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Distributional response of the rare and critically endangered *Ilex nanchuanensis* to climate change in East Asia

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PAPER

Distributional response of the rare and critically endangered *Ilex nanchuanensis* to climate change in East AsiaZhiming Chen¹ , Wenjuan Kang², Guang Li¹ , Renyuan He¹ and Zhuzhu Luo^{1,3} ¹ College of Forestry, Gansu Agricultural University, Lanzhou, 730070, People's Republic of China² Pratacultural College, Gansu Agricultural University, Lanzhou, 730070, People's Republic of China³ College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou, 730070, People's Republic of ChinaE-mail: luozz@gsau.edu.cn**Keywords:** *Ilex nanchuanensis*, global climate change, migration prediction, potential distribution, critically endangered Chinese endemic species

Abstract

Global climate change, dominated by climate warming, is seriously affecting the balance of global ecosystems, but the risk of species extinction is particularly high in low-altitude mountain areas. To clarify the response of the endemic and critically endangered species *Ilex nanchuanensis* to climate change, this study used the MaxEnt model to simulate and predict the potential habitat of *I. nanchuanensis* during the Last Interglacial, Last Glacial Maximum, the current period, and two future periods (the 2050 s and 2070 s). The results showed that the hottest monthly minimum temperature is the most important climatic factor affecting the geographical distribution of *I. nanchuanensis*. Furthermore, *I. nanchuanensis* will be at risk of population shrinkage and extinction in the future, with the center of mass moving further northwest as concentrations of greenhouse gases increase, especially in the 2070 s, when its geographical distribution shrinks the most under the RCP6 scenario. Therefore, to actively respond to the impacts of climate change, protected areas should be established around the geographical distribution centers of species, and core, buffer, and experimental areas should be scientifically and rationally delineated for the conservation and cultivation of germplasm resources.

1. Introduction

Global climate change alters the temperature and precipitation patterns on the Earth's surface [1–5], which in turn affects plant growth and development patterns, morphological structures, and geographic distribution patterns [6–9], ultimately endangering the diversity and stability of global ecosystems [10–12]. Global climate change, dominated by climate warming [13, 14], is one of the greatest threats to, and challenges for, ecosystem balance [15, 16]. The Sixth Assessment Report on Climate Change published by the Intergovernmental Panel on Climate Change (IPCC) in 2021 states that the global surface temperature increased by 0.99 °C from 2001 to 2020 compared to the previous century [17, 18], and global warming is expected to continue to 1.5 °C by 2030—2052 [19]. Thomas *et al* (2004) found that approximately 37% of species globally will be at risk of extinction and habitat loss by 2050 as a result of climate warming [20], while Urban (2015) found that the risk of species extinction accelerates with increasing temperatures [21], especially for some rare and endangered species with small population sizes, high habitat specificity, and severe habitat fragmentation [22, 23]. Daskalova *et al* (2020) found that rare and endangered species with small population sizes and limited geographic distributions will be the first to go extinct [22]. In addition, mountain ranges are crucial for global sustainable development because of their specific geographic features and diverse climates [24]. Global climate change has caused serious harm to species living in mountainous regions [25–29], and such species are more sensitive to climate change and at greater risk of species extinction [30–32]. Species dwelling in low-altitude mountainous regions are subject to the dual influences of altitude and various fluctuating environmental determinants during their vertical migration, which imposes greater constraints on their growth and development and heightens the risk of species

extinction [33–37]. Therefore, using the MaxEnt model to simulate and predict the potential geographical distribution of species in low altitude mountainous areas at different periods and scenario modes will help clarify the main climate factors that affect the geographical distribution of species. In addition, it has significant significance for ecological environment protection work.

Species distribution models (SDMs) are widely used in the fields of endangered species conservation and species invasion [38–41], and helping to clarify the response of species distribution and diversity patterns to climate change [42]. Using SDM can not only clarify the reasons for species extinction in different historical periods, but also predict changes in the distribution range of species in future periods, thus effectively protecting the ecological environment [43]. Several widely used SDMs emerged in the late 20th century, among which the MaxEnt (Maximum Entropy) model not only has stable predictive performance, but also has higher accuracy [2, 44]. By studying the distribution data of 226 species, Elith *et al* (2006) concluded that the MaxEnt model simulated the best results [45]. Meanwhile, Prev  y *et al* (2020) used the MaxEnt model to predict the potential fitness zone and phenology of *Vaccinium membranaceum* (American lingonberry) and found that the simulated results were in good agreement with observations [46]. The MaxEnt model is an ecological niche model based on the theory of maximum entropy [47], and is the preferred model for predicting the potential distributions of critically endangered species because of its simplicity, high degree of accuracy, low sample size requirement, and high stability compared to other modeling methods [48–50]. The MaxEnt model has many advantages compared to other prediction models. Its prediction method is simple and only requires the longitude and latitude information of known species distribution samples and environmental variable information of the study area to make unbiased predictions, without the need for absence samples, and the prediction results are superior to other prediction models; There is no strict requirement for sample size. When screening environmental factors, the model exhibits superior performance in quantitatively describing the dominant environmental factors that affect the geographical distribution of species, and is easy to explain from an ecological perspective; The model can not only use continuous data, but also discrete data to integrate the interactions of different influencing factors.

Ilex nanchuanensis is a species of holly tree endemic to China and is classified as critically endangered in the IUCN's Red List of Threatened Species, standard conservation level. It is mainly found on Jinfo Mountain (the highest peak of the Dalou Mountains in Nanchuan District, Chongqing, China) at altitudes of 600–800 m, Longitude and latitude are 107°27' E and 28°52' N, Belongs to a typical subtropical humid monsoon climate. It has extremely high ornamental value and significant ecological value, mainly reflected in the gradual reduction of its distribution range, which means an increase in greenhouse gas emissions and the intensification of climate change [51, 52]. To date, little research has been reported on *I. nanchuanensis*, and in particular, its response to climate change remains unclear.

In this study, based on current distribution data for *I. nanchuanensis* and climatic factors in different periods, the MaxEnt model, combined with ArcGIS software, was used to simulate the potential habitat of the *I. nanchuanensis* during the Last Interglacial (LIG), the Last Glacial Maximum (LGM), the current period, and two future periods (2050 s and 2070 s), to clarify the response of this cherished and critically endangered species to climate change, as well as provide a theoretical and practical basis for conservation management of not only this species but also other rare and endangered species throughout the world living in fragile habitats.

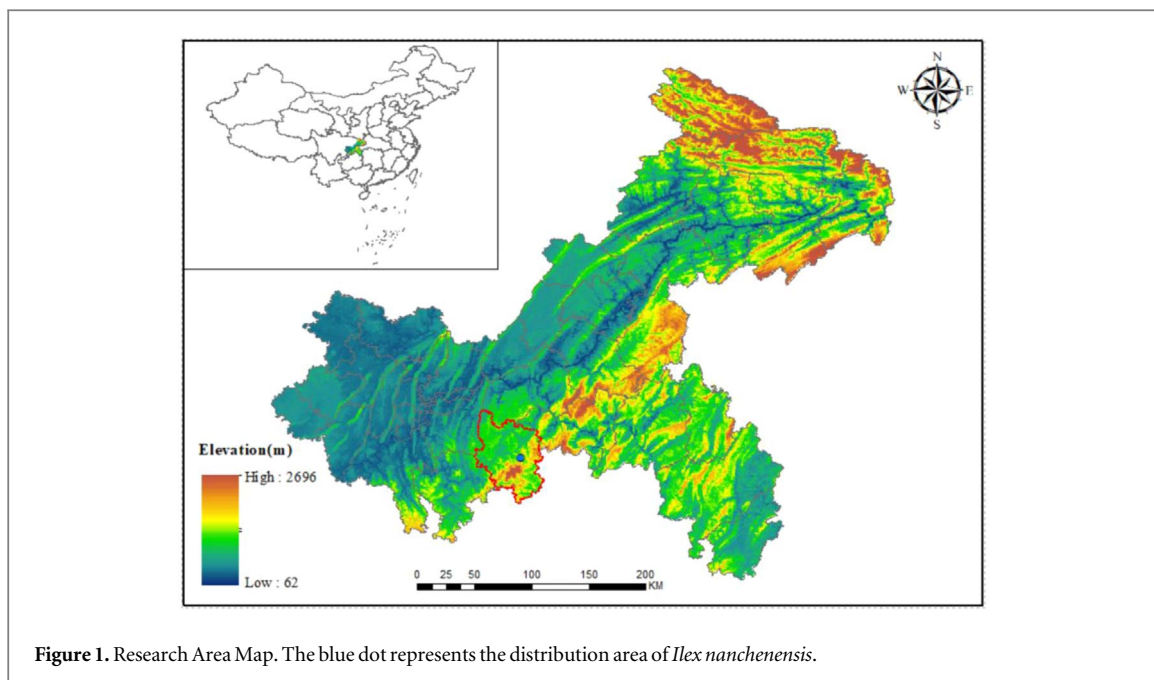
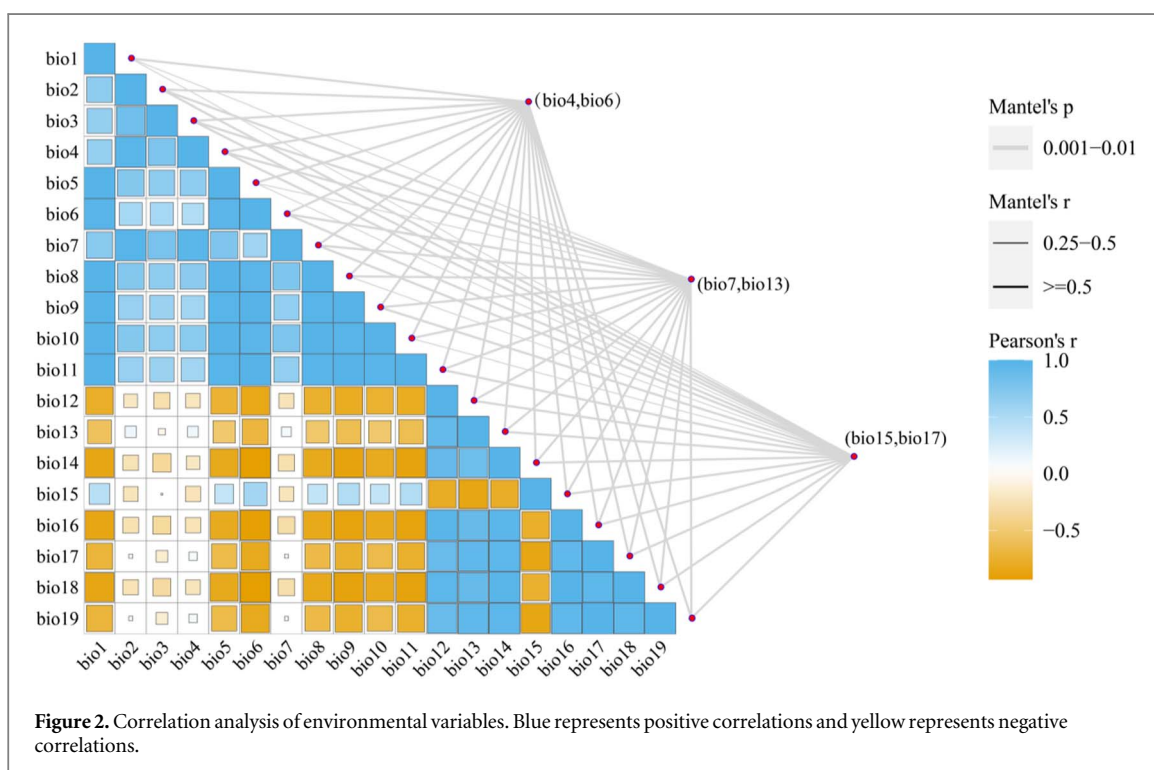
2. Materials and methods

2.1. Species distribution data

Specimen record points were obtained by searching the literature, resource survey reports, and herbaria (e.g., the China Virtual Herbarium, Global Biodiversity Information Facility database, China Biological Species List 2022, Flora of China, Plant Science Data Center) [41, 53]. In actual survey sampling (figure 1), due to sampling costs and transportation issues, it is often chosen to sample in more convenient places such as roads, rivers, and near towns. These uncertain reasons will lead to sampling bias, causing overfitting in the model, and ultimately affecting the predictive ability. Therefore, in order to remove duplicate points, reduce the spatial autocorrelation of distribution points and the negative impact of sampling bias on the model, it is necessary to uniformly divide the area where the distribution points of *Ilex nanchuanensis* are located into 1 km × 1 km grid, ensuring that each grid has only one distribution point of data, 34 samples of Nanchuan holly with clear geographical information were obtained, centered around Nanchuan District, Chongqing, China [42, 54].

2.2. Bioclimatic data acquisition and screening

The bioclimatic data were obtained from the WorldClim database (<http://www.worldclim.com> (accessed on Oct. 25, 2022)) at a resolution of 2.5 arc-min [48, 55]. The data contain four sections: the LIG period (120,000–14,000 years ago), the LGM period (22,000 years ago), the current period (1970–2000), and two future



periods (the 2050 s and 2070 s). They include 19 climatic factors, such as monthly precipitation, monthly mean temperature, monthly maximum temperature, and monthly minimum temperature (figure 2). To avoid the influence of correlation between climatic factors on the simulation results, according to the climatic factor screening method of Yang *et al* (2013) [56], multicollinearity analysis was used in SPSS19.0 to detect the correlation between variables [56]. Environmental variables with correlation values < 0.8 were retained, and their contribution rates were analyzed. Six climatic factors were finally screened to construct the model (table 1): seasonal temperature variation (Bio4); hottest monthly minimum temperature (Bio6); annual mean temperature range (Bio7); wettest monthly precipitation (Bio13); seasonal precipitation (Bio15); and driest quarterly precipitation (Bio17).

With reference to the IPCC's assessment reports, four greenhouse gas emission scenarios (Representative Concentration Pathways, RCPs) were employed: the low emission (RCP2.6) scenario; two moderate emission

Table 1. Description of the climate environmental variables used in MaxEnt.

Variable	Code	Unit
Temperature seasonality (standard deviation)	Bio4	°C
Minimum temperature of warmest month	Bio6	°C
Annual mean temperature range	Bio7	°C
Precipitation of wettest month	Bio13	mm
Precipitation seasonality (coefficient of variation)	Bio15	mm
Precipitation of driest quarter	Bio17	mm

scenarios (RCP4.5 and RCP6), and the high emission (RCP8.5) scenario [57, 58]. Among the various state-of-the-art climate models, it was found that BCC-CSM1.1 (Beijing Climate Center, Climate System Model, version 1.1) was more consistent with the characteristics of climate change in China, while MIROC-ESM (Model for Interdisciplinary Research on Climate, Earth System Model) and CCSM4 (Community Climate System Model, version 4) were used for the LGM period [38].

2.3. MaxEnt model operation and evaluation

Geographical distribution data (in CSV format) and bioclimatic data (in ASC format) were imported into the MaxEnt model for calculation, while the bioclimatic data needed to be modeled separately with the geographical distribution data of the species according to the different periods. Following the method of Moreno *et al* (2011) [59], the bioclimatic factors in the model were set as continuous variables, and then bioclimatic data for the LGM, LIG, and future periods (2050 s and 2070 s) were input in turn to analyze the geographic distribution of *I. nanchuanensis* for each of these periods [59]. Response curves were constructed by selecting the ‘Create response curves’ option. To ensure the accuracy and objectivity of the data, the MaxEnt model should be constructed by randomly selecting 75% of the species’ geographic distribution as training values, while the remaining 25% of the data should be tested by 100 replications to test the model and create ROC (receiver operating characteristic) curves. The remaining model parameters were operated according to the default values of the software [59].

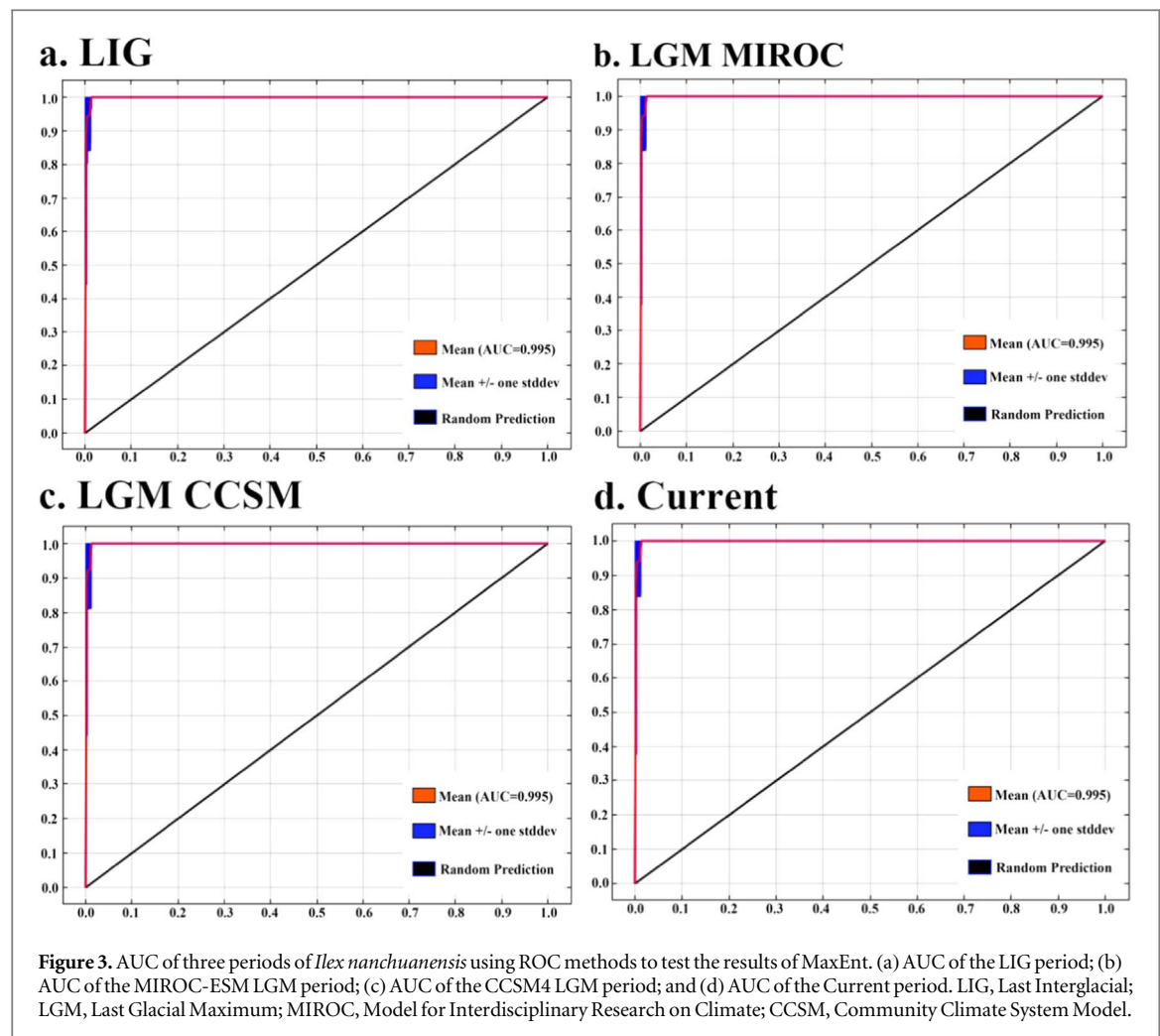
The results of any model simulation need to be evaluated comprehensively. After the MaxEnt model was established, the area under the ROC curve was selected for evaluation in order to verify the accuracy of the evaluation results, and the AUC (area under curve) value was used as an important indicator to measure the predictive ability of the evaluation model. Note that, because the AUC value is the MaxEnt model’s own procedure, the simulation process does not require additional thresholds, is involved in the assessment of simulation predictions of the potential geographic distribution of numerous species, and has a high degree of accuracy [60, 61]. The AUC takes values in the range [0, 1], and values closer to 1 prove that the model’s results are more accurate [45]. In general, when the AUC value is >0.7 , it proves that the model’s simulation results are good, as well as indicating potentially suitable geographic distribution areas for the species [62].

2.4. Classification of habitat suitability

The average value of data from different periods simulated 10 times in the MaxEnt model is used as the output result to import into ArcGIS software in Raster format, using the method of average logical value combined with actual distribution area [42]. In addition, the spatial analysis tool was used to classify and visualize the species’ suitability zones and to obtain a map of the potentially suitable geographic distribution zones of *Ilex nanchuanensis* in different historical periods. The results of the MaxEnt model were interpreted in the form of the fitness probability P of the species occurring in the area to be tested, with P taking values in the range [0, 1]. In addition, based on the actual distribution of *Ilex nanchuanensis* and the methodology reported by the IPCC, the suitable areas for the species were classified into four types: non-suitable ($P < 0.2$), low suitability ($0.2 \leq P < 0.4$), medium suitability ($0.4 \leq P < 0.6$), and high suitability ($P \geq 0.6$). Finally, the areas of different fitness classes of *Ilex nanchuanensis* in the different historical periods were calculated using the area statistics function in the spatial analysis tool [42, 63, 64].

2.5. Analysis of centroid migration in suitable distribution areas

The center of mass is the equilibrium point of moment for species in a region during a historical period, and can effectively represent the spatial aggregation and migration of species over a relative period of time. The Toolbox software in the SDM can capture the location of the species’ center of mass and analyze the changes in the migration of the species’ center of mass in different historical periods by combining geographical information data such as latitude and longitude [64, 65]. The methods were as follows: (1) The results of the MaxEnt model simulating the potential geographic distribution of *I. nanchuanensis* were transformed into a vector binary, and



the suitability of the suitability zone was defined according to the suitability probability P , with $P \geq 0.5$ being the total suitability zone and $P < 0.5$ being the non-suitable zone. (2) Using the Zonal Geometry statistical tool in the Spatial Analysis Tool, the plasmodesmata were selected in the Geometry Type option to capture the specific coordinates of the placenames in the species-suitable zone that were captured. (3) The placenames of *I. nanchuanensis* were analyzed at different times and under different climatic conditions, and the migration direction and distance of *I. nanchuanensis* were finally assessed [42].

3. Results

3.1. Accuracy of model analysis

AUC is the area under the subject operating curve (ROC), which is a threshold independent model performance evaluation commonly used to evaluate the Max Ent model, wherein the closer the AUC value is to 1, the better the simulation results are [46]. In this study, among the simulation results for the LIG period, the LGM period, and the current period, the AUC value was 0.995 (figure 3), indicating that the accuracy of the MaxEnt model simulation in this study was extremely high and the confidence level was excellent. It also shows that both CCSM4 and MIROC-ESM are optimal in the LGM period.

3.2. Dominant environmental factors

Environmental variables influence the potential distribution of the species at different times. As can be seen from table 2, there are six environmental variables that are most important in influencing the potential distribution of *I. nanchuanensis* in different historical periods: Bio4 (standard deviation of seasonal variation in temperature), Bio6 (minimum temperature in the hottest month), Bio7 (annual mean temperature range), Bio13 (precipitation in the wettest month), Bio15 (seasonal coefficient of variation in precipitation), and Bio17 (precipitation in the driest season).

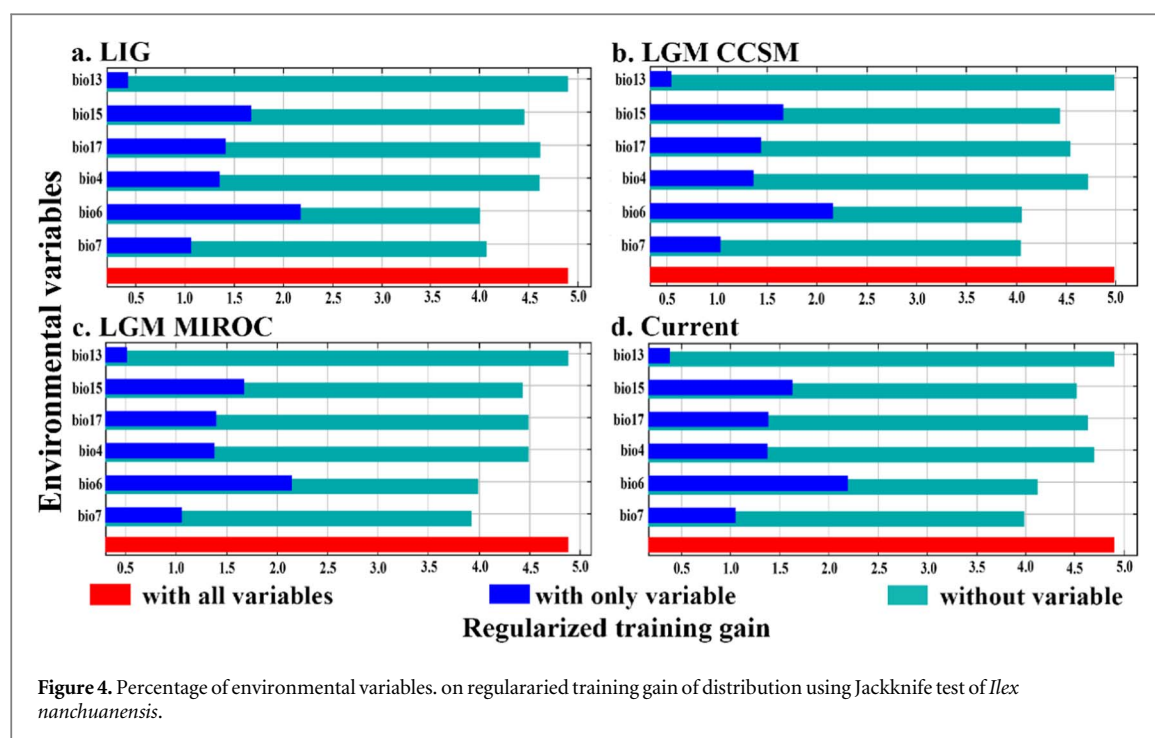


Table 2. Percentage contribution and permutation importance of each environmental variable.

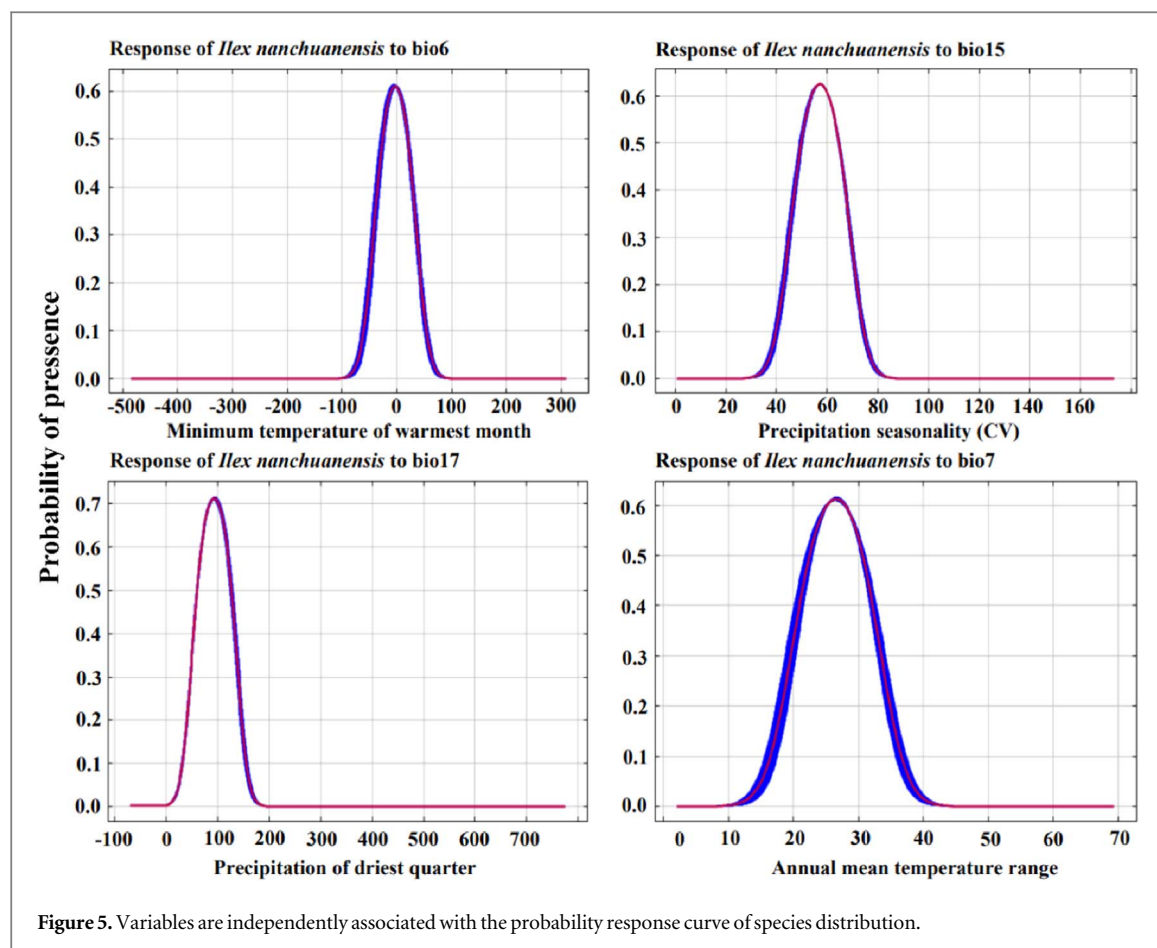
	Period	Bio4	Bio6	Bio7	Bio13	Bio15	Bio17
Percent contribution	LIG	4.7	41.5	15.4	2.0	23.3	13
	LGM (CCSM)	3.7	41.3	16.1	1.5	24.1	13.3
	LGM (MIROC)	6.3	43.2	16.1	0.5	21.7	12.2
	Current	2.8	44.1	15.3	3.5	24.3	10.0
Permutation importance	LIG	10.2	33.3	42.0	1.5	11.5	1.5
	LGM (CCSM)	11.5	27.8	41.0	1.9	15.6	2.2
	LGM (MIROC)	16.6	30.6	43.2	0	8.2	1.3
	Current	13.9	29.2	40.0	2.5	12.6	1.9

Using Jackknife to test the percentage of regularized training gain of environmental variables on the potential distribution of *I. nanchuanensis*, we found (figure 4) that the environmental factors in the LIG period, LGM period (CCSM4 and MIROC-ESM), and current period had the same weighting, from highest to lowest: Bio6, Bio15, Bio17, Bio4, Bio7, Bio13.

Analysis of the probability response curves of environmental variables and species distributions revealed that Bio6, Bio15, Bio17, and Bio7, all four environmental factors, had single-peaked, one-way response curves with probabilities of the presence of major environmental factors >0.5 , which remained largely consistent with the range of environmental factor parameters for highly suitable habitats. The analysis showed (figure 5) that the optimum range for Bio6 was -30°C to 25°C , for Bio15 it was 50–65 mm, for Bio17 it was 70–130 mm, and for Bio7 it was 23°C – 31°C . According to the Jackknife test environmental variable method of simulation detection, the environmental variable that achieves the highest formalized training gain when only one variable is present during the simulation is Bio6. Therefore, Bio6 has the most effective simulation information.

3.3. Suitable species distribution areas

The MaxEnt model was used to simulate the distribution of *I. nanchuanensis* during the LIG period, LGM period (CCSM4 and MIROC-ESM), and current period, and it was found that its distribution range varied significantly during different periods (figure 6). The potential distribution of *I. nanchuanensis* was classified into four classes using the natural break method (grey for unsuitable, green for marginally suitable, yellow for moderately suitable, and red for highly suitable distribution areas). This species of holly is endemic to China, but the large map presented an incomplete map of China, so a small map was used to refine the U-shaped line. As shown in figure 6(d), (I). *nanchuanensis* is currently distributed in China mainly in Nanchuan District, Wulong District, Chongqing Municipality, Wuping Town, Fengdu County, Chongqing Municipality, Nanchuan City, Yichang



City, and Wufeng City, Hubei Province, mainly between 29.00728°N and 30.17125°N, with the highly suitable area being mainly in Nanchuan District, Chongqing Municipality.

The MaxEnt model simulation revealed that the distribution range of *I. nanchuanensis* can be better captured at present. The total suitable distribution area was $37.722223 \times 10^4 \text{ km}^2$; the highly suitable distribution area was $5.708333 \times 10^4 \text{ km}^2$; the moderately suitable distribution area was $11.98785 \times 10^4 \text{ km}^2$; and the marginally suitable distribution area was $20.02604 \times 10^4 \text{ km}^2$. As shown in table 3, comparison with the current distribution area of the species reveals that the highly suitable area decreased by $14.317707 \times 10^4 \text{ km}^2$ and $6.279517 \times 10^4 \text{ km}^2$ compared to the marginally suitable area and moderately suitable area, respectively, while the total suitable area of the species increased compared to the LIG period, CCSM4 LGM period, and MIROC-ESM LGM period, with an increase of $2.348959 \times 10^4 \text{ km}^2$. The total area suitable for this species has increased by $2.348959 \times 10^4 \text{ km}^2$, $5.373267 \times 10^4 \text{ km}^2$ and $3.309025 \times 10^4 \text{ km}^2$, respectively, and it can be seen from figure 5 that the area suitable for each distribution class of *I. nanchuanensis* has shown an increasing trend compared to the LIG, the CCSM4 LGM, and MIROC-ESM LGM periods.

The geographical distribution of *I. nanchuanensis* in two future period (the 2050 s and 2070 s) was also studied using the MaxEnt model, combined with four climate scenarios (RCP2.6, RCP4.5, RCP6, and RCP8.5) under global climate change to simulate the potential geographical distribution range of *I. nanchuanensis* and its suitable distribution area for different classes (table 3, figure 7). It was found that the potential distribution of *I. nanchuanensis* will continue to shrink in the future, especially in the 2070 s, when the total suitable area, highly suitable area, and moderately suitable area will be reduced to varying degrees compared to the current one, especially under RCP6, with a maximum reduction of $9.04688 \times 10^4 \text{ km}^2$, and under RCP2.6, with a minimum reduction of $4.354159 \times 10^4 \text{ km}^2$. The maximum reduction in distribution area under RCP6 was $17.779519 \times 10^4 \text{ km}^2$, and the minimum reduction under RCP4.5 was $3.937494 \times 10^4 \text{ km}^2$. In the highly suitable distribution area, a maximum reduction of $8.055556 \times 10^4 \text{ km}^2$ was found under RCP6, a minimum reduction of $1.286459 \times 10^4 \text{ km}^2$ under RCP2.6, and a small increase under RCP4.5. In the moderately suitable distribution area, a maximum reduction of $7.390623 \times 10^4 \text{ km}^2$ was found under RCP6, and a minimum reduction of $1.286459 \times 10^4 \text{ km}^2$ under RCP8.5. In the marginally suitable distribution area, a maximum reduction of $7.390623 \times 10^4 \text{ km}^2$ was found under RCP6, and a minimum reduction of $0.9375 \times 10^4 \text{ km}^2$ under RCP8.5.

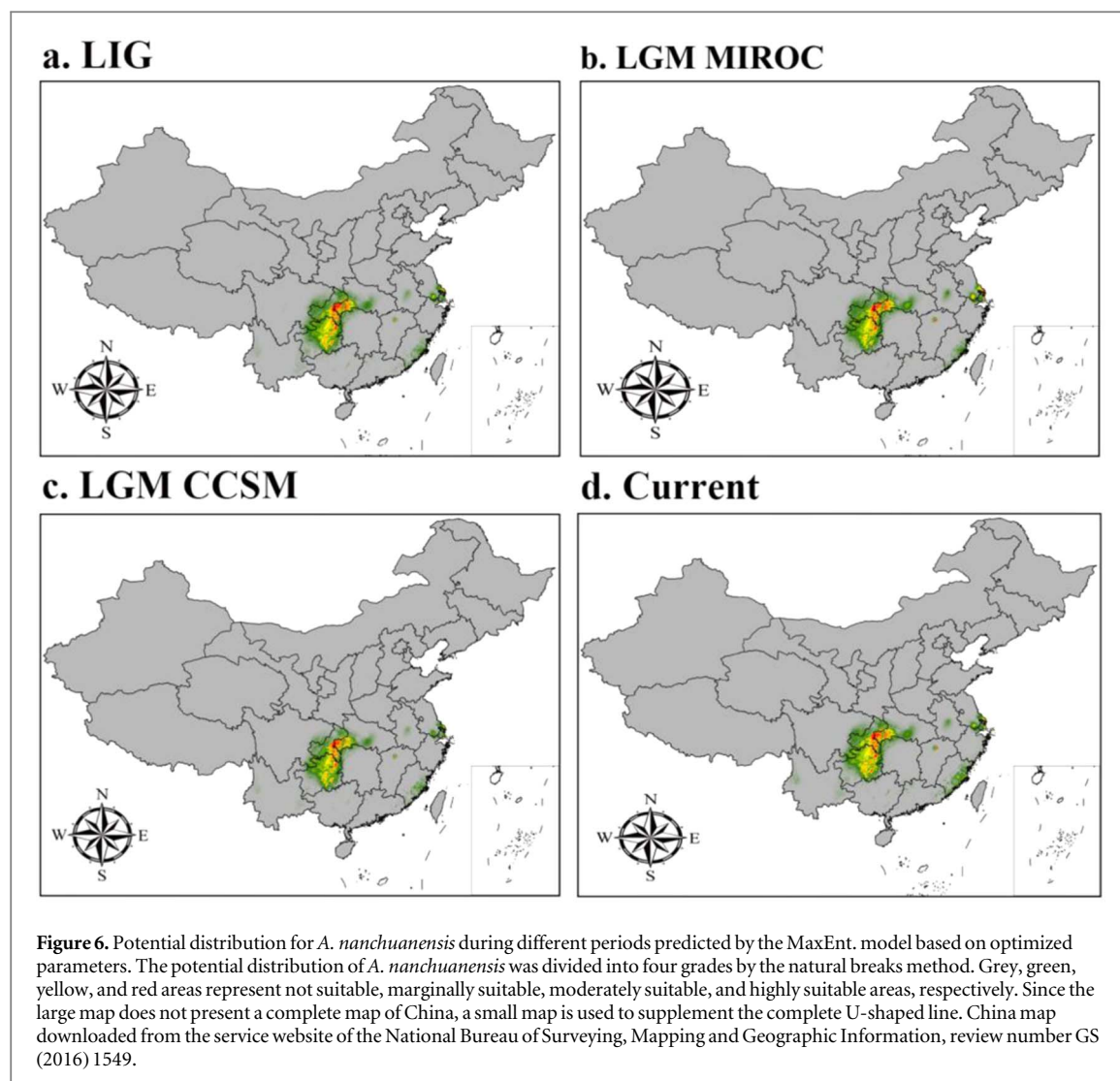
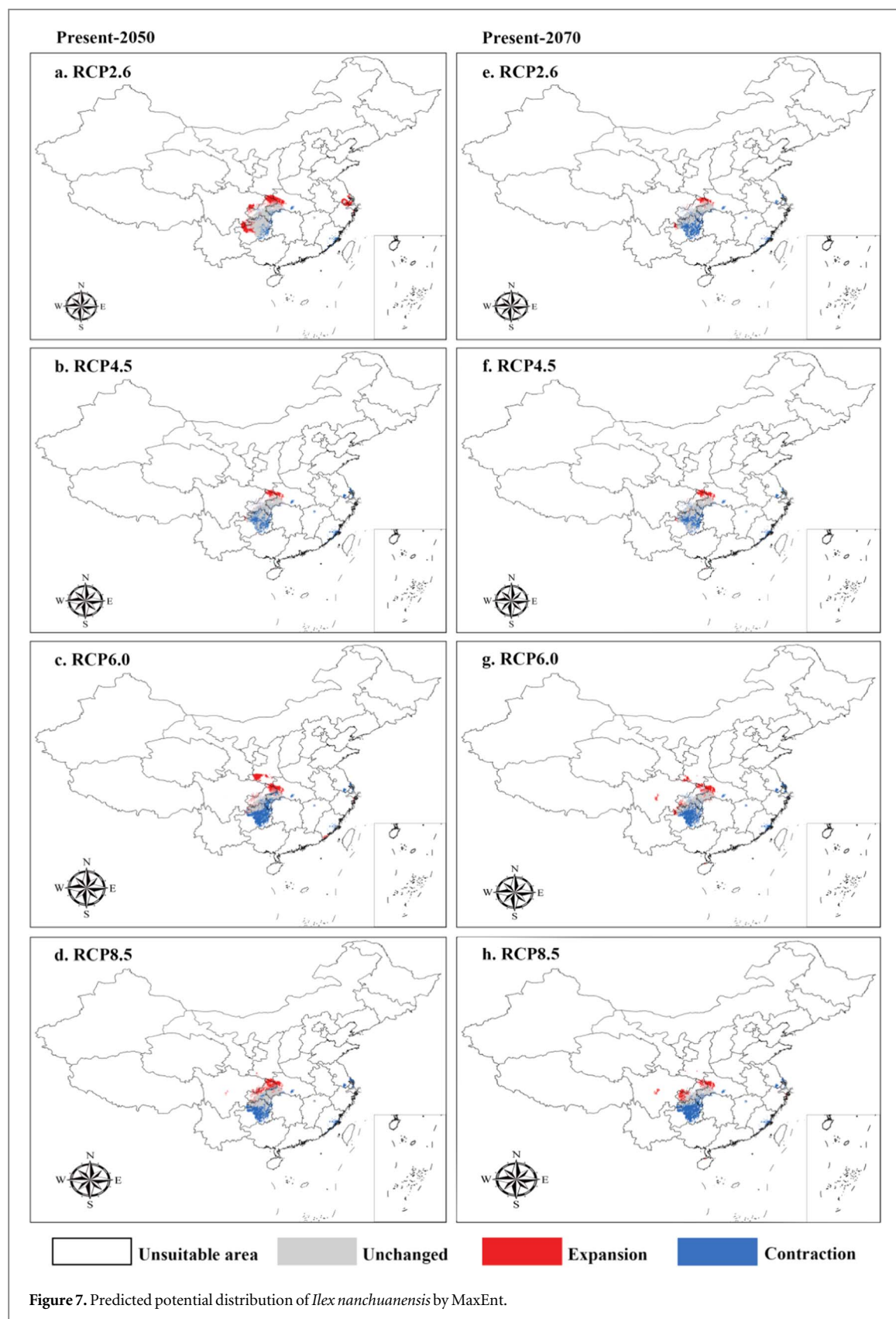


Table 3. Characteristics of potential distribution in different periods for *I. nanchuanensis*.

Period	Area of each suitable region ($\times 10^4 \text{ km}^2$)			
	Marginally suitable region	Moderately suitable region	Highly suitable region	Total suitable region
LIG	19.46181	10.72569	5.185764	35.373264
LGM (CCSM)	17.64583	9.892362	4.810764	32.348956
LGM (MIROC)	17.97049	11.09375	5.348958	34.413198
Current	20.02604	11.98785	5.708333	37.722223
2050RCP2.6	20.61979	16.17708	4.168403	40.965273
2050RCP4.5	21.50868	12.00868	2.602431	36.119791
2050RCP6.0	24.05035	14.31597	8.088542	46.454862
2050RCP8.5	18.48958	11.60417	5.079861	35.173611
2070RCP2.6	19.43924	11.04688	2.881944	33.368064
2070RCP4.5	19.10417	10.43403	2.644097	32.182297
2070RCP6.0	21.71701	6.925347	0.032986	28.675343
2070RCP8.5	18.81424	10.66667	0.03125	29.51216

3.4. Suitable distribution under future climate scenarios

The MaxEnt model was used to predict the distribution of *I. nanchuanensis* under different climate scenarios for the future periods, and the area and distribution of *I. nanchuanensis* in unsuitable, unchanged, expanded, and contracted areas can be seen in table 4 and figure 7. Compared to the potential distribution area of *I. nanchuanensis* in the current period, its distribution range in Sichuan, Chongqing, Hubei, Guizhou, southern



Shaanxi, Jiangsu, and Fujian in China will increase in the 2050 s (figures 7(a)–(d), while it will decrease significantly in the 2070 s (figures 7(e), (f).

3.5. Migration trends of the geometric center of suitable habitat

In order to obtain the centroid migration trajectory and direction of *Ilex nanchuanensis*, the SDM Toolbox in ArcGIS10.6 software and the distribution of *Ilex nanchuanensis* in different periods and scenario modes were

Table 4. Potential distribution area of *Ilex nanchuanensis* in the 2050s and 2070s.

Species	Period	Area of each suitable region ($\times 10^4 \text{ Km}^2$)			
		Unsuitable region	Unchanged region	Expansion region	Contraction region
<i>Ilex nanchuanensis</i>	Current versus RCP2.6-2050s	889.29	42.34	3.25	14.00
	Current versus RCP4.5-2050s	894.40	37.14	8.45	8.90
	Current versus RCP6.0-2050s	893.47	40.52	5.07	9.82
	Current versus RCP8.5-2050s	897.51	36.61	3.81	8.86
	Current versus RCP2.6-2070s	894.11	39.40	6.18	9.19
	Current versus RCP4.5-2070s	887.94	41.85	3.74	15.36
	Current versus RCP6.0-2070s	892.25	42.52	3.66	11.04
	Current versus RCP8.5-2070s	891.08	39.23	7.24	9.24

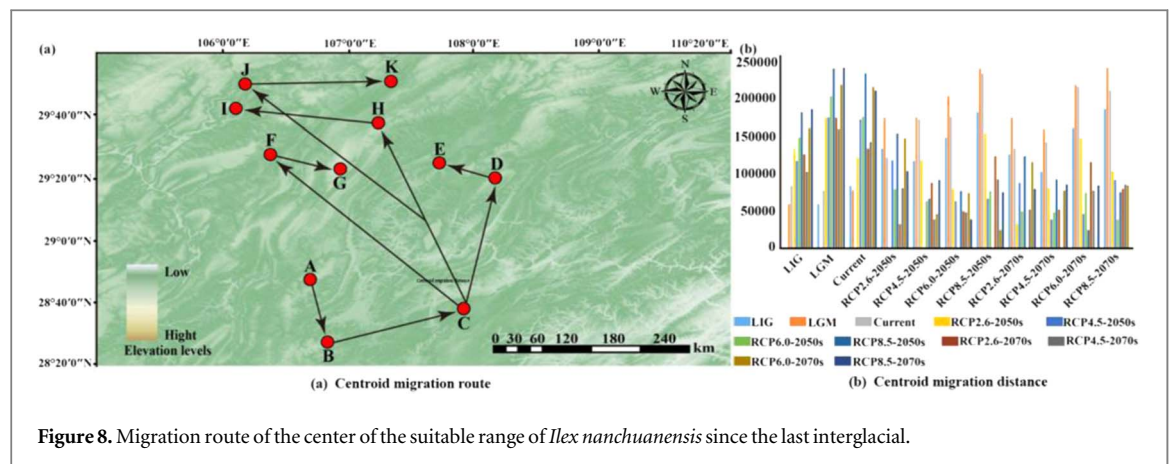


Figure 8. Migration route of the center of the suitable range of *Ilex nanchuanensis* since the last interglacial.

studied and analyzed (figure 8). The distribution area of *I. nanchuanensis* in the current period is located in Nanchuan District, Chongqing, China (29.12382309°N, 107.2505951°E), while in the LIG and LGM periods it is still in Nanchuan District but at (29.02701706°N, 107.146697°E) and (29.02930604°N, 107.164464°E), respectively (figure 7(a)). Although the distribution of *I. nanchuanensis* in the above three periods was in Nanchuan District, Chongqing, in the current period it showed a trend of migration to the northeast compared with that in the LIG and LGM periods (59229 m and 54900 m, respectively) (figure 7(b)). It was found that the distribution of *I. nanchuanensis* in China in the future (2050 s and 2070 s) will migrate to the northwest compared to the current period. By simulating the migration trajectory of *I. nanchuanensis* placenames under different climate scenarios in the future periods, it was found that it migrated 86072 m, 122,762 m, 125,080 m and 166,544 m under RCP 2.6, RCP 4.5, RCP 6 and RCP8.5, respectively, in the 2050 s compared to the current period, and in the 2070 s by 94,894 m, 101,163 m, 153,836 m and 150,276 m (figure 7(b)).

4. Discussion

4.1. Response of species distribution to climate change

Climate change is a major driver of species distributions [66, 67], and species distributions can also reflect climate change characteristics [68–70]. Species change seasonal activity patterns, abundance, and migration in response to challenges such as extreme events, heat stress, and water scarcity brought about by climate change [71]. Studies have found that global climate change is already causing species to migrate to higher altitudes and latitudes [72, 73]. *Ilex nanchuanensis* is a critically endangered species endemic to China, with only one distribution area of < 100 km², and has experienced habitat degradation or even loss due to climate warming [13, 14]. In the present study, *I. nanchuanensis* was found to be migrating northwards in both the current and future periods, demonstrating the stress of climate warming imposed on this species, with the main climatic factors affecting its geographical distribution found to be temperature and precipitation. Similarly, Ning *et al* (2021) [67] found that temperature and precipitation were the most important environmental factors affecting the geographical distribution of *Pinus armandii*, while You *et al* (2018) found that temperature-related variables affected the geographical distribution of *Rhodiola* more profoundly than precipitation [74].

The use of the MaxEnt model to simulate the distribution ranges of species in different historical periods based on current species distribution data and climatic factors can help maintain ecosystem balance and protect rare and critically endangered species [41, 75]. It was found that current global temperatures have increased by 5 °C–12 °C compared to the LGM period and that the current glacial area in China has decreased by 8.4 times compared to the LGM period, and these changes have affected the geographical distribution patterns of species [76]. In the present study, we found that the distribution range of *I. nanchuanensis* in the current period was larger than that of both the LGM period and LIG period, which was related to the species' biological characteristics such as its preference for warmth and tolerance of shade. Willis *et al* (2004) [77] found that mid-latitude and high-latitude regions were affected by glacial cover during the Quaternary period, while Nanchuan District, Chongqing, China belongs to a low latitude area and the complex topography and mountains were able to effectively block the glacial cover [78], confirming the findings of this study that *I. nanchuanensis* migrated to the northeast during the current period [79]. Cornejo-Romero *et al* (2017) [80] found that the range of drought-tolerant plants was less during the current period than during the LIG, which is contrary to the results of this study owing to the fact that the biology of drought-tolerant plants is very different from that of subtropical plants [80]. However, it is worth noting that this model also has certain limitations, such as: (1) The model prediction is based on the assumption of stable and unchanging environment, so the prediction results can only represent the

current situation in a certain period of time. If the environment undergoes significant changes in a short period of time, the applicability of the results will be reduced. (2) There are many factors that affect species distribution, including natural and human factors, and this model is only applicable to simulating species distribution under natural environmental conditions. (3) The selection of sample distribution, setting of constraint conditions, and setting of related parameters all affect the accuracy of the results. (4) For the corresponding climate data, the selection of climate models, the resolution of climate data, and the correlation between various climate factors can all lead to deviations in the prediction result [45]. In addition, this study also has certain limitations as it only considers the impact of climate factors on the potential distribution of species, while land use, soil, historical factors, and interactions between species all profoundly affect the potential distribution of species) [81].

4.2. Potential distribution area changes and conservation of *Ilex nanchuanensis* under future climate scenarios

Climate change is not only forcing species to migrate but also accelerating the risk of extinction [81]. In this study, we found that the distribution range of *I. nanchuanensis* in the future periods (2050 s and 2070 s) is likely to be reduced compared to the current period, and it keeps moving towards the northwest owing to extreme phenomena such as local increases in temperature and water shortages [72, 73]. In addition, the distribution range of *I. nanchuanensis* is projected to shrink in the future periods, especially the 2070 s, with the total suitable area being reduced the most under RCP6 and the least under RCP4.5, which is similar to the findings of other studies on rare and endangered species in China, such as ginkgo (*Ginkgo biloba*) and Taiwan fir [82, 83]. This is closely related to the phenomenon of climate warming in the future, with studies finding a global temperature increase of 1.3 °C by 2050 and a minimum global temperature increase of 2.2 °C by 2070 [84]. This study found that the optimum range for the hottest monthly minimum temperature (Bio6), the most important climatic factor affecting *I. nanchuanensis*, is −30 °C to 25 °C, and that extreme weather and global warming have made it difficult for the species to survive better locally, which is one of the main reasons for the migration of *I. nanchuanensis* to the northwest in the coming period. Also, *I. nanchuanensis* migrated the furthest under RCP6 in the 2070 s, confirming the threat of rising temperatures and increased greenhouse gas emissions to the distribution status of the species, as well as the global ecosystem [85]. Therefore, there is a need to reduce greenhouse gas emissions to protect global species diversity and ecosystem balance. This study also found that the best ranges of climatic factors affecting the geographical distribution of *I. nanchuanensis* were 70–130 mm for the driest seasonal precipitation (Bio17) and 23 °C–31 °C for the mean annual temperature range (Bio7). Meanwhile, *I. nanchuanensis* not only prefers a warm climate but also has a certain degree of cold tolerance, which is another reason for its migration to the northwest in the coming period. To better protect the species, research on drought stress and salt stress should be a focus. Therefore, we recommend the construction of a core reserve in an area centered on Nanchuan District of Chongqing, China, to improve habitat conditions and the conservation of germplasm resources using techniques such as hybrid seeding and genetics to increase the genetic diversity of wild populations. In addition, the management goals and strategies of nature reserves need to consider adapting to climate change. Expanding protected areas will help reduce vulnerability. The design of protected areas should consider long-distance migration of animals and plants, integrated species protection, reducing threats to species in nature reserves, increasing resilience, and creating and restoring buffer zones around nature reserves. The specific strategies for species protection include *in situ* protection, *ex situ* protection, consideration of climate change impacts, reduction of non climate change adverse impacts, and monitoring of impacts; Consider the current and potential spatial distribution of habitats for dynamic and integrated protection; Artificial seed dissemination and pollination; Habitat protection and restoration; Assist in migration; Species reproduction and rejuvenation; Artificially creating good ecological habitats; Consider measures such as reducing other stresses and controlling biological invasion) [42].

5. Conclusions

This study simulated the geographical distribution of *I. nanchuanensis* using the MaxEnt model, and the following conclusions were obtained: (1) The climatic factors affecting the geographical distribution of *I. nanchuanensis* are Bio4, Bio6, Bio7, Bio13, Bio15, and Bio17 (see table 1 for definitions). (2) *Ilex nanchuanensis* migrated to the northeast in historical periods but is projected to migrate northwest in the future. (3) The total suitable area for *I. nanchuanensis* was projected to reduce the most under RCP6 in the 2070 s (17.779519×10^4 km²), and the least (3.937494×10^4 km²) under RCP4.5. To address the threat of global climate change to *I. nanchuanensis*, a protected area centered on Nanchuan District in Chongqing, China, should be established, and germplasm resources protected and cultivated, with core, buffer, and experimental areas scientifically and rationally delineated. In addition, greenhouse gas emissions need to be reduced, and future greenhouse gas emissions need to be controlled within the scenario of RCP4.5. In order to protect precious species resources,

countries around the world should jointly develop conservation strategies around the following aspects: (1) the establishment of natural reserves should consider climate change; (2) the functional design of protected areas should consider species migration; (3) strengthen the ability of non protected species protection to adapt to climate change; (4) strengthen on-site protection, carry out *ex situ* protection, reduce the adverse effects of non climate change, and take dynamic and integrated protection measures.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

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Conflicts of interest

The authors declare that they have no conflict of interest.

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