

Predicting the potential distribution of 12 threatened medicinal plants on the Qinghai-Tibet Plateau (QTP), with a maximum entropy model

Lucun Yang

Chinese Academy of Sciences

Xiaofeng Zhu

Gande County Animal Disease Prevention and Control Center

Wenzhu Song

Chinese Academy of Sciences

Xingping Shi

Qing Hai West Copper Co. LTD

Xiaotao Hang (✉ xthuang@ztu.edu.cn)

Zhaotong University

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Abstract

Climate change is a vital driver of biodiversity patterns and species distributions, understanding how organisms respond to climate change will shed light on the conservation of endangered species. In this study, the MaxEnt model was used to predict the potential suitable area of 12 threatened medicinal plants in the QTP (Qinghai-Tibet Plateau) under the current and future (2050s, 2070s) three climate scenarios (RCP2.6, RCP4.5, RCP8.5). The results showed that the climatically suitable habitats for the threatened medicinal plants were primarily found in the eastern, southeast, southern and some part of the central regions on the QTP. Moreover, 25% of the threatened medicinal plants would have reduced suitable habitat areas within the next 30-50 years in the different future global warming scenario. Among these medicinal plants, FP (*Fritillaria przewalskii*) would miss the most habitat (97.1%), while the RAN (*Rhododendron anthopogonoides*) would miss the least habitat (0.30%). Nevertheless, 41.6% of the threatened medicinal plants showed an increase in their future habitat area because of their physiological characteristics which are more adaptable to a wide range of climate. The climatic suitable habitat for 50% of the threatened medicinal plants would migrate to higher altitudes or higher latitudes regions.

This study provides a data foundation for the conservation of biodiversity and wild medicinal plants on the QTP.

1. Introduction

The interaction and relationship between plants and climate are hot topics in the fields of botany, ecology, and geography [1, 2]. Over the past 100 years from the Industrial Revolution to the present, human activities have led to drastic changes in the global climate. According to the fifth report of IPCC (the Intergovernmental Panel on Climate Change), human activities have emitted a large amount of greenhouse gases such as CO₂, leading to an increase in global temperature. From 1880 to 2012, the average global surface temperature increased by 0.85 °C, and it is projected to increase by 0.3 to 4.8 °C by the end of the 21st century (2081 – 2100) compared to the base period (1986 – 2005) [3]. Under the background of global climate change, climate warming in the coming decades or even centuries may alter the structure and function of terrestrial ecosystems by affecting the distribution of organisms and vegetation composition.

Previous studies have shown that the extinction of some species was resulted from climate change [4], which could lead to the reduction of the suitable distribution area of some species, habitat fragmentation, and accelerated global biodiversity loss [5]. Endangered plants are a major component of biodiversity in a region, and rare and endangered plants have a high extinction rate and may face the risk of extinction in the coming period if their species numbers continue to decline [6]. The geographical distribution of species is one of the key geographical characteristics of species, and each species has a specific distribution range in the world. The drawing of species distribution maps is an important means of studying species distribution, and plays a crucial part in analyzing the origin and distribution law of species populations [7]. In order to further protect global biodiversity and prevent further destruction of

ecosystems, it is necessary to systematically understand the relationship between the potential geographical distribution areas of species and climate change, as well as the potential geographical distribution areas of species in future climate change scenarios, and propose adaptive protection strategies.

Forecasting the potential distribution of species under current and future climate conditions is mainly based on niche models [8]. Niche models can simulate the potential distribution of species using the known distribution points and GIS-based environmental variables, and predict the suitable distribution range and changes of species under future climate change scenarios. At present, there are various species distribution models based on ecological niches [9], which have been widely used in predicting suitable distribution areas for endangered plants. For example, the maximum entropy model MaxEnt [10–14], the ruleset genetic algorithm model GARP [15], and the BIOCLIM model [16] and so on. Among them, MaxEnt, the maximum entropy model, is an intensively used prediction model in recent years, and its prediction results are the most accurate. Even though the species distribution data information and environmental variables in the distribution area are incomplete, it can precisely predict the potential distribution area of species [17, 18]. In addition, the stability of the model is good and the predicted results are basically in line with the actual distribution of species (the average AUC value is the largest).

The QTP (Qinghai-Tibetan Plateau) is of great significance for the geographical environment pattern and climate change of China and Asia. It is an important distribution area of terrestrial ecosystems in China and also an important gene pool of biological species worldwide. The QTP is recognized as the "driving force" and sensitive area of global climate change, and its response to "greenhouse gases" is more sensitive than other regions [19–22]. The QTP is one of the geographical regions with the highest number of medicinal plants in China. There are over 2000 kinds of medicinal plants on the QTP, occupying approximately half of the total number of medicinal plants in China. The unique geographical location and climatic conditions of the QTP had actuated the formation of endemic medicinal plants, and it also had considerably enhanced the richness of medicinal species on the plateau. However, with the continuous development of human society and the increase of population, along with the vigorous development of Tibetan medicine, the Tibetan medicine resources in the QTP have been arbitrarily exploited and plundered for a long time, resulting in the destruction of medicinal vegetation habitats, rapid shrinkage of medicinal plant resources, and some species are on the brink of extinction. In addition, climate change characterized by warming will have a significant impact on the natural environment, ecosystems, and species distribution in this region [23–25]. In addition, climate change with warming as its main feature will have a huge impact on the natural environment, ecosystem, and species distribution in this region, and some endangered wild medicinal plant resources will face greater threats. Therefore, understanding the potential geographical distribution of threatened species and their suitable habitat status is a prerequisite for effective conservation work [26]. However, in reality, the geographical distribution data of many species is scarce, especially for endangered medicinal plants in the QTP.

In this study, the distribution areas of suitable habitats for threatened medicinal plants on the QTP were evaluated on spatial and temporal scales by using the MaxEnt model. And the potential impacts of global

climate change on endangered medicinal plants on the QTP were evaluated for the first time. The main purpose of this study were: (i) identifying the key areas of suitable habitats for the threatened medicinal plants on the QTP and priority areas for conservation; (ii) estimating the influence of climate change on the suitable habitat of the threatened medicinal plants on the QTP region; (iii) determining the migration direction of suitable habitat for the threatened medicinal plants on the QTP; (iv) comparing changes and trends in future suitable habitat among the different threatened medicinal plants.

2. Results

2.1. Habitat distribution models for the threatened medicinal plants of the QTP

The ROC results showed that the average training AUC value for the 10-replicate runs in current and future surpassed 0.9 in all the threatened medicinal plants on the QTP. Furthermore, the standard deviation (SD) values of 10 repetition runs remained below 0.06 in all the threatened medicinal plants on the QTP (Fig. 1). These results indicated that the prediction results of MaxEnt model were accurate and reliable. Thus, we could conduct follow-up analysis.

The models for the present scenario properly predicted the known distribution range of all the threatened medicinal plants on the QTP (Fig. 2). As far as CR medicinal plants was concerned, present distribution model predictions result demonstrated that the most suitable habitats for RAL (*Rhodiola alternata*) were similar with the GL (*Gentiana lhasica*), both of which were located in southern and southeast region of QTP, including Shigatse city and Shannan city in Tibet; however, for RAL it was not distributed in the Changdu city of Sichuan Province on the QTP (Fig. 2A-B). In addition, the GL had a larger area of high and medium suitable habitat than the RAL (Table S1). The high suitable habitats of the EN medicinal plants, being different to the CR medicinal plants, preferred to inhabit the eastern region on the QTP (Fig. 2C-D). These areas include Garzê Tibetan Autonomous Prefecture, Ngawa Tibetan Autonomous Prefecture and Maerkang city in Sichuan Province. The high suitable habitats of the VU medicinal plants showed different distribution ranges: FP (*Fritillaria przewalskii*) (Golog Tibetan Autonomous Prefecture in Qinghai Province, Hezuo city in Gansu Province and Maerkang city in Sichuan Province) and RT (*Rheum tanguticum*) were located in the eastern region on the QTP (Golog Tibetan Autonomous Prefecture in Qinghai Province) (Fig. 2E-F), while ABR (*Arenaria brevipetala*) mainly distributed in southeast and southern region on the QTP (Shannan and Changdu city in Tibet, Garzê Tibetan Autonomous Prefecture, Liangshan yi autonomous prefecture and Ngawa Tibetan Autonomous Prefecture in Sichuan Province) (Fig. 2G), and FD (*Fritillaria delavayi*) was found in southern region on the QTP (Garzê Tibetan Autonomous Prefecture and Liangshan yi autonomous prefecture in Sichuan Province) (Fig. 2H). It was worth noting that ABR (*A. brevipetala*) had the largest area, $34.5 \times 10^4 \text{ km}^2$, of high suitable habitat in the threatened medicinal plants (Table S1). Similarly, it had the largest combined area of high and medium suitable habitat. Notably, the RAL (*R. alternata*) had the minimum area, only $8.2 \times 10^4 \text{ km}^2$ and $17.7 \times 10^4 \text{ km}^2$, of high and medium suitable habitat among the threatened medicinal plants (Table S1).

Among the NT medicinal plants, the largest combine area of high and medium suitable habitat was found in RAN (*Rhododendron anthopogonoides*), with an area of $395.3 \times 10^4 \text{ km}^2$ (Fig. 2K & Table S1). And it was mainly found in the eastern, southeastern and southern regions of the QTP, containing Yushu Tibet Autonomous Prefecture in Qinghai Province, Shangri-la city in Yunnan Province, Changdu city and Linzhi city in Tibet and most of region in Sichuan Province. NI (*Notopterygium incisum*) had the second largest combined area of high and medium suitable habitat, with an area of $293.5 \times 10^4 \text{ km}^2$, which mainly distributed in the eastern and southeastern regions of the QTP, including Haidong city, Haibei city, Huangnan Tibetan Autonomous Prefecture and Golog Tibetan Autonomous Prefecture in Qinghai Province, Gannan Tibetan Autonomous Prefecture in Gansu Province and Garzê Tibetan Autonomous Prefecture, Ngawa Tibetan Autonomous Prefecture in Sichuan Province. The high and medium suitable habitats of AB (*Aconitum brunneum*) were located at eastern region of the QTP, including Gannan Tibetan Autonomous Prefecture in Gansu Province and Ngawa Tibetan Autonomous Prefecture in Sichuan Province. The combined area of high and medium suitable habitat of AE (*Androsace elatior*) was the smallest, only $25.7 \times 10^4 \text{ km}^2$, and it was found sporadically on Garzê Tibetan Autonomous Prefecture, Ngawa Tibetan Autonomous Prefecture in Sichuan Province.

2.2. Future suitable habitat fluctuations

The results of future climate model prediction showed that the high and medium suitable habitats of GL, RAL, FU, NI and AB expanded in all future climate scenarios with global warming by comparison with contemporary prediction results (Fig. 3, Figure S1-S7 and Table S1). Among these medicinal plants, the maximum increasing of high and medium suitability habitats were found in RAL, and the fluctuation ranges were 231.95% ~ 740.04% and 584.78% ~ 810.43%, respectively (Fig. 3 and Figure S1), both of which reached a maximum in the RCP 8.5 climate scenario of 2070 (Fig. 3 and Figure S1). Notably, the high suitability habitats of LA decreased 48.60% in the RCP8.5 climate scenario of 2070, however, in other future climate scenarios it increased, and reached a maximum of 83.66% in the RCP6.0 in 2050 (Fig. 3-B). In addition, high suitability habitats for 25% threatened medicinal plants had a decreased in all future climate scenarios, including FP, RT and RAN (Fig. 3). Among these medicinal plants, the high suitable habitat of FP had the largest decrease, and it achieved a maximum of 97.1% in the RCP 8.5 climate scenario of 2070 (Fig. 3-F). The medium suitable habitats only for LA had a decreased in all future climate scenarios, with the maximum decrease area of habitat of 74.7% in RCP8.5 of 2070 climate scenarios (Figure S1-F). The high and medium suitable habitat of the remaining medicinal plants decreased or increased in different future climate scenarios (Fig. 3 and Figure S1-S7).

2.3. Future migratory trends of the threatened medicinal plants

Barycenter results of the threatened medicinal plants indicated that the GL, LA, FU, RT, FD and NI were likely to migrate northward in the future climatic scenario of global climate change (Fig. 4A, C, D, F, H and I). On the contrary, the FP, AB and RAN were inclined to migrate southward in the future distribution model. And, the barycenter of RAL had a trend of eastward migration (Fig. 4B), whereas the barycenter of

ABR tend to migrate westward in the future climatic scenario of global climate change (Fig. 4G). Distance of barycenter migration results indicated that the maximum migration distance of CR medicinal plants were 82 Km and 193 Km, respectively (Table S2). The maximum migration distance of EN medicinal plants were 93 Km and 127 Km, separately (Table S2). As far as VU medicinal plants were concerned, the maximum migration distance of FP, RT, ABR and FD were 83 Km, 166 Km, 68 Km and 69 Km, respectively. Furthermore, the NI, AB, RAN and AE in NT medicinal plants had a maximum migration distance of 378 Km, 121 Km, 367 Km and 101 Km, separately (Table S2). In addition, the elevation of barycenter of LA, FP, RT, ABR, FD, AB and AE were persistently increased due to future climate change (Fig. 5). And the FU had a consistently decrease of elevation of barycenter in all future climate scenarios. The elevation of barycenter of the remaining threatened medicinal plants showed increase and decrease in different future climate scenario (Fig. 5).

3. Discussion

3.1. Threatened medicinal plants distribution and habitat fluctuations

Combined Maxent model with GIS technology, we predicted potential distribution areas of 12 endangered medicinal plants, and we obtained the spatial distribution pattern and distribution suitability of 12 endangered medicinal plants endemic to the QTP. The AUC values of the models were all more than 0.9, which proved that the prediction results were accurate and could accurately reflect the potential geographical distribution of 12 endangered medicinal plants endemic to the QTP. The results of present suitable habitat distribution models indicated that the low suitability and unsuitability habitats of the threatened medicinal plants were mainly found in the western, northern, northwestern and most part of the central regions on the QTP, while the habits with high and medium suitability were mainly located at the eastern, southeast, southern and some part of the central regions on the QTP. Previous research indicated that the diversity of medicinal plants on the QTP was mainly concentrated in the eastern and southeastern regions, including northwest Yunnan, western Sichuan, and eastern and southeastern Tibet [27–30], which was basically consistent with our results. The rich medicinal plant diversity resources in the eastern and southeastern Tibetan Plateau can be attributed to the complex topographic and geomorphic features [31–32], adequate hydrothermal conditions[33], and the relatively stable environment during the ice age in this region compared to the inland regions. Therefore, we proposed to establish protected areas in eastern, southeast and southern regions on the QTP, using the limited protected areas to maximize the protection of more species.

Climate change plays an important role in species distribution. Temperature and precipitation are the main factors that determine the geographical distribution, growth and reproduction of species. Rising temperatures, changes in water conditions, and extreme climate events have caused widespread impacts on biodiversity and species distribution patterns [34–37]. At different time periods in the future, the distribution pattern of most plants and animals in the world show a clear trend of migration from low

latitude and low altitude areas to high latitude and high-altitude areas, accompanied by varying degrees of reduction or expansion [38, 39]. Compared with the present, the potential habitat areas of GL, RAL, FU, NI and AB on the QTP show an overall trend of expansion in the future. By comparing the terrain characteristics, it was found that the expanded suitable habitats were all located in higher altitude mountainous areas. This may be due to climate warming increasing the species richness in the original habitats of these five medicinal plants, resulting in niche overlap and interspecific competition promoting their migration to higher mountainous areas. This is similar to the research results of Jump et al. [40] and Engler et al. [41]. In addition, under future climate change scenarios, the potential suitable habitats for FP, RT, and RAN are generally showed a decreasing trend, indicating that climate warming will pose a threat to the habitats of these species in the future. Consequently, we considered that the FP, RT and RAN deserved more protection and attention under the global change.

3.2. Trend in migration of barycenter

The results of migration of barycenter showed that about 50% of the threatened medicinal plants on the QTP had a northward migration trend in response to climate change. Meanwhile, the results of barycenter elevation indicated that 58.33% of the threatened medicinal plants on the QTP had a tendency to migrate to higher altitudes in order to alleviate the pressure of climate change. Under different climatic scenarios, the FP and AN of threatened medicinal plants on the QTP tended to continually migrate to lower latitudes. However, in different climate scenarios both of them had an increasing elevation barycenter. We hypothesize that the FP and AN were mainly mitigating the effects of global warming on themselves by moving to higher altitudes. In addition, in the future scenario, the LA, RT and FD have a tendency to migrate to high latitude and high altitude. More and more studies have shown that the distribution pattern of most plants and animals in the world would obviously move from low latitude and low altitude areas to high latitude and high-altitude areas in different time periods in the future. Our findings on endangered medicinal plants on the QTP confirm this perspective. Climate warming has obviously affected the number of plant populations, and the migration of species distribution has led to a decrease in biodiversity at low altitudes and low latitudes, increasing the competition among species at high altitudes and high latitudes, and further increasing the risk of extinction of endangered plants.

In summary, the determination of potential habitats for endangered medicinal plants is of great significance for the collection of wild excellent medicinal provenances and their biological research, and provides basic data for an accurate and comprehensive understanding of the distribution and resource reserves of endangered medicinal plants. The high suitability and suitability areas of 12 endangered medicinal plants can be used as key planning and development areas for the cultivation and planting of endangered medicinal plants in the future. However, this article only used climate factors, soil variables and topographical to simulate the potential geographical distribution areas of the species, and the results obtained may not be suitable for the survival of the species in some areas. In the actual application process, guidance should still be given based on the local hydrological and geological conditions. In future research, more environmental factors such as human interference factors, soil physical and chemical properties, and vegetation type data can be attempted to be added, then conduct on-site

experiments at a small scale to better guide its protection, management, and introduction and cultivation. In addition, this article only selected 12 endangered plants as the research object. It is not yet known whether the potential geographical distribution trend of all endangered plants under future climate change conforms to this law. In the future, more rare and endangered plants need to be added for verification to confirm the universality of the research results.

4. Materials and Methods

4.1. Occurrence records of the threatened medicinal plant on the QTP

In this study, 12 native threatened medicinal plants on the QTP were used by consulting the books and database such as “Flora Qinghaiica”, “Flora of Tibet”, “List of rare and endangered plants in China”, “Chinese Red List of species”, “List of wild plants under State Key Protection (the first batch)”, The IUCN red list of threatened species (<https://www.iucnredlist.org/>), China wild plant conservation association, <https://www.wPCA.org.cn/bhtml>. Then, these 12 medicinal plants were divided into Critically Endangered (CR), Endangered (EN), Vulnerable (VU) and Near Threatened (NT) levels according to the record of the International Union for Conservation of Nature (IUCN) Red List of Endangered Species (Table 1). Since the NT species is close to or likely to become a threatened category not long in the future, it is included. Organism photographs in the flowering stage of 12 native threatened medicinal plants on the QTP were shown in Fig. 6.

Table 1
The endangered status of the threatened medicinal plants on the QTP.

Abbreviated	Scientific Name	Family Name	Order Name	IUCN Level
GL	<i>Gentiana lhasica</i>	Gentianaceae	Contortae	CR
RAL	<i>Rhodiola alterna</i>	Crassulaceae	Rosales	CR
LA	<i>Lomatogoniopsis alpina</i>	Gentianaceae	Contortae	EN
FU	<i>Fritillaria unibracteata</i>	Liliaceae	Liliales	EN
FP	<i>Fritillaria przewalskii</i>	Liliaceae	Liliales	VU
RT	<i>Rheum tanguticum</i>	Polygonaceae	Caryophyllales	VU
ABR	<i>Arenaria brevipetala</i>	Caryophyllaceae	Caryophyllales	VU
FD	<i>Fritillaria delavayi</i>	Liliaceae	Liliales	VU
NI	<i>Notopterygium incisum</i>	Apiaceae	Apiales	NT
AB	<i>Aconitum brunneum</i>	Ranunculaceae	Ranunculales	NT
RAN	<i>Rhododendron anthopogonoides</i>	Ericaceae	Ericales	NT
AE	<i>Androsace elatior</i>	Primulaceae	Primulaceae	NT

The date on the locations of 12 threatened medicinal plants were acquired from field investigation reports from the last 30 years, principally in the specimen libraries, e.g. Chinese Virtual Herbarium(<http://www.cvh.ac.cn/>), Global Biodiversity Information Facility (<https://www.gbif.org/>), China National Specimen Information Infrastructure (<http://www.naii.org.cn>), and the reports in literatures. The total occurrence records for these 12 species are 38, 17, 34, 33, 110, 25, 59, 26,72, 64, 37 and 27, respectively (Table S3). We then used ENMTools.pl (<https://github.com/danlwarren/ENMTools>) to clip occurrence points in order to only one observation was reserved in each 30s grid cell (according with the environment variable data below), to reduce the sampling bias of the data. Finally, all the remaining occurrence records were applied for the ecological niche modeling (ENM) (Table S4).

4.2. Climate Data Collection and Environmental Variables

The correlation and completeness of variables are the key elements of constructing ENM. In this study, we chose three types of environmental variables, including bioclimatic, soil variables and topographical (Table 2). Nineteen bioclimatic and altitude variables were downloaded from WorldClim 1.4 (<https://worldclim.org>) for the current period (1960–1990) at a spatial resolution of 30 arc-seconds (approximately 1 km). Another two topographical variables (slope and aspect) were obtained from Digital Elevation Model using the 3D analyst tools in the software ArcGIS 10.4. We downloaded the eight soil variables from the National Tibetan Plateau Data Center (<https://data.tpdc.ac.cn/zh-hans/>) based on previous studies [42–44]. Furthermore, the old WorldClim version 1.4 (<https://worldclim.org/>) was used to obtain projected future climate data. The average values of representative concentration pathways

(RCPs) under the future Community Climate System Model (CCSM) were selected to predict the suitable area changes in 2050 and 2070. RCPs include RCP4.5 and RCP6.0 (medium greenhouse gas emissions), and RCP8.5 (high greenhouse gas emissions) [45]. However, the available data on the other two types of environmental variables (soil variables and topographical variable) were lack for the future periods according with the same periods. The 12 species are relatively less affected by topography and soil because they are chiefly located in the mountain areas. Therefore, we assumed that these two types of environment variables were constant, as reported in previous studies [46–48].

Table 2

Environmental indicators used in this paper to model the potential distribution of 12 threatened medicinal plants. There are 8 soil and 3 terrain indicators, and 19 bioclimatic indicators.

Index	Name	Mean	Unit
Bioclimatic variables	Bio1	Annual Mean Temperature	°C
	Bio2	Mean Diurnal Range	°C
	Bio3	Isothermality (Bio2 /Bio7) (× 100)	°C
	Bio4	Temperature seasonality (Standard deviation × 100)	CovfV
	Bio5	Max Temperature of Warmest Month	°C
	Bio6	Min Temperature of Coldest Month	°C
	Bio7	Temperature Annual Range	°C
	Bio8	Mean Temperature of Wettest Quarter	°C
	Bio9	Mean Temperature of Driest Quarter	°C
	Bio10	Mean Temperature of Warmest Quarter	°C
	Bio11	Mean Temperature of Coldest Quarter	°C
	Bio12	Annual Precipitation	mm
	Bio13	Precipitation of Wettest Month	mm
	Bio14	Precipitation of Driest Month	mm
	Bio15	Precipitation Seasonality	mm
	Bio16	Precipitation of Wettest Quarter	mm
	Bio17	Precipitation of Driest Quarter	mm
	Bio18	Precipitation of Warmest Quarter	mm
	Bio19	Precipitation of Coldest Quarter	mm
Terrain variables	ASL	Elevation	m
	SLOP	Slope	°
	ASPE	Aspect	°
Top soil variables	PH	Top soil pH (H ₂ O)	Log(H ⁺)
	AN	Available nitrogen	mg/kg
	AK	Available potassium	mg/kg
	AP	Available phosphorus	mg/kg

Index	Name	Mean	Unit
	TN	Total nitrogen	mg/L
	TK	Total potassium	mg/L
	TP	Total phosphorus	mg/L
	Som	Soil organic matter	g/kg

In order to decrease the autocorrelation between the variable data, ArcGIS software was applied to upload all of the variable data and to execute Pearson correlation analysis on variables by multivariate and band collection statistics [49]. For the factor of phase coefficient $|R| > 0.8$ between variables (Fig. 7), on the basis of the contribution rate of each environmental variable to the MaxEnt model and the replacement important value, the variables with a larger contribution rate and replacement important value give preference to take part in MaxEnt modeling and prediction, to avoid overfitting [50]. Therefore, different variables were used as the environmental variables for building the distribution model of 12 threatened medicinal plants (Table S5).

4.3. Optimization of Model Parameters

The regularization multiplier and feature class are the two most important parameters for establishing the species distribution model using the MaxEnt version 3.4.4 software. Therefore, we adopted the Kuenm package (<https://github.com/marloncobos/kuenm>) to optimize these two parameters in the R version 3.6.3 software [51]. In the modeling, we used 75% of the data as the training set. A total of 1240 candidate models, with parameters reflecting all combinations of 40 regularization multiplier settings (from 0.1 to 4, the interval is 0.1), and 31 feature class combinations were evaluated [52, 53].

Model selection was prioritized by statistical significance (partial ROC), predictive power (low omission rate), and complexity (AICc value). First, candidate models were screened and those with statistical significance were retained; second, the set of models were simplified using the omission rate criterion (i.e., $< 5\%$ when possible); finally, we selected the models with lowest delta AICc values (< 2) among the significant and low-omission candidate models [51]. The obtained model of each species had different regularization multiplier and feature class parameters (Table 3).

Table 3

The selected regularization multiplier and feature class parameters for the threatened medicinal plants on the QTP.

Abbreviated	Scientific Name	Regularization multiplier	Feature class
GL	<i>Gentiana lhassica</i>	2.7	qpt
RAL	<i>Rhodiola alterna</i>	0.7	lp
LA	<i>Lomatogoniopsis alpina</i>	1.6	t
FU	<i>Fritillaria unibracteata</i>	3.2	qh
FP	<i>Fritillaria przewalskii</i>	2.4	qt
RT	<i>Rheum tanguticum</i>	3.2	lqth
ABR	<i>Arenaria brevipetala</i>	1.9	lqp
FD	<i>Fritillaria delavayi</i>	1.8	qph
NI	<i>Notopterygium incisum</i>	0.7	lq
AB	<i>Aconitum brunneum</i>	2.1	qp
RAN	<i>Rhododendron anthopogonoides</i>	2.8	lqp
AE	<i>Androsace elatior</i>	0.8	lq

4.4. Species Distribution Model

On the base of the relevant parameter ahead, we established the distribution model of the 12 threatened medicinal plants on QTP with MaxEnt version 3.4.4 and projected it to future periods. In present study, we used 75% of the geographic distribution data as train and 25% of the geographic distribution data to validate the model. Our analysis set 10 replicates and 5000 bootstrap iterations, with default settings for the other parameters [52, 54–56]. We used the area under the receiving operator curve (AUC) to estimate model performance [57, 58]. The AUC ranged from 0 to 1. The model with AUC value greater than 0.9 was regarded as excellent [59].

Subsequently, we loaded the arithmetic results from MaxEnt into ArcGIS10.4 to execute suitability classification and visualization and thereby generate the potential distribution of 12 threatened medicinal plants. It was vital to select an applicable threshold when shifting the continuous species suitability prediction results into a Boolean classification of suitable and unsuitable habitats. The maximum test sensitivity plus specificity logistic threshold approach was proved to be superior to other threshold division methods [60]. Then we used the maximum test sensitivity plus specificity threshold as a threshold or “cutoff” value for each scenario, and habitat suitability was divided into four classes: high suitability, moderate suitability, low suitability and unsuitability (Table S6).

4.5. Distribution barycenter migration of threatened medicinal plants

In the case of further investigating the dynamic migration paths of the 12 threatened medicinal plants, we calculated the centroids of the 12 threatened medicinal plants from their current distribution to their future distribution by using a Python-based SDM toolbox [61]. The analysis centralized the species distribution into an independent central point and established a vector file depicting the magnitude and direction of changes over time [62]. We observed the distributional shifts by tracking the centroid changes among different SDMs.

5. Conclusion

The conservation of endangered species is based on a systematic understanding of the relationship between the potential geographical range of species and climate change, and the potential geographical range of species under future climate change scenarios. In this study, the suitable habitats for the threatened medicinal plants on the QTP were found in the eastern, southeast, southern and some part of the central regions on the QTP, containing southeastern region in Tibet Province, eastern and central regions in Qinghai Province and northwestern region in Sichuan Province. In addition, 25% of threatened medicinal plants showed a reduction of the area of suitable habitat in different future scenarios. However, the area of suitable habitat of the 41.6% threatened medicinal plants showed an increase on different degrees due to their more responsive ability to respond to environmental stresses. Among these medicinal plants, the most negatively influenced by climate change is FP, which will miss 97.1% of suitable habitat in 2070 when the carbon emissions are at high (RCP8.5). And, the least negative affected by climate change is RAN, whose area of suitable habitat will increase by 740.04% in 2070 when the carbon emissions are at high (RCP8.5). Then, the suitable habitat for 50% of the threatened medicinal plants would migrate to higher altitudes or higher latitudes regions in the climate change future. Based on these findings, in addition to controlling greenhouse gas emissions, we appealed that the endangered species on the QTP with the reduction of the area of suitable habitat should be given more attention in the conservation measures.

Declarations

Authorship contribution: **Lucun Yang:** Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Xiaofeng Zhu:** Software, Investigation. **Wenzhu Song:** Investigation, Data curation. **Xingping Shi:** Investigation. **Xiaotao Huang:** Supervision, Writing – review & editing.

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Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Ethical guidelines

Not applicable

References

1. Jiang X, Ni J. Species-climate relationships of 10 desert plant species and their estimated potential distribution range in the aridlands of northwestern China. *Chin J Plant Ecol.* 2005; 29(1): 98-107. <https://doi.org/10.17521/cjpe.2005.0013>
2. Wang J, Ni J. Review of modelling the distribution of plant species. *Chin J Plant Ecol.* 2006; 30(6):1040-1053. <https://doi.org/10.17521/cjpe.2006.0133>
3. Hartmann DL, Klein Tank AMG, Rusticucci M. Chapter 2: observations: atmosphere and surface[R]//Stocker TF, Qin D, Plattenr GK, et al. IPCC, 2013: climate change 2013: the physical science basis. Contribution of Working Group to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press 39.
4. Sharma E, Chettri N, Tsering K. et al. Climate change impacts and vulnerability in the eastern Himalayas. Kathmandu: International Centre for Integrated Mountain Development, 2009.
5. Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE. Extinction risk from climate change. *Nature.* 2004, 427:145-148. <https://doi.org/10.1038/nature02121>
6. Menges ES. Population viability analysis for an endangered plant. *Conserv Biol.* 1990; 4(1): 52-62. <https://doi.org/10.1111/j.1523-1739.1990.tb00267.x>
7. Zhang WJ, Chen JK. Research progress of species distribution. *Biodiversity.* 2003; 11(005): 364-369.
8. Leroy B, Paschetta M, Canard A, Bakkenes M, Isaia M, Ysnel F. First assessment of effects of global change on threatened spiders: potential impacts on *Dolomedes plantarius* (Clerck) and its conservation plants. *Biol Conserv.* 2013; 161 (5):155-163 <https://doi.org/10.1016/j.biocon.2013.03.022>

9. Elith J, Graham CH, Anderson RP, Dudík M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manion G, Moritz C, Nakamura M, Nakazawa Y, Overton JMM, Peterson AT, Phillips SJ, Richardson K, Scachetti-Pereira R, Schapire RE, Soberón J, Williams S, Wisz MS, Zimmermann NE. Novel methods improve prediction of species' distributions from occurrence data. *Ecography*. 2006; 29(2):129-151. <https://doi.org/10.1111/j.2006.0906-7590.04596.x>
10. Zhang Q, Shen X, Jiang X, Fan T, Liang X, Yan W. MaxEnt Modeling for Predicting Suitable Habitat for Endangered Tree *Keteleeria davidiana* (Pinaceae) in China. *Forests*. 2023; 14: 394. <https://doi.org/10.3390/f14020394>.
11. Zhang H, Zhao HX. Study on rare and endangered plants under climate: maxent modeling for identifying hot spots in northwest China. *Cerne*. 2001; 27: e-102667. <https://doi.org/10.1590/01047760202127012667>
12. Abdelaal M, Fois M, Fenu G, Bacchetta G. Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crep. in Egypt. *Ecol Inform*. 2019; 50: 68-75. <https://doi.org/10.1016/j.ecoinf.2019.01.003>
13. Gao XX, Liu J, Huang ZH. The impact of climate change on the distribution of rare and endangered tree *Firmiana kwangsiensis* using the Maxent modeling. *Ecol Evol*. 2022; 12(8): e9165. <https://doi.org/10.1002/ece3.9165>
14. Ma SM, Zhang ML. Phylogeography and conservation genetics of the relic *Gymnocarpos przewalskii* (Caryophyllaceae) restricted to northwestern China. *Conserv Genet*. 2012; 13: 1531-1541. <http://doi.10.1007/s10592-012-0397-z>.
15. Li GD, Xiong Y, Zhong XM, Song DD, Kang ZJ, Li DJ, Tang JH, Wang YP, Wu L. Changes in overwintering ground of small yellow croaker (*Larimichthys polyactis*) based on MaxEnt and GARP models: A case study of the southern Yellow Sea stock. *J Fish Biol*. 2023;102(6):1358-1372. <https://doi.org/10.1111/jfb.15383>.
16. Semwal DP, Pandey A, Gore PG, Ahlawat SP, Yadav SK, Kumar AV. Habitat prediction mapping using BioClim model for prioritizing germplasm collection and conservation of an aquatic cash crop 'makhana' (*Euryale ferox* Salisb.) in India. *Genet Resour Crop Evol*. 2021; 68: 3445-3456. <https://doi.org/10.1007/s10722-021-01265-7>
17. Phillips SJ, Dudík M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography*. 2008; 31(2):161-175. <https://doi.org/10.1111/j.0906-7590.2008.5203.x>
18. Warren DL, Seifert SN. Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecol Appl*. 2011; 21(2):335-342. <https://doi.org/10.1890/10-1171.1>.
19. Pan BT, Li JJ. Qinghai-Tibetan Plateau: A Driver and Amplifier of the Global Climatic Change. III. The effects of the uplift of Qinghai-Tibetan Plateau on Climatic Changes. *J Lanzhou Univ (Med Sci)*. 1996; 32(1):108-115. <http://doi.org/10.13885/j.issn.0455-2059.1996.01.024>

20. Yao T, Thompson LG, Mosbrugger V, Zhang F, Ma Y, Luo T, Xu B, Yang X, Joswiak DR, Wang WJED. Third pole environment (TPE). *Environ Develop.* 2012; 3: 52-64.
<https://doi.org/10.1016/j.envdev.2012.04.002>
21. Yao T, Thompson L, Chen D, Zhang Y, Wang N, Zhao L, Che T, Xu B, Wu G, Zhang FJB. Third Pole climate warming and cryosphere system changes. 2020; 69, 1.
22. Zhang GQ, Yao TD, Xie HJ, Yang K, Zhu LP, Shum CK, Bolch T, Yi S, Allen S, Jiang LG, Chen WF, Ke CQ. Response of Tibetan Plateau lakes to climate change: trends, patterns, and mechanisms. *Earth Sci Rev.* 2020; 208: 103269. <https://doi.org/10.1016/j.earscirev.2020.103269>
23. Fitzpatrick MC, Gove AD, Sanders ND, Dunn RR. Climate change, plant migration, and range collapse in a global biodiversity hotspot: The *Banksia* (Proteaceae) of Western Australia. *Glob Chang Biol.* 2008; 14:1337-1352. <http://doi.org/10.1111/j.1365-2486.2008.01559.x>
24. Descombes P, Wisz MS, Leprieur F, Parravicini V, Heine C, Olsen S, Swingedouw D, Kulbicki M, Mouillot D, Pellissier L. Forecasted coral reef decline in marine biodiversity hotspots under climate change. *Glob Change Biol.* 2015; 21(7): 2479-2487. <https://doi.org/10.1111/gcb.12868>
25. Allen JL, Lendemer JC. Climate change impacts on endemic, high-elevation lichens in a biodiversity hotspot. *Biodiv Conserv.* 2016; 25(3): 555-568. <https://doi.org/10.1007/s10531-016-1071-4>
26. Pearce J, Boyce M. Modelling distribution and abundance with presence-only data. *J Appl Ecol.* 2006; 43: 405-412. <https://doi.org/10.1111/j.1365-2664.2005.01112.x>
27. Fan Z, Bai X. Scenarios of potential vegetation distribution in the different gradient zones of Qinghai-Tibet Plateau under future climate change. *Sci Total Environ.* 2021; 796:148918.
<https://doi.org/10.1016/j.scitotenv.2021.148918>
28. Xing Y, Shi J, De K, Wang X, Wang W, Ma Y, Zhang H, He M, Liu Q. The Current Distribution of *Carex alatauensis* in the Qinghai–Tibet Plateau Estimated by MaxEnt. *Agronomy.* 2023; 13: 564.
<https://doi.org/10.3390/agronomy13020564>
29. Song D, Li Z, Wang T, Qi Y, Han H, Chen Z. Prediction of Changes to the Suitable Distribution Area of *Fritillaria przewalskii* Maxim. in the Qinghai-Tibet Plateau under Shared Socioeconomic Pathways (SSPs). *Sustainability.* 2023; 15: 2833. <https://doi.org/10.3390/su15032833>
30. Chen K, Wang B, Chen C, Zhou G. MaxEnt Modeling to Predict the Current and Future Distribution of *Pomatosace filicula* under Climate Change Scenarios on the Qinghai-Tibet Plateau. *Plants.* 2022; 11: 670. <https://doi.org/10.3390/plants11050670>.
31. Wu SD, Wang Y, Wang ZF, Shrestha N, Liu JQ. Species divergence with gene flow and hybrid speciation on the Qinghai-Tibet Plateau. *New Phytol.* 2022; 234:392-404. <https://doi.org/10.1111/nph.17956>
32. Li S, Currie BS, Rowley DB, Ingalls M. Cenozoic paleoaltimetry of the SE margin of the Tibetan Plateau: constraints on the tectonic evolution of the region. *Earth Planet Sci Lett.* 2015; 432: 415e424.
33. Favre A, Packert M, Pauls S.U, Jahnig SC, Uhl D, Michalak I, Muellner-Riehl AN. The role of the uplift of the Qinghai-Tibetan Plateau for the evolution of Tibetan biotas. *Bio Rev.* 2015; 90: 236-253.

<https://doi.org/10.1111/brv.12107>

34. Wu JG. The potential effects of climate change on the distributions of 7 plants in China. *Guihaia*. 2011; 31(5):595-607. <http://doi.org/10.3969/j.issn.1000-3142.2011.05.008>
35. Lenoir J, Gégout JC, Marquet PA, Ruffray PD, Brisse H. A Significant Upward Shift in Plant Species Optimum Elevation During the 20th Century. *Science*. 2008; 320:1768-1771. <https://doi.org/10.1126/science.1156831>
36. Hu HW, Wei YQ, Wang WY, Suonan J, Wang SX, Chen Z, Guan JH, Deng YF. Richness and distribution of endangered orchid species under different climate scenarios on the Qinghai-Tibetan Plateau. *Front Plant Sci*. 2022; 13: 948189. <https://doi.org/10.3389/fpls.2022.948189>
37. Ma B, Sun J. Predicting the distribution of *Stipa purpurea* across the Tibetan Plateau via the MaxEnt model. *BMC Ecol*. 2018; 18:10. <http://doi.org/10.1186/s12898-018-0165-0>.
38. Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature*. 2003; 421(6918):37-42. <https://doi.org/10.1038/nature01286>.
39. Root TL, Price J, Hall KR, Schneider SH, Rosenzweig C, Pounds A. Fingerprints of global warming on wild animals and plants. *Nature*. 2003; 421:57-60. <https://doi.org/10.1038/nature01333>.
40. Jump AS, Penuelas J. Running to stand still: adaptation and the response of plants to rapid climate change. *Ecol Lett*. 2005; 8(9): 1010-1020. <https://doi.org/10.1111/j.1461-0248.2005.00796.x>
41. Engler R, Randin CF, Thuiller W, et al. 21st century climate change threatens mountain flora unequally across Europe. *Glob Change Biol*. 2011; 17(7): 2330-2341 <https://doi.org/10.1111/j.1365-2486.2010.02393.x>
42. GuoY, Li X, Zhao Z, Nawaz Z. Predicting the impacts of climate change, soils and vegetation types on the geographic distribution of *Polyporus umbellatus* in China. *Sci Total Environ*. 2019; 648: 1-11. <https://doi.org/10.1016/j.scitotenv.2018.07.465>
43. Li KD, Zhang GF, Zhang Y, Griffith MP. A noteworthy case of rewilding Chinese yew from a garden population in eastern China. *PeerJ*. 2021; 9: e12341. <https://doi.org/10.7717/peerj.12341>
44. Ru WM. Study on the ecology of endangering plant *Taxus chinensis* var. *mairei*. Shanxi University, 2006.
45. Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim Change*. 2011; 109: 77-94. <https://doi.org/10.1007/s10584-011-0151-4>
46. Evans A, Janssens S, Jacquemyn H. Impact of climate change on the distribution of four closely related Orchis (Orchidaceae) species. *Diversity*. 2020; 12(8): 312-324. <https://doi.org/10.3390/d12080312>
47. Lv T, Harris AJ, Liu Y, Liu T, Liang R, Ma Z, Su X. Population genetic structure and evolutionary history of *Psammochloa villosa* (Trin.) Bor (Poaceae) revealed by AFLP marker. *Ecol Evol*. 2021; 11(15):10258-10276. <https://doi.org/10.1002/ece3.7831>

48. Zhang ZX, Capinha C, Usio N, Weterings R, Liu X, Li YM, Landeira JM, Zhou Q, Yokota M. Impacts of climate change on the global potential distribution of two notorious invasive cray fishes. *Freshw Biol.* 2019; 65(3): 353-365. <https://doi.org/10.1111/fwb.13429>
49. Narkis MS, Fernandes CI, Victoria BG. MaxEnt's parameter configuration and small samples: Are we paying attention to recommendations? A systematic review. *PeerJ.* 2017; 5: e3093. <https://doi.org/10.7717/peerj.3093>
50. Hill MP, Hoffmann AA, Mccoll SA, Umina PA. Distribution of cryptic blue oat mite species in Australia: Current and future climate conditions. *Agric For Entomol.* 2012; 14: 127-137. <https://doi.org/10.1111/j.1461-9563.2011.00544.x>
51. Cobos ME, Peterson AT, Barve N, Osorio-Olvera L. Kuenm: a R package for detailed development of ecological niche models using Maxent. *PeerJ.* 2019; 7: e6281. <https://doi.org/10.7717/peerj.6281>
52. Phillips SJ, Anderson RP, Schapire RE. Maximum entropy modeling of species geographic distributions. *Ecol Modell.* 2006; 190(3-4):231-259. <https://doi.org/10.1016/j.ecolmodel.2005.03.026>
53. Phillips SJ, Dudík M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography.* 2008; 31(2):161-175. <https://doi.org/10.1111/j.0906-7590.2008.5203.x>
54. Hazzi NA, Moreno JS, Ortiz-Movliav C, Palacio RD. Biogeographic regions and events of isolation and diversification of the endemic biota of the tropical Andes. *Proc Natl Acad Sci USA.* 2018; 115(31): 7985-7990. <https://doi.org/10.1073/pnas.1803908115>
55. Morales NS, Fernández IC, Baca-González V. MaxEnt's parameter configuration and small samples: are we paying attention to recommendations? A systematic review. *PeerJ.* 2017; 5: e3093. <https://doi.org/10.7717/peerj.3093>
56. Radosavljevic A, Anderson RP. Making better MAXENT models of species distributions: complexity, overfitting and evaluation. *J Biogeogr.* 2014; 41(4): 629-643. <https://doi.org/10.1111/jbi.12227>
57. Allouche O, Tsoar A, Kadmon R. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J Appl Ecol.* 2006; 43(6): 1223-1232. <https://doi.org/10.1111/j.1365-2664.2006.01214.x>
58. Swets JA. Measuring the accuracy of diagnostic systems. *Science.* 1988; 240(4857): 1285-1293. <https://doi.org/10.1126/science.3287615>
59. Guisan A, Thuiller W. Predicting species distribution: offering more than simple habitat models. *Ecol Lett.* 2005; 8(9): 993-1009. <https://doi.org/10.1111/j.1461-0248.2005.00792.x>
60. Poirazidis K, Bontzorlos V, Xofis P, Zakkak S, Xirouchakis S, Grigoriadou E, Kechagioglou S, Gasteratos I, Alivizatos H, Panagiotopoulou M. Bioclimatic and environmental suitability models for capercaillie (*Tetrao urogallus*) conservation: Identification of optimal and marginal areas in Rodopi Mountain-Range National Park (Northern Greece). *Glob Ecol Conserv.* 2019; 17: e00526. <https://doi.org/10.1016/j.gecco.2019.e00526>
61. Brown JL. SDMtoolbox: 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->

62. Hu XG, Jin YQ, Wang XR, Mao JF, Li Y. Predicting impacts of future climate change on the distribution of the widespread conifer *platycladus orientalis*. PloS One. 2015; 10(7): e0132326. <https://doi.org/10.1371/journal.pone.0132326>

Figures

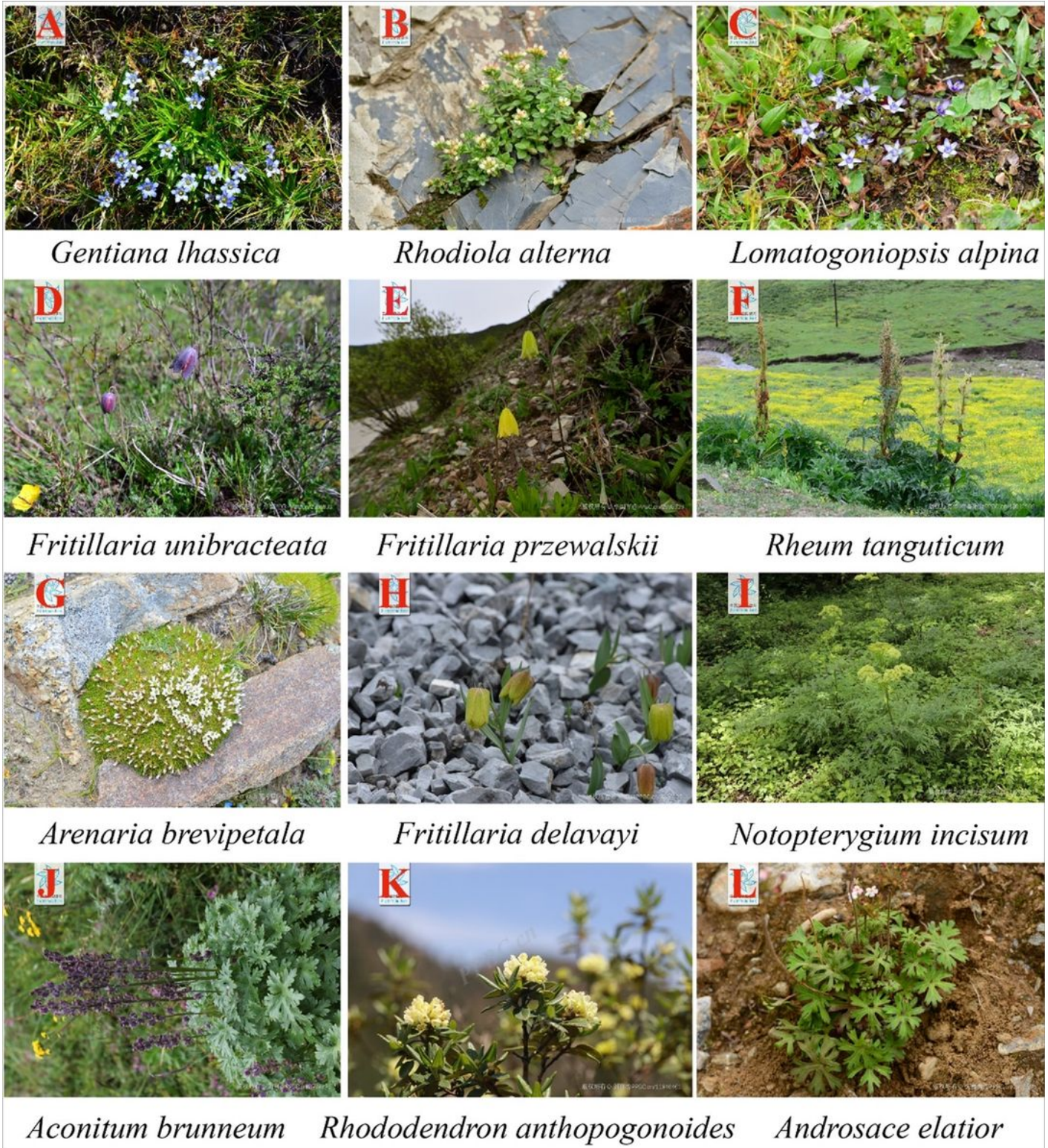


Figure 1

Organism photograph of the 12 threatened medicinal plants on the QTP.

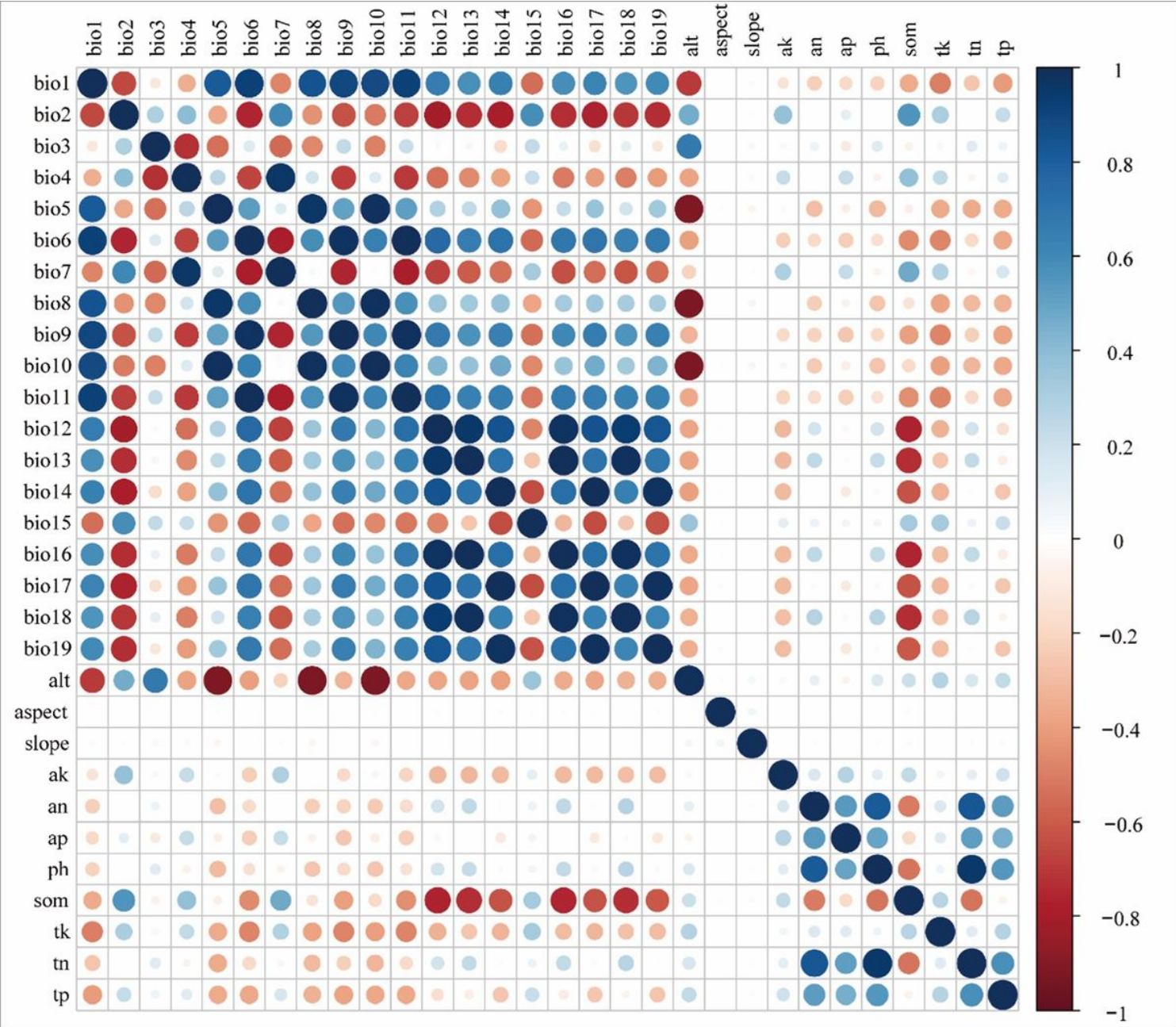


Figure 2

Correlation analysis between variables

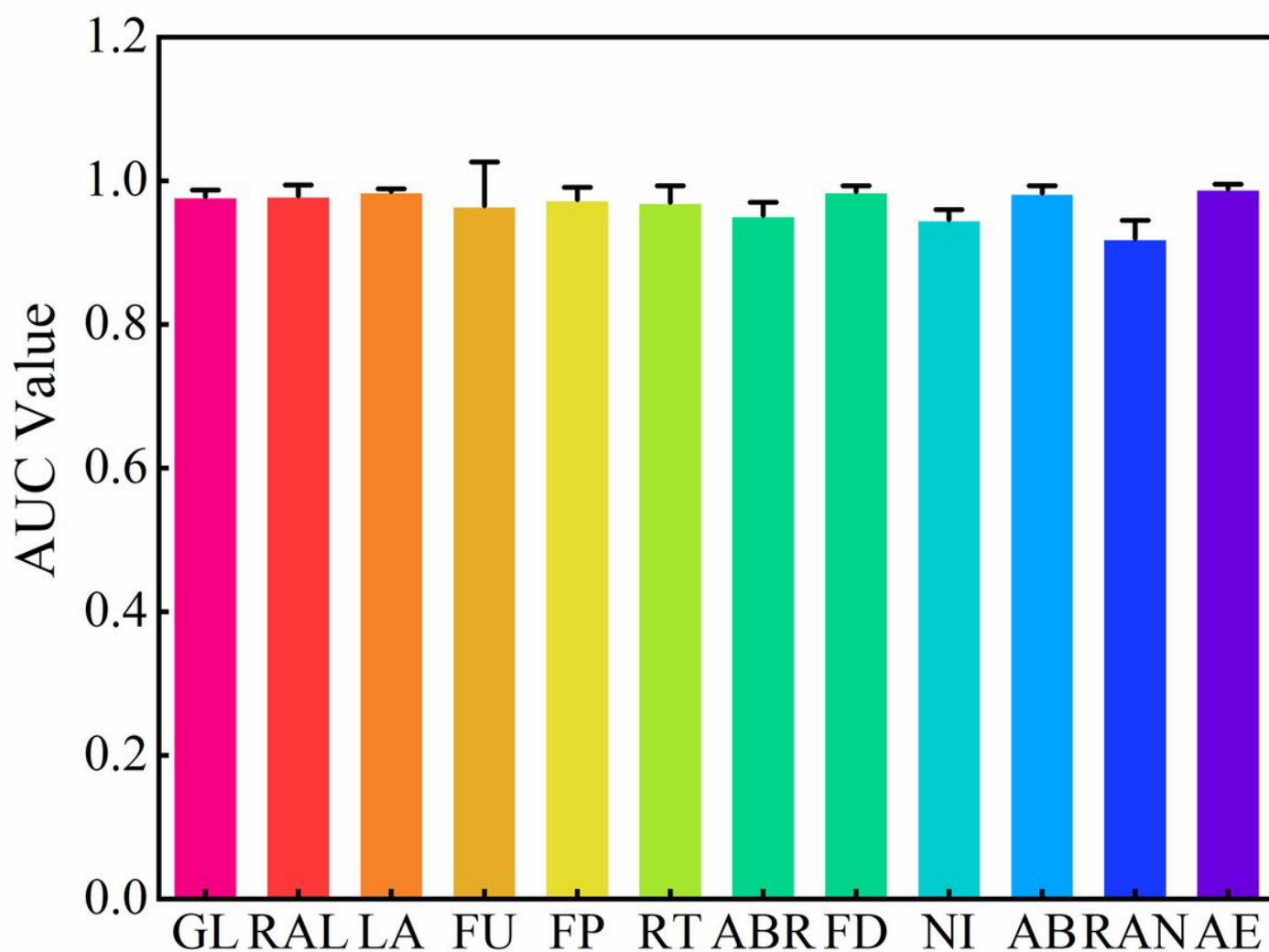


Figure 3

The simulations AUC values of the MaxEnt for the threatened medicinal plants on the QTP.

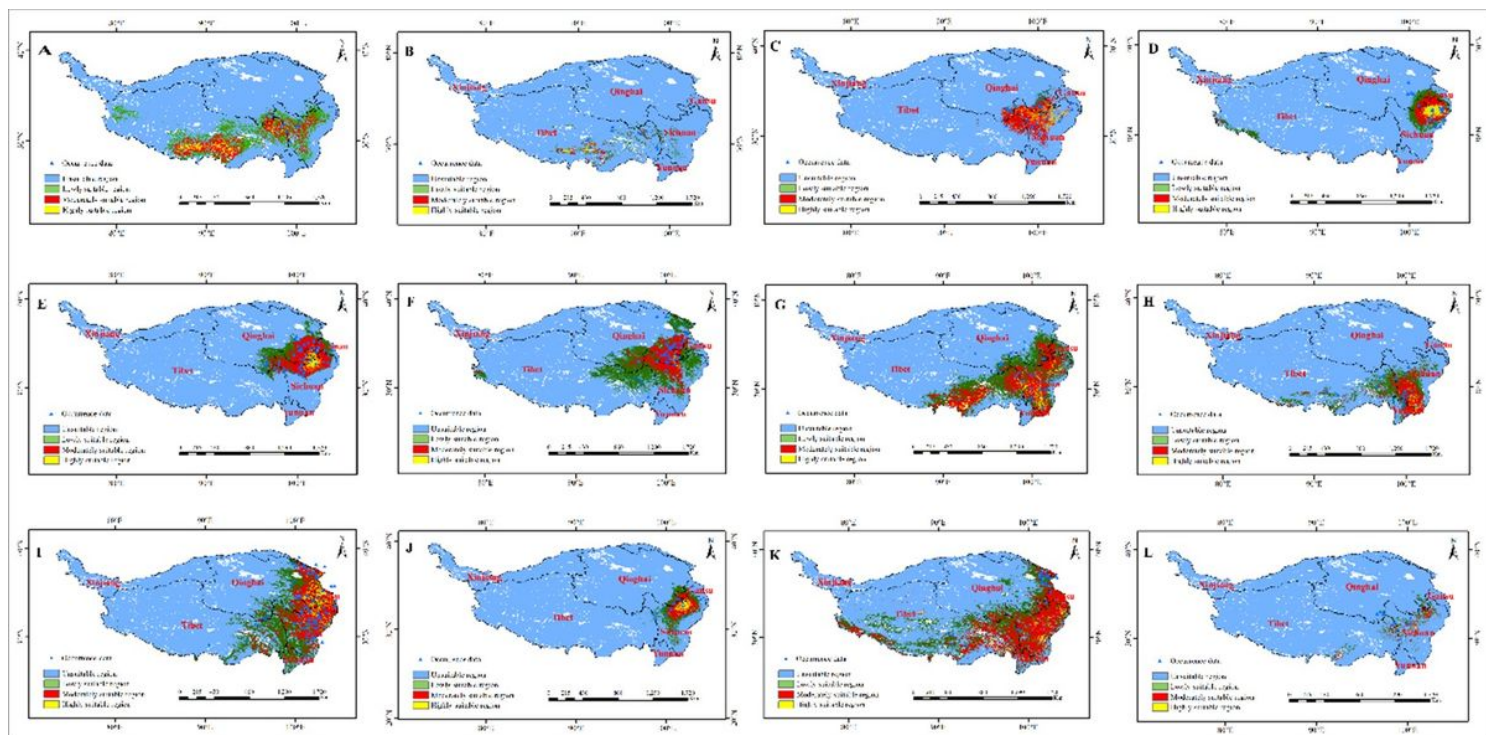


Figure 4

Habitat distribution of the threatened medicinal plants on the QTP. (A) GL; (B) RAL; (C) LA; (D) FU; (E) FP; (F) RT; (G) ABR; (H) FD; (I) NI; (J) AB; (K) RAN; (L) AE

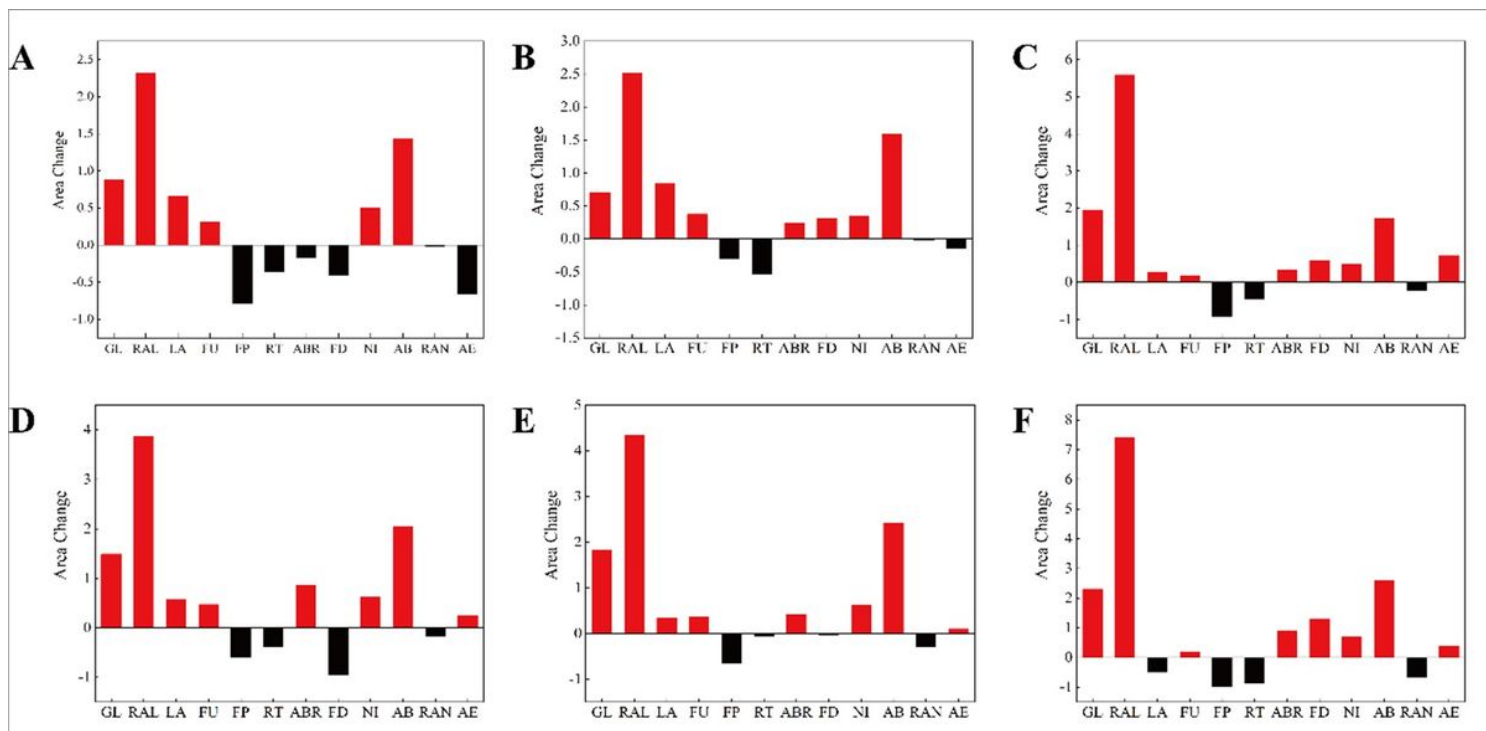


Figure 5

Area changes of high suitable habitat of the threatened medicinal plants in different climate scenarios on the QTP. (A) RCP4.5 climate scenarios in 2050; (B) RCP6.0 climate scenarios in 2050; (C) RCP8.5 climate scenarios in 2050; (D) RCP4.5 climate scenarios in 2070; (E) RCP6.0 climate scenarios in 2070; (F) RCP8.5 climate scenarios in 2070.

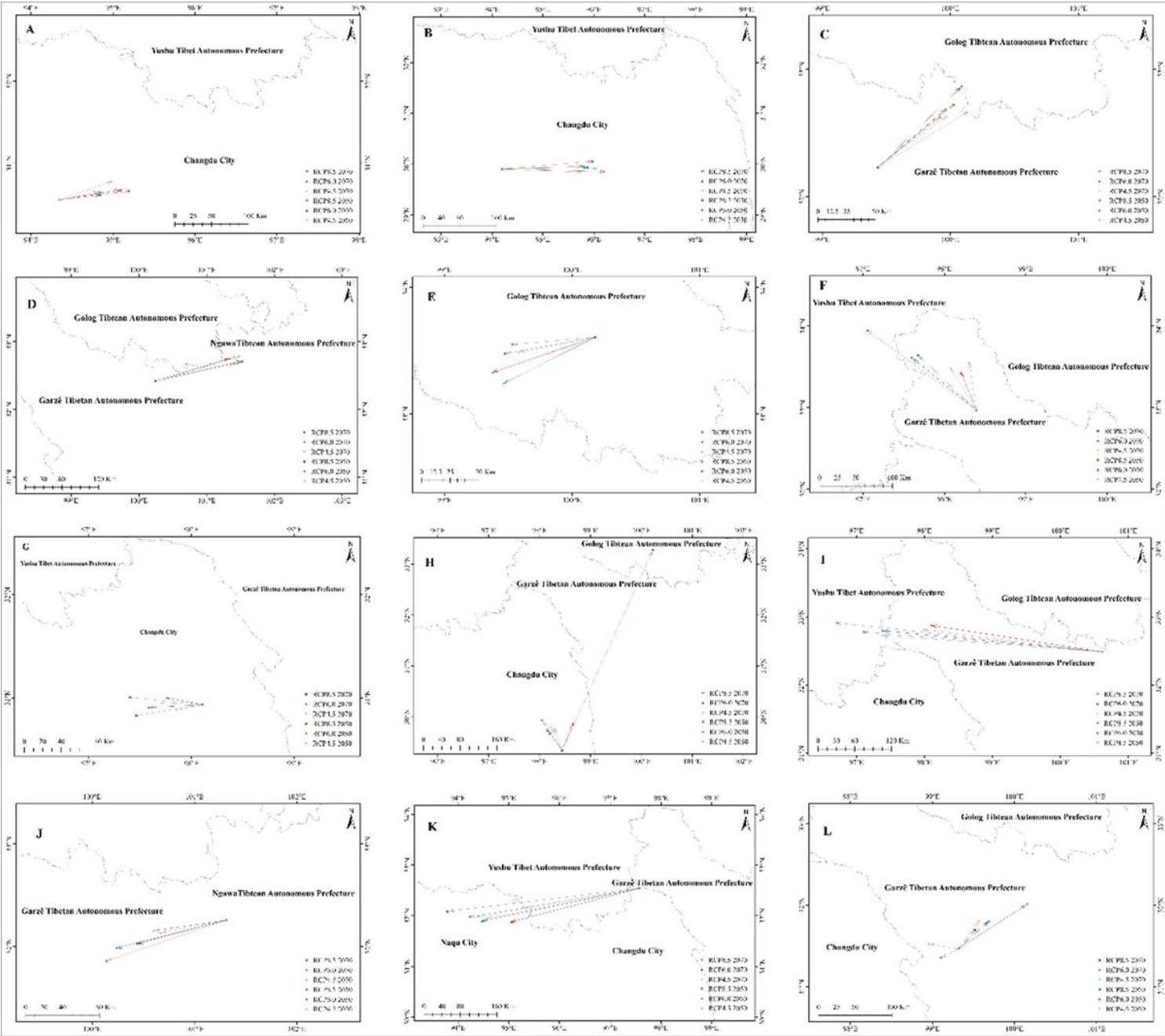


Figure 6

The barycenter migration of the threatened medicinal plants in the future climate scenario.

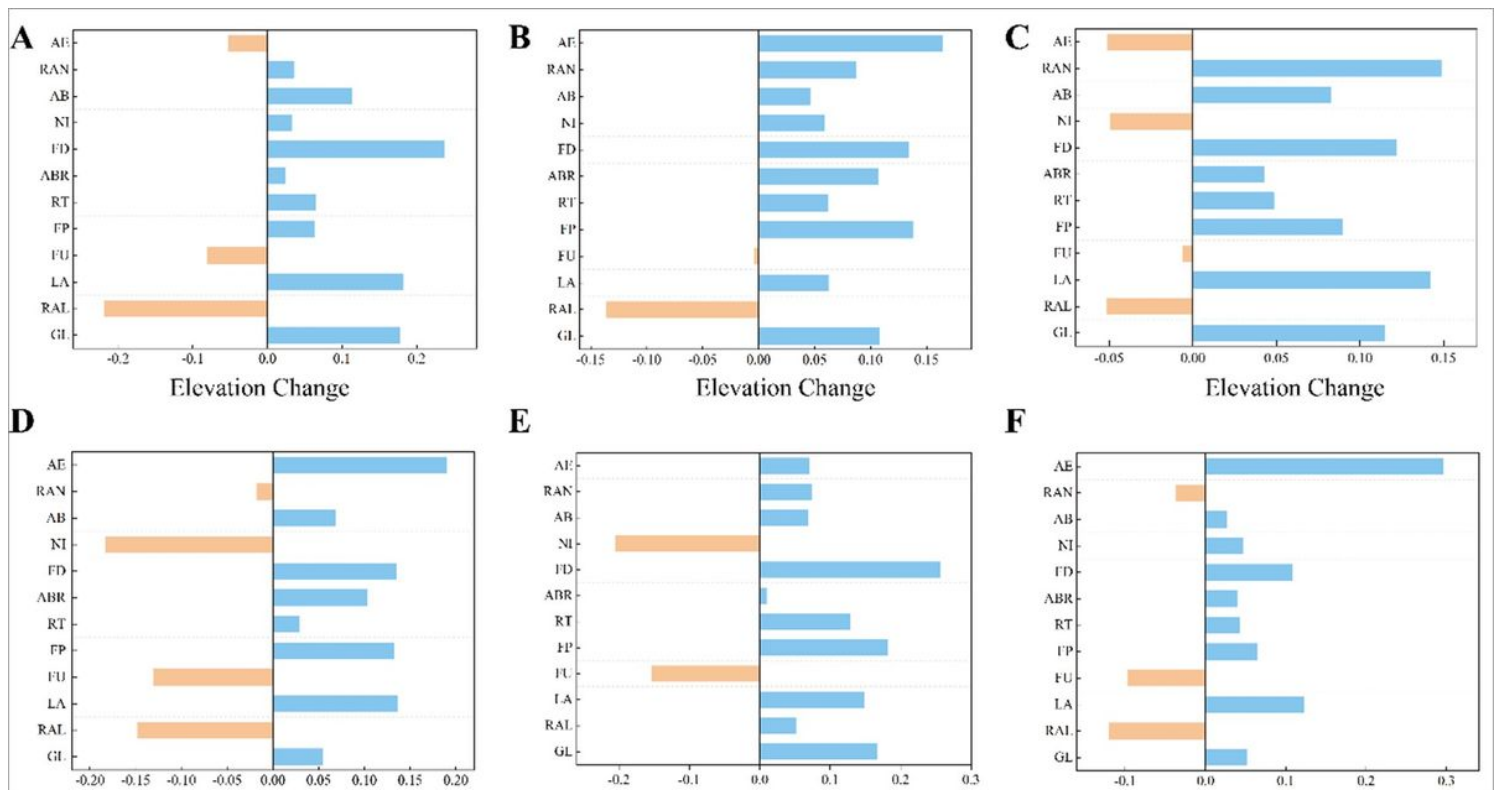


Figure 7

The barycenter elevation change of the threatened medicinal plants on the QTP in the different future climate scenario (A) RCP4.5 climate scenarios in 2050; (B) RCP6.0 climate scenarios in 2050; (C) RCP8.5 climate scenarios in 2050; (D) RCP4.5 climate scenarios in 2070; (E) RCP6.0 climate scenarios in 2070; (F) RCP8.5 climate scenarios in 2070.

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