Predicting the potential habitats of two Lycium species and the quality suitability of Lycium Chinese Mill. Cortex under climate change

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Abstract

Lycii Cortex is a frequently utilized traditional Chinese medicine with notable therapeutic properties. The impact of climate change on its distribution and quality of *Lycii Cortex* is a significant concern. In this study, it investigated the geographic distribution of two sources of plants for *Lycii Cortex* and collected data on the distribution of samples from different origins via an online survey. HPLC was employed to ascertain the concentrations of kukoamine B and kukoamine A in the samples. Subsequently, the integrated ecological factor data were employed to forecast the prospective expansion areas of *Lycium Chinese* Mill. and *Lycium barbarum* L. under future climatic conditions, the migration trajectory of suitable habitat centers of mass, and the potential impact of climatic factors on the quality of *Lycii Cortex* at varying times using Maxent and ArcGIS. The current climate scenario indicates that suitable habitats for L. *barbarum* are primarily distributed in the northern, northwestern, and southwestern regions of China, while L. *Chinese* is predominantly distributed in the central, southern, and southeastern regions of China. In the RCP4.5 from 2050s to 2070s, the total area deemed suitable for both two *Lycii Cortex* species is significantly reduced. The mean distribution center of L. *barbarum* shifted towards higher latitudes, while that of L. *Chinese* shifted towards lower latitudes. It was predicted that in the future, the area of suitable quality of *Lycii Cortex* would appear to decrease. The results of this study can provide a reference for the determination of the suitable cultivation area of *Lycii Cortex* in China and the sustainable development of two *Lycium* species resources.

Background

Climatic factors significantly influence the geographical distribution of species. The growth of the population has been demonstrated to result in increased resource demand and energy consumption, which has been shown to lead to elevated carbon emissions. These changes will lead to an increase in adverse impacts on future climate and a continuous rise in global temperatures [1]. Global warming and the increased frequency of extreme weather events are expected to alter the geographical distribution of numerous plant species [2–4]. It is predicted that under future climate scenarios, the distribution area of *Acacia mearnsii*, a harmful weed, will expand in Asia. Furthermore, global climate change is likely to increase the risk of invasion of this plant in Asia [5]. Vishnu posited that climate fluctuations may result in a reduction of suitable habitats for the *Indigenthus virus* (Roxb.) in India and Sri Lanka, both currently and in the future [6]. Moreover, the effects of climate change on the distribution and bioactive components of medicinal plants warrant further investigation [7]. For instance, Uranishi et al studied the significant changes in the content of chlorogenic acid and dicaffeoylquinic acid isomers in the leaves of *Chrysanthemum indicum* L. under the influence of environmental factors. And climatic change was found to have the most significant impact on the suitability of its habitat [8]. It can be reasonably deduced that the suitability of a habitat has a considerable influence on the accumulation of secondary metabolites in medicinal plants [9–11].

Lycii Cortex, commonly referred to as wolfberry root, is derived from the dried root bark of the Solanaceae plant *Lycium chinense* Mill. or *Lycium barbarum* L. [12]. *Lycii Cortex* is widely used in proprietary Chinese medicines and Chinese herbal formulas [13], and can effectively treat vomiting blood, hemoptysis, and lung-heat cough. Recent studies have demonstrated that *Lycii Cortex* has the capacity to reduce blood sugar, blood pressure, blood lipids, and anti-osteoporotic activity [14, 15]. A considerable number of active ingredients are present in *Lycii Cortex* [16]. However, there is currently no established standard for determining the content of indicator ingredients in *Lycii Cortex* as outlined in the Chinese Pharmacopoeia [12]. In recent years, there have been many reports of alkaloids such as kukoamine B and kukoamine A in *Lycii Cortex* [17, 18]. Li et al. mention that kukoanes B may regulate nuclear transcription factors to reduce inflammation [19]. Kukoanes A and B have been demonstrated to treat Alzheimer's disease (AD) and type 2 diabetes (T2D) by inhibiting amyloid aggregation [20]. Studies indicate that *Lycii Cortex* requires 4–5 years of growth to accumulate adequate active ingredients [21]. It is plausible that climate factors exert a considerable influence on its growth. Furthermore, previous historical research on the origin of *Lycii Cortex* indicates that climate change may also affect the changes in the origin of two sources of plants for *Lycii Cortex* [22]. Climate change and environmental overexploitation have significantly diminished the wild resources of *Lycii Cortex* [23]. Nevertheless, the majority of studies on the composition and pharmacological activity of *Lycii Cortex* have concentrated on its components [24, 25]. In contrast, studies examining the overall distribution and quality evaluation of this plant are scarce, with a greater focus on the study of Chinese wolfberry [26–28].

To evaluate the influence of climate change on species distribution, this study utilizes representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5) for the 2050s and 2070s, which model potential greenhouse gas emissions [29–31]. The focal point of this study is the direct impact of natural environmental variables on species distribution, precluding the involvement of socio-economic driving factors such as urbanization and agricultural expansion. Consequently, the Representative Concentration Pathways (RCPs) provide clear climate forcing pathways, thereby circumventing uncertainty introduced by complex socio-economic parameters. Consequently, the Shared Socioeconomic Pathways (SSP) pathway, which incorporates a more comprehensive range of socio-economic factors, was not selected. The Maximum Entropy Model (Maxent) is a statistical model that correlates species occurrence with environmental variables. Its objective is to predict potential spatial shifts, identify influencing factors and determine the likely direction of migration of species distribution [32]. Maxent is widely utilized for its simplicity, rapid modeling capabilities [33], and effectiveness in predicting species distribution, particularly with small sample sizes and limited geographic ranges [34]. It is also recognized for its accuracy and reliability [35]. Maxent has been extensively applied to predict suitable regional and geographic distributions of various medicinal plant species, including simulations of climate change effects on the distribution of C. *arabica* in Ethiopia [36]. Hosseini et al. utilized the Maxent model to predict the distribution area of two *Thymus* species in Iran under climate change [37]. Furthermore, there have been studies employing the Maxent model to investigate the impact of climate change on the future distribution of three *Ferulago* species in Iran [38]. Similarly, Waheed et al. employed the Maxent model to forecast the potential geographic range of invasive species, such as *X. strumarium*, in Pakistan under the influence of climate change [39]. Furthermore, researchers studying *Lonicera japonica* Flos. integrated chemical content analysis with Maxent to assess the influence of ecological factors on quality, predict suitable habitats under various scenarios, and generate high-resolution habitat maps [40]. Various chemical indicators have been employed in these studies to evaluate how habitat suitability affects medicinal quality [41]. HPLC is used to determine the content of chemical components, which has high sensitivity and can quickly and efficiently separate and detect the type and content of compounds in samples. It is instrumental in assessing differences in secondary metabolites of medicinal plants across various regions [42]. Alkaloids represent the primary active ingredients within the secondary metabolites of *Lycii Cortex*. Among these, kukoamine B and kukoamine A are the predominant alkaloid components within *Lycii Cortex*. Accordingly, two alkaloidal components, kukoamine B and kukoamine A, were selected for this study as indicators for the determination of the content of active ingredients of *Lycii Cortex*. The objective of this study is to evaluate the habitat suitability of two sources of plants for *Lycii Cortex*, L. *barbarum* and L. *Chinese*, derived from disparate sources, in the context of both the present and future climates.

To this end, the study will integrate data on their geographical distribution, information on the quality of their effective ingredients, and climate factors. Explore the relationship between climate factors and two bioactive alkaloids in *Lycii Cortex*, conduct quality suitability analysis, predict the quality suitability areas, and provide scientific basis for the sustainable development of two *Lycium* species and environmental protection of suitable planting areas.

Materials and methods

Species occurrence records and sample collection

Data from L. *barbarum* and L. *Chinese* sources across China were obtained from the China Virtual Herbarium (CVH) (https://www.cvh.ac.cn/) and the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/). L. *barbarum* and L. *Chinese* samples were found throughout China. L. *barbarum* was predominantly distributed in Ningxia, Xinjiang, and Inner Mongolia, aligning with recent studies on its distribution [43]. In contrast, L. *Chinese* was mainly found in central and southern China, consistent with Tang et al.'s observations [44]. Additionally, 14 records of *Lycii Cortex* were collected from various provinces: 4 from Henan, 2 from Shanxi, 2 from Jiangsu, and 1 each from Shaanxi, Hebei, Hubei, Anhui, Guangdong, and Jilin.

The 154 occurrences for L. *barbarum* and 740 occurrences for L. *Chinese* were collected in this study. To reduce sampling bias, we remove duplicate samples and obvious geocoding errors or blurred data as much as possible. At the same time, considering the large scale of the study, we refer to other people’s data screening methods and the rationality and accuracy of the model operation [45]. To minimize sampling bias and eliminate the risk of counting the same points more than once, we consider non-overlapping observations obtained using a fishing net [46], and samples were screened within 16 km × 16 km geographic grids based on established data screening methods [47, 48]. For grids with multiple *Lycii Cortex* samples, the sample nearest to the grid center was chosen as the representative sample. After applying the fishing net screening in ArcMap, 70 L. *barbarum* occurrences and 216 L. *Chinese* occurrences were identified (Fig. 1). The occurrence records for two sources of plants for *Lycii Cortex* were compiled into a '.csv' file for model construction using Maxent software.

Model construction of the species distribution

The 19 bioclimatic variables were identified as critical factors in developing niche models for the distribution of two species. Data from the Geospatial Data Cloud (https://www.gscloud.cn/) and the Global Climate Database (http://www.worldclim.org/) were utilized, covering the current period (1970–2000) and future projections for the 2050s (2041–2060) and 2070s (2061–2080). Bioclimatic variables (Bio1 ~ Bio19) had a spatial resolution of 1 km × 1 km and were analyzed under three greenhouse gas emission scenarios: RCP2.6, RCP4.5, and RCP8.5, derived from the Fifth Assessment Report of IPCC (Table S1).

The 19 climate variables were screened by using Pearson correlation analysis, minimizing the risk of overfitting due to multicollinearity [49]. Climatic factors with high collinearity ($r > 0.8$) which deemed significant for two *Lycium* species growth were retained, and therefore were retained for analysis. The jackknife test method was employed to assess the relative importance of each environmental variable [50]. Subsequently, on the basis of the actual growth conditions of two *Lycium* species and the extant literature on the environmental response of *Lycium* plants and closely related taxa, a subset variable was retained for further analysis [43, 44]. We iteratively run the Maxent model, removing variables with 0 contribution at each step, and repeat this process ten times to obtain the final set of participating climate factors, with all other parameters set to default values. Based on previous researchers' methods, correlation analysis and Jackknife experiments (Fig. S1) identified 9 climatic factors for L. *barbarum* and 11 for L. *Chinese*, which were used for Maxent modeling (Table 1) [45]. This model was used to predict the potential distributions of L. *barbarum* and L. *Chinese* under current and future scenarios. The model was constructed using Maxent software (version 3.3.3k, Steven Phillips et al., New York, NY, USA). The software prevents sampling from non-occurrence habitats of the target species or compensates for survey bias using coordinate data [51].

In this study, the maximum number of background points was set to 1×10^4, while the maximum number of iterations was set to 1×10^6 during data processing. The Maxent model utilizes an ASCII-coded file containing geographical distribution and environmental factor information for two sources of plants for *Lycii Cortex*. The 75% percent of the randomly selected distribution data was used to train the model, while the remaining 25% was reserved for testing and validation. The model's predictive power was evaluated by calculating the area under the receiver operating characteristic (ROC) curve (AUC) [52]. The AUC value indicates the model's performance, ranging from 0 to 1, with values closer to 1 representing stronger predictive accuracy. The AUC > 0.9 signifies optimal modeling results, AUC values between 0.7 and 0.9 are considered good, while the AUC < 0.7 generally indicates moderate model performance [53, 54]. Using the reclassification tool in ArcMap10.8 and referring to the method of Li et al., it was used to categorize the occurrence probability of the two *Lycii Cortex* species into four levels: unsuitable area (0-

0.2), poorly suitable area (0.2–0.4), moderately suitable area (0.4–0.6), and highly suitable area (0.6-1) [45]. Next, the center of suitability in the ecologically suitable area was analyzed using centroid migration. The spatial statistics tool was used to determine the average center of the ecologically suitable area, while local analysis merged periods under the same greenhouse gas emission scenario. The centroid migration trajectory was last derived using the point set transfer line function.

HPLC chemical composition analysis

Store the collected *Lycii Cortex* samples in a cool, dry, and well-ventilated area. Add 0.5 g of sample powder to 5 mL of a methanol-0.5% acetic acid aqueous solution, followed by ultrasonication for 35 min and centrifugation for 20 min. The supernatant is then filtered through a 0.22 μm membrane to prepare the test solution. The chemical composition was analyzed using HPLC equipped with a Zorbax SB-AQ C_{18} column (250 mm × 4.6 mm, 5 μm). The mobile phase consisted of acetonitrile (A) and 0.1% trifluoroacetic acid in water (B). The gradient elution protocol was as follows: 0–20 min, 90–85% B; 20–30 min, 85–82% B; 30–35 min, 82–78% B; 35–50 min, 78–55% B; 50–60 min, 55–5% B; 60–65 min, 5% B. The total run time was 65 min, with a flow rate of 1.0 $mL{\bullet}min^{-1}$, detection wavelength of 280 nm, injection volume of 10 μL, and column temperature maintained at 40°C. Concurrently, the content of kukoamine B and kukoamine A in 14 *Lycii Cortex* samples from different habitats were measured, with the total content calculated as the sum of these two components.

Lycium Chinese Mill. Cortex quality suitability analysis

The concentrations of kukoamine B and kukoamine A were measured in *Lycium Chinese* Mill. *Cortex* samples from various production regions. The levels of these two compounds were employed as the primary criteria for evaluating quality in this study. 14 collection sites, identified as fitting the L. *Chinese* suitability distribution, were analyzed for their quality suitability. Regression analysis of the two components in the samples was performed using SPSS 23.0 (IBM, Shanghai, China), developing a model that links their concentrations to climatic factors. Although yearly variations in the quality of *Lycii Cortex* at the same location were noted, they were less significant than the effect of environmental factors on quality across different locations. To ensure the accuracy of environmental data at the collection sites, this study referenced previous studies [55] and employed environmental parameters from a 1 km × 1 km grid to predict the quality suitability area. The grid calculator and fuzzy overlay function in Arcmap 10.8 were applied to integrate spatial distribution maps of the two chemical components with ecological suitability maps, producing current and future integrated quality suitability maps [56]. Lastly, the mask extraction function was used to generate an integrated quality area map for the two alkaloid components of *Lycii Cortex*.

Results

Prediction and model evaluation of the distribution of two Lycium species

Verification of modeling results

In this study, the AUC values of the training set for both L. *barbarum* and L. *Chinese* exceeded 0.900 (Table 2). The results indicated that the Maxent model effectively predicted the suitable habitat distribution of two sources of plants for *Lycii Cortex*, demonstrating high confidence and accuracy in the model's calculations of habitat suitability.

Environmental variables analysis

The values presented in the variable contributions table of the Maxent analysis represent the average percentage contribution derived from 10 replicate runs. The results indicated that Bio2 (31.8%), Bio6 (16.4%), and Bio17 (15.5%) were the three primary environmental factors influencing L. *barbarum* distribution, with a cumulative contribution of 63.7%. However, based on Permutation Importance (PI), the three most impactful environmental factors were Bio12 (23.7%), Bio13 (22.4%), and Bio1 (15.5%). Consequently, the Maxent model was integrated with jackknife test analysis, revealing that Bio6, Bio1, and Bio13 are the most critical factors for L. *barbarum* habitat distribution, indicating that these factors provide the most valuable and unique information for determining L. *barbarum* distribution. The response curves of the primary ecological factors revealed that climatic influences on L. *barbarum* generally increased with rising factor values, with distribution probability initially rising before declining. Among these factors, the suitable range for the minimum temperature of the coldest month (Bio6) is -18 to -6.2°C, with an optimal temperature of -11°C, as shown in Fig. 2A. In Fig. 2B, the suitable range for annual average temperature (Bio1) is 5 to 12.5°C, with an optimal temperature of approximately 9°C. In Fig. 2C, the suitable range for precipitation in the wettest month (Bio13) is 2.5 to 13 mm, with optimal precipitation around 6 mm.

The three most important environmental variables with the greatest impact on L. *Chinese* were Bio1 (44.6%), Bio13 (33.6%) and Bio4 (5.4%), with a cumulative contribution rate of 83.6%. However, Bio13 (43.7%), Bio11 (9.6%), and Bio4 (9.4%) have greater PI. According to the results of jackknife, the three most important factors affecting the distribution of L. *Chinese* are Bio1, Bio13, and Bio12. The response curves of the primary ecological factors indicate that the suitable range for annual average temperature (Bio1) is 13.2 to 23°C, with an optimal temperature of 18°C, as shown in Fig. 2D. As shown in Fig. 2E, the suitable range for the wettest monthly precipitation (Bio13) is 16 to 56 mm, with an optimal precipitation of 25 mm. In Fig. 2F, the suitable range for average annual precipitation (Bio12) is 75 to 180 mm, with an optimal precipitation of 162.5 mm, as depicted in Fig. 2D-F.

Predicted distribution under different scenarios

Predicting the distribution of L. barbarum

Figure 3 illustrates the potential distribution of two sources of plants for *Lycii Cortex*, as estimated by the Maxent model under current climate conditions. Based on the available data, the optimal growth regions for L. *barbarum* (Fig. 3A) in current are predominantly concentrated in northern and northwestern China. The total suitable area reaches 2.6919 × 10^6 km², representing 25.75% of the total research area. The highly suitability area is primarily concentrated in Northwest China, central and southwestern Shanxi, western Hebei, central and eastern Tibet, and western Sichuan, collectively accounting for 4.26% of the total research area (Table 3).

According to the predictions for the future period (Fig. 3B-G), L. *barbarum* showed a decrease in the total suitable area of three suitable habitats compared to current scenarios, except for the RCP2.6 scenario in 2070s where the total suitable area increased. Specifically, in the RCP2.6-2050s and RCP2.6-2070s, the total suitable area of L. *barbarum* will decrease by 5.84% and increase by 5.83%, respectively, compared with the current period. The total suitable area for L. *barbarum* will decrease by 13.71% and 12.20% respectively by RCP4.5-2050s and RCP4.5-2070s. For the emission scenario of RCP8.5, the total suitable area for L. *barbarum* will decrease by 8.32% and 1.33% respectively by 2050s and 2070s.

Additionally, the highly suitability area for L. *barbarum* exhibited varying degrees of decline under different emission scenarios, while the areas of moderately and poorly suitability showed both increases and decreases. The highly suitability area for L. *barbarum* is projected to decrease by 7.67% in the 2050s and by 11.38% in the 2070s under the RCP2.6 scenario; for the RCP4.5 scenario, it is expected to decrease by 8.93% and 7.48% in the 2050s and 2070s; it is anticipated to decrease by 13.38% in the RCP8.5-2050s and by 12.25% in the RCP8.5-2070s. The moderately suitable area is projected to increase by 0.32% and 1.41% in the RCP2.6-2050s and RCP2.6-2070s; under the RCP4.5 scenario, it is expected to decrease by 12.56% in the 2050s and by 5.08% in the 2070s; it is anticipated to decrease by 19.04% in the RCP8.5-2050s but increase by 11.84% in the RCP8.5-2070s. The poorly suitability area is projected to decrease by 8.09%, 15.61%, and 2.04% under different emission scenarios by the 2050s; under the RCP2.6-2070s, it is expected to increase by 12.77%, while under the RCP4.5-2070s and RCP8.5-2070s, it is anticipated to decrease by 16.77% and 4.12%, respectively.

Predicting the distribution of L. Chinese

The areas deemed suitable for cultivation of L. *Chinese* (Fig. 3H) in current are primarily concentrated in North China, Central China, South China, East China, and Southwest China, with some distribution in Northeast and Northwest China. The total area deemed suitable is 3.3516 × 10^6 km², representing 32.07% of the total research area. The highly suitability area is primarily situated in central China, central Hebei, central Shaanxi, central Zhejiang, northern Guangdong, north-eastern Guangxi, Chongqing, eastern Sichuan, and other regions, collectively accounting for 2.53% of the total research area (Table 4).

For L. *Chinese*, the total suitable area in future projections (Fig. 3I-N) is not expected to change significantly, although a general reduction in area is anticipated (Table 4). The total suitable area for L. *Chinese* is projected to decrease by 4.26% in the RCP2.6-2050s and by 4.55% in the RCP2.6-2070s. The total suitable area for L. *Chinese* is anticipated to decrease by 2.67% in the RCP4.5-2050s and by 2.48%

in the RCP4.5-2070s. In the RCP8.5-2050s and RCP8.5-2070s, the total suitable area for L. *Chinese* is expected to decrease by 4.20% and 3.35%.

The areas of highly and moderately suitability for L. *Chinese* have significantly decreased under various scenarios, while the area of poorly suitability has increased in all scenarios except for the RCP8.5-2070s. Under the RCP2.6 scenario, highly and moderately suitability areas are projected to decrease by 10.60% in the 2050s and by 27.62% in the 2070s; they are expected to decrease by 10.40% in RCP4.5-2050s and by 22.37% in RCP4.5-2070s; they are anticipated to decrease by 12.92% and 19.56% in the RCP8.5-2050s and RCP8.5-2070s. The moderately suitability area is projected to decrease by 11.04% in RCP2.6-2050s and by 5.38% in RCP2.6-2070s; it is expected to decrease by 6.39% in RCP4.5-2050s and by 6.24% in RCP4.5-2070s; for the RCP8.5 scenario, it is anticipated to decrease by 16.57% and 2.33% in the 2050s and 2070s. The poorly suitability area is projected to increase by 6.36% in the 2050s and by 1.28% in the 2070s under the RCP2.6 scenario; it is expected to increase by 6.41% in RCP4.5-2050s and by 6.73% in RCP4.5-2070s; under the RCP8.5 scenario, it is anticipated to increase by 14.08% in the 2050s but decrease by 1.45% in the 2070s.

The migration trend of geometric centers of suitable habitats for different periods of L. barbarum and L. Chinese under climate change

In this study, the geometric center represents the central spatial location of the potentially the total suitable area for two sources of plants for *Lycii Cortex* under three emission scenarios, spanning from the present to the 2050s and 2070s. At present, the location of the most suitable habitat for the potential geometric center of L. *barbarum* is identified as Gande County Qinghai Province (100.663555°E, 34.224862°N). The geometric center of L. *barbarum* in the RCP2.6 scenario exhibited a migration of 92.76127 km from Gande County Qinghai Province, to Zeku County Qinghai Province, and subsequently, an additional 81.13688 km to Tongde County Qinghai Province. Under the RCP4.5 scenario, the geometric center initially migrated 85.52054 km within Gande County Qinghai Province, and subsequently migrated 88.34171 km to Maqin County Qinghai Province. Under the RCP8.5 scenario, the geometric center exhibits a migration of 129.36854 km from Gande County Qinghai Province to Zeku County Qinghai Province, followed by a further migration of 62.16803 km to Tongde County Qinghai Province (Fig. 4A).

In the current scenario, the most suitable habitat for the geometric center of L. *Chinese* is located in Shizhu Tujia Autonomous County, Chongqing (108.165436°E, 29.867593°N). In the RCP2.6 scenario, the predicted geometric center of the suitable habitat for L. *Chinese* will migrate 82.9126 km from Shizhu Tujia Autonomous County Chongqing city to Qianjiang District Chongqing city, and then 44.0186 km to Pengshui Miao Tujia Autonomous County Chongqing city from 2050s to 2070s. For the RCP4.5 scenario, the predicted migration distance is 27.8479 km from Shizhu Tujia Autonomous County Chongqing city to Pengshui Miao and Tujia Autonomous County Chongqing city, followed by a further 33.88568 km to Shizhu Tujia Autonomous County Chongqing city. In the RCP8.5 scenario, the predicted migration distance is 86.2666 km from Shizhu Tujia Autonomous County in Chongqing city to Xianfeng County in

Hubei Province, followed by an additional 115.61227 km to Xiushan Tujia and Miao Autonomous County in Chongqing city (Fig. 4B).

Quality suitability analysis

The content of alkaloid active ingredients in L. Chinese Cortex

The contents of two alkaloids, kukoamine B and kukoamine A, were measured in the collected L. *Chinese Cortex* samples (Table 5). Among these samples, S1 was collected from highly suitable area, S2 to S11 were collected from moderately suitable area, and S12 to S14 were collected from poorly suitable area. The average contents of the two alkaloids in the samples from each suitability category were calculated, considering the unequal number of samples in each area. The results indicated that the average total alkaloid content in samples from highly and moderately suitable areas was higher than that in poorly suitable area.

Correlation between the content of environmental variable components

This study developed models to describe the relationship between the content of kukoamine B and kukoamine A and various ecological factors. The model describing the relationship between kukoamine B content and ecological factors is: Y_1=-575.744-0.291X_1-4.662X_2 + 21.452X_3 + 2.932X_4-0.186X_5 + 0.319X_6-10.116X_7 + 3.747X_8 (P< 0.05, Y_1 represents the kukoamine B content in *Lycii Cortex*, X_1 = Bio1, X_2 = Bio2, X_3 = Bio3, X_4 = Bio5, X_5 = Bio12, X_6 = Bio13, X_7 = Bio14, X_8 = Bio19). The regression analysis results indicated that within specific ranges, Bio1, Bio2, Bio12, and Bio14 limit kukoamine B accumulation, while Bio3, Bio5, Bio13, and Bio19 promote its accumulation. The model describing the relationship between kukoamine A content and ecological factors is: Y_2 = 0.196X_1-0.006X_2-0.526X_3 + 0.178X_4 (P< 0.05, Y_2 represents kukoamine A content, X_1 = Bio3, X_2 = Bio12, X_3 = Bio14, X_4 = Bio19). The analysis revealed that Bio3 and Bio19 promote kukoamine A accumulation within specific ranges, whereas Bio12 and Bio14 restrict its accumulation within similar ranges.

Different periods quality suitability analysis

Table 6 shows the current quality suitable areas and the proportion of area. The current spatial distribution and suitable area of kukoamine B content in L. *Chinese* are presented in Fig. 5A (Table S2). The poorly suitability area for kukoamine B decreases in the 2070s under the RCP8.5 scenario but increases during other periods. The decrease in moderately suitable area is most pronounced in the 2050s under the RCP8.5 scenario, while the most significant decrease in highly suitable area occurs in the 2070s under the RCP2.6 scenario. The total suitable area is smaller than the current suitable area (Fig. 5B-G). The current spatial distribution and suitable area of kukoamine A content in L. *Chinese* are presented in Fig. 5H (Table S3). For kukoamine A, the poorly suitability area increases in the 2050s under the RCP4.5 and RCP8.5 scenarios but decreases during other periods. The moderately suitable area decreases in all periods except for the 2070s under the RCP8.5 scenario, while the highly suitable area increases in the 2050s under the RCP8.5 scenario but decreases in other periods (Fig. 5I-N). The future predictions indicate that under all three emission scenarios, the areas of highly and moderately suitability for the two alkaloids in L. *Chinese* generally show a decreasing trend compared to the current period. The areas of poorly suitability area, with some increases and decreases. Overall, changes in the quality-suitable areas for *Lycii Cortex* align closely with the ecologically suitable areas, both showing a general decline.

Comprehensive quality suitability analysis

Based on the previous research, the spatial distribution maps of the two alkaloid components were overlaid to conduct a comprehensive analysis of L. *Chinese*'s quality area, identifying the optimal areas for *Lycii Cortex* growth and component accumulation (Table 7). The distribution map is presented in Fig. 6A. The results indicate that the comprehensive quality-suitable areas are primarily located in southern Beijing, central and southern Hebei, southern Henan, central and southern Shaanxi, northern Sichuan, as well as in Hunan, Hubei, Anhui, Jiangxi, and Zhejiang. Furthermore, some high-quality areas are identified in central Ningxia, southern Gansu, Tibet, northern Yunnan, and northern Guangxi. The highly suitable area encompasses 0.1754×10^6 km², representing 6.68% of the study area. The total suitable area constitutes 27.36% of the total area, equivalent to 2.6264×10^6 km². The quality area of L. *Chinese* (Fig. 6B-G), derived from the combined analysis of the two components, decreases to varying extents under different emission scenarios. The changes in different quality-suitable areas were similar to those of kukoamine A, with the most pronounced decrease occurring in the 2050s under the RCP2.6 scenario.

Discussions

Lycii Cortex is a widely used therapeutic agent in clinical practice, with a significant evidence base supporting its efficacy. In recent years, it has been the subject of close scrutiny by scholars from a range of countries. Given that the growth and accumulation of active ingredients in *Lycii Cortex* necessitates a period of four to five years or longer, this study predicts the potential influence of climate change on two sources of plants for *Lycii Cortex* used ArcGIS and Maxent.

Environmental variables affecting the distribution of Lycium spp.

In order to minimize the risk of overfitting caused by multicollinearity, climate variables were screened through correlation analysis combined with jackknife in the study [57], and factors with importance of 0 were removed from Maxent. The remaining factors were then used for Maxent modelling. While the contribution of certain variables may be less substantial, it is our contention that these factors are nevertheless significant for the growth, distribution or component accumulation of *Lycii Cortex*. Consequently, they remain an integral component of the model construction. Our research identifies the key climatic variables influencing the suitable distribution of L. *barbarum* as the minimum temperature of coldest month (Bio6), annual average temperature (Bio1), and precipitation of wettest month (Bio13).

The suitable range of Bio1 is 5–12.5°C, which is similar with the 8–9°C range of L. *barbarum* studied by Wang [43]. And L. *barbarum* are mainly distributed within the suitable range of winter average temperature – 10°C to 10°C [43]. As the temperature falls below – 15°C, the germination rate of dormant branches is known to undergo a significant decrease [58]. Furthermore, L. *barbarum* can also survive during the winter dormancy period when the lowest temperature reaches – 41.5°C [59]. Consequently, we consider that L. *barbarum* can thrive within the optimal range of -18 to -6.2°C for Bio6. The primary climatic factors determining the suitable distribution of L. *Chinese* are annual average temperature (Bio1), precipitation of wettest month (Bio13), and annual precipitation (Bio12). Tang et al. also concluded that precipitation of wettest month (Bio13) and minimum temperature of coldest month (Bio6) were the primary climatic variables for L. *Chinese*. Although L. *Chinese* demonstrates a degree of drought tolerance, it still requires a certain amount of precipitation for its survival [44]. The cold resistance and water avoidance characteristics of two *Lycium* species may be closely related to the ecological environment of their origin and geographical distribution areas [44]. This finding is consistent with the research results that have previously been obtained.

Predicted distribution potential of Lycium spp.

It is anticipated that climate change will have an impact on the geographical distribution of certain species, resulting in a reduction in growth and range [60]. The present study predicted changes in the distribution of suitable areas for L. *barbarum* and L. *Chinese*. The highly suitable areas for L. *barbarum* are currently located in provinces such as Hebei, Inner Mongolia, Shaanxi, Shanxi, Gansu, Ningxia, Qinghai, and Xinjiang, similar to the research by Wang et al. [61, 62]. In the current period, L. *Chinese* is mainly distributed in the southern, southwestern, central, and eastern regions, as well as provinces such as northeastern China, Hebei, Shanxi, Shaanxi, and Gansu. This distribution is similar to the research results of Tang et al. [44]. Despite the strong adaptability exhibited by L. *Chinese* and its distribution across numerous regions of China, the species remains sensitive to external environmental changes and requires favorable conditions for sustained growth. Consequently, the suitability index is suboptimal in the majority of regions. Two *Lycium* species demonstrate a preference for light conditions, exhibit drought tolerance, and evade waterlogging, thereby exhibiting a certain degree of adaptability to temperature and precipitation [44]. During the early stage of growth and development, *Lycium* species requires less precipitation. However, as the fruit approaches maturity, greater precipitation is required to ensure the stability of the root system and the completion of the maturation process. The soil moisture content is typically found to be within the range of 16% and 22%. Excessive water or waterlogging has been demonstrated to result in diminished plant growth [63]. Such conditions have been shown to cause root rot and death. Furthermore, the distribution of two *Lycium* species is predominantly associated with subtropical monsoon climate and temperate monsoon climate, characterized by hot summers and cold winters. In the context of global climate change, there has been an observed increase in extreme precipitation events [64]. This is not conducive to the expansion of the distribution area of two *Lycium* species. This finding is consistent with the conclusion drawn in the present study that the total suitable area of L. *barbarum* and L. *Chinese* will generally decline in the future.

Prediction of centroid migration of two Lycium species

Due to ongoing global warming, many species may shift to more favorable habitats, with their distribution centers moving toward colder, wetter regions [65] or shifting to higher latitudes or altitudes [66]. This may explain why the suitable distribution centers for L. *barbarum* are projected to migrate from southeast to northwest, aligning with findings from Wang et al. [43] and resembling Dong et al.'s prediction of the centroid migration of *Astrolus membranaceus* var. *mongholicus* [41]. However, as the climate continues to warm, the accelerated water cycle leads to increased total precipitation, making global humid regions even wetter [67]. This study speculated that the current distribution center of L. *Chinese*, located in the mid-latitude region, will shift toward areas with decreasing precipitation, moving from northwest to southeast. The survival prospects of two *Lycium* species are anticipated to improve. In conclusion, precipitation and temperature significantly influence the distribution of ecologically suitable areas for *Lycii Cortex*.

Predicted quality suitable area of Lycii Cortex

The quality of traditional Chinese medicine (TCM) can be evaluated based on the secondary metabolites of medicinal plants. Climate change and rising global carbon dioxide levels can provide carbon substrates for secondary metabolism in medicinal plants. The synthesis and accumulation of these substances are strongly influenced by the growth environment of TCM, leading to a significant increase in alkaloid content [68]. To maintain the medicinal value of *Lycii Cortex*, it is crucial to understand the influence of environmental variables on its growth. Lu et al. demonstrated that the accumulation of most chemical components in wolfberry is influenced by precipitation and temperature factors [26]. Research has indicated that the alkaloid components of kukoamine B and kukoamine A in *Lycii Cortex* can be utilized as quality markers to evaluate the quality of *Lycii Cortex* [69]. As Li et al. demonstrate in their research, the total alkaloid content of *Lycii Cortex* is closely related to its quality and growth environment [70]. This study was conducted for the purpose of determining and calculating the content of two alkaloids in *Lycium Chinese* Mill. *Cortex*, with a view to conducting a quality suitability analysis. The results showed that the quality of *Lycii Cortex* in highly and moderately suitable areas was superior to that in poorly suitable area. These high-quality areas are characterized by four distinct seasons, moderate temperatures, sufficient precipitation, and abundant sunshine [70]. It has been demonstrated that the content of alkaloids may be subject to an increase in response to environmental stress conditions, such as drought [71]. However, according to the characteristics of *Lycium* species, a soil moisture content of 16–22% is conducive to growth [63]. The increase in precipitation probability may lead to soil moisture levels exceeding this range, thus breaking drought stress and potentially causing root waterlogging and plant death. This phenomenon is not conducive to the accumulation of alkaloids in *Lycii Cortex*, and also impacts the distribution of areas conducive to the quality of *Lycii Cortex*, thereby reducing the *Lycii Cortex* quality suitable area. It has been shown that annual precipitation (Bio12) and precipitation of driest period (Bio14) have a restrictive effect on the accumulation of alkaloids in *Lycii Cortex*. Research conducted by Rong et al. has indicated that Bio12 demonstrates a negative correlation with the accumulation of alkaloid content. This finding also aligns with the results obtained in this study

[57]. In summary, the quality suitable area of *Lycii Cortex* will be affected, resulting in a decrease in the quality suitable area.

Research limitations

Protecting their habitats based on distribution advantages is essential to minimize the potential impact of future environmental fluctuations on ecosystems and to ensure the sustainable use of resources. In addition, it is imperative that urgent protective measures be implemented in order to mitigate the risk of extinction of these two *Lycium* species in the wild. In regions where wild *Lycium* species are present, in situ conservation measures should be reinforced and the harvesting of *Lycii Cortex* should be prohibited to prevent excessive extraction. Furthermore, it is imperative that policies and measures related to protection are promulgated in order to encourage reasonable planting and resource conservation in pre-determined potential suitable habitat areas. Currently, the limited number of data obtained from literature reviews and collecting pose samples constraints on the quality suitability analysis. Therefore, more extensive sampling is needed for in-depth future research. Although the Maxent model used in this study is appropriate, future studies should incorporate ensemble modeling to predict the potential distribution and quality suitability of *Lycii Cortex*, which may enhance predictive accuracy under future climatic conditions.

Conclusion

This study used the Maxent model and ArcGIS, combined with HPLC, to predict the potential distributions of two *Lycium* species under climatic influences, along with *Lycium Chinese* Mill. *Cortex* quality suitability analysis. In reference to the findings of the present study, it is posited that a scientific reference has been furnished for the purpose of predicting the future distribution of two sources of plants for *Lycii Cortex* in China. Furthermore, it is suggested that guidance has been provided for the selection of optimal cultivation sites for *Lycii Cortex*.

Declarations

Ethics approval and consent to participate

Not applicable (animal or human trials are not addressed in this paper).

Consent for publication

Not Applicable.

Availability of data and materials

The authors confirm that data supporting the results of this study are available in the article and its supplementary material.

Competing interests

The authors declare that they have no conflict of interest.

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Authors' contributions

LYT: Data curation, methodology, formal analysis, visualization, and writing-original draft preparation; LZK: Data curation, formal analysis, writing—review and editing; FXR: Data curation, reviewing and editing; WCH reviewing and editing; FC: formal analysis, methodology; SYX: visualization, reviewing and editing; GX: reviewing and editing; PL: funding acquisition, formal analysis; CTC: reviewing and editing; MDL: Project administration, funding acquisition, resources, methodology, and writing-reviewing and editing.

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References

1. Tan Z, Yuan Y, Huang S, Ma Y, Hong Z, Wang Y, et al. Geographical distribution and predict potential distribution of *Angelica* L. genus. Environ Sci Pollut Res. 2023;30:46562–73. https://doi.org/10.1007/s11356-023-25490-y.
2. Ostad-Ali-Askari K, Ghorbanizadeh KH, Shayannejad M, Zareian MJ. Effect of climate change on pre cipitation patterns in an arid region using GCM models: case study of Isfahan-Borkhar Plain. Nat Hazards Rev. 2020;21(2):1–6. https://doi.org/10.1061/(ASCE)NH.
3. Applequist WL, Brinckmann JA, Cunningham AB, Hart Robbie E, Heinrich M, Katerere DR. Scientists' warning on climate change and medicinal plants. Planta Med. 2020;86:10–8. https://doi.org/10.1055/a-1041-3406.
4. Anna JB, Adrian W, Paweł JD, Anna BK, Monika S, Grzegorz K. Expanding the boundaries in the face of global warming: A lesson from genetic and ecological niche studies of Centaurium erythraea in Europe. Sci Total Environ. 2024;953:176134. https://doi.org/10.1016/j.scitotenv.2024.176134.
5. Poudel A, Adhikari P, Adhikari P, Choi SH, Yun JY, Lee Y, et al. Predicting the Invasion Risk of the Highly Invasive *Acacia mearnsii* in Asia under Global Climate Change. Plants. 2024;13:2846. https://doi.org/10.3390/plants13202846.

6. Vishnu SB, Pandi V, Madola I, Gopallawa B, Abraham G, Gayathri R et al. Modeling the Current and Future Distribution of *Indianthus virgatus* (Roxb.) Suksathan & Borchs. A Monotypic Plant Endemic to the Western Ghats-Sri Lanka Biodiversity Hotspot. Ecology and Evolution. 2024; 14: e70489. https://doi.org/10.1002/ece3.70489
7. Patni B, Bhattacharyya M, kumari A, purohit VK. Alarming influence of climate change and compromising quality of medicinal plants. Plant Physiol. 2022;27:1–10. https://doi.org/10.1007/s40502-021-00616-x.
8. Uranishi R, Aedla R, Alsaadi DHM, Wang D, Kusakari K, Osaki H, et al. Evaluation of Environmental Factor Effects on the Polyphenol and Flavonoid Content in the Leaves of *Chrysanthemum indicum* L. and Its Habitat Suitability Prediction Mapping. Molecules. 2024;29:927. https://doi.org/10.3390/molecules29050927.
9. Guo Y, Zhao Z, Li X. Moderate warming will expand the suitable habitat of Ophiocordyceps sinensis and expand the area of O. *sinensis* with high adenosine content. Sci Total Environ. 2021;787:147605. https://doi.org/10.1016/j.scitotenv.2021.147605.
10. Li YQ, Kong DX, Fu Y, Sussman MR, Wu H. The effect of developmental and environmental factors on secondary metabolites in medicinal plants. Plant Physiol Biochem. 2020;148:80–9. https://doi.org/10.1016/j.plaphy.2020.01.006.
11. Pant P, Pandey S, Dall'Acqua S. The influence of environmental conditions on secondary metabolites in medicinal plants: a literature review. Chem Biodivers. 2021;18(11):e2100345. https://doi.org/10.1002/cbdv.202100345.
12. Commission CP. Pharmacopoeia of the People's Republic of China. Volume I. Beijing: China Medical Science; 2020. pp. 333–4.
13. Zhao JC, Jin Y, Yan YM, Qin K, Qian D, Zhang W, et al. Herbal Textual Research on Lycii Fructus and Lycii Cortex in Chinese Classical Prescriptions. Mod Chin Med. 2020;22(08):1269–86. https://doi.org/10.13313/j.issn.1673-4890.20200422005.
14. Xu HR, Zhao L, Zhang XN, Hua JL, Wang M, Zhao H. Research progress on the chemical constituents and biological effects of *Cortex Lycii*. China Deterg Cosmet. 2021;51(05):450–6. (in Chinese).
15. Son HR, Kim IM, Kim MH, Guo S, Lee DH, Lim GM, et al. Potential of *Lycii Radicis Cortex* as an Ameliorative Agent for Skeletal Muscle Atrophy. Pharmaceuticals. 2024;17(4):462. https://doi.org/10.3390/ph17040462.
16. Li XR, Wu M, Jia YX, Si MD, Ma DL, Zheng YG. Study on HPLC fingerprint and spectrum effect relationship of inhibition of α-glucosidase activity in *Lycii Cortex*. Lishizhen Med Mater Med Res. 2021;32(05):1079–82. https://doi.org/10.13863/j.issn1001-4454.2021.08.022.
17. Park E, Kim J, Kim MC, Yeo S, Kim J, Park S, et al. Anti-Osteoporotic Effects of Kukoamine B Isolated from *Lycii Radicis Cortex* Extract on Osteoblast and Osteoclast Cells and Ovariectomized Osteoporosis Model Mice. Int J Mol Sci. 2019;20(11):2784. https://doi.org/10.3390/ijms20112784.
18. Hadjipavlou-Litina D, Garnelis T, Athanassopoulos CM, Papaioannou D. Kukoamine A analogs with lipoxygenase inhibitory activity. J Enzyme Inhib Med Chem. 2009;24(5):1188–93.

https://doi.org/10.1080/14756360902779193.

19. Li YY, Stewart DA, Ye XM, Yin LH, Pathmasiri WW, McRitchie SL, et al. A Metabolomics Approach to Investigate Kukoamine B—A Potent Natural Product With Anti-diabetic Properties. Front Pharmacol. 2019;9:1575. https://doi.org/10.3389/fphar.2018.01575.
20. Jiang G, Takase M, Aihara Y, Shigemori H. Inhibitory activities of kukoamines A and B from *Lycii Cortex* on amyloid aggregation related to Alzheimer's disease and type 2 diabetes. J Nat Med. 2020;74(1):247–51. https://doi.org/10.1007/s11418-019-01337-0.
21. Li XR, Wu M, Jia YX, Si MD, Zheng YG, Ma DL. Study on the Quality Differences of *Lycii Cortex* with Different Growth Years Based on the Primary Metabolites. J Chin Med Mater. 2021;44:1901–5. https://doi.org/10.13863/j.issn1001-4454.2021.08.022.
22. Li XR, Si MD, Wen ZS, Ma DL, Zheng YG. Herbal Textual Research on the Variety, Origin Change and Harvesting and Processing of *Lycii Cortex*. Mod Chin Med. 2020;6948–54. https://doi.org/10.13313/j.issn.1673-4890.20191108005.
23. Zhao ZN, Yan LW, Zhao K. Study on the fingerprint of *Lycii Cortex* from different producing area and different grades. West China J. 2020;35(05):518–22. https://doi.org/10.13375/j.cnki.wcjps.2020.05.011.
24. Wang X, Zhang J, He F, Jing W, Li M, Guo X et al. Differential Chemical Components Analysis of *Periplocae Cortex*, *Lycii Cortex*, and *Acanthopanacis Cortex* Based on Mass Spectrometry Data and Chemometrics. Molecules. 2024; 29(16): 3807. https://doi.org/10.3390/molecules29163807
25. Li YY, Di R, Baibado JT, Cheng YS, Huang YQ, Sun HY, et al. Identification of kukoamines as the novel markers for quality assessment of *Lycii Cortex*. Food Res Int. 2014;55:373–80. https://doi.org/10.1016/j.foodres.2013.11.008.
26. Lu YY, Guo S, Yan H, Zhang F, Wang HQ, Jin L, et al. Regionalization of production of medicinal and edible fruit of *Lycium barbarum* associated with ecological factors and chemical constituents. Acta Pharm Sin. 2020;55(10):2466–77. https://doi.org/10.16438/j.0513-4870.2020-0572.
27. Hua Y, Zhang ZL, Zhang SQ, Sun L, Rong B, Li YC. Fine Regionalization of Climatic Adaptability of Wolfberry Planting in Jinghe County Based on GIS. Desert Oasis Meteor. 2021;15(04):138–43.
28. Yossa Nzeuwa IB, Xia Y, Qiao Z, Feng F, Bian J, Liu W, et al. Comparison of the origin and phenolic contents of *Lycium ruthenicum* Murr. by high-performance liquid chromatography fingerprinting combined with quadrupole time-of-flight mass spectrometry and chemometrics. J Sep Sci. 2017;40(6):1234–43. https://doi.org/10.1002/jssc.201601147.
29. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. Ecol Lett. 2012;15:365–77. https://doi.org/10.1111/j.1461-0248.2011.01736.x.
30. Albuquerque F, Benito B, Rodriguez MÁM, Gray C. Potential changes in the distribution of *Carnegiea gigantea* under future scenarios. Peer J. 2018;19(6):e5623. https://doi.org/10.7717/peerj.5623.
31. Wani IA, Khan S, Verma S, Al-Misned FA, Shafik HM, El-Serehy HA. Predicting habitat suitability and niche dynamics of *Dactylorhiza hatagirea* and *Rheum webbianum* in the Himalaya under projected

climate change. Sci Rep. 2022;12:13205. https://doi.org/10.1038/s41598-022-16837-5.

32. Sun SX, Zhang Y, Huang DZ, Wang H, Cao Q, Fan PX, et al. The effect of climate change on the richness distribution pattern of oaks (Quercus L.) in China. Sci Total Environ. 2020;744:140786. https://doi.org/10.1016/j.scitotenv.2020.140786.
33. Phillips SJ, Anderson RP, Schapire RE. Maximum entropy modeling of species geographic distributions. Ecol Model. 2006;190(3–4):231–59. https://doi.org/10.1016/j.ecolmodel.2005.03.026.
34. Guisan A, Zimmermann NE, Elith J, Graham CH, Phillips S, Peterson AT. What matters for predicting the occurrences of trees: techniques, data, or species' characteristics? Ecol Monogr. 2007;77(4):615–30. https://doi.org/10.1890/06-1060.1.
35. Pili AN, Tingley R, Sy EY, Diesmos MLL, Diesmos AC. Niche shifts and environmental non-equilibrium undermine the usefulness of ecological niche models for invasion risk assessments. Sci Rep. 2020;10:7972. https://doi.org/10.1038/s41598-020-64568-2.
36. Adane A. Analysis of current and future bioclimatic suitability for C. arabica production in Ethiopia. PLoS ONE. 2024;19(10):e0310945. https://doi.org/10.1371/journal.pone.0310945.
37. Hosseini N, Ghorbanpour M, Mostafavi H. The influence of climate change on the future distribution of two *Thymus* species in Iran: MaxEnt model-based prediction. BMC Plant Biol. 2024;24:269. https://doi.org/10.1186/s12870-024-04965-1.
38. Hosseini N, Mostafavi H, Sadeghi SMM. Impact of climate change on the future distribution of three *Ferulago* species in Iran using the MaxEnt model. Integr Environ Assess Manag. 2024;20(4):1046–59. https://doi.org/10.1002/ieam.4898.
39. Waheed M, Haq SM, Arshad F, Vitasović-Kosić I, Bussmann RW, Hashem A, et al. *Xanthium strumarium* L., an invasive species in the subtropics: prediction of potential distribution areas and climate adaptability in Pakistan. BMC Ecol Evo. 2024;24:124. https://doi.org/10.1186/s12862-024-02310-6.
40. Cheng J, Guo F, Wang L, Li Z, Zhou C, Wang H, et al. Evaluating the impact of ecological factors on the quality and habitat distribution of Lonicera japonica Flos using HPLC and the MaxEnt model. Front Plant Sci. 2024;15:1397939. https://doi.org/10.3389/fpls.2024.1397939.
41. Dong P, Wang L, Qiu D, Liang W, Cheng JL, Wang HY, et al. Evaluation of the environmental factors influencing the quality of *Astragalus membranaceus* var. *mongholicus* based on HPLC and the Maxent model. BMC Plant Biol. 2024;24:697. https://doi.org/10.1186/s12870-024-05355-3.
42. Kong DX, Li YQ, Bai M, He HJ, Liang GX, Wu H. Correlation between the dynamic accumulation of the main effective components and their associated regulatory enzyme activities at different growth stages in Lonicera japonica. Ind Crops Prod. 2017;96:16–22. https://doi.org/10.1016/j.indcrop.2016.11.024.
43. Wang LJ, Jiang P, Xu DJ, Wang R, Sun Q. Analysis of Geographic Distribution Patterns of *Lycium barbarum* in the Context of Climate Oscillations. Acta Bot Boreal Occident Sin. 2022;42(12):2133–42. https://doi.org/10.7606/j.issn.1000-4025.2022.12.2133.

44. Tang Y, Zhao RN, Ren G, Cao FL, Zhu ZL. Prediction of potential distribution of *Lycium chinense* based on MaxEnt model and analysis of its important influencing factors. J Beijing Univ. 2021;43(06):23–32. https://doi.org/10.12171/j.1000-1522.20200103.
45. Li X, Gu X, Mao F, Guo H, Qiu J, Liu Y, et al. Assessment of the potential habitat suitability and ephedrine quality of two *Ephedra* species in China under climate change. Plant Biosystems - Int J Dealing All Aspects Plant Biology. 2024;158(3):479–89. https://doi.org/10.1080/11263504.2024.2327115.
46. Schnase JL, Carroll ML, Gill RL, Tamkin GS, Li J, Strong SL, et al. Toward a Monte Carlo approach to selecting climate variables in MaxEnt. PLoS ONE. 2021;16(3):e0237208. https://doi.org/10.1371/journal.pone.0237208.
47. Boria RA, Olson LE, Goodman SM, Anderson RP. Spatial filtering to reduce sampling bias can improve the performance of ecological niche models. Ecol modell. 2014;275:73–7. https://doi.org/10.1016/j.ecolmodel.2013.12.012.
48. Fourcade Y, Engler JO, Rödder D, Secondi J. Mapping species distributions with Maxent using a geographically biased sample of presence data: a performance assessment of methods for correcting sampling bias. PLoS ONE. 2014;9(5):e97122. https://doi.org/10.1371/journal.pone.0097122.
49. Shen YF, Tu ZH, Zhang YL, Zhong WP, Xia H, Hao ZY, et al. Predicting the impact of climate change on the distribution of two relict Liriodendron species by coupling the MaxEnt model and actual physiological indicators in relation to stress tolerance. J Environ Manage. 2022;322:116024. https://doi.org/10.1016/j.jenvman.2022.116024.
50. Pearson RG, Raxworthy CJ, Nakamura M, Peterson AT. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. J Biogeogr. 2007;34(1):102–17. https://api.semanticscholar.org/CorpusID:82263959.
51. Brown JL. SDM toolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. Methods Ecol Evol. 2014;5(7):694–700. https://doi.org/10.1111/2041-210X.12200.
52. Lobo JM, Jiménez-Valverde A, Real R. AUC: a misleading measure of the performance of predictive distribution models. Glob Ecol Biogeogr. 2008;17(2):145–51. https://doi.org/10.1111/j.1466-8238.2007.00358.x.
53. Wakie TT, Evangelista PH, Jarnevich CS, Laituri M. Mapping current and potential distribution of non-native Prosopis juliflora in the Afar region of Ethiopia. PLoS ONE. 2014;9(11):e112854. https://doi.org/10.1371/journal.pone.0112854.
54. Li JJ, Wu J, Peng KZ, Fan G, Yu HQ, Wang WG, et al. Simulating the effects of climate change across the geographical distribution of two medicinal plants in the genus Nardostachys. Peer J. 2019;7:e6730. https://doi.org/10.7717/peerj.6730.
55. Yue JQ, Li ZM, Zuo ZT, Wang YZ. Evaluation of ecological suitability and quality suitability of Panax notoginseng under multi-regionalization modeling theory. Front Plant Sci. 2022;13:818376.

https://doi.org/10.3389/fpls.2022.818376.

56. Shu YX, Sun KF, Xu WF, Chen YR, Sun QW, Wang B. Ecology suitability and quality regionalization analysis on Miao medicine *Laportea bulbifera*. Chin J Exp Form. 2023;29(03):160–9. https://doi.org/10.13422/j.cnki.syfjx.20221617.
57. Rong W, Huang X, Hu S, Zhang X, Jiang P, Niu P, et al. Impacts of Climate Change on the Habitat Suitability and Natural Product Accumulation of the Medicinal Plant *Sophora alopecuroides* L. Based on the MaxEnt Model. Plants. 2024;13:1424. https://doi.org/10.3390/plants13111424.
58. Qi Y, Geng W, Zhou W, Wang J, Wang Q, Wang W, et al. Study on the cold resistance of two Chinese wolfberry species. Xinjiang Agr Sci. 2016;53:2203–9. https://doi.org/10.6048/j.issn.1001-4330.2016.12.006.
59. Li HF, Qi GM, Guo XN. A Climate suitable regionalization of *Lycium barbarum* L. in Qaidam Basin of Qinghai Province. J Anhui Agric Sci. 2016;44(19):201–3. https://doi.org/10.13989/j.cnki.0517-6611.2016.19.066.
60. Liu L, Wang RL, Zhang YY, Mou QY, Gou YS, Liu K, et al. Simulation of potential suitable distribution of *Alnus cremastogyne* Burk. In China under climate change scenarios. Ecol Indic. 2021;133:108396. https://doi.org/10.1016/j.ecolind.2021.108396.
61. Wang XY, Chen HP, Yin L, Liu YP. A Brief overview on the plant resources of *Lycium* L. in China. Pharm Clin Chin Mater Med. 2011; 2(5): 1-350. https://doi.org/CNKI:SUN:LCZY.0.2011-05-002
62. Wang HQ, Wang Q, Ma L, Ding R, Di TY, An W, et al. Production regionalization study of Lycii Fructus. Chin J Chin Mater Med. 2016;41(17):3127–31. https://doi.org/10.4268/cjcmm20161703.
63. Zhang HL. Analysis of the climate conditions for the growth of Lycium planted in Nomuhong. Farmers Consultant. 2018;13:74. (in Chinese).
64. Li Y, Bai J, You Z, Hou J, Li W. Future changes in the intensity and frequency of precipitation extremes over China in a warmer world: Insight from a large ensemble. PLoS ONE. 2021;16(5):e0252133. https://doi.org/10.1371/journal.pone.0252133.
65. Li L, Chen JK. Influence of climate change on wild plants and the conservation strategies. Biodivers Sci. 2014;22(5):549–63. https://doi.org/10.3724/SP.J.1003.2014.14124.
66. Mi XC, Feng G, Hu YB, Zhang J, Chen L, Corlett RT, et al. The global significance of biodiversity science in China: an overview. Natl Sci Rev. 2021;8(7):nwab032. https://doi.org/10.1093/nsr/nwab032.
67. Zhang W, Furtado K, Wu P, Zhou T, Chadwick R, Marzin C, et al. Increasing precipitation variability on daily-to-multiyear time scales in a warmer world. Sci Adv. 2021;7(31):eabf8021. https://doi.org/10.1126/SCIADV.ABF8021.
68. Sun Y, Alseekh S, Fernie AR. Plant secondary metabolic responses to global climate change: A meta-analysis in medicinal and aromatic plants. Glob Chang Biol. 2023;29(2):477–504. https://doi.org/10.1111/gcb.16484.
69. Li YY, Di R, Hsu WL, Huang YQ, Cheung HY. Quality control of *Lycium chinense* and *Lycium barbarum* cortex (Digupi) by HPLC using kukoamines as markers. Chin Med. 2017;12:4.

https://doi.org/10.1186/s13020-016-0121-x.

70. Li KN, Wang KC, Liang YF, Tang XL, Jin GD, Ju MQ, et al. Resource investigation and quality evaluation of *Lycium Chinense* of coastal tidal mudflat in Yancheng Jiangsu. Mod Chin Medic. 2015;17(7):646–50. https://doi.org/10.13313/j.issn.1673-4890.2015.7.002.
71. Alami MM, Guo S, Mei Z, Yang G, Wang X. Environmental factors on secondary metabolism in medicinal plants: exploring accelerating factors. Med Plant Biol. 2024;3:e016. https://doi.org/10.48130/mpb-0024-0016.

Tables

Table 1 Percentage contribution of key environment variables used for modeling.

Abbreviation	Description	contribution (%)	Permutation importance (%)
Lycium barbarum L.			
Bio 2	mean diurnal range/℃	31.8	11.3
Bio 6	minimum temperature of coldest month/℃	16.4	8.1
Bio 17	precipitation of driest quarter/mm	15.5	9.1
Bio 10	mean·temperature of warmest quarter/℃	14.4	0.9
Bio 1	annual mean temperature/℃	10.4	15.5
Bio 13	precipitation of wettest period/mm	5.1	22.4
Bio 12	annual precipitation/mm	5.1	23.7
Bio 3	isothermally·[(Bio2/Bio7) *100]	0.6	7.0
Bio 19	precipitation of coldest quarter /mm	0.5	1.9
Lycium Chinense Mill.			
Bio 1	annual mean temperature/℃	44.6	9.0
Bio 13	precipitation of wettest period/mm	33.6	43.7
Bio 4	temperature seasonality	5.4	9.4
Bio 12	annual precipitation/mm	4.8	2.3
Bio 7	temperature annual range (Bio5~Bio6)/℃	2.5	3.9
Bio 10	mean·temperature of warmest quarter/℃	2.5	5.0
Bio 11	mean temperature of coldest quarter/℃	2.2	9.6
Bio 17	precipitation of driest quarter/mm	1.3	5.1
Bio 2	mean diumnal range/℃	1.3	4.2
Bio 14	precipitation of driest period/mm	1.1	5.3
Bio 18	precipitation of warmest quarter/mm	0.7	2.5

Table 2 Use the Maxent model to calculate the AUC values of two *Lycium* species at different periods.

Origin	NO.	Various periods	AUC
Lycium barbarum L.	1	Current	0.956
	2	RCP2.6-2050s	0.911
	3	RCP2.6-2070s	0.917
	4	RCP4.5-2050s	0.917
	5	RCP4.5-2070s	0.918
	6	RCP8.5-2050s	0.917
	7	RCP8.5-2070s	0.909
Lycium Chinense Mill.	1	Current	0.961
	2	RCP2.6-2050s	0.919
	3	RCP2.6-2070s	0.916
	4	RCP4.5-2050s	0.924
	5	RCP4.5-2070s	0.919
	6	RCP8.5-2050s	0.921
	7	RCP8.5-2070s	0.918

Figures

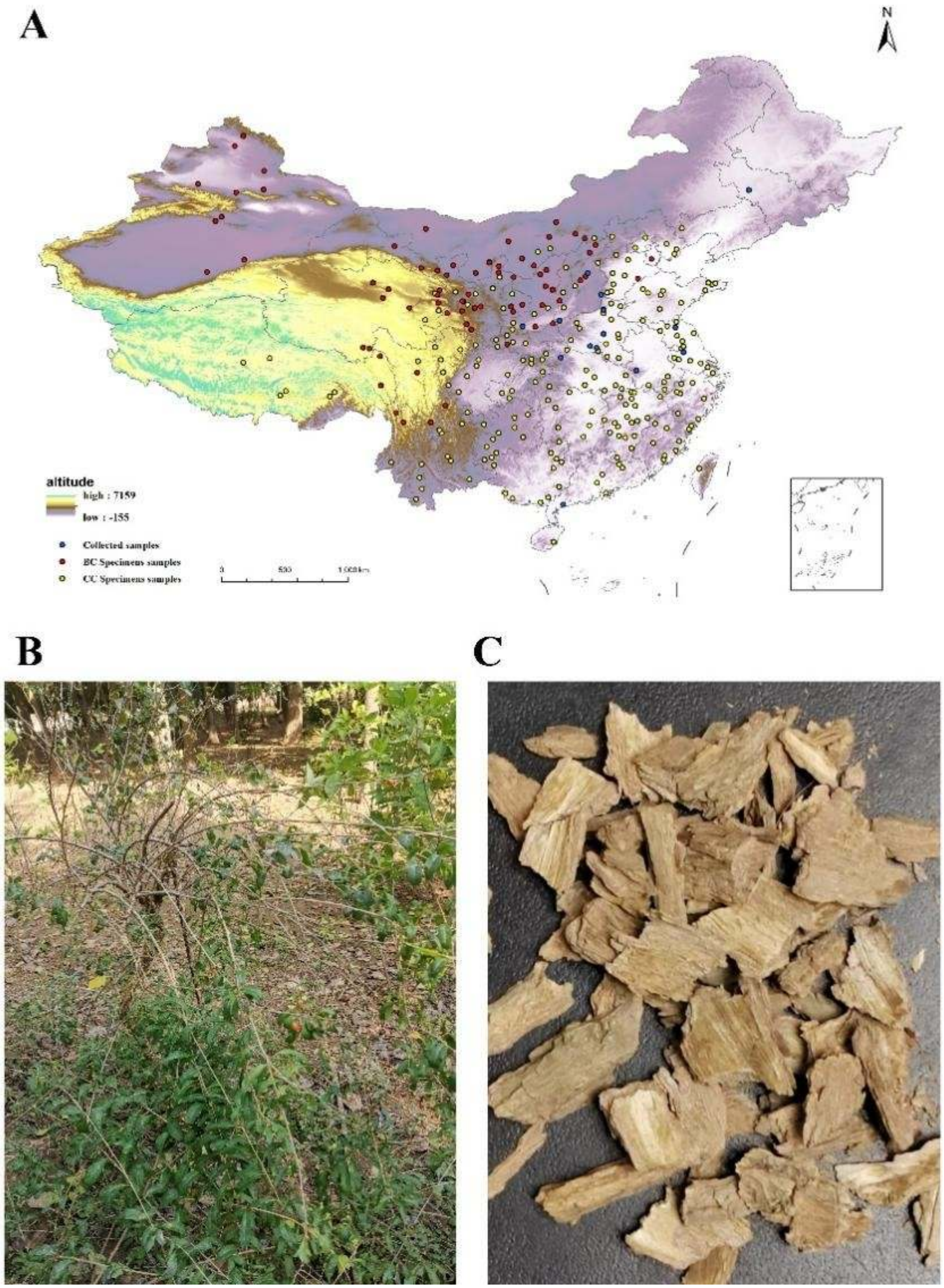

Figure 1

Distribution records of two *Lycii Cortex* species samples and Collected samples (**A**), habitat of *Lycii Cortex* (**B**) and single plant of *Lycii Cortex* (**C**).

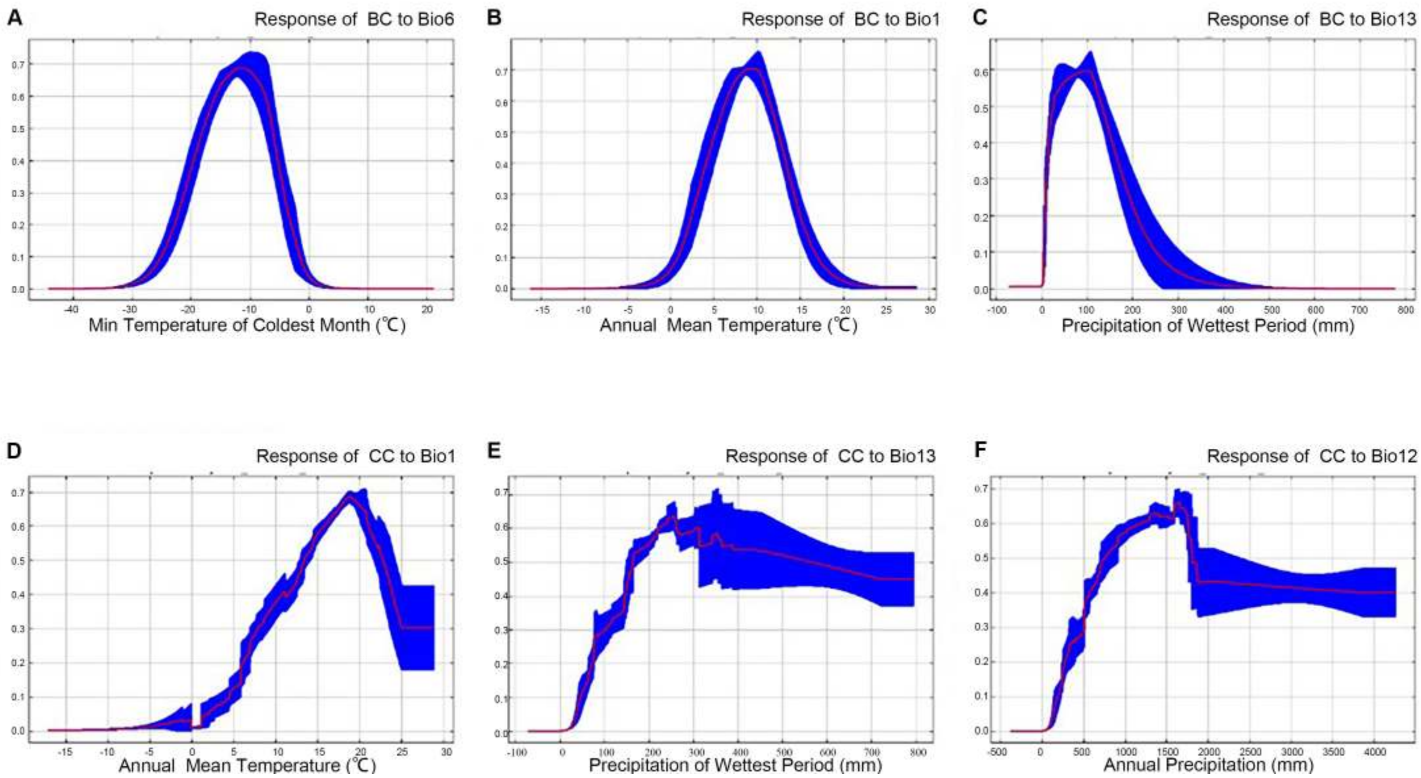

Figure 2

The response curves of the current existence probability of *Lycium barbarum* L. (**A**-**C**) and *Lycium Chinense* Mill. (**D**-**F**) to the top three environmental variables.

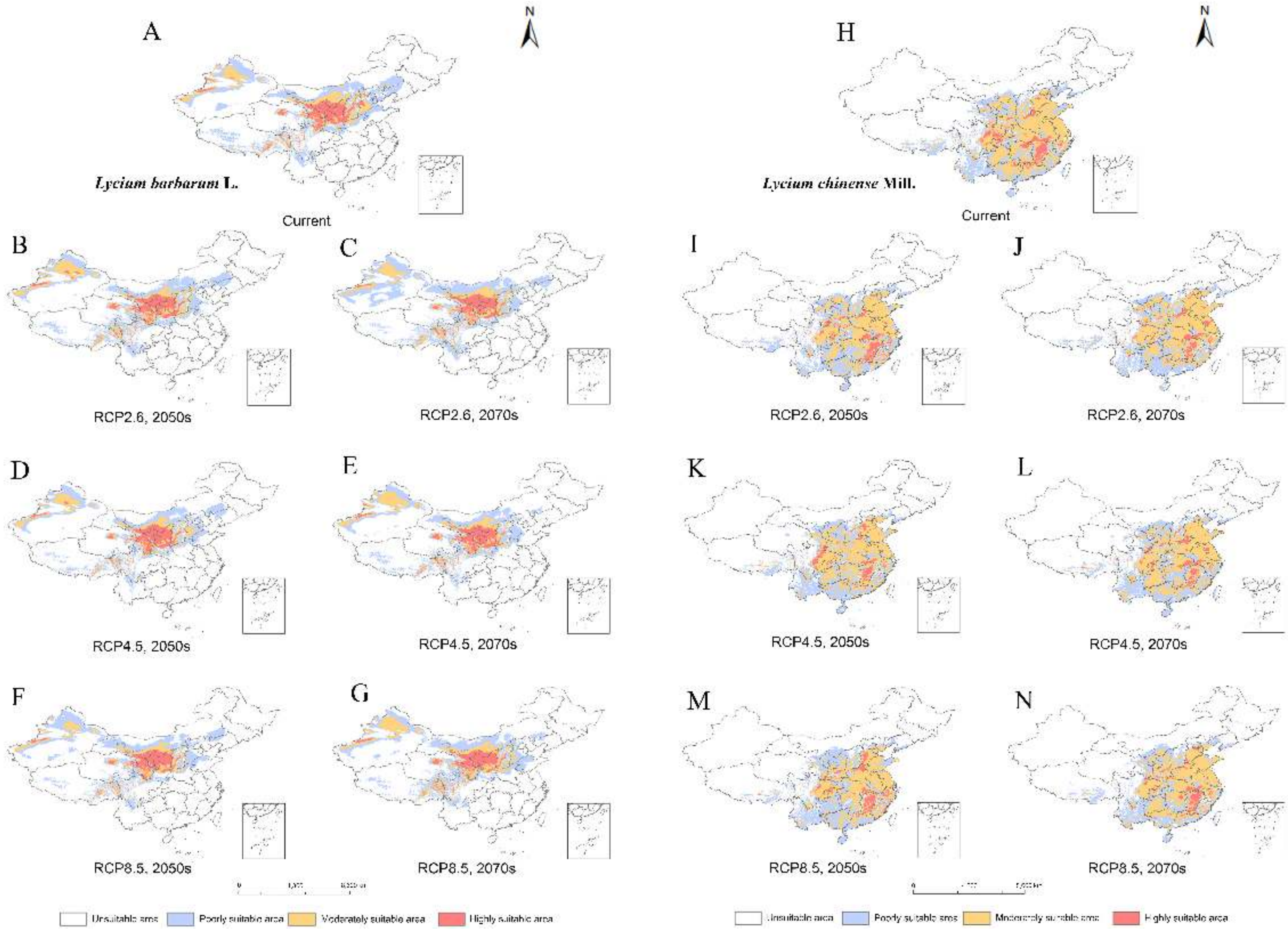

Figure 3

The habitat distribution of *Lycium barbarum* L. (**A**) and *Lycium Chinense* Mill. (**H**) under current climate conditions, as well as the suitable habitat changes of *Lycium barbarum* L. (**B-G**) and *Lycium Chinense* Mill. (**I-N**) under three climate scenarios in the future (2050s, 2070s).

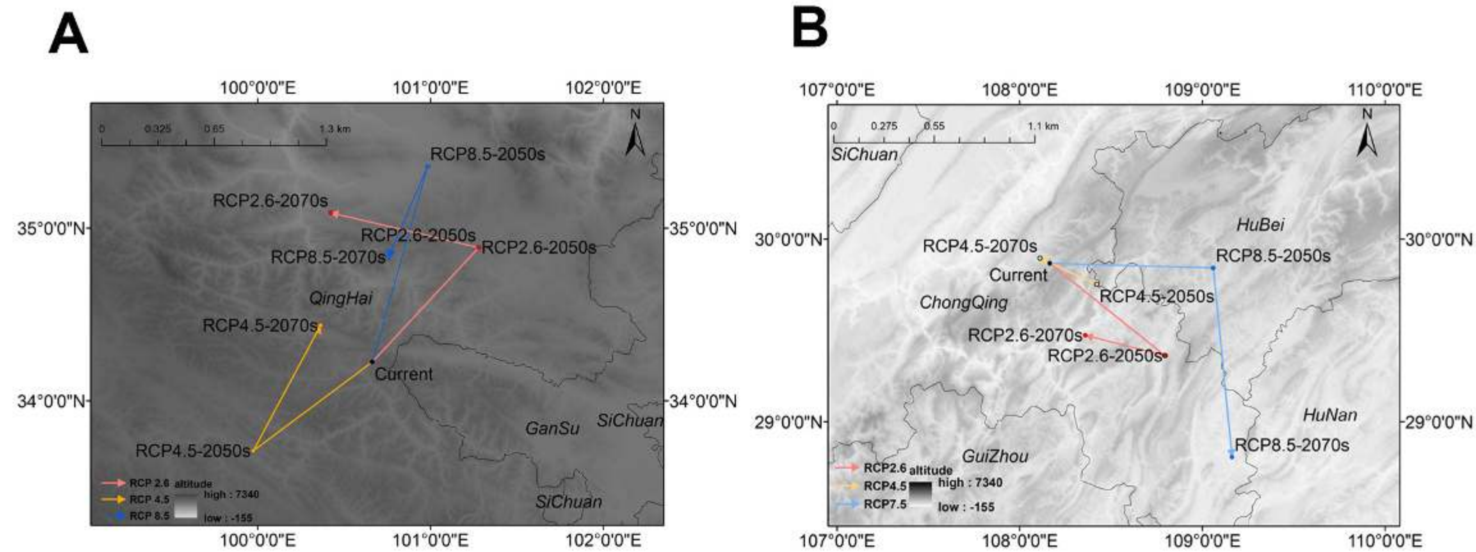

Figure 4

Centroid migration map of suitable habitat of L. *barbarum* (**A**) and L. *Chinese*(**B**).

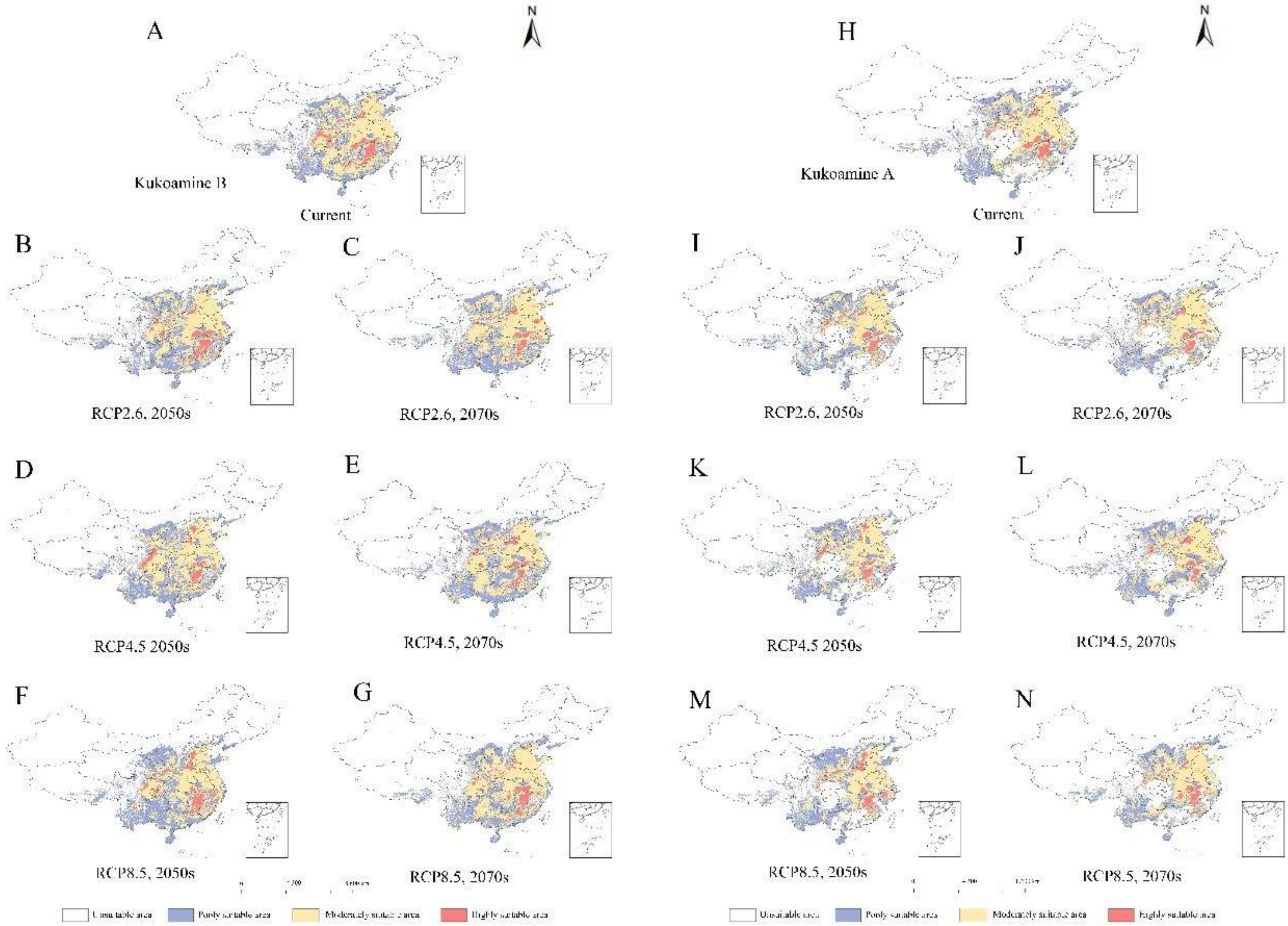

Figure 5

The distribution of suitable quality areas for kukoamine B (**A**) and kukoamine A (**H**) under current climate conditions, as well as the changes in the distribution of suitable quality areas for kukoamine B (**B-G**) and kukoamine A (**I-N**) under three climate scenarios in the future (2050s and 2070s).

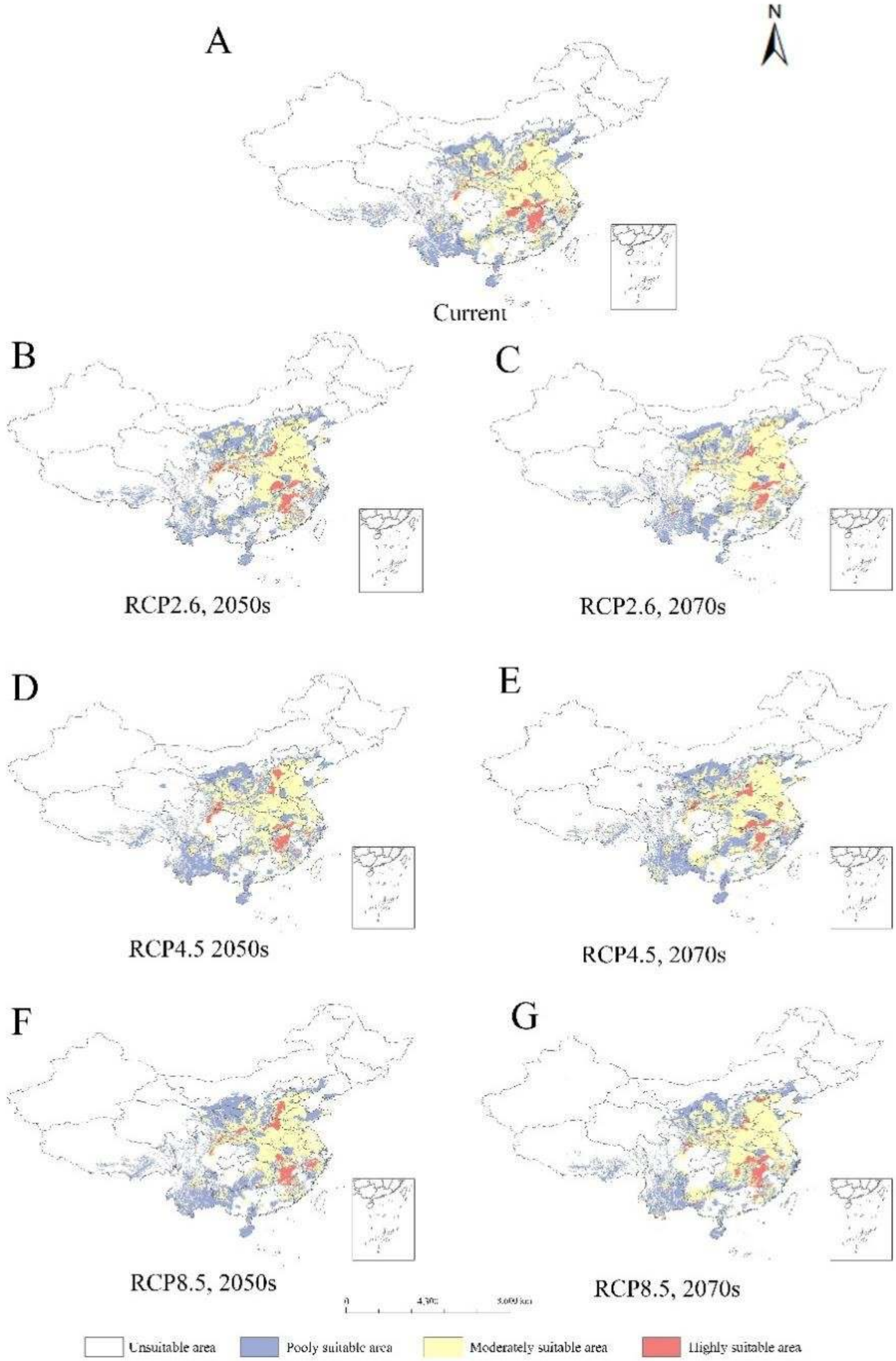

Figure 6

The distribution of L.*Chinese* comprehensive suitable quality areas under current climate conditions (**A**), as well as the changes in the distribution of suitable quality areas under three climate scenarios in the 2050s and 2070s in the future (**B-G**).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx