SPATIO-TEMPORAL CHANGES OF *DIOSCOREA PANTHAICA* UNDER CLIMATE CHANGE, AN ENDEMIC MEDICINAL AND EDIBLE PLANT IN CHINA

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Abstract. *Dioscorea panthaica* (*D. panthaica*) is a unique medicinal and edible plant endemic to China. In recent years, the distribution of wild resources of this species has faced significant challenges due to severe ecological degradation and the exacerbation of climate change. This study utilizes 93 valid species distribution records of *D. panthaica* and 37 environmental variables, employs the MaxEnt and ArcGIS to predict the potential habitat distribution patterns of *D. panthaica* under present conditions and two future periods (the 2050s and 2090s) across two climate scenarios (SSP126 and SSP585). The results indicate that the MaxEnt model performed well (AUC > 0.9), demonstrating high accuracy and reliability. The dominant environmental variables influencing the distribution of *D. panthaica* include: mean temperature of wettest quarter (BIO_7, 22.1 ~ 28.3°C), temperature seasonality (BIO_4, 415.9 ~ 700.1), mean temperature of coldest quarter (BIO_11, 2.7 ~ 12.8°C), and minimum temperature of coldest month (BIO_6, -5.2 ~ 6.5°C). Under present climatic conditions, highly suitable habitats for *D. panthaica* are primarily concentrated in the regions of Yunnan, Guizhou, and Sichuan. Under future climate scenarios, the suitable habitat range for *D. panthaica* is expected to undergo significant changes. Specifically, under the SSP126 scenario, the total area of suitable habitat is projected to increase, with an increase of 3.95% by the 2050s and 8.90% by the 2090s. In contrast, under the SSP585 scenario, the area of suitable habitat is expected to continue to expand, with an increase of 8.18% by the 2050s and a substantial increase of 28.61% by the 2090s. This research provides a scientific basis for the conservation and sustainable utilization of *D. panthaica* resources and offers important references for formulating conservation strategies and cultivation plans in response to climate change.
Keywords: *MaxEnt, ArcGIS, potential geographical distribution, future climate change*

Introduction

Dioscorea panthaica (*D. panthaica*) is a herbaceous climbing plant belonging to the *Dioscoreaceae* family, primarily distributed in the provinces of Yunnan, Guizhou, and Sichuan in China (Zhang et al., 2021; Li et al., 2021). Its rhizomes are utilized in traditional medicine to promote qi circulation, alleviate pain, dispel wind, and remove dampness, as well as for treating conditions such as gastric pain and rheumatoid arthritis (Li et al., 2021). The principal bioactive compounds in *D. panthaica*, namely diosgenin and dioscin, are critical for the treatment of cardiovascular diseases and are extensively employed in traditional Chinese medicine formulations, such as “Di’ao Xinxuekang,” aimed at improving conditions like coronary heart disease (Li et al., 2021; Zhang et al., 2021). These compounds are often referred to as “medicinal gold” due to their

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foundational role in the synthesis of steroidal drugs, including contraceptives and hormone preparations, underscoring the significant position of *D. panthaica* within the high-value pharmaceutical industry. Additionally, this species possesses considerable nutritional value, as its tubers are rich in starch, protein, amino acids (notably glutamic acid, among 17 different types), and trace elements (Wang et al., 2024b). Therefore, *D. panthaica* is recognized as a plant of high economic value and medicinal potential, serving both dietary and therapeutic purposes.

However, the ongoing global demand for diosgenin has led to severe resource depletion of this species (Shen et al., 2018), as it is primarily harvested from wild populations. This depletion is exacerbated by unsustainable harvesting practices driven by its high economic value and medicinal potential, alongside the compounded effects of climate change and land-use alterations, which further endanger wild populations. As diosgenin is mainly extracted from wild *Dioscorea* species, the declining availability of these resources restricts the supply of medicinal compounds (Shen et al., 2018). This scarcity not only jeopardizes the sustainable production of traditional medicine but may also contribute to biodiversity loss (Sun et al., 2017). For instance, in Asia, the distribution of wild *Dioscorea* species, including *D. panthaica*, has sharply declined due to habitat degradation and unregulated development. Therefore, there is an urgent need to assess and predict the potential geographical distribution of this species through scientific methods to support resource conservation, cultivation, and sustainable utilization (Sun et al., 2017; Shen et al., 2018).

Predicting the potential geographic distribution of species through scientific models can guide resource conservation and rational cultivation practices, ensuring the stability of medicinal herb quality and preventing gaps in healthcare resources caused by resource shortages (Wang et al., 2024a; Li et al., 2025b). The Maximum Entropy model (MaxEnt) model is a probabilistic statistical model based on the principle of maximum entropy, utilized for predicting suitable habitat distributions of species. Its core functionality involves spatial predictions that maintain high accuracy while utilizing limited species distribution data. This model has been widely applied in habitat analysis and potential distribution studies of medicinal plants (Ahmadi et al., 2023; Morales et al., 2017). In the context of medicinal plant distribution, the MaxEnt model can significantly enhance predictive performance through the optimization of parameters such as feature classes (FC) and regularization multipliers (RM). For instance, it has been employed to simulate the current and future potential distributions of alpine medicinal plants, identifying key ecological and geographical factors influencing these distributions, such as temperature and precipitation. The model's effectiveness has been evaluated using six metrics, demonstrating that the optimized model outperforms the default settings (Bao et al., 2022). Additionally, the model has been applied to predict the distribution patterns of other medicinal plants, including *Thymus* species in Iran, the traditional Chinese medicine *Bletilla striata*, and various Tibetan medicinal plants, incorporating environmental variables to forecast distribution range changes under climate change scenarios (Hosseini et al., 2024; Wang et al., 2025; Luo et al., 2025). This information can guide artificial cultivation and resource conservation efforts.

In light of this background, the objectives of this study are: (1) to integrate Pearson correlation analysis, ArcGIS spatial technology, and the MaxEnt model in order to predict the suitable habitat distribution of *D. panthaica* under both current and future climate scenarios (SSP126 and SSP585 for the 2050s and 2090s); (2) to identify the dominant environmental variables shaping its distribution; (3) to analyze spatiotemporal

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changes in habitat extent and geographic shifts, particularly toward higher elevations; and (4) to provide a scientific basis for conservation strategies and sustainable utilization of this species in light of ongoing climate change and anthropogenic pressures.

Materials and methods

Species geographic distribution Information

Distribution data for *Dioscorea panthaica* (*D. panthaica*) were compiled from three biodiversity repositories: the Chinese Virtual Herbarium (CVH; http://www.cvh.ac.cn), National Specimen Information Infrastructure (NSII; http://www.nsii.org.cn/2017/home.php), and Global Biodiversity Information Facility (GBIF; https://www.gbif.org/). Specimen coordinates were processed using ArcGIS 10.8. To minimize spatial autocorrelation, the "Spatially Rarefy Occurrence Data for SDMs" tool in SDM Toolbox filtered specimens within 5 km of each other (Huang et al., 2024), resulting in 93 spatially independent points for modeling (*Fig. 1*).

Environmental variables acquisition and processing

This study incorporated three habitat variable categories for *D. panthaica*: bioclimatic, edaphic, and topographic factors. Bioclimatic parameters (19 variables representing historical [1970-2000] and future projections) were obtained from WorldClim (http://www.worldclim.org) at 2.5-arc-minute resolution. Future climate projections used the BCC-CSM2-MR model (Wu et al., 2019)—validated for Chinese climate simulations—for the 2050s (2041-2060) and 2090s (2081-2100) under two Shared Socioeconomic Pathways: SSP126 (low emissions) and SSP585 (high emissions, fossil-fueled development). These SSP frameworks address projection uncertainty using standardized socioeconomic-climate narratives. Soil and topographic data came from the Harmonized World Soil Database (https://www.fao.org/soils-portal) and WorldClim. The details of all variables are presented in *Table 1*. Variable selection involved: (1) Initial screening via iterative MaxEnt 3.4.4 calculations with occurrence data and contemporary variables, retaining parameters with > 0% contribution; (2) Spatial extraction of values using ArcGIS' "Sampling" tool; (3) Pearson correlation analysis in SPSS 26, eliminating collinear variables ($|r| > 0.8$) (Hao et al., 2024) exhibiting near-zero contribution rates. The refined set proceeded to modeling.

Modeling and data processing

MaxEnt modeled the distribution of 93 *D. panthaica* occurrences against 10 environmental variables. Parameters included: 75% training/25% testing data split, 10,000 background points, 1,000,000 maximum iterations, and 10-fold cross-validation. Model performance was evaluated using the area under the receiver operating characteristic curve (AUC), with values > 0.9 indicating high accuracy. Variable contributions were assessed via Jackknife testing and response curve optimization (Wang et al., 2018). Probability outputs (range: 0 ~ 1) were thresholded at $p \geq 0.5$ to determine optimal environmental ranges, with peak probabilities defining adaptation thresholds (Zhang et al., 2023). Subsequent ArcGIS 10.8 processing involved: (1) Converting ASCII outputs to rasters; (2) Consolidating predictions using Spatial Analyst's Reclassify tool; (3) Classifying habitat suitability via Jenks' natural breaks: unsuitable (0 ~ 0.1), generally (0.1 ~ 0.3), moderately

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(0.3 ~ 0.5), and highly suitability (0.5 ~ 1) (Brismar, 1991). Habitat area estimates were calculated from reclassified attribute tables based on class-specific grid proportions.

Centroid migration

We calculated habitat centroids for *D. panthaica* across climate scenarios and time periods using ArcGIS 10.8's "Mean Center" spatial statistics tool. This determined centroid positions and displacement trajectories to track optimal habitat migration under changing climate regimes (Liu et al., 2018).

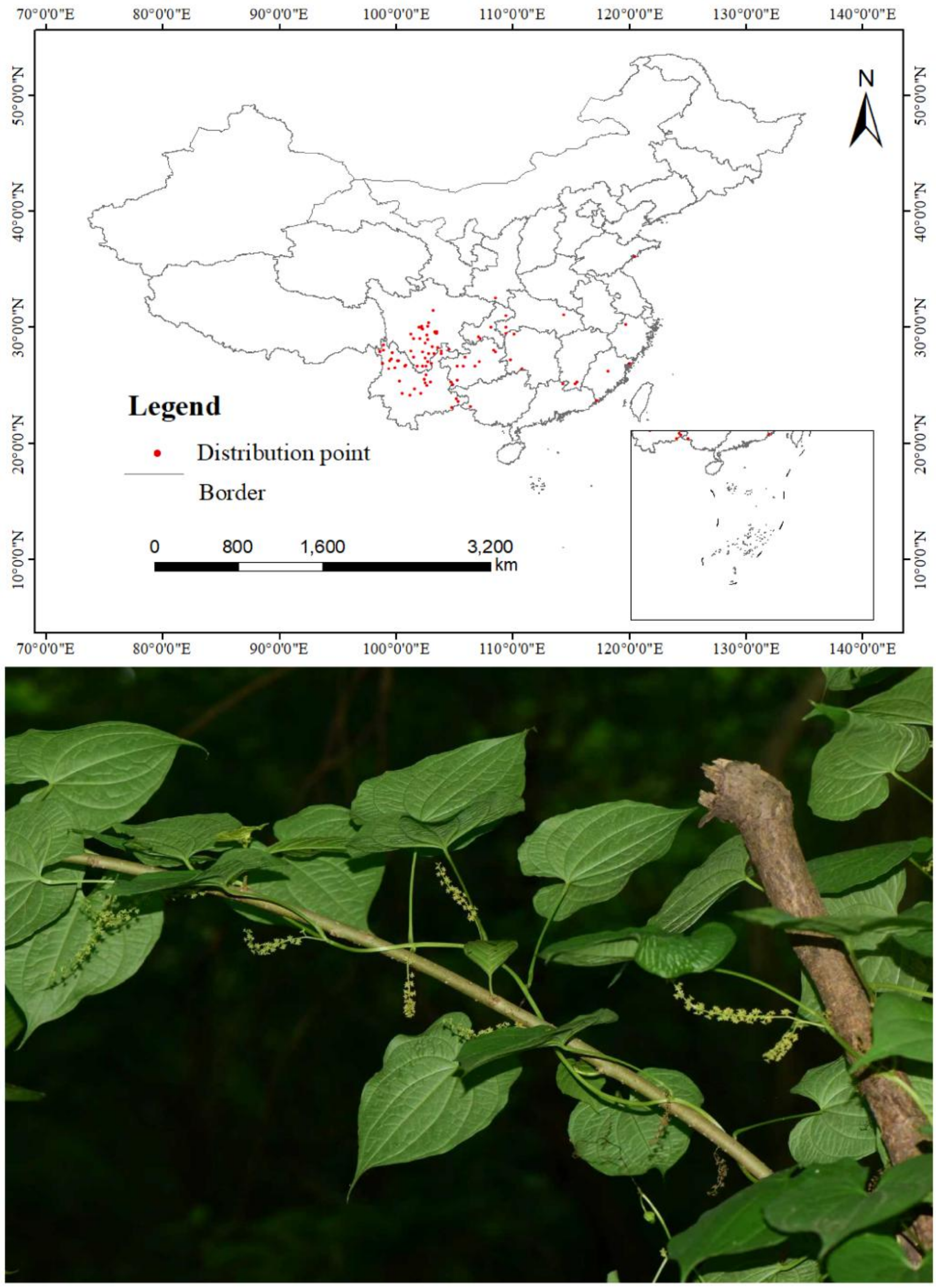

Figure 1. *The distribution information of Dioscorea panthaica and field growth map of its suitable areas*

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Table 1. *The details of all environmental variables*

Variables	Name	Unit
BIO_1	Annual mean temperature	℃
BIO_2	Mean diurnal temperature range	℃
BIO_3	Isothermality	/
BIO_4	Temperature seasonality	/
BIO_5	Maximum temperature of the warmest month	℃
BIO_6	Minimum temperature of the coldest month	℃
BIO_7	Mean temperature of the wettest quarter	℃
BIO_8	Mean temperature of the wettest quarter	℃
BIO_9	Mean temperature of the driest quarter	℃
BIO_10	Mean temperature of the warmest quarter	℃
BIO_11	Mean temperature of the coldest quarter	℃
BIO_12	Annual precipitation	mm
BIO_13	Precipitation of the wettest month	mm
BIO_14	Precipitation of the driest month	mm
BIO_15	Precipitation seasonality	/
BIO_16	Precipitation of the wettest quarter	mm
BIO_17	Precipitation of the driest quarter	mm
BIO_18	Precipitation of the warmest quarter	mm
BIO_19	Precipitation of the coldest quarter	mm
Awc_class	Soil available water content	%
Slope	Slope	°
Elev	Elevation	m
Aspect	Aspect	/
T_ph_h2o	Topsoil pH	-log(H^+)
S_ph_h2o	Subsoil pH	-log(H^+)
T_oc	Topsoil organic carbon content	%weight
S_oc	Subsoil organic carbon content	%weight
T_clay	Topsoil clay content	%weight
S_clay	Subsoil clay content	%weight
T_sand	Topsoil sand content	%weight
S_sand	Subsoil sand content	%weight
T_silt	Topsoil silt content	%weight
S_silt	Subsoil silt content	%weight
T_ece	Topsoil electrical conductivity	ds/m
S_ece	Subsoil electrical conductivity	ds/m
T_caco3	Topsoil carbonate or lime content	%weight
S_caco3	Subsoil carbonate or lime content	%weight

Results

Modeling variables and evaluation of model accuracy

Pearson correlation analysis of 24 environmental variables (*Fig. 2A*) selected 10 key predictors for MaxEnt modeling (*Table 2*). Model performance, evaluated via the AUC, yielded 0.928 (*Fig. 2B*). This exceeds the 0.9 threshold for high predictive reliability, confirming strong discrimination capacity.

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Table 2. *Environmental variables for the MaxEnt*

Environmental variables	Name	Unit
BIO_1	Annual mean temperature	℃
BIO_4	Temperature seasonality	/
BIO_6	Minimum temperature of the coldest month	℃
BIO_7	Mean temperature of the wettest quarter	℃
BIO_11	Mean temperature of the coldest quarter	℃
BIO_14	Precipitation of the driest month	mm
BIO_17	Precipitation of the driest quarter	mm
Elev	Elevation	m
S_ph_h2o	Subsoil pH	-log(H^+)
S_caco3	Subsoil carbonate or lime content	%weight

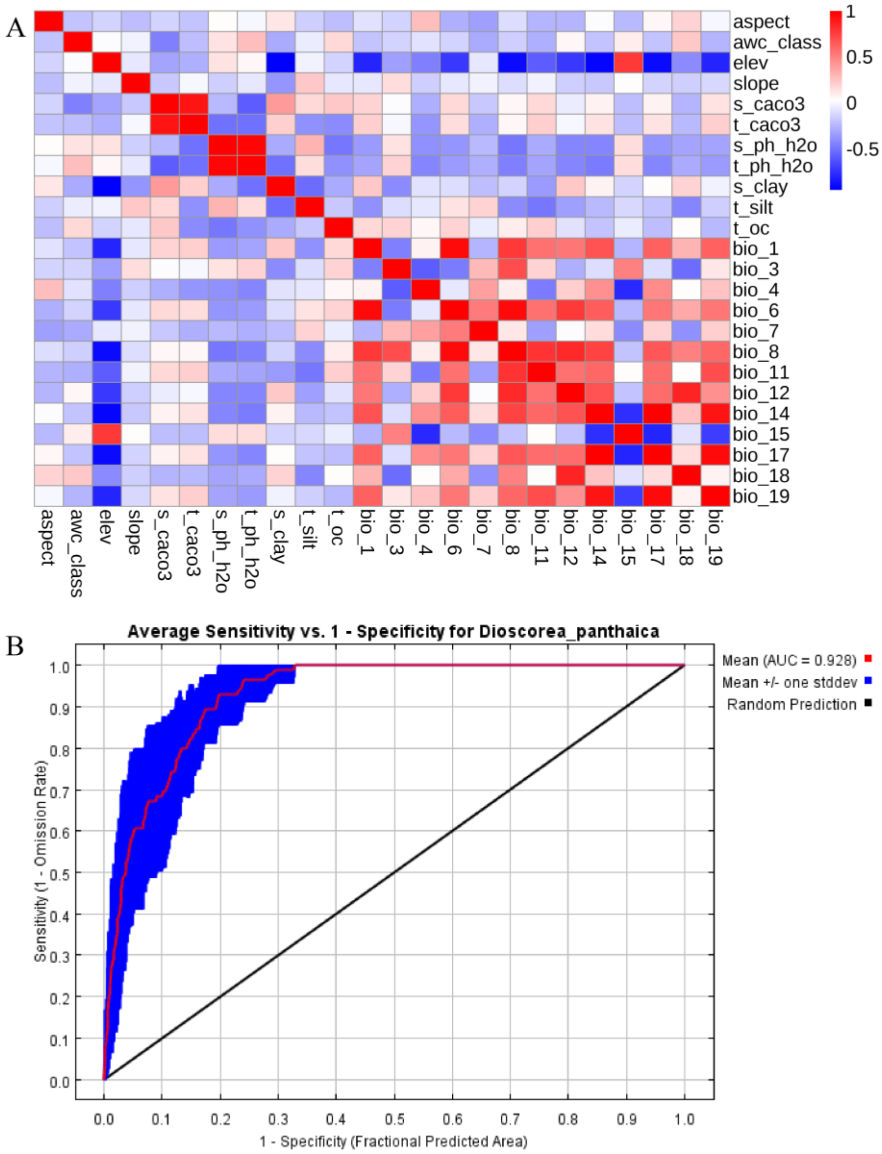

Figure 2. *Modeling variables and evaluation of model accuracy: Correlation analysis heatmap (A); ROC curve (B)*

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Dominant environmental variables

Variable impact on the distribution model was assessed using contribution percentages and regularized training gains. Under current climate conditions, four environmental variables collectively explained 82.4% of model variance (*Table 3*): Mean temperature of the wettest quarter (BIO_7; > 70% contribution), Temperature seasonality (BIO_4), Mean temperature of the coldest quarter (BIO_11), and Minimum temperature of the coldest month (BIO_6). Each contributed > 2%. Jackknife analysis of training gain (*Fig. 3*) confirmed the significance of Bio_7, Bio_4, Bio_11, and Bio_6, all showing gains > 1. Integrating contribution percentages and training gains, BIO_7, BIO_4, BIO_11, and BIO_6 were identified as the key variables governing *D. panthaica*'s distribution.

Table 3. *Environmental variables contributions*

Environmental variables	Name	Percent contribution (%)
BIO_7	Mean temperature of the wettest quarter	71.4
BIO_4	Temperature seasonality	5.3
BIO_11	Mean temperature of the coldest quarter	3.5
BIO_6	Minimum temperature of the coldest month	2.2

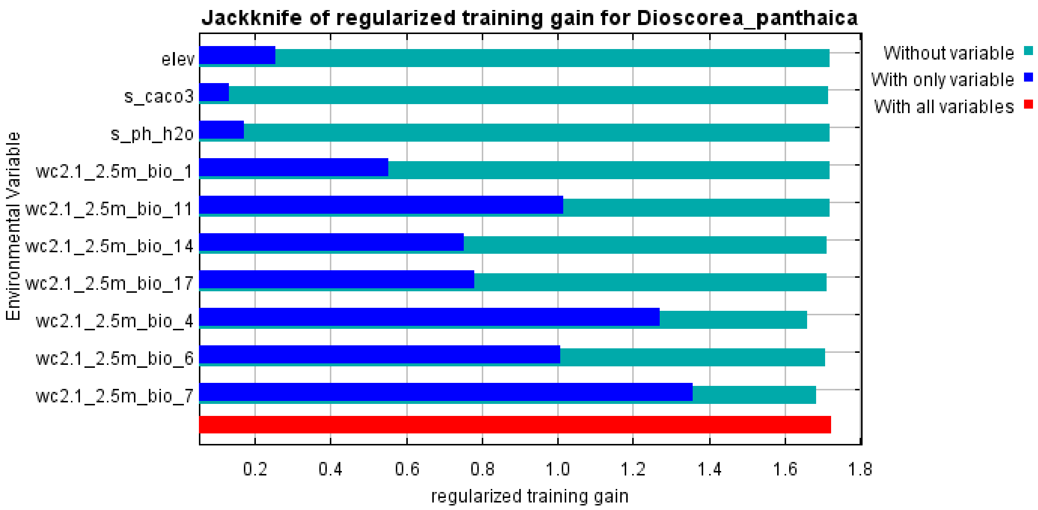

Figure 3. *Gain of each variable*

Suitable habitat range

MaxEnt-generated response curves characterized *D. panthaica*'s environmental relationships, identifying optimal ranges and tolerance thresholds. For the four key predictors, occurrence probability > 0.5 defined optimal intervals (*Fig. 4; Table 4*): Mean temperature of wettest quarter (BIO_7, 22.1 ~ 28.3℃); Temperature seasonality (BIO_4, 415.9 ~ 700.1); Mean temperature of coldest quarter (BIO_11, 2.7 ~ 12.8℃); Minimum temperature of coldest month (BIO_6, -5.2 ~ 6.5℃). These constrained ranges confirm temperature as the primary determinant of species distribution.

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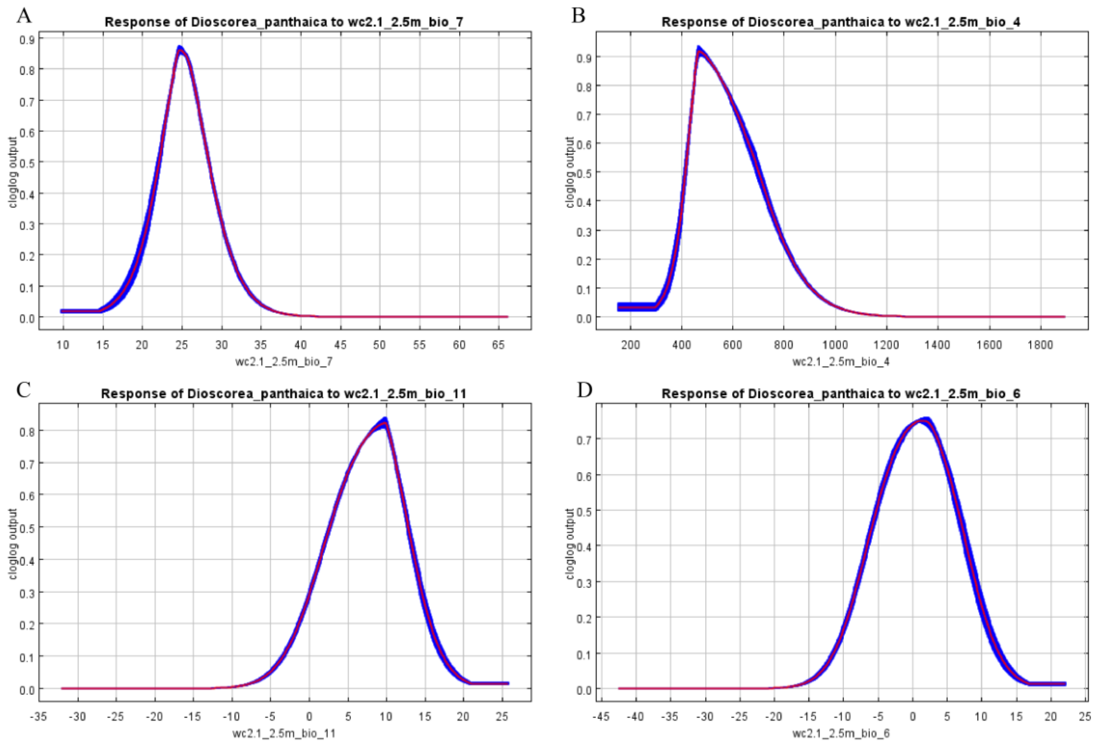

Figure 4. *The response curve of dominant environmental variables: Mean temperature of the wettest quarter (A); Temperature seasonality (B); Mean temperature of the coldest quarter (C); Minimum temperature of the coldest month (D)*

Table 4. *The suitable range for the dominant environmental variables*

Environmental variables	Suitable range	Adaptive threshold
BIO_7	22.1 ~ 28.3℃	24.6℃
BIO_4	415.9 ~ 700.1	466.5
BIO_11	2.7 ~ 12.8℃	9.8℃
BIO_6	-5.2 ~ 6.5℃	1.4℃

Potential distribution under present climate

This study successfully constructed a spatial distribution map of the potential suitable habitat for D. panthaica (*Fig. 5*). The predicted results are visually represented using a four-color gradient to illustrate habitat suitability: blue indicates unsuitable areas, green represents generally suitable areas (94.46 × 10^4 km²), yellow denotes moderately suitable areas (49.18 × 10^4 km²), and red indicates highly suitable areas (37.54 × 10^4 km²). The total area of suitable habitats amounts to 181.18 × 10^4 km². Spatial analysis reveals that marginally suitable areas primarily extend from the southeastern coast to the middle and lower reaches of the Yangtze River, with a concentrated distribution in the southern regions of Fujian, Zhejiang, Jiangxi, northern Guangdong, northern Guangxi, central Yunnan, northwestern Hunan, southeastern Hunan, northwestern Hubei, southern Shaanxi, and southeastern Gansu. Moderately suitable areas exhibit a transition towards the southwestern inland, predominantly represented by regions such as Chongqing, central Fujian, northeastern Guizhou, eastern Sichuan, and

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central Yunnan. Notably, highly suitable areas form a continuous distribution belt from the southern edge of the Sichuan Basin to the Yunnan-Guizhou Plateau, with core regions concentrated in southern Sichuan, western Guizhou, and northern Yunnan.

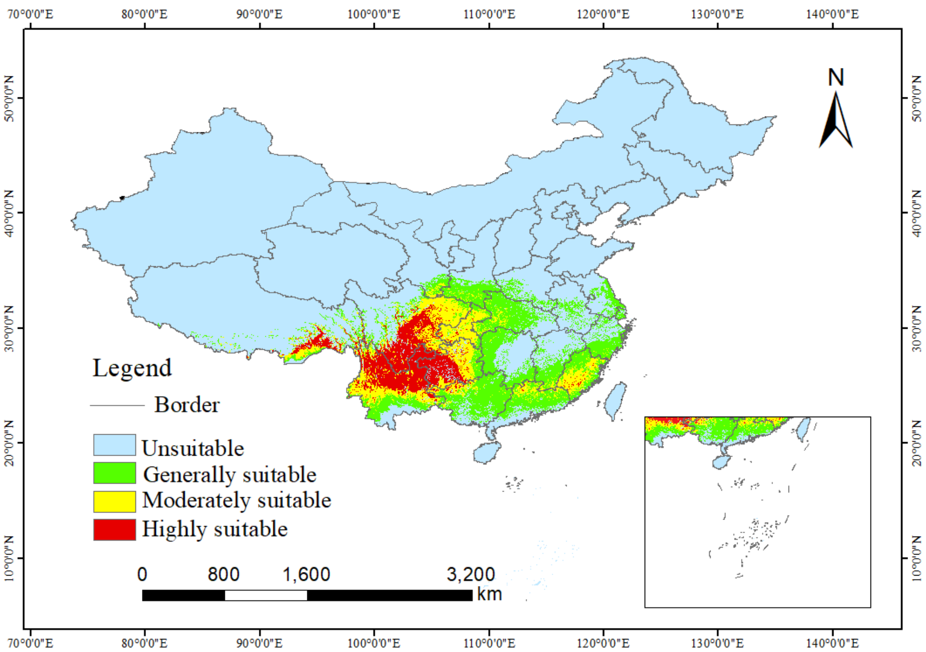

Figure 5. *Potential distribution of Dioscorea panthaica under present climate*

Potential distribution under future climate

Under the SSP126 scenario, the total suitable area for *D. panthaica* increases from the present 181.18 × 10^4 km² to 188.35 × 10^4 km² (a net gain of 3.96%) by the 2050s, and further to 197.32 × 10^4 km² (an increase of 8.91%) by the 2090s. Although highly suitable areas decrease from 37.54 × 10^4 km² to 32.41 × 10^4 km² (a reduction of 13.67%) by the 2090s, this decline is offset by substantial expansion in moderately and generally suitable habitats. Moderately suitable areas grow from 49.18 × 10^4 km² to 62.33 × 10^4 km² (an increase of 26.74%) in the 2050s, followed by a slight contraction to 48.89 × 10^4 km² in the 2090s. Generally suitable areas exhibit continuous growth, reaching 116.02 × 10^4 km² by the 2090s, an increase of 22.82% compared to the present.

Under the SSP585 scenario, the total suitable area shows a more pronounced increasing trend, reaching 196.01 × 10^4 km² (an increase of 8.18%) in the 2050s and expanding significantly to 233.02 × 10^4 km² (a gain of 28.65%) by the 2090s. Highly suitable areas remain relatively stable, with a slight increase to 38.01 × 10^4 km² (1.24% growth) in the 2050s and 37.76 × 10^4 km² (0.58% growth) in the 2090s. Moderately suitable areas expand considerably from 49.18 × 10^4 km² to 65.87 × 10^4 km² (33.94% growth) in the 2050s and further to 67.79 × 10^4 km² (37.87% growth) in the 2090s. Generally suitable areas also show substantial growth, increasing to 127.47 × 10^4 km² by the 2090s, a rise of 34.93% from the present (*Fig. 6; Table 5*).

These shifts indicate that while highly suitable habitats may contract or remain stable in certain scenarios, the overall suitable area for *D. panthaica* is projected to expand under future climate conditions, primarily driven by the increase in moderately and generally suitable areas.

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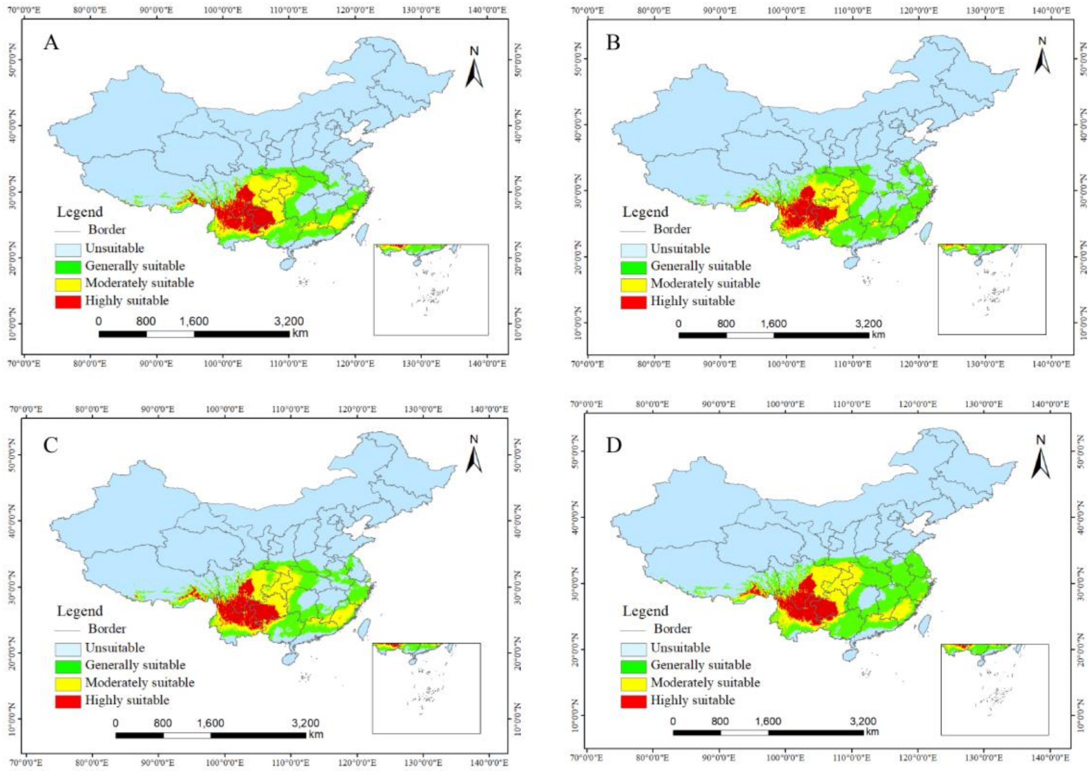

Figure 6. *Potential distribution of Dioscorea panthaica under future climate: 2050s, SSP126 (A); 2090s, SSP126 (B); 2050s, SSP585 (C); 2090s, SSP585 (D)*

Table 5. *Suitable area of Dioscorea panthaica under different scenarios and periods*

Periods	Scenarios	Highly suitable ($\times 10^4$ km^2)	Moderately suitable ($\times 10^4$ km^2)	Generally suitable ($\times 10^4$ km^2)	Total suitable area ($\times 10^4$ km^2)
Present		37.54	49.18	94.46	181.18
2050s	SSP126	37.38	62.33	88.64	188.35
	SSP585	38.01	65.87	92.13	196.01
2090s	SSP126	32.41	48.89	116.02	197.32
	SSP585	37.76	67.79	127.47	233.02

Centroid migration

This study utilized ArcGIS to calculate the centroid migration trends of the suitable habitat for D. panthaica under various climate scenarios and time periods. We compared the present and future centroid locations and inferred potential migration pathways (*Fig. 7*). The latitude and longitude coordinates of the centroids and migration distances for each period and scenario are detailed in *Table 6*. Currently, the centroid of the suitable habitat for D. panthaica is located at 106.91°E, 28.49°N. Under the SSP126 scenario, the centroid initially migrates 633.99 km to the northwest, followed by a subsequent migration of 266.88 km to the southeast. In the SSP585 scenario, the centroid first migrates 538.06 km to the northwest and then 79.06 km to the southwest. The results indicate that future climate change may drive the distribution range of D. panthaica towards the high-altitude mountains in the western regions.

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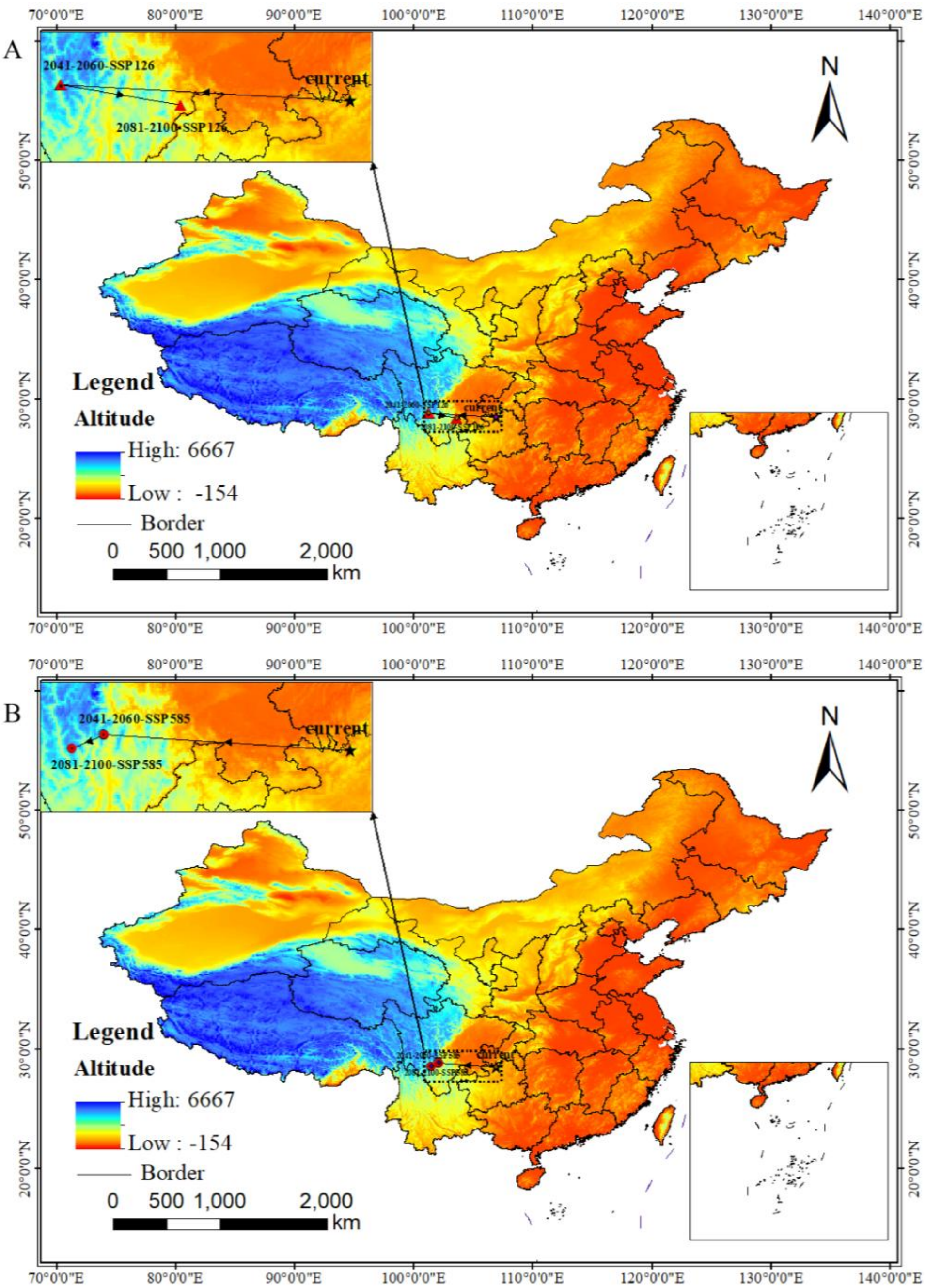

Figure 7. *Centroid migration routes for Dioscorea panthaica: 2050s -2090s, SSP126 (A); 2050s -2090s, SSP585 (B)*

Table 6. *Changes in the centroid of Dioscorea panthaica*

Climate scenarios	Periods	Longitude (°E)	Latitude (°N)	Migration distance (km)
	Present	106.91	28.49	
SSP126	2050s	101.23	28.81	633.99
SSP126	2090s	103.58	28.41	266.88 (2050s to 2090s)
SSP585	2050s	102.09	28.81	538.06
SSP585	2090s	101.44	28.55	79.06 (2050s to 2090s)

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Discussion

The MaxEnt model, a commonly used method for ecological niche modeling, has demonstrated strong performance in predicting the potential suitable habitats for species (Luo et al., 2025; Zhang et al., 2024). This model is particularly well-suited for predicting the distribution of crops and medicinal plants (Luo et al., 2025; Gong et al., 2022), yielding results with high accuracy (Kang et al., 2025; Li et al., 2025a). In this study, we utilized the MaxEnt model to simulate the potential suitable habitat distribution of the medicinal and edible plant *Dioscorea panthaica* in China. The model's predictive accuracy was notably high (AUC > 0.9), indicating that the results are reliable (Luo et al., 2025; Kang et al., 2025; Li et al., 2025a).

D. panthaica, a plant utilized for both medicinal and culinary purposes (Wang et al., 2024b), exhibits significant regional distribution characteristics. According to the "Flora of China," this species is primarily found in Yunnan, western Guizhou, western Sichuan, Enshi in Hubei, and northwestern Hunan. Predictive analyses based on the MaxEnt model indicate that its present potential suitable habitats are concentrated in the central, southwestern, and southeastern coastal regions of China, particularly south of the Yangtze River. Notably, the highly suitability areas align closely with the core distribution regions recorded in the literature for Yunnan, Guizhou, and Sichuan. *D. panthaica* is a twining herbaceous vine, and, like most species in the *Dioscorea* genus (Lu et al., 2024), it typically inhabits areas beneath shrubs, along forest edges, or beside mountain roads at altitudes ranging from 1000 to 3500 m. The community characteristics of this species exhibit spatial differentiation influenced by regional climatic and soil conditions. The southwestern region, currently identified as a highly suitability area, experiences a subtropical monsoon climate characterized by summer rainfall and dry winters. Additionally, the topographical effects of the Sichuan Basin, Yungui Plateau, and Hengduan Mountains contribute to the formation of local climatic patterns, where water and thermal parameters (such as seasonal wetness, duration, and precipitation intensity) vary systematically with latitude and altitude (Jinreng et al., 1994). Such environments provide ideal habitats for the *Dioscoreaceae* family (Obidiegwu et al., 2020), which comprises approximately 650 species across 10 genera, predominantly found in tropical and subtropical regions. In China, 93 species of *Dioscoreaceae* have been documented, with major distribution areas concentrated in Guangxi, Hebei, and Henan (Chen et al., 2020). Environmental factor analysis reveals that temperature variables (including the mean temperature of the wettest quarter, temperature seasonality, mean temperature of the coldest quarter, and minimum temperature of the coldest month) are key drivers of *D. panthaica* distribution, consistent with its tropical and subtropical habitat preferences (Maurin et al., 2016). Model predictions indicate that current highly suitability areas are concentrated in southern and central Sichuan, western and southern Guizhou, northeastern Yunnan, and southeastern Tibet. Future climate warming may prompt shifts in its distribution towards higher latitude and altitude regions. The mean temperature of the wettest quarter, identified as a primary limiting factor, provides a scientific basis for developing resource conservation strategies for this species.

This study predicts the future geographical distribution of *D. panthaica* under two shared socioeconomic pathways (SSPs): SSP 126 (low emissions, limiting global warming to below 2°C) and SSP 585 (high emissions) for the decades of the 2050s and 2090s. Under the SSP 126 scenario, although the area of highly suitable habitat decreases slightly (by 0.44% in the 2050s and by 13.67% in the 2090s), the area of

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moderately suitable habitat increases significantly (by 35.03% in the 2050s and by 0.79% in the 2090s), resulting in an overall increase in suitable habitat area (by 3.95% in the 2050s and by 8.90% in the 2090s). This suggests that climate change mitigation measures may benefit the overall suitable habitat for *D. panthaica*, particularly by promoting the expansion of moderately suitable habitats and facilitating the transition of unsuitable habitats to suitable ones. In the SSP 585 scenario, the area of highly suitable habitat increases slightly (by 1.24% in the 2050s and by 0.58% in the 2090s), while the area of moderately suitable habitat increases substantially (by 44.45% in the 2050s and by 49.57% in the 2090s), leading to a continuous increase in the total suitable habitat area (by 8.18% in the 2050s and by 28.61% in the 2090s). Even under high emissions scenarios, the overall suitable habitat area continues to expand, likely due to the transition of generally suitable habitats to moderately and highly suitable ones. Under future climate change scenarios, the centroid of the total suitable habitat for *D. panthaica* is projected to shift westward into mountainous regions, with an average migration distance of 537.86 km. This shift may be associated with complex topography and species-specific habitat conditions, indicating a potential concentration of suitable habitats in the Yungui Plateau region. In both scenarios, the suitable habitat range for *D. panthaica* expands, primarily focusing on Central China (southern Henan, eastern Hubei, western Hunan, and southern Hunan) and Eastern China (western, eastern, and southern Anhui, southern Jiangsu, eastern Jiangsu, Shanghai, Zhejiang, and northern Jiangxi), which could serve as alternative regions for the future cultivation of *D. panthaica*.

D. panthaica, an important medicinal and edible species, possesses significant medicinal value and potential for industrial development. However, its wild resources are currently threatened by habitat degradation and overharvesting, leading to a contraction of its distribution range and a decline in population. Additionally, the artificial cultivation technology for this species remains underdeveloped, and the absence of high-quality, high-yield cultivation models hampers the industrialization process, resulting in a pronounced conflict between resource conservation and utilization. To achieve sustainable utilization, the following strategies are proposed: (1) Establish a legislative regulatory mechanism to strictly control the intensity of wild harvesting, ensuring the natural regeneration capacity of populations. (2) Identify and establish cultivation bases in areas with optimal temperature and precipitation conditions, enhancing yield and quality through optimized cultivation practices, thereby reducing reliance on wild resources. (3) Focus on constructing a germplasm resource bank in highly suitable areas, systematically conducting surveys of wild populations, conservation efforts, and the breeding of stress-resistant varieties. (4) Strengthen the regulation of cultivation in suitable areas, promoting large-scale planting and industrial development through policy guidance and technological promotion in collaboration with enterprises and farmers. Through a tri-dimensional approach that integrates scientific conservation, technological innovation, and policy support, effective ecological preservation and efficient utilization of *D. panthaica* resources can be achieved, providing a model for the sustainable management of biological resources.

Conclusions

This study integrates Pearson correlation analysis, ArcGIS spatial technology, and the MaxEnt model to predict the suitable habitat distribution of *D. panthaica* under

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current and future climate scenarios (SSP126/SSP585 for the 2050s and 2090s) and to identify key environmental drivers: Mean Temperature of the Wettest Quarter (BIO_7, 22.1 ~ 28.3°C); Temperature Seasonality (BIO_4, 415.9 ~ 700.1); Mean Temperature of the Coldest Quarter (BIO_11, 2.7 ~ 12.8°C); and Minimum Temperature of the Coldest Month (BIO_6, -5.2 ~ 6.5°C). The current suitable habitat, covering an area of 181.19×10^4 km², is primarily concentrated in the regions of Yunnan, Guizhou, and Sichuan in China. Future suitable habitats are projected to migrate towards higher elevations in the western regions, with an overall trend of increasing area. It is important to note that due to human disturbances, the actual distribution range may be smaller than predicted by the model. Therefore, there is an urgent need to establish standardized cultivation bases in core suitable areas to coordinate resource conservation (through regulated harvesting and population restoration) with sustainable use (ensuring the quality of medicinal materials and ecological safety).

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