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Prediction of the globally ecological suitability of *Panax quinquefolius* by the geographic information system for global medicinal plants (GMPGIS)

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[ABSTRACT] American ginseng (*Panax quinquefolius* L.) is a well-known Asian traditional herbal medicine with a large market demand. The plant is native to eastern North America, and its main producing areas worldwide are decreasing due to continuous cropping obstacles and environmental changes. Therefore, the identification of maximum similarities of new ecological distribution of *P. quinquefolius*, and prediction of its response to climate change in the future are necessary for plant introduction and cultivation. In this study, the areas with potential ecological suitability for *P. quinquefolius* were predicted using the geographic information system for global medicinal plants (GMPGIS) based on 476 occurrence points and 19 bioclimatic variables. The results indicate that the new ecologically suitable areas for *P. quinquefolius* are East Asia and the mid-eastern Europe, which are mainly distributed in China, Russia, Japan, Ukraine, Belarus, North Korean, South Korea, and Romania. Under global climate change scenarios, the suitable planting areas for *P. quinquefolius* would be increased by 9.16%–30.97%, and expanding north and west over the current ecologically suitable areas by 2070. The potential increased areas that are ecologically suitable include northern Canada, Eastern Europe, and the Lesser Khingan Mountains of China, and reduced regions are mainly in central China, the southern U.S., and southern Europe. Jackknife tests indicate that the precipitation of the warmest quarter was the important climatic factor controlling the distribution of *P. quinquefolius*. Our findings can be used as a useful guide for *P. quinquefolius* introduction and cultivation in ecologically suitable areas.

[KEY WORDS] American ginseng; *Panax quinquefolius*; Ecological suitable area; Climate change; GMPGIS; Jackknife test

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Introduction

Plant distribution and biodiversity will be affected by global climate change [1]. The global average temperature has been increased 0.85 °C from 1880 to 2012 [2]. The Intergovernmental Panel on Climate Change (IPCC) estimates that a 0.2 °C temperature increase will occur for each future decade that is subject to greenhouse gas emissions, and the temperature increase will exert harmful effects on numerous species [3]. Recent research shows that many plants will likely be unable to change their range to suitable areas with sufficient speed under the current rate of climate change. The extinction rate of species would subsequently increase, and warmer temperatures will impact plant growth and yield [4-6]. Hence, detecting the extent of climate change in the coming decades, and the use of alternative methods to assess its impact on medicinal plant distribution are helpful for designing conservation and cultivation plans in the future.

American ginseng (*Panax quinquefolius* L.) is a well-known medicinal species that is native to the mid-eastern United States and southern Canada, and was first introduced

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into China in 1975 [7]. The plant is valuable due to its extensive medicinal benefits, such as anti-tumor, anti-inflammatory, anti-aging, anti-oxidative, and immunoregulatory effects [8-9]. However, the number of wild *P. quinquefolius* plants are decreasing and threatened by excessive harvesting and climate change, and the species has been listed in CITES Appendix II (Convention on International Trade in Endangered Species of Wild Fauna and Flora) since 1975 [10]. Additionally, the main producing areas for this plant are decreasing because of continuous cropping obstacles, which reduce its root yield and quality [11].

As an important medicinal plant, *P. quinquefolius* has been studied mainly with respect to plantation development, including breeding, management, and planting, but the research on climatically suitable habitats and global ecologically suitable areas for *P. quinquefolius* under global warming conditions remains poor [12]. CHEN *et al.* assessed the distribution patterns of species and habitats across China *via* the traditional Chinese medicine geographic information system (TCMGIS) and identified suitable areas for cultivating *P. quinquefolius*, mostly in the northeast and northern regions of China [13]. XIE *et al*. used maximum entropy (MaxEnt) to show that the potential distribution areas of *P. quinquefolius* were in the United States, Canada, China, and North Korea [14].

As a high-latitude medicinal plant, *P. quinquefolius* distribution is also sensitive to climatic factors. HUANG *et al*. used the geographic information system for global medicinal plants (GMPGIS) to show that four other *Panax* species distributed in the low latitudes of China were critically affected by the mean temperature of the coldest quarter [15]. Therefore, detecting the extent of climate change in the coming decades and identification of ecologically suitable areas for *P. quinquefolius* is helpful for designing conservation and cultivation plans for the future.

With the development of geographic information systems (GISs), ecological niche models (ENMs) have been applied to predict the impact of climate on species distribution [16], such as GMPGIS, MaxEnt, and so on [15, 17]. The GMPGIS is a spatial distribution model for predicting ecologically suitable areas for medicinal plants using climate databases [18-19]. Previous evaluation of other medicinal plants indicates that the model provides accurate predictions in accordance with the existing medicinal plant distribution patterns [15]. MaxEnt is also a widely used prediction software for predicting species distribution, with reference to the prediction map, the climatic factor controlling the distribution of species can be predicted using MaxEnt with the function of the jackknife test [20]. In this study, the combination of GMPGIS and jackknife test can provide a comprehensive map of ecologically suitable habitats for medicinal plants on a global scale.

In this study, GMPGIS was used to predict ecologically suitable areas for *P. quinquefolius* starting from the current climate conditions in 2050 and 2070 under future climate change scenarios, and the main climatic factors controlling the geographical distribution of *P. quinquefolius* were analyzed by using a jackknife test. Our results will provide a useful reference for the conservation and cultivation of American ginseng worldwide.

Materials and Methods

Materials

Distribution sites for *P. quinquefolius* were mainly obtained from the Global Biodiversity Information Facility Data Portal (GBIF, http: //www.gbif.org/), the Kew Gardens (http: //www.kew.org/), the Chinese Virtual Herbarium (CVH, http: //www.cvh.org. cn/), the National Specimen Information Infrastructure (NSII, http: //www.nsii.org.cn/), and relevant literature [21-24]. In the current study, the sample points without latitude and longitude data were eliminated, whereas only one occurrence point was kept when duplicated. A total of 476 herbarium data points with longitude and latitude information were valid and used for prediction (Fig. 1). And the sampling

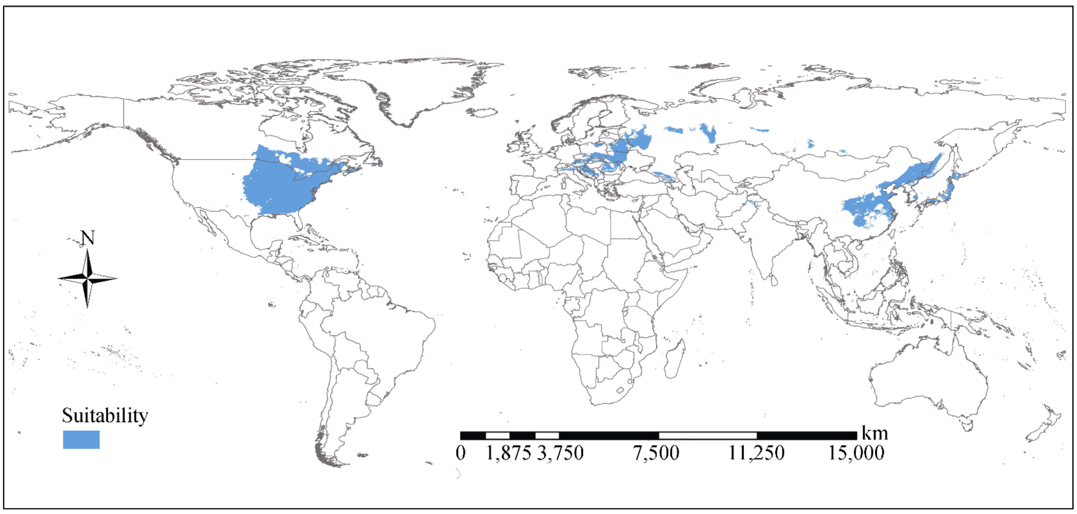

Fig. 1 The ecological suitability assessment based on GMPGIS for *P. quinquefolius*. The map was plotted using ArcGIS software version 10.2 (ESRI, Redland, CA. URL http: //www.esri.com/)

points were mainly collection from the U.S. (Wisconsin, Minnesota, Illinois, etc.), Canada (Quebec, Ontario, Montreal, etc.), and China (Jilin, Shandong, Beijing, Shanxi, etc.). All experiments involving with the plant distribution prediction were conducted in a key biosafety laboratory of plantation and ecology.

Climate is considered to be the most important environmental factor influencing the distribution of plants [25]. In this study, a total of 19 climate variables were obtained from WorldClim (http: //www.worldclim.org/) and used for distribution prediction. The climate variables were the average climate data from 1970 to 2000, with a spatial resolution of approximately 1 km^2 (Table 1) [4, 26]. To analyze the effect of climate change on *P. quinquefolius* distribution, Global Climate Model (GCMs) data until 2050 and 2070 under three future climate scenarios (RCP 2.6, 4.5, and 8.5) based on the 5th assessment report of the IPCC (http: //www. worldclim.org/CMIP5) [27-28] was applied in this study, which representing the high-, mid- and low-range climate change scenarios. Among all the GCM data, BCC-CSM1.1 (Beijing Climate Centre, China Meteorological Administration) was a model that has higher acceptability and is often studied for its predicted precipitation [29]. In the current study, after the pre-experiment, the BCC-CSM1.1 model was used for prediction of the global ecologically suitable areas for *P. quinquefolius*. With this forecast method, a total of six prediction maps were completed for *P. quinquefolius* in 2050 and 2070.

Table 1 Ecological factors extracted from current *P. quinquefolius* habitats by GMPGIS

Code	Variables description	Range	Mean ± SD	*CV* (%)
Bio1	Annual mean temperature	−1.30−19.20	8.13 ± 4.33	53.30
Bio2	Mean diurnal range	6.10−14.90	11.75 ± 1.65	14.27
Bio3	Isothermality	0.20−0.45	0.29 ± 0.05	18.41
Bio4	Temperature seasonality	61.04−150.66	105.18 ± 2.22	21.12
Bio5	Max temperature of warmest month	22.60−35.10	27.93 ± 2.48	8.88
Bio6	Min temperature of coldest month	–31.20−3.60	–13.72 ± 8.60	62.68
Bio7	Temperature annual range	29.00−55.70	41.65 ± 7.21	17.30
Bio8	Mean temperature of wettest quarter	–2.50−26.60	18.06 ± 4.76	26.36
Bio9	Mean temperature of driest quarter	–21.90−26.00	–3.96 ± 10.77	272.13
Bio10	Mean temperature of warmest quarter	15.30−27.00	21.00 ± 24.75	11.79
Bio11	Mean temperature of coldest quarter	–21.90−11.00	–6.21 ± 7.36	118.53
Bio12	Annual precipitation	533.00−2007.00	935.53 ± 246.49	26.36
Bio13	Precipitation of wettest month	80.00−276.00	146.99 ± 45.48	30.94
Bio14	Precipitation of driest month	2.00−152.00	37.89 ± 31.07	82.01
Bio15	Precipitation seasonality	6.00−138.00	52.08 ± 38.74	74.38
Bio16	Precipitation of wettest quarter	229.00−664.00	383.18 ± 94.34	24.62
Bio17	Precipitation of driest quarter	9.00−470.00	128.32 ± 101.11	78.80
Bio18	Precipitation of warmest quarter	219.00−664.00	365.93 ± 98.65	26.96
Bio19	Precipitation of coldest quarter	9.00−508.00	141.97 ± 122.04	85.96

Note: all values are indicated as the mean ± SE (n = 476)

Methods

GMPGIS is a model that uses global geographic information systems to predict medicinal plant geographic distribution, and it was developed by the ICMM (Institute of Chinese Materia Medica, China Academy of Chinese Medical Sciences) in 2015 [19]. The model was designed according to the k-means method and uses the Euclidean distance algorithms, which can process run presence-only data [14, 19]. The GMPGIS ecological database was mainly obtained from WorldClim (http://www.worldclim.org/). The system has been used to guide the introduction and plantation of six *Panax* species in China, and the reliability of the system has been successfully verified [15, 18, 30]. In this study, suitable ecological factors and a habitat map for *P. quinquefolius* were established according to the following formula: (1) linear normalization (v_i), the v_i of A to v_i in the range [*newminA*, *newmaxA*] (a); (2) an improved k-means based on Euclidean space distance was adopted to evaluate GMPGIS models (b and c), E is the sum of the squared error for all samples in this study, p is the sampling point in space representing a given object, d_i is the scope of cluster D_i, *newminA* is the minimum value after normalizing the layer, and *newmaxA* is the maximum value after normalizing the layer; (3) grid-based spatial clustering; and (4) vector-based overlaying and suitable region analysis [15, 19].

$$v_i = (v_i - min_A) / (\max_A - \min_A) \times 100 \quad \text{(a)},$$

$$E = \sum_{i=1}^{k} \sum_{p \in D_i} dist(p, d_i)^2 \qquad \text{(b)},$$

$$dist(p, d_i) = \text{IF}\,[\min \le vi \le \max, 0, \min(|\, vi' - newminA \,|, \,|\, vi' - newmaxA \,|)] \qquad \text{(c)}.$$

The analysis steps for the ecological suitability for *P. quinquefolius* in GMPGIS are as follows. (1) The spatial distribution data for *P. quinquefolius* were collected from filed investigations, the literature, and plant databases. (2) Vector coordinate shape files were created through GPS coordinate transformation, and the data were imported into the GMPGIS platform. (3) Next, 19 ecological factors were downloaded from the WorldClim database into GMPGIS, and the ecological suitability of these areas with improved Euclid distance was analyzed. (4) Areas sharing similar ecological factors at a rate of 1 were regarded as ecologically suitable areas for *P. quinquefolius*.

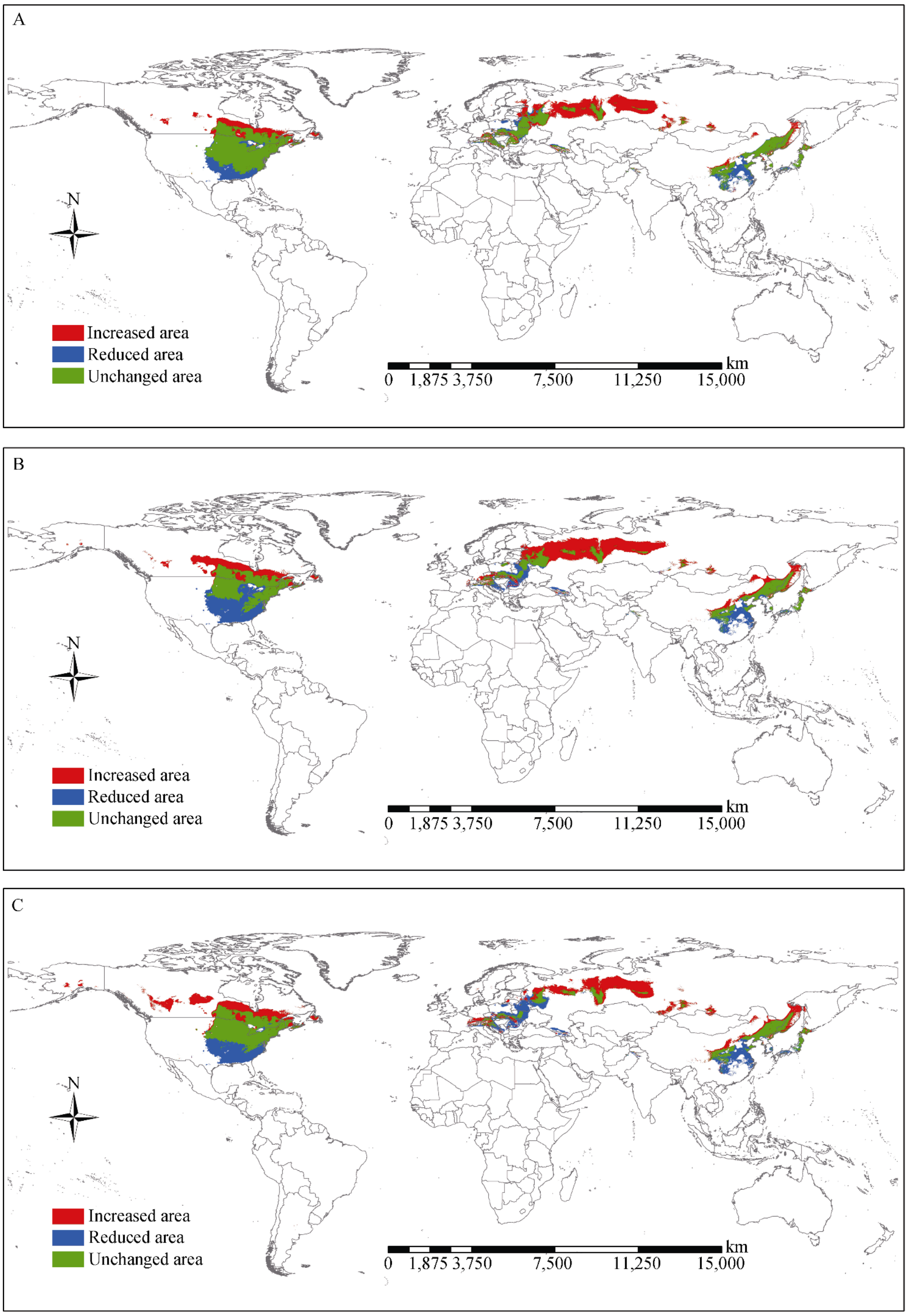

Fig. 2 Results of the ecological suitability assessment based on GMPGIS for *P. quinquefolius* from the current time to 2050 in the bc26, bc45, and bc85 scenarios. A: Based on GMPGIS in the bc26 scenario, B: based on GMPGIS in the bc45 scenario, C: based on GMPGIS in the bc85 scenario. The map was plotted using ArcGIS software version 10.2 (ESRI, Redland, CA. URL http: // www.esri.com/)

MaxEnt is a frequently-used predictor of species' environmental niches [20]. As mentioned above, it aims to calculate the suitable habitat areas of species using maximum entropy. For the current study, version 3.3.3k of MaxEnt was used, along with the standard protocols described in the software instructions. By repeated analysis and testing, the optimal model sets of environmental variables and proportion of occurrence data for testing and training were obtained. The division number and the threshold value of prediction map was classified according to the classification standard of MaxEnt and comparing the previous results [31-37], the final potential distribution map of *P. quinquefolius* had a range of values from 0 to 1 which was regrouped into four classes, least potential (0.0–0.2), moderate potential (0.2–0.4), good potential (0.4–0.6), high potential (0.6–0.8) and core potential (0.8–1.0). To evaluate the models' performance, a jackknife test was used to measure the variable importance in the model.

Results

Ecological factor data performance

The ecological factor data for *P. quinquefolius* was extracted from collected sampling points and calculated in the GMPGIS (Table 1). The variables significantly differed among different native habitats, with a coefficient of variation ranging from 8.88% for the maximum temperature of the warmest month to 272.13% for the mean temperature of driest quarter. Annual mean temperature was increased approximately 4 °C for 2070 under the bc85 scenario compared with the current climatic variables. Annual precipitation was increased by approximately 34.61−79.89 mm for 2070 under three future climate scenarios. However, mean diurnal range, isothermality, annual temperature range were slightly decreased for 2070. The proportional contributions of the main factors were precipitation of warmest quarter (40.22%), temperature seasonality (25.42%), mean temperature of warmest quarter (17.52%), and annual precipitation (7.67%). The other 15 climatic factors had a combined contribution of 9.17%, according to the jackknife test. The precipitation of the warmest quarter was the most important factor for *P. quinquefolius* distribution (Table 2).

Table 2 The percentage contribution of eight mainly climatic variables for *P. quinquefolius* based on jackknife tests

Variable	Contribution (%)
Precipitation of warmest quarter (Bio18)	40.22
Temperature seasonality (Bio04)	25.42
Mean temperature of warmest quarter (Bio10)	17.52
Annual precipitation (Bio12)	7.67
Annual mean temperature (Bio01)	1.93
Minimum temperature of coldest month (Bio06)	1.20
Mean diurnal range (Bio2)	0.93
Precipitation seasonality (Bio15)	0.92
Total	95.81

Current ecologically suitable areas

The potential ecologically suitable areas for *P. quinquefolius* were obtained by GMPGIS. The potential suitable areas mainly distributed in mid-eastern North America (Great Lakes and Appalachian Mountains), East Asia (Changbai Mountains, Shandong Peninsula, the Central Plains of China and Korean peninsula), Central and Eastern Europe by GMPGIS (Fig. 1). And the total ecological suitable area for cultivation in the future is 94.24 × 10^5 km^2, and new extends across 12 main countries: China, Russia, Japan, Ukraine, Belarus, Romania, Poland, North Korea, Austria, and South Korea. The top three distribution areas are the U.S., China, and Canada, with a suitable climatic area more than 5.00 × 10^5 km^2, comprising the largest suitable planting regions for *P. quinquefolius*. The potential areas in the U.S are mainly in Wisconsin, Minnesota, Illinois, Ohio, Michigan, Indiana, North Carolina, Pennsylvania, and Kentucky; in China, they include Jilin, Shandong, Liaoning, Beijing, Shanxi, and Anhui Provinces; and in Canada, they include Quebec, Ontario, and Montreal.

Ecologically suitable areas in 2050

Future climate change is expected to increase the ecologically suitable areas for *P. quinquefolius* in the bc26, bc45 and bc85 scenarios by 2050 (Fig. 2). The GMPGIS map indicates that the total ecologically suitable area is approximately 108.58 × 10^5 km^2, indicating a 15.22% increase in the bc26 scenario compared to the current distribution areas (Table 3). In the bc45 scenario, the total ecologically suitable area is approximately 103.37 × 10^5 km^2, indicating a 9.69% increase in global proportion (Table 3). In the bc85 scenario, the suitable area is approximately 101.46 × 10^5 km^2, indicating a 7.66% increase in global proportion (Table 3). The potential increase in suitable areas occurs mainly in the northern and western parts of Canada, the central and eastern parts of Europe, and the northern area of East Asia. The potential suitable areas will shrink in the U.S, China, Japan, Belarus, and Poland, and will increase mainly in Canada, Russia, and Ukraine.

Table 3 The total area predicted to be potentially suitable for *P. quinquefolius* per GMPGIS from the current time to 2070 (× 10^5 km^2)

Scenarios	GMPGIS	
	2050	2070
bc26	108.58	127.87
bc45	103.37	118.61
bc85	101.46	102.87

Ecologically suitable areas in 2070

Future climate change will increase the ecologically suitable areas for *P. quinquefolius* in the three scenarios by 2070 (Fig. 3). The ecologically suitable areas in the GMPGIS map totaled approximately 127.87 × 10^5 km^2, marking a 30.97% global increase in the bc26 scenario compared to the distribution areas from current climate conditions (Table 3). In the bc45 scenario, the total ecologically suitable area was approximately 118.61 × 10^5 km^2, which globally increased by 25.86% (Table 3). In the bc85 scenario, the total ecologically suitable area was approximately 102.87 × 10^5 km^2, which was globally increased by 9.16% (Table 3). The potential increased area contains the northern and western part of Canada, the Lesser Khingan Mountains of China, and the Korean peninsula, and reduced regions are mainly in central China, Ukraine, and the Great Lakes of the U.S..

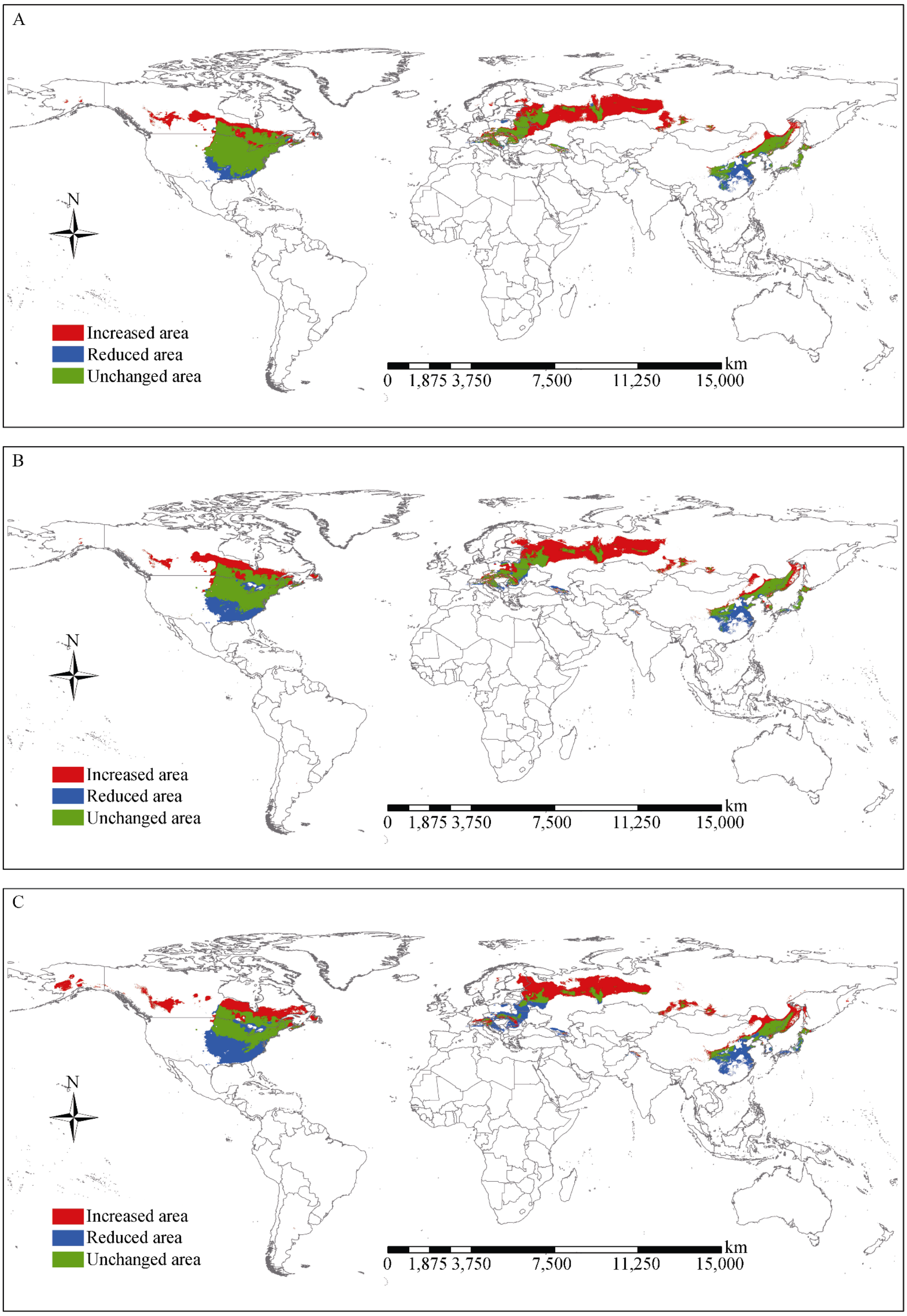

Fig. 3 Results of the ecological suitability assessment based on GMPGIS for *P. quinquefolius* from the current time to 2070 in the bc26, bc45, and bc85 scenarios. A: Based on GMPGIS in the bc26 scenario, B: based on GMPGIS in the bc45 scenario, C: based on GMPGIS in the bc85 scenario. The map was plotted using ArcGIS software version 10.2 (ESRI, Redland, CA. URL http: // www.esri.com/)

Discussion

Distribution models are commonly used for predicting the impact of climate change upon certain species. This technique has been applied for the protection and cultivation of a number of species to date [38]. In this study, GMPGIS was used to prediction global ecological suitable areas for *P. quinquefolius*. Result show that the ecologically suitable areas for *P. quinquefolius* are East Asia, the middle and eastern North America, and the mid-eastern Europe. In order to compares the prediction areas of GMPGIS, MaxEnt analysis for *P. quinquefolius* was predicted in this study. It's indicated that suitable areas were mainly concentrated in eastern Asia, the middle and eastern North America, and parts of Europe. The high and core area (0.6–1.0) is mainly concentrated in mid-eastern U.S., Changbai Mountains and Shandong Peninsula of China. The general trend of ecologically suitable areas by MaxEnt's is similar to GMPGIS. And GMPGIS can provide prediction for a larger area than MaxEnt. The reason is the Euclidean distance calculation based on the threshold value of each environmental factor was used in GMPGIS, and the potential distribution area of the species could coverage all suitable areas of predicted species. *P. quinquefolius* has been introduced into China for the past three decades, and because of the environmental changes and long-term production practices, Jilin, Shandong, and Beijing have become three sizable production areas in China [39]. In the current study, the cultivation areas in China were predicted by means of GMPGIS. Therefore, the GMPGIS can provide a precise map of ecologically suitable habitats for medicinal plants on a global scale.

Previous habitat studies have demonstrated that selecting proper occurrence points for plants is a method for identifying potentially suitable regions [40]. In the current study, there were 476 sample points collected, and new plantation in Shanxi Liuba, China and the main distribution points of *P. quinquefolius* in North America were added. This resulted in additional accuracy of the potential global distribution prediction, and the potential suitable area was larger than that previously reported [13-14]. Our simulation results indicated that new suitable distribution areas for *P. quinquefolius* are mainly located in the Changbai Mountain, Shandong Peninsula, the Korean peninsula, Japan Islands, and the mid-east Europe. The undiscovered potential areas identified in this research could be useful for the future cultivation of this plant.

Simulation-based estimates suggest that suitable planting areas for *P. quinquefolius* would increase and move north and west in 2070 compared to those for the current climate conditions, which include Russia, Canada, China, Japan, Ukraine, and Belarus. However, a slightly southern shift of ecologically suitable areas would lead to the result that areas in the U.S., China, Italy, South Korea, and France become unsuitable for *P. quinquefolius* cultivation. According to the results of a suitable production area assessment based on GMPGIS, the global ecologically suitable areas for *P. quinquefolius* will increase by (8.63−33.63) × 10^5 km^2 in 2070, result in a larger and more abundant planting areas that are suitable for *P. quinquefolius* introduction and cultivation in the future. However, the suitable planting areas only represent regions with similar environmental conditions compared to current distribution region, but does not consider cultivar, economic or other environmental factors variation. It needs to be field investigation or cultivation in the potential distribution to identify suitable areas for introduction and cultivation of *P. quinquefolius*.

Research shows that different medicinal plants require various climates and habitats for their growth and accumulation of secondary metabolic products [41]. XIE *et al*. showed that in a certain range of lower temperatures, *Panax ginseng* (C. A. Mey.) accumulates larger amounts of ginsenosides [42]. The simulation operation conducted herein was undertaken to avoid blind cultivation. From the environmental variable contribution analysis, we found that the *P. quinquefolius* population growth is affected by the precipitation of the warmest quarter. *P. quinquefolius* is an ecologically fragile plant, and its distribution is sensitive to climate change, as it requires suitable levels of humidity and rainfall for optimal growth. An increase in global temperature in the 1.85−4.15 °C range is predicted by 2070 due to global warming, which is expected to cause frequent drought and heavy rain events in areas inhabited by *P. quinquefolius*, and will also affect plant growth and ginsenosides production [43-44]. The limiting factor map shows the distribution area of *P. quinquefolius* moving north on a global scale with an increase in temperature seasonality, which is valuable information for controlling the plant's distribution areas. Regions for growing *P. quinquefolius* that are predicted to increase, such as Canada, China, Russia, Ukraine, and Belarus, are mainly in the marginal habitat, and their distribution tends to move north and west on a global scale with an increase in temperature seasonality. These results show a strong correlation between climatic factors and the distribution of medicinal plants.

P. quinquefolius is an important type of medicinal materials, the wild resources have been gradually declining, due to market demand and global climate change in recent years. Therefore, identification of new potential suitable planting areas is necessary for *P. quinquefolius* production. In this study, climate change is an important contributing factor affecting range shifts of *P. quinquefolius*. However, many other factors affect the production of plants that were not analyzed in this manuscript. These factors include soil conditions, pests, diseases, growth form, and habitat specificity [45]. *P. quinquefolius* is a perennial plant, and its replantation usually fails due to various problems associated with continuous cropping. Soil cultivated with *P. quinquefolius* must be improved with many years of crop rotation before second-round planting could be initiated [46]; thus, arable soils in the current planting areas for *P. quinquefolius* cultivation have become rather scarce. Therefore, more ecological factors should be added in the future to improve the accuracy of the ecological niche models, and reduce the economic loss and the workload by blind introduction. In summation, this study provides valuable information for identifying current and future potential regions with climatically suitable habitats for *P. quinquefolius*, and thus, it can be used as a useful guide for *P. quinquefolius* conservation, introduction and cultivation in currently non-planted areas.

Conclusion

P. quinquefolius is a widely used medicinal plant with a huge potential market value; however, its main producing fields have rapidly decreased due to excessive harvesting and continuous cropping problems. Currently, this plant urgently requires introduction and cultivation in new areas. In this study, we successfully predicted ecologically suitable habitats for *P. quinquefolius* that are mainly distributed in eastern North America, East Asia, and mid-eastern Europe. Under global warming conditions, the suitable planting areas for *P. quinquefolius* will increase and move north and west over the current ecological suitability areas for the years 2050 and 2070, and the precipitation of the warmest quarter was the most important climatic factor controlling the distribution of *P. quinquefolius*. This study greatly improves the management of growing areas for *P. quinquefolius*, and provides a useful reference for plant introduction and cultivation in the future.

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