, ornamental characteristics, and habitat destruction for cultivating commercial plants have contributed to its population decline. Therefore, it has been classified as a first-level protected species and is listed in *National Key Protected Wild Plants* in China. At present, there is limited research on this species, especially regarding its geographical distribution and the factors that shape its habitat.

This research employed the MaxEnt model to understand *C. segmentifida* species distribution characteristics and ecological adaptability to climate change. Furthermore, it furnishes theoretical references for the utilization and protection of wild *C. segmentifida* large-scale cultivation in the future. The research objectives of this study were: (1) to identify and restrict *C. segmentifida's* potential spatial distribution pattern in China; (2) to assess the association between environmental variables and potentially suitable distribution pattern; (3) to predict the suitable habitat for *C. segmentifida* under current climatic changes.

Material and methods

Establishing species occurrence records: To obtain accurate species distribution point data for *C. segmentifida*, online databases, including the Global Biodiversity Information Facility (https://www.g bif.org), Chinese Virtual Herbarium (http://www.cvh.ac.cn), Plant Photo Bank of China (http://www.Plantphotophoto.cn), National Specimen Information Infrastructure (http://www.n-sii.org.cn), and the China National Knowledge Infrastructure (https://www.cnki.net) were searched. Duplicative occurrences and any samples without comprehensive longitude and latitude data were excluded. Finally, 38 valid occurrence data of *C. segmentifida* were selected in this research. Information on the latitude and longitude geographic distribution points was acquired were obtained from ArcGIS10.8. Subsequently, using the Excel software, all distribution point data were recorded and converted into CSV formats following the requirements of the MaxEnt model (Fig. 1).

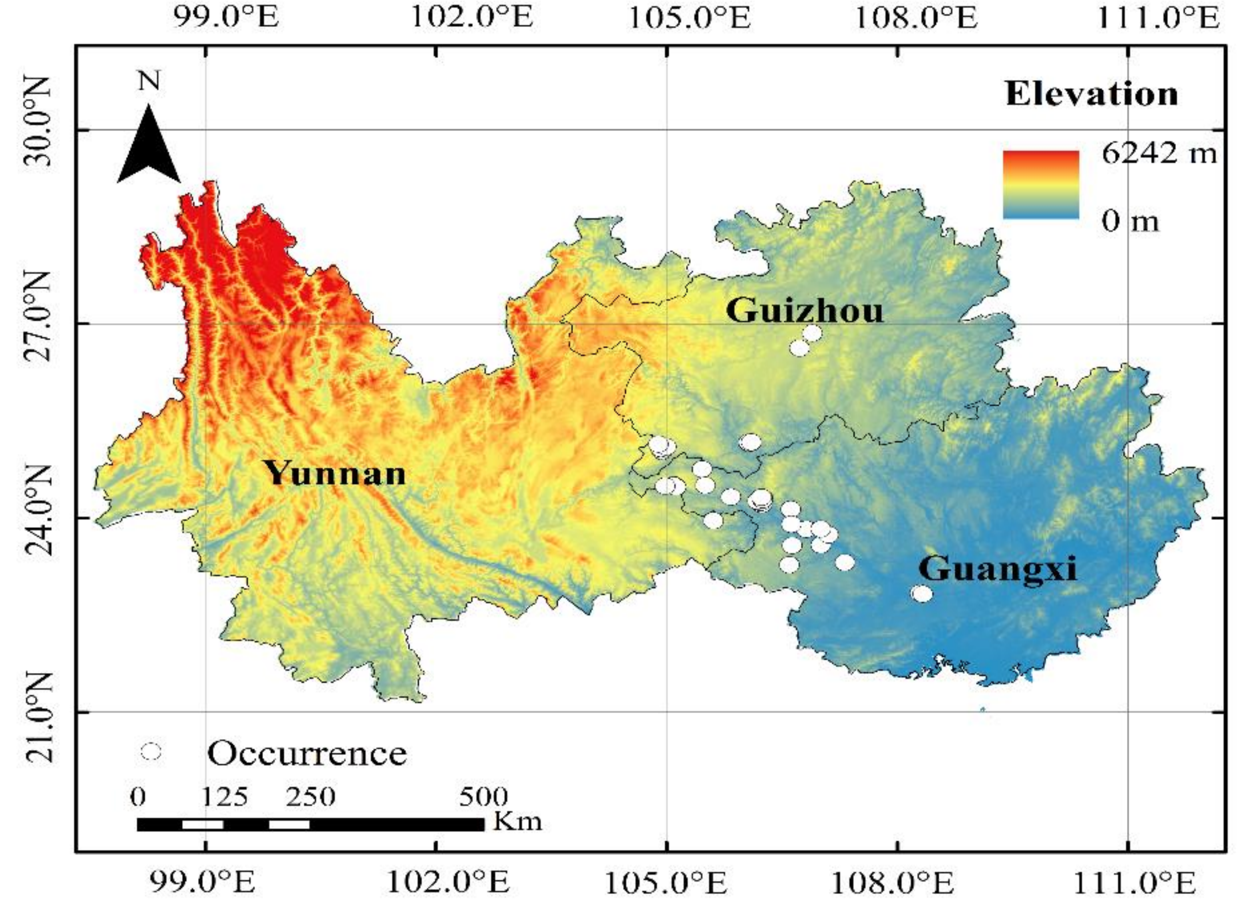

Fig. 1. The representative *Cycas segmentifida* images and their distribution areas (white circles) in three Southwest China provinces.

Selecting environmental variables: For the current climate, using the WorldClim database (http://www.worldcli-m.org), 19 bioclimatic factors with 30 arc seconds (~1 km) spatial resolution were identified and utilized species distribution models (Fick & Hijmans, 2017; Table 1). Pearson Correlation Coefficient (r) was employed to test the multicollinearity, and those with r<0.8 were retained, while variables with low contribution and high correlation (r≥0.80) were eliminated (Yang *et al*., 2013; Xie *et al*., 2021). Finally, 8 of the 19 factors were selected as variables for establishing the MaxEnt modeling for *C. segmentifida* geographical distribution in this study.

Table 1. List of environmental variables used for model construction. The eight variables shown in bold font were used in MaxEnt modeling.

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

Modeling species distribution: The 8 environmental variables and *C. segmentifida* species data were added into MaxEnt 3.4.0 software (http://www.cs.princeton.edu/wschapire /Maxent/) to establish and elucidate the models. Jacknife tests are useful in the application of different variables for prediction. Then the receiver operating characteristic (ROC) curves were constructed to test the accuracy of the models, and the areas under the curve (AUCs) were assessed for the three scenarios (zero, 1, and all variables) (Wu *et al*., 2021). The AUC value ranged from 0.5 to 1; a higher value demonstrated that the simulation object's geographic distribution was farther away from the random distribution, indicating that substantial association between the environmental factors and simulation data, i.e., the model had higher accuracy (Phillips *et al*., 2006; Wei *et al*., 2018). The AUC statistic was categorized into 5 performance groups: fail (0.5-0.6), poor (0.6-0.7), fair (0.7-0.8), good (0.8-0.9), and excellent (0.9-1.0) (Beale & Lennon, 2012). For visualization and further assessment, the MaxEnt model results predicting the *C. segmentifida* (0-1 range) distribution were utilized as input for the ArcGIS software (10.8), and using the reclassify tool of ArcGIS software, the comprehensive probability of suitable distribution region was divided into 4 categories: excellent (>0.6), good (0.4-0.6), fair (0.2-0.4), poor (<0.2).

Results

Model's performance evaluation: The generated model was elucidated by assessing the AUC of the ROC plot. The ROC curve indicated that the reconstructed MaxEnt model's AUC value was "excellent" (AUC_{mean}=0.994, Fig. 2), which was ≥0.5 of a random model, indicating high reliability of the model and could efficiently reflect the distribution areas of *C. segmentifida* under the current climate scenarios.

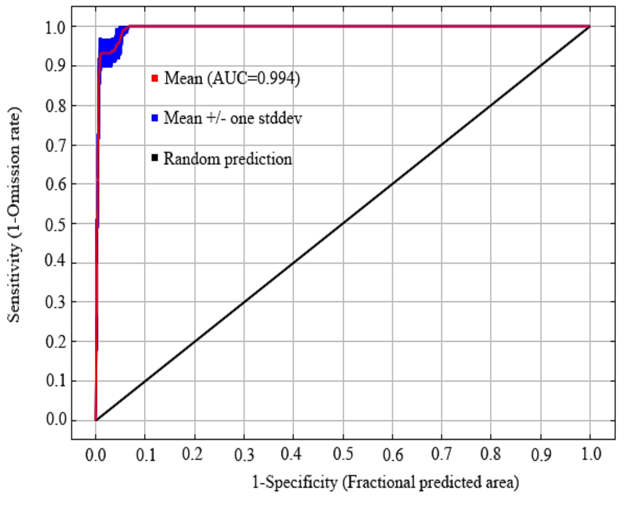

Fig. 2. ROC curve for the prediction model for *C. segmentifida* distribution.

Key environmental variables and validation of the modeling results: Based on the jackknife test results and climate variables contribution rates calculated by the model, the primary environmental factors affecting the differences in *C. segmentifida* distribution were determined (Table 2). The contribution data indicated that precipitation of the warmest quarter (Bio18, 49.5%), precipitation of the driest quarter (Bio17, 22.8%), and temperature seasonality (Bio4, 13.9%) had the highest contributions, accounting for 86.2% of the model prediction (Table 2). Considering the importance of permutation, precipitation of the warmest quarter (Bio18, 42.2%), temperature seasonality (Bio4, 37.8%), and precipitation of the driest month (Bio12, 10.1%) were much higher than others (Table 2). That is, temperature (Bio4) and precipitation (Bio18) were critical in predicting the possible *C. segmentifida* distribution.

Furthermore, the jackknife test indicated that temperature seasonality (Bio4) had the highest gain in regularized testing and training. Temperature annual range (Bio7) had the highest AUC gain, suggesting it contributes the most to the *C. segmentifida* distribution (Fig. 3). In contrast, the mean temperature of the wettest quarter (Bio8) was the least important and the lowest gain, with little impact on predicting species distribution (Fig. 3). The results indicated that compared to the precipitation, temperature had a greater effect on *C. segmentifida* distribution (Fig. 3).

Table 2. Permutation importance levels and percent contribution of the 8 environmental variables were selected for the MaxEnt models, ranked by percentage contribution.

Code	Bioclimatic variable	Percent contribution	Permutation importance
Bio18	Precipitation of the warmest quarter	49.5	42.2
Bio17	Precipitation of the driest quarter	22.8	2.8
Bio4	Temperature seasonality	13.9	37.8
Bio12	Annual precipitation	9.0	10.1
Bio8	Mean temperature of the wettest quarter	2.8	0.4
Bio6	Minimum temperature of the coldest month	0.9	5.2
Bio7	Temperature annual range	0.8	1.2
Bio13	Precipitation of the wettest month	0.2	0.2

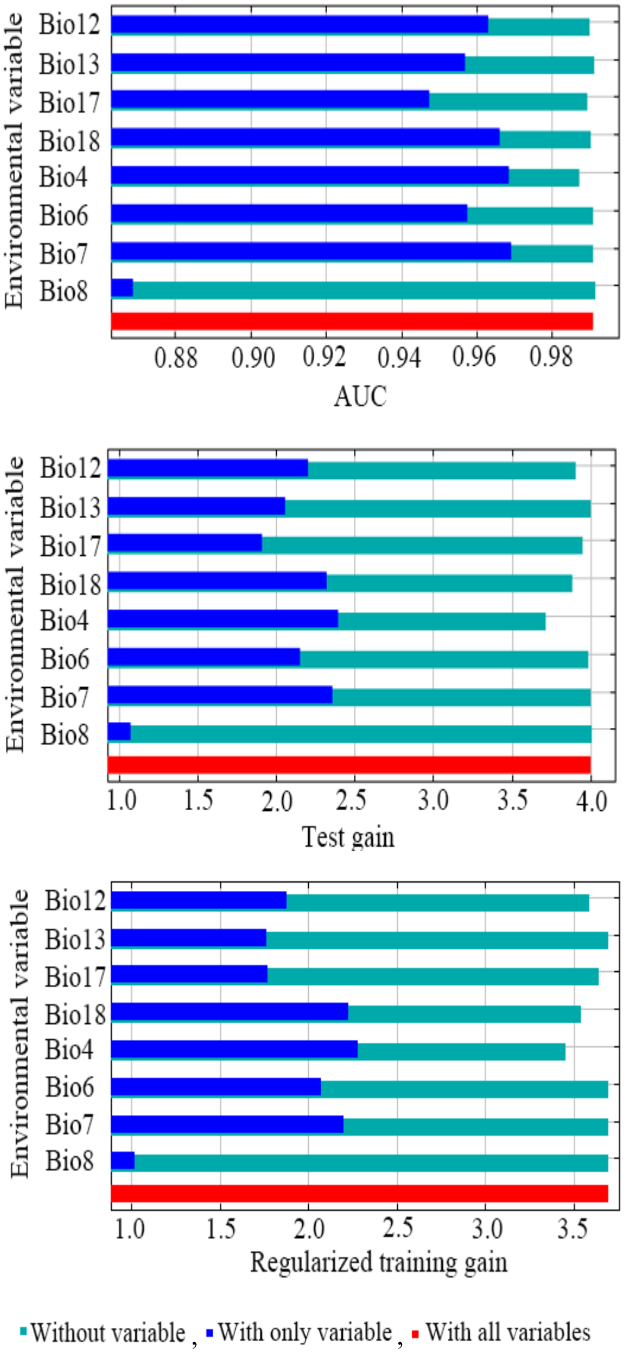

Fig. 3. Assessment of the predictive abilities of the eight environmental variables by the jackknife test and AUC values in MaxEnt models.

The MaxEnt-generated response curves between species presence probability and environmental variables demonstrated the effects of the environmental factors on the species abundance (Fig. 4). Bio4, Bio6, Bio7, Bio12, Bio13, Bio17, and Bio18 revealed single-peaked curves, indicating that *C. segmentifida* had substantially adapted to these environmental variables. The response curves of temperature seasonality (Bio4) and precipitation in the wettest quarter (Bio18) indicated the impact of altering bioclimatic values on the distribution probability of *C. segmentifida* (Fig. 4). When the temperature seasonality (Bio4) was 420-640℃, and the precipitation in the wettest quarter (Bio18) was 540-780 mm, the *C. segmentifida* distribution probability peaked (Fig. 4).

Predicting the suitable habitat of *C. segmentifida* in China: The MaxEnt predicted potential suitable *C. segmentifida* distribution indicated that the most suitable areas under current climatic conditions were situated in Guangxi, Guizhou, Yunnan, Guangdong, Sichuan, Chongqing, Fujian, and Taiwan (Fig. 5). The assessment indicated 142.599×10^4 km^2 as being poorly suitable, 6.383×10^4 km^2 as fairly suitable, 3.698×10^4 km^2 as good, and 2.655×10^4 km^2 as having excellent suitability, comprising 14.854%, 0.665%, 0.385%, and 0.277%, respectively, of the overall land area of China (Table 3). Only Guangxi, Guizhou, and Yunnan had excellent suitability among these regions at 2.115×10^4 km^2, 0.392×10^4 km^2 and 0.148×10^4 km^2 (Table 3). However, there were no distribution records in Guangdong, Sichuan, Chongqing, Fujian, and Taiwan researchs, indicating that this endangered plant's current distribution range may expand to fill the potential area.

Table 3. Areas predicted to be suitable for *C. segmentifida* under current climatic conditions in the provinces and autonomous regions of China (10^4 km^2).

Province or autonomous region	Predicted suitable area ratio			
	Poor	Fair	Good	Excellent
Guangxi	14.554	2.080	2.288	2.115
Guizhou	13.196	1.325	1.068	0.392
Yunnan	32.957	0.818	0.340	0.148
Guangdong	15.882	0.099	0.000	0.000
Sichuan	43.929	1.832	0.002	0.000
Chongqing	7.679	0.024	0.000	0.000
Fujian	11.234	0.012	0.000	0.000
Taiwan	3.168	0.193	0.000	0.000
Total	142.599	6.383	3.698	2.655

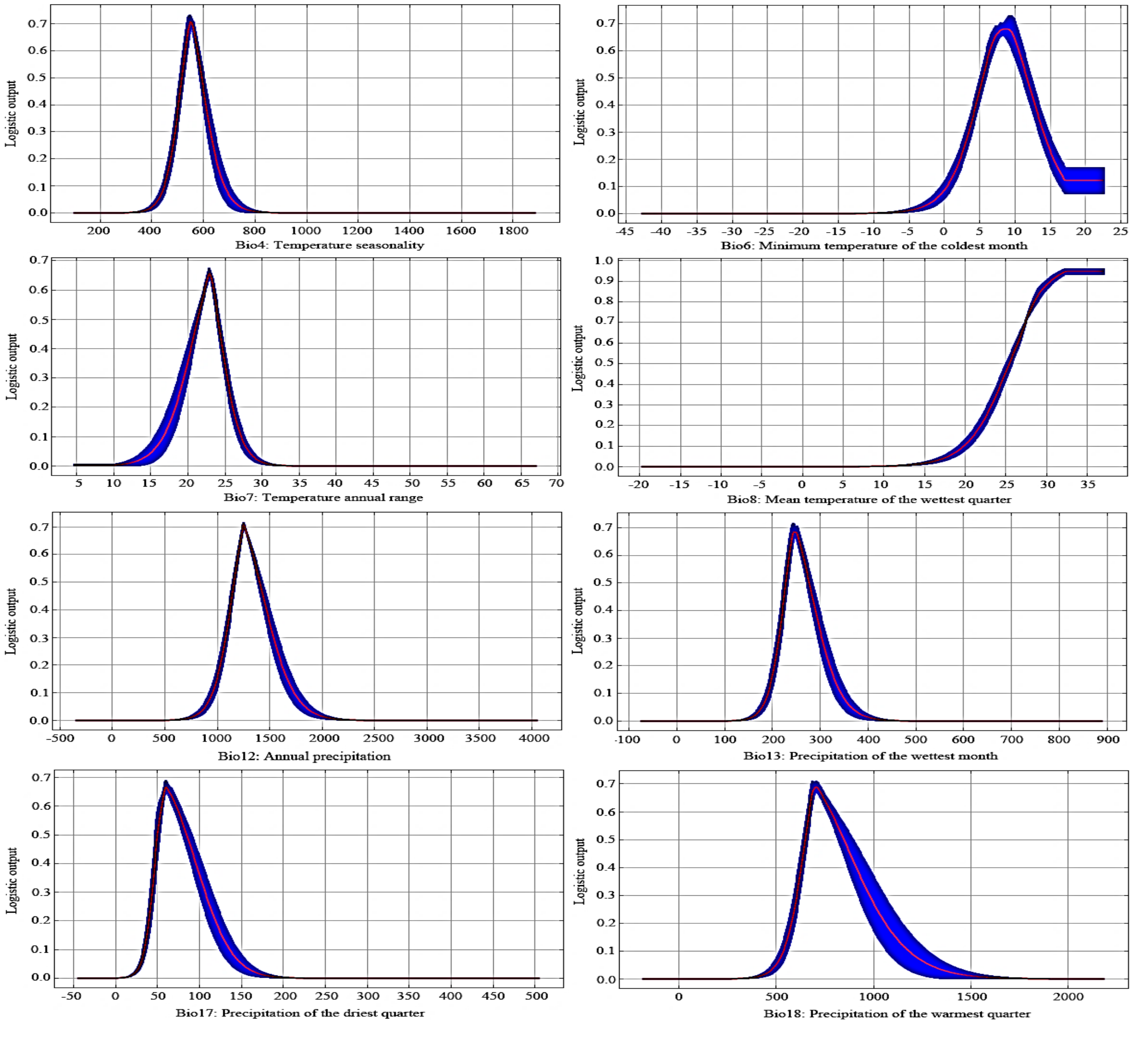

Fig. 4. Response curves of the environmental variables to distribution probability.

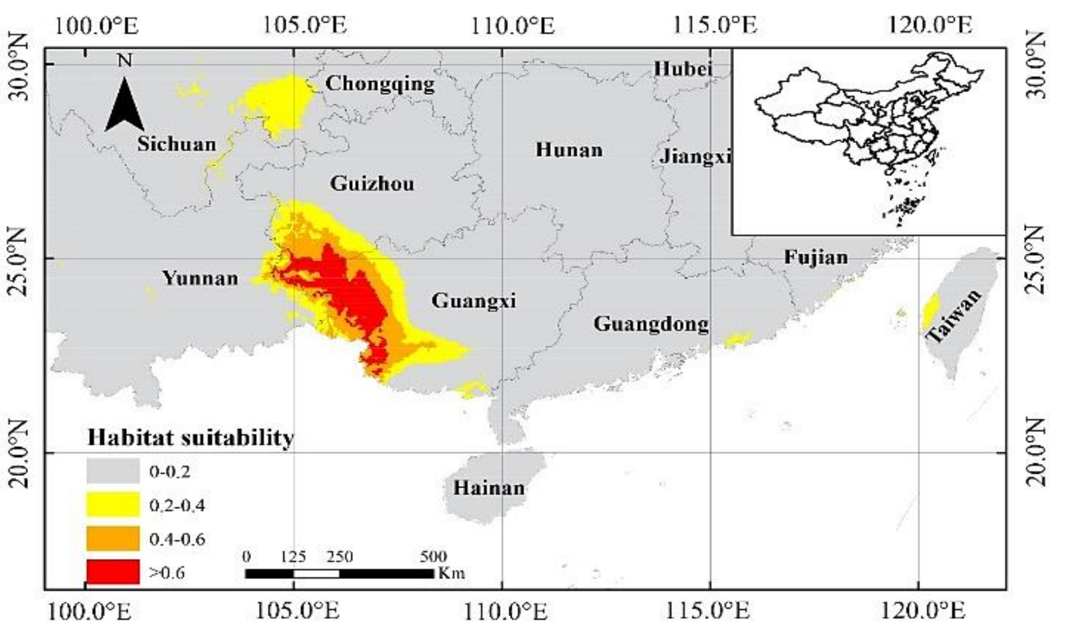

Fig. 5. The predicted distribution range of *C. segmentifida* predicted by MaxEnt modeling.

Discussion

This is the first research of the influence of climate change on the geographical distribution and predicted environmental suitability of *C. segmentifida*'s habitat in China using the MaxEnt model. Here, each factor's contribution rate to the MaxEnt model was assessed to identify the key environmental ariables, and those with small contribution rates and high correlations were eliminated. Finally, 8 crucial environmental variables were selected, and the model was reconstructed (Table 2), which improved the accuracy of habitat suitability predictions. The final threshold-independent AUC reached 0.994 (Fig. 2), indicating that the MaxEnt model accurately predicted the habitat suitability of *C. segmentifida*. The results also demonstrated that the MaxEnt model could avoided overfitting resulting in effective predictions using a restricted sample size, providing a useful tool for the conservation and management of endangered species with extremely small populations (Phillips *et al*., 2006; Alcala-Canto *et al*., 2019).

The association of species and environment is essential for understanding the ecological requirements and spatial distribution of species (Xu *et al*., 2019), especially temperature, which can substantially determine plant functions and biochemical mechanisms and essentially shape their distribution (Khanum *et al*., 2013; Wang *et al*., 2022). This research elucidated the relationship of *C. segmentifida* existence probability with key environmental variables and acquired the relevant response curves. It was indicated that the temperature seasonality (Bio4) was the predominant variable influencing the potential distribution of *C. segmentifida* (Table 2; Fig. 3), and the optimum temperature seasonality (Bio4) was about 420-640 ℃ (Fig. 4). Temperature seasonality is defined as the variations in the temperature over one year, and the greater the standard deviation, the greater the coefficient of variation (Liu *et al*., 2019; Qi *et al*., 2022), indicating that *C. segmentifida* is unsuitable for a habitat with a high annual temperature difference. Temperature seasonality changes within a certain range can enhance the adaptability of endangered plants to environmental alterations and habitat conditions (Borbororah *et al*., 2020). However, beyond a given temperature peak, the habitat range of the endangered plant will shrink or disappear (Khodorova & Boitel-Conti, 2013). Other studies have shown that the extreme value and variation range of temperature were closely linked with species distribution landscape patterns (Yang *et al*., 2022). Based on existing distribution data (Fig. 1), *C. segmentifida* mainly in karst habitats, where vegetation is dense, and the temperature seasonality changes are not significant.

The results of the MaxEnt model indicated that precipitation of the warmest quarter (Bio18) was the primary factor affecting the potential distribution of *C. segmentifida* (Table 2; Fig. 3). Precipitation an environmental factor affecting plant growth, can be utilized to identify the effect of climate change on the diversity of plant species (Isaiah *et al*., 2014). Precipitation linked with multiple environmental factors influencing the plant's physiological processes, such as suitable rainfall significantly increasing soil's water content, providing an excellent environment for the growth and maturation of plant fruits. However, excessive rainfall may cause plant death due to root respiration obstruction, which promotes pest invasion and disease, especially during high temperatures and extremely high humidity (Duan *et al*., 2022). Here, the optimal Bio18 value of *C. segmentifida* was 540-780 mm (Fig. 4), indicating a requirement for moisture consistent with its current distribution. The reason might be associated with the physiological features of *C. segmentifida*. According to the existing distribution data, these endangered plants are primarily distributed in karst habitats, where the area lacks surface runoff, the spatial distribution of soil is uneven and the rate of rock exposure is high. After the hot summer sunshine, much water in the soil evaporates is lost. Thus, a large amount of precipitation is needed in the warmest quarter to maintain the normal physiological activity of these plants.

A deeper knowledge of the potentially suitable region for *C. segmentifida* will help collect germplasm resources, protect genetic diversity, and promote genetic improvement. The simulation data indicated that the excellent suitability area of *C. segmentifida* was only 2.655×10^4 km^2 (Table 3), primarily located in Guangxi, Guizhou, and Yunnan provinces, indicating a limited range of suitable geographical distribution for its population. Furthermore, it is possible that the current distribution range of *C. segmentifida* may expand to include areas that were predicted to be suitable for its growth (Fig. 1; Fig. 5). The observed discrepancy between the current and potentially suitable ranges might be because of insufficient research data to accurately define the specie's environmental requirements or insufficient or over-fitting models, resulting in overestimating of the predicted distribution region. Moreover, it is assessed by the characteristics of the Maxent model, which only considers niche-based presence data and predicts the species's fundamental niche rather than the realized niche, resulting in over-estimated results (Kumar & Stohlgren, 2009; Yang *et al*., 2013). Additionally, predicting species distribution should consider their physiological constraints, driving changes, competition of ecological communities, and response to external factors, which may cause the actual geographical distribution of a species to lag behind climate change (Zhang *et al*., 2019).

It has been acknowledged that a plant's spatial distribution is affected by both biotic and abiotic factors, including predation, vegetation, human disturbances, temperature, precipitation, soil type, altitude, and geographical barriers, among others (Asanok *et al*., 2020). Especially after years of human interference, the distribution of plant habitats has ceased to exist, and the use of forest land has changed. The distribution records of the herbarium are not from the same year, nor are they new survey results in recent years. Therefore, based on a detailed research of the distribution status of endangered plants, it is necessary to combine different types of biological and abiotic factors to predict the impact of climate change on the suitable spatial distribution of endangered plants (Blach-Overgaard *et al*., 2010).

Some measures could sustain and expand the *C. segmentifida* distribution range. They require comprehensive cognate research to augment current knowledge and apply the findings to conservation. These comprise key issues such as basic research, the distributions of pollinators and seed dispersers, establishing more natural small protected areas in high-risk regions, the protection of existing fruiting mother trees, increasing seed production and thus reproduction, and maximum protection of this endangered species under climate change (Fricke *et al*., 2022). Other factors, such as species interactions, regional microclimate, historical distribution, topography, soil, human activities, and spatial constraints, should be investigated to acquire more accurate and comprehensive spatial data to refine the distribution simulation of *C. segmentifida* habitat.

Conclusion

This research predicted suitable areas for *C. segmentifida* in China using the MaxEnt niche model and ArcGIS. The most suitable habitats were only identified in China's Guangxi, Guizhou, and Yunnan provinces. Furthermore, the key environmental variables that modulate its distribution include the temperature seasonality (Bio4, optimal=420-640 ℃) and precipitation of the warmest quarter (Bio18, optimal=540-780 mm). These results highlight the specific conditions necessary for optimal *C. segmentifida* growth, and provide a foundation for the improved conservation and management of this endangered plant.

Acknowledgement

This study was supported by the Guangxi Natural Science Foundation (No.2023GXNSFAA026422); Scientific; Research Foundation of Guangxi Normal University for Nationalities (No.2021BS002; No.2022YB032); This study was supported by the basic ability enhancement program for Young and Middle-Aged Teachers of Guangxi (No.2024KY0782); Scientific Research Projects of Universities in Anhui Province (No.2022AH051052), and the open research project of Anhui University Engineering Technology Research Center of Aquatic biological protection and water ecological restoration (No.AO202303), and Doctoral startup fund of Anqing Normal University (No.191007). The funders did not influence the decision to publish or prepare the manuscript at any point in the study's development, data collection, or analysis.

References

Alcala-Canto, Y., A. Alberti-Navarro, J.A. Figueroa-Castillo, F. Ibarra-Velarde, Y. Vera-Montenegro and M.E. Cervantes-Valencia. 2019. Maximum Entropy ecological niche prediction of the current potential geographical distribution of eimeria species of Cattle, Sheep and Goats in Mexico. *J. Anim. Sci.*, 9(2): 234-248.

Asanok, L., T. Kamyo and D. Marod. 2020. Maximum entropy modeling for the conservation of hopea odorata in Riparian Forests. Central Thailand. *Biodiversitas*, 21(10): 4663-4670.

Beale, C.M. and J.J. Lennon. 2012. Incorporating uncertainty in predictive species distribution modelling. *Philos. T. R. Soc. B*., 1586(367): 247-258.

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. *Ecol. Lett*., 15(4): 365-377.

Blach-Overgaard, A., J.C Svenning, J. Dransfield, M. Greve and H. Balslev. 2010. Determinants of palm species distributions across Africa: the relative roles of climate, non-climatic environmental factors, and spatial constraints. *Ecography*, 33(2): 380-391.

Borborah, K., K. Deka, D. Saikia, S.K. Borthakur and B. Tanti. 2020. Habitat distribution mapping of *Musa flaviflora* Simmonds-a wild banana in Assam, India. *Acta Ecol. Sinica*, 40(2): 122-127.

Çoban, H.O., Ö.K. Örücü and E.S. Arslan. 2020. MaxEnt modeling for predicting the current and future potential geographical distribution of *Quercus libani* Olivier. *Sustainability*, 12(7): 2671.

Cotrina, S.A., B.N.B. Rojas, S. Bandopadhyay, G. Subhasis, C.T. Guzmán, O. Manuel, B.K. Guzman and R.S. López. 2021. Biogeographic distribution of *Cedrela* spp. genus in Peru using MaxEnt modeling: A conservation and restoration approach. *Diversity*, 13(6): 261.

Dawson, T. P., S.T. Jackson, J.I. House, I.C. Prentice and G.M. Mace. 2011. Beyond predictions: biodiversity conservation in a changing climate. *Science*, 332(6025): 53-58.

Duan, X.G., J.Q. Li and S.H. Wu. 2022. MaxEnt modeling to estimate the impact of climate factors on distribution of *Pinus densiflora*. *Forests*, 13(3): 402.

Dubuis, A., J. Pottier, V. Rion, L. Pellissier, J.P. Theurillat and A. Guisan. 2011. Predicting spatial patterns of plant species richness: A comparison of direct macroecological and species stacking modelling approaches. *Divers. Distrib.*, 17(6): 1122-1131.

Duflot, R., C. Avon, P. Roche, L. Bergès. 2018. Combining habitat suitability models and spatial graphs for more effective landscape conservation planning: An applied methodological framework and a species case study. *J. Nat. Conserv.*, 46: 38-47.

Feng, X., J. Liu, Y. C. Chiang and X. Gong. 2017. Investigating the genetic diversity, population differentiation and population dynamics of *Cycas segmentifida* (Cycadaceae) endemic to Southwest China by multiple molecular markers. *Front. Plant. Sci*., 8: 839.

Ferrarini, A., J. Dai, Y. Bai and J.M. Alatalo. 2019. Redefining the climate niche of plant species: A novel approach for realistic predictions of species distribution under climate change. *Sci. Total. Environ.*, 671: 1086-1093.

Fick, S.E. and R.J. Hijmans. 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.*, 37(12): 4302-4315.

Fortunel, C., C.E.T. Paine, P.V.A. Fine, N.J.B. Kraft and C. Baraloto. 2014. Environmental factors predict community functional composition in Amazonian forests. *J. Ecol.*, 102(1): 145-155.

Fricke, E.C., A. Ordonez, H.S. Rogers and J.C. Svenning. 2022. The effects of defaunation on plants' capacity to track climate change. *Science*, 375(6577): 210-214.

Isaiah, G., M. Amon, D.S. Munyaradzi, M. Masocha and C. Chapano. 2014. Precipitation of the warmest quarter and temperature of the warmest month are key to understanding the effect of climate change on plant species diversity in Southern African savannah. *Afr. J. Ecol.*, 52(2): 209-216.

Kaky, E. and F. Gilbert. 2016. Using species distribution models to assess the importance of Egypt's protected areas for the conservation of medicinal plants. *J. Arid Environ.*, 135: 140-146.

Kaky, E., V. Nolana, A. Alatawi and F. Gilbert. 2020. A comparison between Ensemble and MaxEnt species distribution modelling approaches for conservation: A case study with Egyptian medicinal plants. *Ecol. Inform.*, 60: 101150.

Kamyo, T. and L. Asanok. 2020. Modeling habitat suitability of *Dipterocarpus alatus* (Dipterocarpaceae) using MaxEnt along the Chao Phraya River in Central Thailand. *For. Sci. Technol.*, 16(1): 1-7.

Khanum, R., A.S. Mumtaz and S. Kumar. 2013. Predicting impacts of climate change on medicinal asclepiads of Pakistan using Maxent modeling. *Acta. Oecol*., 49: 23-31.

Khodorova, N. and M. Boitel-Conti. 2013. The role of temperature in the growth and flowering of geophytes. *Plants*, 2(4): 699-711.

Knapp, A.K., B. Claus, D.D. Briske, A.T. Classen, Y. Luo, R. Markus, M.D. Smith, S.D Smith, J.E. Bell and P.A. Fay. 2008. Consequences of more extreme precipitation regimes for terrestrial ecosystems. *BioScience*, 58: 811-821.

Koch, R., J.S. Almeida-Cortez and B. Kleinschmit. 2017. Revealing areas of high nature conservation importance in a seasonally dry tropical forest in Brazil: combination of modelled plant diversity hot spots and threat patterns. *J. Nat. Conserv*., 35: 24-39.

Kouhi, S.M.M and M.B. Erfanian. 2020. Predicting the present and future distribution of medusahead and barbed goatgrass in Iran. *Ecopersia*, 8(1): 41-46.

Kumar, S. and T.J. Stohlgren. 2009. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. *J. Ecol. Nat. Environ*., 1(4): 94-98.

Liu, L., L.L. Guan, H.X. Zhao, Y. Huang, Q.Y. Mou, K. Liu, T.T. Chen, X. Y. Wang, Y. Zhang, B. Wei and J.Y. Hu. 2021. Modeling habitat suitability of *Houttuynia cordata* Thunb (Ceercao) using MaxEnt under climate change in China. *Ecol. Inform*., 63: 101324.

Liu, Y., P. Huang, F.R. Lin, W.Y. Yang, H. Gaisberger, K. Christopher and Y.Q. Zheng. 2019. MaxEnt modelling for predicting the potential distribution of a near threatened rosewood species (*Dalbergia cultrata* Graham ex Benth). *Ecol. Eng*., 141: 105612.

Mahmoodi, S., M. Heydari, K. Ahmadi, N.R. Khwarahm, O. Karami, K. Almasieh, B. Naderi, P. Bernard and A. Mosavi. 2022. The current and future potential geographical distribution of *Nepeta crispa* Willd., an endemic, rare and threatened aromatic plant of Iran: Implications for ecological conservation and restoration. *Ecol. Indic*., 137: 108752.

Manish, K., Y. Telwala, D.C. Nautiyal and M.K. Pandit. 2016. Modelling the impacts of future climate change on plant communities in the Himalaya: A case study from Eastern Himalaya, India. *Model. Earth. Syst. Env*., 2: 92.

Petitpierre, B., C. Kueffer, O. Broennimann, C. Randin, C. Daehler and A. Guisan. 2012. Climatic niche shifts are rare among terrestrial plant invaders. *Science*, 335: 1344-1348.

Phillips, S.J., R.P. Anderson and R.E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. *Ecol. Model*., 190: 231-259.

Qi, S., W. Luo, K.L. Chen, X. Li, H.L. Luo, Z.Q. Yang and D.M. Yin. 2022. The prediction of the potentially suitable distribution area of *Cinnamomum mairei* H. Lév in China based on the MaxEnt model. *Sustainability*, 14: 7682.

Remya, K., A. Ramachandran and S. Jayakumar. 2015. Predicting the current and future suitable habitat distribution of *Myristica dactyloides* Gaertn. using MaxEnt model in the Eastern Ghats, India. *Ecol Eng*., 82: 184-188.

Román-Palacios, C. and J.J. Wiens. 2020. Recent responses to climate change reveal the drivers of species extinction and survival. *Proceed. Nat. Acad. Sci*., 117(8): 4211-4217.

Sarma, K., S.J. Roy, B. Kalita, P.S. Baruah, A. Bawri, M.J. Nath, U.D. Baruah, D. Sahariah, A. Saikia and B. Tanti. 2022. Habitat suitability of *Gymnocladus assamicus*-A critically endangered plant of Arunachal Pradesh, India using machine learning and statistical modeling. *Acta Ecol. Sinica*, 42(3): 398-406.

Selwood, K., M.A. McGeoch and R.M. Nally. 2015. The effects of climate change and land-use change on demographic rates and population viability. *Biol. Rev*., 90(3): 837-853.

Stalin, N. and P.S. Swamy. 2015. Prediction of suitable habitats for *Syzygium caryophyllatum*, an endangered medicinal tree by using species distribution modelling for conservation planning. *Eur. J. Cell. Biol*., 5(11): 12-19.

Tuan, N.T., I. Gliottone, M.P. Pham and D.D. Vu. 2021. Current and future habitat suitability map of *Cunninghamia konishii* hayata under climate change in northern vietnam European. *J. Ecol*., 7(2): 1-17.

Urbina-Cardona, N., M.E. Blair, M.C. Londoño, R. Loyola, J. Vela´squez-Tibata´ and H. Morales-Devia. 2019. Species distribution modeling in Latin America: A 25-year retrospective review. *Trop. Conserv. Sci*., 12: 1-19.

Veloz, S.D., J.W. Williams, J.L. Blois, F. He, B. Otto-Bliesner and Z.Y. Liu. 2012. No-analog climates and shifting realized niches during the late quaternary: implications for 21st-century predictions by species distribution models. *Global. Change. Biol*., 18: 1698-1713.

Wang, Y.Y., P. Dong, W.J. Hu, G.C. Chen, D. Zhang, B. Chen and G.C. Lei. 2022. Modeling the climate suitability of northernmost mangroves in China under climate change scenarios. *Forests*, 13(1): 64.

Wasowicz, P., E.M. Przedpelska-Wasowicz and H. Kristinsson. 2013. Alien vascular plants in Iceland: Diversity, spatial patterns, temporal trends, and the impact of climate change. *Flora*, 208: 648-673.

Wei, B., R.L. Wang, K. Hou, X.Y. Wang and W. Wu. 2018. Predicting the current and future cultivation regions of *Carthamus tinctorius* L. using MaxEnt model under climate change in China. *Glob. Ecol. Conserv*., 16: e00477.

Wu, B.C., L.J. Zhou, S. Qi, M.L. Jin, J. Hu and J.S. Lu. 2021. Effect of habitat factors on the understory plant diversity of *Platycladus orientalis* plantations in Beijing mountainous areas based on MaxEnt model. *Ecol. Indic*., 129: 107917.

Xie, C.P., B.Y. Huang, C.Y. Jim, W.D. Han and D.W. Liu. 2021. Predicting differential habitat suitability of *Rhodomyrtus tomentosa* under current and future climate scenarios in China. *Forest. Ecol. Manag*., 501: 119696.

Xu, D.P., Z.H. Zhuo, R.L. Wang, M. Ye and B. Pu. 2019. Modeling the distribution of *Zanthoxylum armatum* in China with MaxEnt modeling. *Glob. Ecol. Conserv*., 19: e00691.

Yang, J.T., X. Jiang, H. Chen, P. Jiang, M. Liu and Y. Huang. 2022. Predicting the potential distribution of the endangered plant *Magnolia wilsonii* using MaxEnt under climate change in China. *Pol. J. Environ. Stud*., 31: 4435-4445.

Yang, X.Q., S.P.S. Kushwaha, S. Saran, J. Xu and P.S. Roy. 2013. Maxent modeling for predicting the potential distribution of medicinal plant, *Justicia adhatoda* L. in Lesser Himalayan foothills. *Ecol. Eng*., 51: 83-87.

Zhang, L., Z.N. Jing, Z.Y. Li, Y. Liu and S.Z. Fang. 2019. Predictive modeling of suitable habitats for *Cinnamomum Camphora* (L.) presl using maxent model under climate change in China. *Int. J. Environ. Res. Pub. He*., 16: 3185.

Zheng, Y., J. Liu, X.Y. Feng and G. Xun. 2017. The distribution, diversity, and conservation status of Cycas in China. *Ecol. Evol*., 7: 3212-3224.

(Received for publication 30 August 2023)