The impacts of climate change on the potential ecologically suitable planting areas of *Macadamia* sp. in China

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Abstract

Climate change profoundly affects plant distribution patterns. Macadamia (Macadamia sp.) is a tropical to subtropical montane plant with extremely high economic value and significant ecological value. Predicting its potential ecologically suitable areas under the background of climate change is of great significance for economic development and soil and water conservation in mountainous areas of China. This study combined the MaxEnt model and ArcGIS software, based on environmental factors such as climate, topography, and soil, as well as existing distribution data of Macadamia (Macadamia sp.) in China, to identify the key factors affecting its distribution in China and to explore the distribution patterns and changes of potential suitable areas for Macadamia in China during four future periods: the 2040s, 2060s, 2080s, and 2100s. The results showed that: (1) the MaxEnt model can simulate the potential distribution of Macadamia in China extremely well. (2) Mean annual temperature, annual precipitation, isothermality, and annual temperature range are the key factors affecting the distribution of Macadamia. (3) Under each climate scenario, Macadamia has the largest distribution area in Yunnan Province, followed by southeastern coastal regions such as Guangdong and Guangxi. (4) Under the three future climate scenarios, the total area of potential suitable habitats for Macadamia gradually decreases over time, the degree of internal fragmentation of suitable habitats gradually increases, and the overall centroid shifts are all relatively small. The results of this study further clarify the distribution pattern of ecologically suitable areas for Macadamia in China and can provide a scientific basis for formulating large-scale planting plans for Macadamia.

Full Text

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The impacts of climate change on the potential ecologically suitable planting areas of *Macadamia* sp. in China

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Abstract: Climate change profoundly affects the distribution patterns of plants. *Macadamia* sp. is a tropical to subtropical montane plant with extremely high economic value and significant ecological value. Under the background of climate change, predicting its potential ecologically suitable areas is of great importance for economic development and soil and water conservation in mountainous regions of China. This study combined the MaxEnt model and ArcGIS software. Based on environmental factors such as climate, topography, and soil, as well as current distribution data for *Macadamia* sp. in China, the key factors influencing the distribution of *Macadamia* sp. in China were screened, and the distribution patterns and changes of its potential suitable areas in China during four future periods—the 2040s, 2060s, 2080s, and 2100s—were explored. The results showed that: (1) The MaxEnt model could simulate the potential distribution of *Macadamia* sp. in China extremely well. (2) Mean annual temperature, annual precipitation, isothermality, and annual temperature range were key factors affecting the distribution of *Macadamia* sp. (3) Under all climate scenarios, the distribution area of *Macadamia* sp. was largest in Yunnan Province, followed by Guangdong and Guangxi, as well as other southeastern coastal regions. (4) Under the three future climate scenarios, the total area of potential suitable habitats for *Macadamia* sp. gradually decreased over time, the degree of fragmentation within suitable areas gradually increased, and the overall centroid shift was relatively small. These results further clarify the distribution pattern of ecologically suitable areas for *Macadamia* sp. in China and can provide a scientific basis for formulating plans for large-scale cultivation of *Macadamia* sp.

Keywords: *Macadamia* sp.; potential suitable area; MaxEnt model; climate change; China

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The impacts of climate change on the potential ecologically suitable plantation area of *Macadamia* sp. in China

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Abstract: Climate change has exerted profound impacts on the distribution patterns of plant species. *Macadamia* sp., a tropical to subtropical montane plant, possesses considerable economic and ecological significance. Understanding its potential ecologically suitable habitats under future climate change scenarios is of great importance for promoting sustainable economic development and soil and water conservation in mountainous regions of China. This study integrated the MaxEnt model with ArcGIS technology to analyze current distribution data of *Macadamia* sp. in China, along with environmental variables including climatic, topographic, and soil factors. Key environmental determinants influencing its distribution were identified, and the potential distribution patterns of suitable habitats were projected for four future time periods: the 2040s,

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2060s, 2080s, and 2100s. The results were as follows: (1) The MaxEnt model demonstrated high accuracy in simulating the potential geographic distribution of *Macadamia* sp. in China. (2) Annual mean temperature, annual mean precipitation, isothermality, and temperature annual range were identified as the most influential environmental variables shaping its distribution. (3) Across all climate scenarios, Yunnan Province consistently exhibited the largest area of suitable habitat, followed by the southeastern coastal provinces such as Guangdong and Guangxi. (4) Under all three future climate scenarios, the total area of suitable habitats gradually decreased over time, accompanied by increasing fragmentation, while the spatial shifts of the overall centroid remained minimal. These findings provided a comprehensive understanding of the potential ecological distribution patterns and requirements of *Macadamia* sp. in China, offering a scientific basis for the development of large-scale, climate-adaptive cultivation strategies.

Key Words: *Macadamia* sp., potentially suitable area, MaxEnt model, climate change, China

Climate change has significantly affected the survival and reproduction of animals and plants. Intense climate change has led to frequent extreme events such as high-temperature droughts, heat waves, and rainstorm floods; species habitats have been severely damaged, and habitat loss and fragmentation have become increasingly serious, leaving species survival facing severe challenges (Bellard et al., 2012; Mantyka-pringle et al., 2012; Harrison et al., 2020; Yang Jiayue et al., 2025). Climate—heat and moisture—is one of the main factors constraining biological distributions, and to a large extent controls the distribution, growth, and reproduction of plants (Wang Jijun and Pei Tiepan, 2004; Lü Jiajia and Wu Jianguo, 2009). Therefore, assessing species' adaptability to climate is urgent; understanding the geographic distribution patterns of species and their interactions with environmental factors is crucial for managers to carry out subsequent agricultural production and formulate measures for biodiversity conservation.

Species distribution models (SDMs), based on mathematical statistical methods, combine species and environmental variable data and are an effective means of predicting the probability of species distribution (Zhao et al., 2021). At present, commonly used species distribution models mainly include the bioclimatic model (BOICLIM) (Beaumont et al., 2005; Booth et al., 2014; Li Yao et al., 2014), the biological population growth model (CLIMEX) (Taylor et al., 2013; Ramirezcabral et al., 2017), the genetic-algorithm-based rule-set production model (GARP) (Stockman et al., 2006; Fu et al., 2024), the generalized linear model (GLM) (Guisan et al., 1999), the artificial neural network (ANN) (Zenebe et al., 2024), random forest (RF) (Guo Yiqi et al., 2021; Zhao et al., 2022), and the maximum entropy model (MaxEnt) (Phillips et al., 2006; Zhang et al., 2021; Ying Bangbei et al., 2024). Among them, the MaxEnt model, based on maximum entropy theory, can predict the potential distribution range of species by using species distribution data and related environmental variables. It is simple to operate and has high prediction accuracy (Phillips et al., 2006; Zhu Qiuping and Qiao Huijie, 2016; Chen Chenghao et al., 2023; Zeng Weiying et al., 2025), and has been widely applied to predictions of ecologically suitable distributions for rare and endangered wild animals and plants (Zhang Dianbo et al., 2019; Chen Yuguang et al., 2022; Wang Ya et al., 2023; Yang Shanyun et al., 2023; Lü Zengwei et al., 2024; Shi Xiaoqing et al., 2025), economic crops (Wang Wei et al., 2017; Wang Cuihua et al., 2020; Liu Panfeng et al., 2020; Li Zhanggui et al., 2024), and alien plants (Li Jianyu et al., 2023; Zheng Xiaoyi et al., 2024).

Macadamia (*Macadamia* sp.), also known as the Queensland nut, is a perennial evergreen tree of the family Proteaceae and the genus *Macadamia*. It is native mainly to tropical regions such as eastern mainland Australia, Sulawesi Island, and Madagascar (Editorial Committee of *Flora of China*, Chinese Academy of Sciences, 1988; He Xiyong et al., 2015). Macadamia is known as the "queen of dried fruits" and has extremely high economic value. It is one of China' s important woody oil plants; its kernels contain up to 70% oil and can be used to produce refined salad oil and various foods (Jiao Yun et al., 2008; Zhu Qiuping and Qiao Huijie, 2016). Macadamia also has rich medicinal value. Its high content of unsaturated fatty acids (Liu Jianfu and Huang Li, 2005) can not only prevent and ameliorate diseases such as atherosclerosis, cardiovascular and cerebrovascular diseases, diabetes, tumors, and rheumatoid arthritis, but also enhance the skin' s anti-aging capacity (Du Liqing et al., 2010). Macadamia is a foreign native tree species. It was introduced into Guangxi in 1974; later, during large-scale conversion of steep cropland to forest in Yunnan Province in the 1990s, it was introduced into Yunnan, and it has also been successfully introduced and cultivated in Guangdong, Guangxi, Fujian, and Hainan in China. In 2022, China' s macadamia planting area exceeded 33.6×10^5 hm^2, making China the country with the fastest development of the macadamia industry and the largest planting area in the world (Li Zhanggui et al., 2024; Zhang Fenghua et al., 2024). Therefore, the introduction and cultivation of macadamia play an important role in promoting economic growth in relevant regions and alleviating the pressure of the "three rural issues."

In recent years, research related to macadamia has mainly focused on yield (Howlett et al., 2015; Perdoná & Soratto, 2015), product-development tech[[unclear: text continues beyond page]]

···technology (Somwongin et al., 2023), cultivation-management techniques and industrial development (Ai Jingwen et al., 2018; He Xiyong et al., 2022; Wang Wenlin et al., 2022; Nie Yanli et al., 2023). Some scholars have also studied the climatic factors affecting the global potential suitable distribution of macadamia (Wang Wei et al., 2017), and analyzed the influence of climatic factors on macadamia cultivation in Yunnan Province (Wang Cuihua et al., 2023; Li Zhanggui et al., 2024). However, these studies have mostly focused on global large-scale regions or on specific provinces, and have considered only the response of the geographical distribution of macadamia to climatic factors, while neglecting the effects of topographic and soil factors. Therefore, this study combines the MaxEnt model with ArcGIS to screen the key environmental factors affecting the distribution of macadamia in China, and to explore changes in the potential suitable areas of macadamia under different greenhouse-gas emission scenarios–SSP1-2.6, SSP2-4.5, and SSP5-8.5–during different periods from 2020 to 2100. This provides an important basis for formulating scientifically sound plans for the planting range of macadamia. The study aims to answer the following questions: (1) What are the key environmental factors affecting the potential suitable areas of macadamia in China? (2) How will the spatial distribution of the potential ecologically suitable areas of macadamia change under different future climate scenarios? (3) Under different climate scenarios, will the potential suitable areas of macadamia change over time?

1 Materials and Methods

1.1 Collection of macadamia distribution data

The macadamia distribution data were mainly obtained from the National Specimen Information Infrastructure of China (http://www.nsii.org.cn/), the Chinese Virtual Herbarium (http://www.cvh.ac.cn/), the Global Biodiversity Information Facility (https://www.Gbif.org/), and relevant literature, books, and other materials. After retrieval, a total of 97 global macadamia distribution records were obtained. In ArcGIS 10.7, the study area was divided into 1 km × 1 km grids, and the collected distribution-point data were screened to ensure that each grid contained only one record. Sample points with erroneous or duplicate localities were removed, ultimately yielding 72 valid distribution points (Fig. 1).

Visible figure legend: Main rivers; Main lakes; Country boundary; Province boundary; Macadamia, *Macadamia* sp.; Elevation (m): ≤ 200, 200–500, 500–1 000, 1 000–2 000, 2 000–3 000, 3 000–4 000, 4 000–5 000, 5 000–6 000, ≥ 6 000; scale: 0, 500, 1 000, 2 000 km.

The map is based on the standard map No. GS(2024)0650, and the base map is not modified. The same below.

Fig. 1 Distribution points of *Macadamia* sp. in China [elevation grading reference: Li Bingyuan et al. (2008)]

1.2 Environmental variables

This study selected a total of 40 environmental variables to construct the model, including 19 bioclimatic variables, 18 soil factors, and 3 topographic datasets (Table

1). Climate data were obtained from the global climate database (https://www.worldclim.org/). Current climate data (1970–2020) and future climate data used the HadGEM3-GC31-LL climate model (Williams et al., 2021; Michaelides, 2023; Adhikari et al., 2024), including the latest greenhouse-gas emission scenario data for three future shared socioeconomic pathways (SSPs), namely SSP1-2.6, SSP2-4.5, and SSP5-8.5, covering four future periods: 2021–2040 (2040s), 2041–2060 (2060s), 2061–2080 (2080s), and 2081–2100 (2100s), with a spatial resolution of 30″. Among them, SSP1-2.6 represents a low-radiative-forcing scenario in which greenhouse-gas emissions stabilize at 2.6 $W \cdot m^{-2}$ in 2100; SSP2-4.5 represents a medium-radiative-forcing scenario in which greenhouse-gas emissions stabilize at 4.5 $W \cdot m^{-2}$ in 2100; and SSP5-8.5 represents a high-radiative-forcing scenario in which greenhouse-gas emissions stabilize at 8.5 $W \cdot m^{-2}$ in 2100. Soil data were downloaded from the Harmonized World Soil Database version (HWSD), with a spatial resolution of 1 km. Digital elevation model (DEM) data were downloaded from the Geospatial Data Cloud platform (http://www.gscloud.cn), and ArcGIS software was used to extract slope (aspect) and aspect (slope), with a spatial resolution of 30 m. All environmental variables were resampled to 1 km in ArcGIS 10.7.

Table 1 Explanatory table of environmental variables

Variable	Description	Unit
BIO1	Annual mean temperature	°C
BIO2	Mean diurnal range	°C
BIO3	Isothermality (BIO2 / BIO7) (*100)	%
BIO4	Temperature seasonality	–

Variable	Description	Unit
BIO5	Max temperature of the warmest month	°C
BIO6	Min temperature of the coldest month	°C
BIO7	Temperature annual range	°C
BIO8	Mean temperature of the wettest quarter	°C
BIO9	Mean temperature of the driest quarter	°C
BIO10	Mean temperature of the warmest quarter	°C
BIO11	Mean temperature of the coldest quarter	°C
BIO12	Annual mean precipitation	mm
BIO13	Precipitation of the wettest month	mm
BIO14	Precipitation of the driest month	mm
BIO15	Precipitation seasonality	mm
BIO16	Precipitation of the wettest quarter	mm
BIO17	Precipitation of the driest quarter	mm
BIO18	Precipitation of the warmest quarter	mm
BIO19	Precipitation of the coldest quarter	mm
DEM	Digital elevation model	m
Aspect	Aspect	–
Solpe	Slope	°
T_bs	Base saturation	%
T_CaCO$_3$	Carbonate content	%weight
T_CaSO$_4$	Sulfate content	%weight
T_cec_clay	Cation exchange capacity of cohesive layer soils	coml · kg^{-1}
T_cec_soil	Cation exchange capacity of soil	coml · kg^{-1}
T_ece	Electric conductivity	dS · m^{-1}
T_gravel	Percentage of crushed stone by volume	%vol

Variable	Description	Unit
T_oc	Soil organic carbon content	%weight
T_ph_H2O	Soil pH	-log(H^+)
T_ref_bulk	Soil bulk density	$kg \cdot dm^{-3}$
T_sand	Soil sand and gravel content	%wt
T_silt	Soil silt content	%wt
T_teb	Exchangeable base	$coml \cdot kg^{-1}$
T_texture	Soil texture grading	–
Awc_class	Available soil moisture	–
T_esp	Exchangeable sodium salt	%
T_clay	Clay content	%wt

1.2 Treatment and Selection of Environmental Variables

To overcome the influence of multicollinearity, this study used the spatial analysis function to conduct Spearman correlation analysis on data for 19 bioclimatic variables, topographic data, and 18 soil variables. Environmental variables with correlations below 0.80 were retained; if the correlation between two variables was higher than 0.80, the variable with stronger ecological significance was retained (Fick et al., 2017; Liu Panfeng et al., 2020). The macadamia distribution data and the initially screened factors were input into the MaxEnt model, and the jackknife method was used to screen environmental factors. The model was run until none of the selected environmental variables had a contribution rate of 0. Ultimately, seven factors were selected as the final input variables for the model: annual mean temperature (BIO1), annual precipitation (BIO12), isothermality (BIO3), annual temperature range (BIO7), percentage of soil gravel volume (T_gravel), soil silt content (T_silt), and precipitation of the driest quarter (BIO17).

Fig. 2 Spearman correlation analysis of 40 environmental variables

1.3 MaxEnt Model Prediction

To ensure the accuracy of the model, 25% of the data were randomly selected as the test-set data, and the remaining 75% of the macadamia distribution-point data were used as the training-set data. The number of iterations was set to 10 000, and the operation was repeated 10 times. The area under the receiver operating characteristic curve (ROC curve), namely the AUC value, was used to evaluate the accuracy of the prediction model. The range of AUC values is 0–1; the closer the value is to 1, the more accurate the prediction (Swets, 1988). Finally, the jackknife method was used to test the contribution of each environmental variable to distribution gain (Miller, 1974; Shcheglovitova et al., 2013), thereby identifying the key environmental factors affecting the potential distribution of macadamia.

1.4 Habitat-suitability classification This study combined the actual distribution of macadamia in China with the natural breaks method and, according to the occurrence probability P, divided the suitable habitat of macadamia into four grades (Chen Chenghao et al., 2023): $P < 0.41$ was classified as unsuitable habitat, $0.41 \leq P < 0.62$ as low-suitability habitat, $0.62 \leq P < 0.85$ as medium-suitability habitat, and $P \geq 0.85$ as high-suitability habitat. GIS software was used to statistically analyze the distribution range and area of each suitability class, calculate the area of suitable habitat for macadamia under the current climate and future climate scenarios, and obtain the ranges and areas of suitable habitat that would expand, contract, or remain under future climate scenarios, thereby analyzing the effects of climate change on the distribution area of potential suitable habitat for macadamia.

1.5 Centroid analysis To analyze changes in the centroid of macadamia suitable habitat under different climate scenarios, raster data were reclassified in ArcGIS 10.7, assigning suitable habitat a value of 1 and all other areas as Nodata. The zonal statistics tool was used to calculate the centroid of the potential suitable habitat under each climate scenario, thereby analyzing changes in the centroid. The centroid was calculated as follows:

$$X_G = \frac{\sum_{i=1}^{n} A_i X_i}{\sum_{i=1}^{n} A_i}, \quad Y_G = \frac{\sum_{i=1}^{n} A_i Y_i}{\sum_{i=1}^{n} A_i} \tag{1}$$

where X_G and Y_G are the coordinate positions of the centroid, respectively; A_i is the mass point; i is the current mass point; n is the number of mass points; and X_i and Y_i are the coordinate positions of the i-th discrete target object, respectively.

2 Results and analysis

2.1 Accuracy test of the MaxEnt model

Under the current climate, the mean AUC values of the training set and test set of the ROC curve in this study were 0.979 and 0.966, respectively. Under different future climate scenarios, the AUC values all reached above 0.960 (Fig. 3), indicating that the MaxEnt model had excellent predictive performance and could simulate the potential distribution of macadamia very well.

Figure legend: training-set AUC; test-set AUC.
Vertical axis: AUC under different climate scenarios.
Horizontal axis: current climate; 2040s_SSP1-2.6; 2040s_SSP2-4.5; 2040s_SSP5-8.5; 2060s_SSP1-2.6; 2060s_SSP2-4.5; 2060s_SSP5-8.5;

2080s_SSP1-2.6; 2080s_SSP2-4.5; 2080s_SSP5-8.5; 2100s_SSP1-2.6; 2100s_SSP2-4.5; 2100s_SSP5-8.5.

Fig. 3 AUC under different climate scenarios

2.2 Results of environmental-variable screening

The jackknife method (Fig. 4) showed that the training gain scores of four factors—annual mean temperature (BIO1), annual temperature range (BIO7), annual precipitation (BIO12), and precipitation of the driest quarter (BIO17)—all exceeded 1.4. Among them, BIO1 had the highest score (> 2.2), while the scores of the remaining factors···

had not yet exceeded 1. The four factors with the highest contribution rates were annual mean temperature (BIO1), annual precipitation (BIO12), isothermality (BIO3), and temperature annual range (BIO7), with contribution rates of 63.4%, 14.9%, 11.5%, and 3.6%, respectively, and a cumulative contribution rate of 93.4%. Climatic factors were the main factors for predicting suitable areas for macadamia.

In this study, variables with a cumulative contribution rate > 90% and not less than 3% were selected as the dominant environmental variables affecting the potential suitable areas for macadamia. To facilitate identification of the environmental-variable ranges most suitable for macadamia growth and development, this study set the threshold of presence probability (P) in the MaxEnt model to 0.5. Annual mean temperature (BIO1), annual precipitation (BIO12), isothermality (BIO3), and temperature annual range (BIO7) were ultimately selected as the dominant environmental variables restricting the distribution of macadamia for analysis (Fig. 5). Fig. 5 shows the response curves between environmental variables and presence probability. The curves indicate that the optimal suitable ranges for macadamia are as follows: BIO1, 20–25 °C; BIO12, 1 500–4 300 mm; BIO3, 45%–54%; and BIO7, <8 °C.

Fig. 4 Jackknife test and contribution rate of environmental variables

Fig. 5 Response curves of dominant environmental variables

2.3 Prediction of current potential suitable areas for macadamia in China

Under the current climate scenario, the results are shown in Fig. 6. Macadamia was most densely distributed in southwestern China and the southeastern coastal region; only southern Sichuan, southwestern Chongqing, Guizhou, Hubei, Hunan, Jiangxi, Hong Kong, Zhejiang, and other places showed fragmented distributions. The geographical distribution range was 91.0–122.0° E,

18.1°–31.6° N, with a total area of 40.15×10^4 km^2, accounting for 4.18% of China' s total land area.

The areas of the low-, medium-, and high-suitability zones were 24.56×10^4 km^2 (2.56%), 15.31×10^4 km^2 (1.59%), and 0.28×10^4 km^2 (0.29%), respectively. The suitable areas for macadamia were distributed from north to south in contiguous belts of low, medium, and high suitability. The low-suitability areas surrounded the medium-suitability areas, while the medium-suitability areas extended outward around the high-suitability areas. Among them, the high-suitability areas were mainly concentrated in Xizang (Nyingchi City); Yunnan (Dehong City, Lincang City, Pu' er City, Xishuangbanna Prefecture, Chuxiong Prefecture, Yuxi City, and Honghe Prefecture); Guangxi (Baise City, Chongzuo City, Nanning City, and Beihai City); Guangdong (Zhanjiang City, Maoming City, Yangjiang City, Jiangmen City, Dongguan City, and Shanwei City); Hainan; and the western coastal plains of Taiwan.

In-figure labels: A; B; Unsuitable area; Low suitable area; Middle suitable area; High suitable area; Distribution area of each suitable area under current climate ($\times 10^4$ km^2); 0.28×10^4 km^2; 15.31×10^4 km^2; 24.56×10^4 km^2; 0; 500; 1 000 km.

MO. Macao; FJ. Fujian; GD. Guangdong; GX. Guangxi; GZ. Guizhou; HI. Hainan; HB. Hubei; HN. Hunan; JX. Jiangxi; SC. Sichuan; TW. Taiwan; XZ. Xizang; HK. Hong Kong; YN. Yunnan; ZJ. Zhejiang; CQ. Chongqing. The same below.

Fig. 6 Current distribution of suitable areas for *Macadamia* sp. in China

2.4 Prediction of suitable areas for macadamia in China under different future climate scenarios

At different time periods, the suitable-area extent differed substantially among climate scenarios (Figs. 7 and 8). In the 2040s, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 climate scenarios, the total suitable area for macadamia was 19.40×10^4, 20.47×10^4, and 19.22×10^4 km^2, respectively, accounting for 2.02%, 2.13%, and 2.00% of the total area, respectively. Among them, under SSP5-8.5 in the 2040s, Yunnan Province had the largest suitable area, reaching 7.24×10^4 km^2. In the 2060s, the suitable areas ranked from largest to smallest as SSP1-2.6 (20.30×10^4 km^2, 2.11%) > SSP2-4.5 (19.69×10^4 km^2, 2.05%) > SSP5-8.5 (18.51×10^4 km^2, 1.93%), with suitable areas increasing in Yunnan, Xizang, Fujian, Hainan, and other regions. In the 2080s, the suitable areas were, in order, SSP1-2.6 (19.89×10^4 km^2, 2.07%) > SSP2-4.5 (19.70×10^4 km^2, 2.05%) > SSP5-8.5 (18.82×10^4 km^2, 1.96%). In the 2100s, the suitable areas were, in order, SSP1-2.6 (20.84×10^4 km^2, 2.17%) > SSP5-8.5 (19.98×10^4 km^2, 2.08%) > SSP2-4.5 (19.03×10^4 km^2, 1.98%). Thus, the SSP1-2.6 scenario is more favorable for the growth and development of macadamia.

Changes in the area of highly suitable zones also differed among climate scenarios. Under the SSP1-2.6 climate scenario, the highly suitable area for macadamia showed a decreasing trend, with the 2040s being the period with the largest highly suitable area (0.42×10^4 km^2). Under the SSP2-4.5 climate scenario, the highly suitable area showed an increasing trend, rising to 0.57×10^4 km^2 in the 2100s. Under the SSP5-8.5 climate scenario, the highly suitable area from 2020 to 2100 showed a pattern of "increase-decrease-increase-decrease" ; the highly suitable areas in the 2040s, 2060s, 2080s, and 2100s were 0.51×10^4, 0.39×10^4, 0.69×10^4, and 0.27×10^4 km^2, respectively.

SSP1-2.6

A 2040s
0.42×10^4 km^2
5.28×10^4 km^2
13.70×10^4 km^2

D 2060s
0.20×10^4 km^2
7.03×10^4 km^2
13.06×10^4 km^2

G 2080s
0.26×10^4 km^2
6.21×10^4 km^2
13.42×10^4 km^2

J 2100s
0.27×10^4 km^2
5.67×10^4 km^2
14.90×10^4 km^2

SSP2-4.5

B 2040s
0.21×10^4 km^2
5.51×10^4 km^2
14.75×10^4 km^2

E 2060s
0.29×10^4 km^2
6.63×10^4 km^2
12.76×10^4 km^2

H 2080s
0.53×10^4 km^2
6.44×10^4 km^2
12.73×10^4 km^2

K 2100s
0.57×10^4 km^2

5.39×10^4 km^2
13.07×10^4 km^2

SSP5-8.5

C 2040s
0.51×10^4 km^2
5.54×10^4 km^2
13.17×10^4 km^2

F 2060s
0.39×10^4 km^2
5.82×10^4 km^2
12.31×10^4 km^2

I 2080s
0.69×10^4 km^2
5.57×10^4 km^2
12.57×10^4 km^2

L 2100s
0.27×10^4 km^2
6.47×10^4 km^2
13.25×10^4 km^2

Legend: unsuitable area; low suitable area; middle suitable area; high suitable area.
Scale: 0, 750, 1,500 km.

Figure 7. Changes in the area of different suitability classes of *Macadamia* sp. under different climatic scenarios

Figure 8. Changes in the area of suitable zones for *Macadamia* sp. in different provinces (regions) of China under different climate scenarios

Panel labels: A 2040s_SSP1-2.6; B 2040s_SSP2-4.5; C 2040s_SSP5-8.5; D 2060s_SSP1-2.6; E 2060s_SSP2-4.5; F 2060s_SSP5-8.5; G 2080s_SSP1-2.6; H 2080s_SSP2-4.5; I 2080s_SSP5-8.5; J 2100s_SSP1-2.6; K 2100s_SSP2-4.5; L 2100s_SSP5-8.5.

Y-axis: Distribution area of each suitable zone ($\times 10^4$km^2).
Province/region labels: MO Macao; FJ Fujian; GD Guangdong; GX Guangxi; GZ Guizhou; HN Hainan; JX Jiangxi; SC Sichuan; TW Taiwan; XZ Tibet; HK Hong Kong; YN Yunnan; CQ Chongqing.
Legend: High suitable zone; Middle suitable zone; Low suitable zone.

2.5 Changes in the extent of suitable areas for macadamia

Compared with the current climate, from 2020 to 2100, the total area suitable for macadamia under the four climate scenarios shows a declining trend. Over time, the area of suitable habitat for macadamia fluctuates, and the interior of the suitable area gradually becomes fragmented, shifting from a concentrated and contiguous distribution to a discontinuous, fragmented distribution (Fig. 9). Compared with the current climate, the total suitable area decreases by 48.10%-53.89%. The suitable areas are mainly distributed in southwestern and southern China, including Yunnan, Guangxi, Guangdong, and Hainan, with sporadic distributions in Sichuan, Chongqing, Jiangxi, Macao, and Hong Kong. Among them, Yunnan Province has the largest suitable area for macadamia, followed by Guangdong and Guangxi.

Under the SSP1-2.6 climate scenario, with changes over time, the suitable area for macadamia first contracts and then expands slightly, showing an overall contraction trend,

From the current climate to the 2040s, the macadamia suitable area showed the greatest contraction in area $\left(25.27 \times 10^4\ \mathrm{km}^2\right)$, with a contraction proportion of 51.63%; the contraction zones were concentrated in Yunnan, central and southwestern Guangxi, Guangdong, Hainan, and other areas. From the 2040s to the 2060s, the macadamia suitable area showed a slight expansion trend, with an expansion area of $2.46 \times 10^4\ \mathrm{km}^2$. From the 2060s to the 2080s, the macadamia suitable area changed relatively little, with expansion and contraction areas of $2.05 \times 10^4\ \mathrm{km}^2$ and $2.56 \times 10^4\ \mathrm{km}^2$, respectively. From the 2080s to the 2100s, the expansion area of the potential macadamia suitable area was the largest $\left(3.24 \times 10^4\ \mathrm{km}^2\right)$; the expansion zones were concentrated in Yunnan and Fujian, while the contraction zones were concentrated in Guangxi, Guangdong, Taiwan, and Tibet.

Under the SSP2-4.5 climate scenario, from the current climate to the 2040s, the distribution range of the macadamia suitable area contracted, with a contraction area of $23.97 \times 10^4\ \mathrm{km}^2$ and a contraction proportion of 48.97%. From the 2040s to the 2060s, the contraction area $\left(2.59 \times 10^4\ \mathrm{km}^2\right)$ was larger than the expansion area $\left(1.58 \times 10^4\ \mathrm{km}^2\right)$, and the contraction zones were mainly concentrated in central-eastern Yunnan, northwestern Guangxi, and the coastal areas of Guangdong. From the 2060s to the 2080s, the expansion area reached $2.96 \times 10^4\ \mathrm{km}^2$, with an expansion proportion of 10.69%; the expansion zones were mainly concentrated in Yunnan, Hainan, and central-eastern Guangxi. From the 2080s to the 2100s, the range of the potential macadamia suitable area showed a contraction trend, with a contraction area of $3.27 \times 10^4\ \mathrm{km}^2$; the contraction zones were concentrated in Yunnan, western Guangxi, the coastal areas of Guangdong, northern Hainan, and northeastern Taiwan.

Under the SSP5-8.5 climate scenario, from the current climate to the 2060s, the macadamia suitable area showed a contraction trend. During the first 20 years, it contracted by $25.57 \times 10^4\ \mathrm{km}^2$, with a contraction proportion of 52.24%; the contraction zones were mainly in central Yunnan, central-eastern Guangxi, most of Hainan, and northeastern Taiwan. From the 2060s to the 2100s, the macadamia suitable area showed an expansion trend, with expansion areas of

2.07×10^4 km^2 and 3.62×10^4 km^2, respectively; the expansion zones were distributed in the Nyingchi and Shannan regions of Tibet, southern Yunnan, central-eastern Guangxi, Hainan, Fujian, and Taiwan.

In-figure labels for Fig. 9

- Column headings: SSP1-2.6; SSP2-4.5; SSP5-8.5.
- Panel A, 2040s: expansion area 0.04×10^4 km^2; contraction area 25.27×10^4 km^2; unchanged area 23.63×10^4 km^2.
- Panel B, 2040s: expansion area 0.07×10^4 km^2; contraction area 23.97×10^4 km^2; unchanged area 24.92×10^4 km^2.
- Panel C, 2040s: expansion area 0.06×10^4 km^2; contraction area 25.57×10^4 km^2; unchanged area 23.32×10^4 km^2.
- Panel D, 2060s: expansion area 2.46×10^4 km^2; contraction area 1.40×10^4 km^2; unchanged area 22.27×10^4 km^2.
- Panel E, 2060s: expansion area 1.58×10^4 km^2; contraction area 2.59×10^4 km^2; unchanged area 22.39×10^4 km^2.
- Panel F, 2060s: expansion area 1.10×10^4 km^2; contraction area 1.97×10^4 km^2; unchanged area 21.42×10^4 km^2.
- Panel G, 2080s: expansion area 2.05×10^4 km^2; contraction area 2.56×10^4 km^2; unchanged area 22.18×10^4 km^2.
- Panel H, 2080s: expansion area 2.96×10^4 km^2; contraction area 2.56×10^4 km^2; unchanged area 22.18×10^4 km^2.
- Panel I, 2080s: expansion area 2.07×10^4 km^2; contraction area 1.66×10^4 km^2; unchanged area 20.86×10^4 km^2.
- Panel J, 2100s: expansion area 3.24×10^4 km^2; contraction area 2.05×10^4 km^2; unchanged area 22.18×10^4 km^2.
- Panel K, 2100s: expansion area 2.43×10^4 km^2; contraction area 3.27×10^4 km^2; unchanged area 20.68×10^4 km^2.
- Panel L, 2100s: expansion area 3.62×10^4 km^2; contraction area 2.15×10^4 km^2; unchanged area 20.77×10^4 km^2.
- Legend: expansion area; contraction area; unchanged area. Scale: 0, 750, 1,500 km.

Fig. 9 Changes in the distribution of *Macadamia* sp. suitable areas in China under different climate scenarios.

2.6 Changes in the Distribution of the Centroid of Suitable Areas for Macadamia Under Climate Scenarios

Centroid analysis showed that the current centroid coordinates of macadamia are (107.67° E, 23.23° N), located in Nanning City, Guangxi. Using the centroid under the current climate as the reference, the overall displacement of the suitable-area range of macadamia under different climate scenarios and at different periods was relatively small (Figure 10).

Under the SSP1-2.6 climate scenario, across the four periods, the centroid of the suitable area for macadamia first migrated 63.17 km southwestward (2040s, 107.24° E, 22.85° N), then moved slightly 8.06 km northeastward (2060s, 107.28° E, 22.91° N), subsequently migrated 6.72 km southward (2080s, 107.28° E, 22.85° N), and then migrated 35.16 km northeastward (107.60° E, 22.90° N). In all four periods, it was located to the south-southwest of the current climate. Under the SSP2-4.5 climate scenario, the centroid of the suitable area for macadamia first shifted 48.94 km southeastward (2040s, 107.69° E, 22.80° N), then moved 35.15 km northwestward (2060s, 107.37° E, 22.88° N), subsequently migrated 72.40 km eastward (2080s, 108.05° E, 22.95° N), and by the 2100s migrated 92.75 km westward (107.18° E, 23.03° N), lying southwest of the centroid of the suitable area for macadamia under the current climate scenario. Under the SSP5-8.5 climate scenario, the centroid of the suitable area for macadamia showed the greatest southward displacement; in all four periods it was located southwest of the current climate centroid, with the largest migration distance occurring in the 2040s, at 53.43 km.

Under the SSP1-2.6 climate scenario, the centroid showed a migration trend of southwest-northeast-south-northeast; under the SSP2-4.5 climate scenario, it showed a migration trend of south-northwest-northeast-west; and under the SSP5-8.5 climate scenario, it showed a migration trend of southwest-southwest-southeast-southwest.

Figure 10. Changes in the center of mass of suitable areas for *Macadamia* sp. under different climate scenarios

3 Discussion

3.1 Reliability of MaxEnt Model Prediction Results

Based on the CMIP6 climate model (Li et al., 2020), this study selected three representative climate scenarios—SSP1-2.6, SSP2-4.5, and SSP5-8.5—on the basis of the current climate to simulate and analyze changes in the potential suitable areas of macadamia from the 2040s to the 2100s. Under each climate scenario, the AUC values of the model runs were above 0.900, indicating accurate prediction results.

Although MaxEnt has been widely applied in studies predicting potential geographic distributions, the MaxEnt model still has certain limitations. For example, improper selection or omission of environmental variables and species sample sizes may have certain effects on model operation and prediction results (Zhu Gengping et al., 2013; Wang Yusheng et al., 2019). In this study, environmental variables such as climate, topography, and soil were selected as inputs to the MaxEnt model, and the jackknife method was used to remove variables with relatively small contribution rates.

environmental variables. Although this reduced the influence of other redundant information on the simulation results, it considered only commonly used abiotic factors and ignored the effects of biotic factors—such as interspecific interactions and vegetation types—as well as human activities and other environmental variables on the ecological niche. Subsequent studies should comprehensively consider other environmental variables to ensure the accuracy of model predictions, thereby helping to expand the range for the introduction and artificial cultivation of macadamia.

3.2 Dominant Factors Affecting the Distribution of Macadamia in China

Different environments profoundly affect plant growth, development, and geographic distribution patterns (Yang Jiayue et al., 2025), and the key factor in tree introduction is climate (Lü Zengwei et al., 2024). This study found that the distribution of macadamia in China is mainly affected by temperature and precipitation. Macadamia showed the highest suitability when the annual mean temperature was 20–25 °C, annual precipitation was within the range of 1,550–4,800 mm, isothermality was 45%–54%, and the range of variation in annual mean temperature was <8 °C. Previous studies have suggested that macadamia can tolerate low temperatures and mild drought, and that the most ideal growth conditions are an annual mean temperature of 20–25 °C and annual precipitation >1,500 mm (Feng Yuan et al., 1999), which is generally consistent with the results of this study.

Macadamia is native to the subtropical rainforest regions of Australia (25°–30° S), which is similar to the distribution range of highly suitable areas for macadamia in China (19°–29° N). This indicates that the distribution range of macadamia in China broadly corresponds to the climatic conditions of its place of origin. In addition, Southwest China and the coastal areas of South China are influenced by the South Asian monsoon and East Asian monsoon, with abundant precipitation and long wet periods (Du Junkai et al., 2023). Precipitation also affects soil P content and macadamia biomass (Tang Tao et al., 2024). In the future, long-term fixed-site climate monitoring can be carried out in different regions, and superior provenances can be introduced for planting to obtain more adaptable germplasm, thereby expanding the range for macadamia introduction.

3.3 Distribution of Potentially Suitable Areas for Macadamia

With the aid of various environmental factors, this study evaluated the distribution and suitability of macadamia in China, aiming to provide a scientific basis for macadamia planting regionalization and large-scale cultivation, and to offer important theoretical significance and practical value for promoting regional advantageous specialty industries and the development of economic chains. Under different scenarios, the spatial distribution of macadamia shifted and gradually showed characteristics of fragmentation and area reduction. The highly suitable areas in China were mainly distributed in tropical and subtropical regions such as southern Tibet, Yunnan, Guangxi, Guangdong, Hainan, southern Sichuan, southwestern Chongqing, Guizhou, Hubei, Hunan, Jiangxi, Hong Kong, and Zhejiang. Under the current climate, suitable areas are concentrated in provinces and regions such as Yunnan, Guangxi, Guangdong, Hainan, and Taiwan; among them, Yunnan has the widest distribution of suitable areas for macadamia, followed by Guangdong. Macadamia tends to grow in areas with sufficient heat and abundant precipitation. Under different future climate scenarios, the potential suitable areas for macadamia are stably distributed in Southwest and South China, the southeastern margin of Tibet, Hainan, and Taiwan. At present, macadamia germplasm resources are continually being improved. To ensure the quality and yield of macadamia, large-scale macadamia cultivation should likewise consider the influence of hydrothermal conditions on macadamia, formulate macadamia planting zoning according to local conditions, and develop a modern macadamia industry. In newly added suitable areas in the future, appropriate superior varieties may be selected for planting; rational ecological regulation measures should be formulated according to local habitat characteristics, and artificial introduction and cultivation experiments should be carried out gradually.

This study found no records of macadamia distribution in Tibet, but the output of the MaxEnt model indicated that under the current climate, macadamia is concentrated in Shannan City in southeastern Tibet and the southern part of Nyingchi City. This region belongs to the southern Tibetan valley area, where there are no high mountains blocking it, and warm, moist air currents from the Indian Ocean to the south bring heat and moisture, giving it subtropical climatic characteristics (Chen Yuguang et al., 2022). Therefore, macadamia is suitable for growth and development there. In 2017, the Vegetable Research Institute of the Tibet Academy of Agricultural and Animal Husbandry Sciences introduced macadamia and successfully planted it in southeastern Tibet, indicating that the results of this study are consistent with reality (Wang Wenhua et al., 2018). However, inland regions such as southern Tibet and Yunnan are far from the ocean and have abundant light and heat, but uneven precipitation distribution makes drought problems likely (Feng Yuan et al., 1999). Therefore, reasonable protective measures should be formulated for subsequent introduction and cultivation. Macadamia has a relatively shallow root system and weak wind resistance (Liu Yao et al., 2023). Regions such as Taiwan, Hainan, and South China are close to the ocean and are prone to typhoons in summer; therefore, when planting in coastal areas, leeward slopes should be selected or windbreak forests should be established.

4 Conclusion

The MaxEnt model simulated the potential distribution of macadamia in China extremely well (AUC = 0.966), and identified annual mean temperature as the most critical dominant factor affecting the potential distribution of macadamia in China, with a contribution rate of 64.9%. It was followed by annual precipitation and isothermality, with contribution rates of 14.9% and 11.5%, respectively.

The optimal growth conditions for macadamia are an annual mean temperature of 20–25 °C, annual precipitation greater than 1,500 mm, and humid tropical-subtropical regions with relatively high isothermality.

Under the current climate scenario, the present potential ecologically suitable range of macadamia in China is 91.0°–122.0° E and 18.1°–31.6° N. The total suitable area is 40.15 × 10^4 km^2, accounting for 4.18% of China' s total land area. Compared with the current climate scenario, in each period under the various climate-change scenarios,

The area of suitable habitat for macadamia in China and Australia decreased substantially. Under the SSP5-8.5 climate scenario, the suitable habitat area for macadamia in Australia was the smallest, and the areas of moderate- and low-suitability habitat in all periods and under all climate scenarios were lower than those under the current climate. This indicates that, compared with the other future climate scenarios, the SSP5-8.5 climate scenario is less favorable for the growth of macadamia in Australia. Among the provinces of China, under the three future climate scenarios, macadamia had the largest distribution area in Yunnan Province, followed by southeastern coastal regions such as Guangdong and Guangxi. During climate change, the distribution range of suitable habitat for macadamia in China showed both contraction and expansion. As temperature increased, although the total area of potential suitable habitat for macadamia decreased, the area of highly suitable habitat continued to increase. Under future climate scenarios, the centroid shifts of suitable habitat for macadamia varied, but the centroid of suitable habitat always remained in tropical regions.

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