Simulation of suitable growth areas for the endangered species of Ephedra sinica in China

Minxia Liu (liumx@nwnu.edu.cn)
Northwest Normal University
Le Li
Northwest Normal University
Siyuan Wang
Northwest Normal University
Shirui Xiao
Northwest Normal University
Jiale Mi
Northwest Normal University

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Abstract

Ephedra sinica is a rare and endangered species in China, and the survival environment of *Ephedra sinica* was seriously threatening. Predicting the suitable growth areas and constructing ecological corridors for *Ephedra sinica* in China will help to protect it scientifically. Based on 306 valid distribution records and 13 selected environmental factors, the maximum entropy (MaxEnt) model was used to simulate the current Habitat zones and potential future (2050 and 2070) Habitat zones of *Ephedra sinica* under four change scenarios. The minimum cumulative resistance (MCR) model was applied to extract important ecological corridors of *Ephedra sinica*. The results indicate that: (1) Under the current environment, the total area of the suitable habitat for *Ephedra sinica* in China is 42.24×10^5 km^2, mainly distributed in Northwest China and North China. (2) Future expansion of the suitable area as the RCP (representative concentration pathway) rises. The center of mass of the Habitat zone moved northward from Shaanxi Province to Ordos City in Inner Mongolia Autonomous Region. (3) Of the 13 environmental factors selected, the primary factor was elevation (20.8%), followed by wettest month precipitation (18.2%) and temperature seasonality (15.2%). (4) Nineteen ecological corridors have been constructed, with a total corridor length of 430.2km, including seven long-distance passages and 12 short-distance corridors. All galleries are far from the artificial surface, mostly near high-altitude areas. In addition, the minimum cost distance has a good continuity within Ulanqab City, which can realize the connection between the Huitengxile grassland in the northwest of Ulanqab City and the Sumu Mountain Forest Park area in the southwest.

1. Introduction

Environmental change profoundly affects the structure and function of most ecosystems in the biosphere, the composition of biological groups, and species distribution patterns. Plants scattered in higher altitude regions responded more strongly than in lower altitude regions (Srivastava et al., 2020). At the same time, species are losing their original habitats due to the overuse of resources by humans and changes in land use patterns, leading to a decline in species diversity. Therefore, how to take adequate measures to conserve biodiversity has become a focus of attention at home and abroad (Kafash et al., 2022). Due to the uneven distribution of suitable habitats for species and different threat levels, Species distribution hotspot studies have become an approach to maximize the benefits of biodiversity conservation (Mishra et al., 2021).

Species distribution models (SDMs) have become one of the essential methods for identifying species distribution hotspots for research. The species distribution model is based on the geographic location data of the available samples (Camarero et al., 2021), based on a specific algorithm to simulate the ecological niche of the species (Yang et al., 2021), reflecting the habitat adaptation of the species in the form of the probability of future occurrence in this location (Soares et al., 2021). There are various types of species distribution models, among which the maximum entropy model (MaxEnt) and the genetic algorithm for rule set generation (GARP) are more widely used (Xu et al., 2022). MaxEnt model has the advantages of low required sample size, flexible variable processing, sound noise reduction, and high budget accuracy (Runquist et al., 2021). It has recently been widely used in ecology (Phillips et al., 2008).

Habitat is where wild plants and animals live and reproduce and is the basis for their survival and development (Marcillo et al., 2008). Urbanization has led to a series of problems, such as decreasing species numbers, increasing mortality, and decreasing migration rates, causing a decrease in species'genetic diversity (Ramirez et al., 2021). With the continuous development of biodiversity conservation theory and practice, it was found that isolated nature reserves and other ecological reserves could no longer meet the requirements for species conservation. As critical pathways for species life, movement, and migration, ecological corridors promote and maintain connectivity between patches (Moreira et al., 2021), enabling species to move between fragmented habitats through corridors, preventing population isolation, maintaining minimum population size, and conserving biodiversity. Therefore, maintaining connectivity between habitat patches and constructing ecological corridors has become a meaningful way to eliminate habitat fragmentation. Therefore, maintaining connectivity between isolated habitat patches and constructing ecological corridors has become a meaningful way to eliminate habitat fragmentation.

As an endangered species in China, *Ephedra sinica* has an irreplaceable role in maintaining semi-arid regions' ecological stability and security. Due to the frequent occurrence of soil sanding and salinization and river cut-offs caused by irrational irrigation and other agricultural and economic activities, the conservation and restoration of *Ephedra sinica* cannot be delayed (Pinnegar et al., 2021). Previous conservation and restoration efforts of *Ephedra sinica* have focused on studying its physiological indicators (Nzei et al., 2021), population structure, community species diversity, and how to cultivate it in captivity. It ignores the conservation of the current and future habitat in which the *Ephedra sinica* is located and the environment in which it may migrate and does not reflect well the impact of environmental changes on the *Ephedra sinica* (Michelle et al., 2007). Therefore, this study combined the MaxEnt model and the environmental, ecological niche model (ENMTools) to predict the suitable habitat of Chinese *Ephedra sinica* and integrated the climatic conditions, geographical factors, and vegetation cover. The minimum cumulative resistance (MCR) model is used to construct potential ecological corridors for *Ephedra sinica*, providing realistic guidance and essential information for the conservation and habitat reconstruction planning of *Ephedra sinica*.

2. Materials And Methods

2.1 Data sources

2.1.1 Species distribution point data

Species distribution data for *Ephedra sinica* were obtained from the Chinese Virtual Herbarium (CVH; http://www.cvh.ac.cn) and the Global Biodiversity Information Facility (GBIF; http://www.gbif.org). A total of 306 species distribution data are collected. The longitude and latitude of the species were derived using Google Earth. Then the redundant species distribution points were removed using the ENMTools tool (Javier et al., 2013), resulting in 190 valid data for the Chinese National Grade II protected plant *Ephedra sinica* (Fig. 1).

2.1.2 Environment variable data

Modeling of predicted species distributions using bioclimatic variables downloaded from the WorldClim 2.0 database (http://www.worldclim.org/) (Comino et al., 2021). These variables include past climate data (1970–2000) and future climate data (2050:2041–2060, 2070:2061–2080) under four emission models (Table 1) with a resolution of 2.5’ (Schnase et al., 2021). They are increasingly important in predicting climate change and its related research and supporting climate policy decisions. Slope data obtained from the Geospatial Data Cloud (https://www.gscloud.cn/), land use data from the Ministry of Natural Resources (http://wwww.ngcc.cn), and NDVI (vegetation cover) data were downloaded from the Data Center for Resource and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn).

Table 1
Four emission scenarios

Emission	Description
SSP1–2.6	SSP1 (Low forcing scenario) Upgrade to RCP2.6 scenario based on (Radiative forcing reaches 2.6 W/m^2 in 2100)
SSP2–4.5	SSP2 (Medium forcing scenario) Upgrade to RCP4.5 scenario based on (Radiative forcing reaches 4.5 W/m^2 in 2100)
SSP3–7.0	SSP3 (Medium forcing scenario) New RCP7.0 emission path based on (Radiative forcing will reach 7.0 W/m^2 in 2100)
SSP5–8.5	SSP5 (High Forcing Scenario) Upgrade to RCP8.5 scenario based on (SSP5 is the only SSP scenario that can achieve radiative forcing to 8.5 W/m^2 in 2100)

2.2 Research Methodology

2.2.1 ENMTools

ENMTools is used to perform measurements on environmental and ecological niche models, providing additional support for model optimization through software packages that enable a simplified interface for variable selection and the visualization of correlations between predicted values. ENMTools also provides a method to calibrate the model using continuous Boyce measurements to explore the relationship of predictors (Warren et al., 2021). Filtering the collected species points by the buffer method will cause some data to be mistakenly deleted and some redundant data to be incompletely deleted, so the species points are eliminated using the ENMTools tool. ENMTools automatically matches the size of the raster used for analysis and can remove redundant data within the same raster instead of data based on the distance method (Jesse et al., 2015).

2.2.2 Environmental data processing

In this study (Fig. 2), 23 variables were correlated using the ENMTools tool (Rafael et al., 2015) to eliminate environmental variables that did not contribute significantly to the MaxEnt model prediction results. Bivariate variables with correlations greater than 0.9 were eliminated, resulting in the selection of 12 bioclimatic variables (Table 2) and one topographic variable.

Table 2
Environmental data used in the research

Code	Description
Bio1	Annual Mean Temperature (℃)
Bio2	Mean Diurnal Range (Mean of monthly (max temp–min temp)) (℃)
Bio3	Isothermality (BIO2/BIO7) (×100)
Bio4	Temperature Seasonality (standard deviation × 100)
Bio8	Mean Temperature of Wettest Quarter(℃)
Bio9	Mean Temperature of Driest Quarter (℃)
Bio13	Precipitation of Wettest Month (mm)
Bio15	Precipitation Seasonality (Coefficient of Variation)
Bio17	Precipitation of Driest Quarter (mm)
Wind	wind speed ($m \cdot s^{-1}$)
Vapr	water vapor pressure (kPa)
Srad	solar radiation ($kJ \cdot m^{-2} \cdot day^{-1}$)
Elev	Elevation(m)

2.2.3 MaxEnt model

MaxEnt is considered to build some of the best-performing models for forecasting species distribution with limited records (Zhang et al., 2021). From the MaxEnt model, the output map values range from 0 to 1 (0 most petite and one most suitable species probability pixels). In our models, 75% of the occurrence records were used for training, whereas 25% were used for testing the model (Zhao et al., 2021). The background points and the number of iterations were set at no more than 10,000 and 1000, respectively. The ensemble processes were repeated in a ten-fold cross-validation to improve the model's performance. The area under the working characteristic curve (AUC) values of the model's subjects indicate poor prediction at 0.5–0.6, poor prediction at 0.6–0.7, good prediction at 0.7–0.8, good prediction at 0.8–0.9, and greater than 0.9 indicates high prediction confidence (Jz et al., 2021). The evaluation of the model is more objective because the AUC values are not influenced by thresholds (Bellamy et al., 2021). The knife-cut method (folding knife test) was used to determine the weights of each variable affecting the suitable growth area of *Ephedra sinica* (Guga et al., 2021).

2.2.4 Construction of Ephedra sinica Ecological Corridor

Construction of ecological corridors suitable for the dispersal of *Ephedra sinica* using the minimum cumulative resistance model (MCR). The model describes the shortest path or least cost path required to overcome resistance during the movement of a species from the source to the target; the lower the opposition, the easier the ecological flow is to proceed (Li et al., 2015).

(1)Establishment of ecological source sites

Based on the distribution state of the *Ephedra sinica* habitat generated by the maximum entropy model, relatively independent areas in the habitat base data are characterized, classified, and extracted by attributes as individual independent ecological source sites. This paper selected 11 ecological source sites as the basis for subsequent studies.

(2) Ecological resistance surface construction
A resistance gradient was constructed for ephedra populations based on their minimum resistance to spread in the habitat. A total of six resistance levels (1–6) were identified in the study, with the highest resistance level being six and the smallest being 1 (Table 3). The resistance values among the resistance factors were analyzed in combination with statistical analysis software (yaahp) to establish the resistance value correlation matrix. Then the weights of each resistance factor were derived according to the hierarchical analysis model (Lu et al., 2009).

Table 3
Environmental factor resistance value weighting analysis table

Resistance level	DEM	Slope	LUCC	NDVI
1	1258–1738	10–25	grassland	0.16–0.26
2	1738–2100	25–40	woodland	0.1–0.16
3	1000–1258	40–50	wetlands	0.26–0.4
4	2100–2749	0–10	waterbody	0.0-0.1
5	500–1000	50–60	arable land	0.4–0.6
6	1-500	60–69	artificial surface	0.6–0.92

(3) Potential ecological corridor construction

Using each ecological source site as an input element, we generated the ecological cost resistance value required for dispersing the *Ephedra sinica* population in that ecological source site. We then used the cost path tool to generate the minimum resistance path for distributing the ecological source site to the outside.

(4) Extraction of important ecological corridors

The gravity model is used to evaluate the magnitude of the interaction force between the source and the target, and the higher the point represented, the more critical the corridor (Brandao et al., 2015).

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left(\frac{\ln(S_i)}{P_i}\right) \times \left(\frac{\ln(S_j)}{P_j}\right)}{\left(\frac{L_{ij}}{L_{max}}\right)^2} = \frac{{L_{max}}^2 \ln(S_i) \ln(S_j)}{L_{ij}^2 P_i P_j} \quad (1)$$

Where G_{ij} is the interaction force between core plates i and j, the magnitude of this value reflects the importance of potential ecological corridors between ecological corridors. N_i and N_j are the weight values, D_{ij} is the normalized value of potential corridor resistance between two patches i and j, P_i is the patch i resistance value, and S_i is the area of patch i. L_{ij} is the cumulative resistance value of the corridor between patches i and j, and L_{max} is the maximum value of the resistance.

3. Results And Analysis

3.1 Credibility and accuracy of zoning results

The accuracy of the diagnostic test was determined by the area enclosed by the receiver operating characteristic curve (ROC) and the coordinate axis (AUC). The ROC curve was obtained by changing the diagnostic threshold and getting multiple pairs of true and false positive rate values, with the false positive rate as the horizontal coordinate and the actual positive momentum as the vertical coordinate. The highest AUC value was 0.915 based on 229 current distribution records and 13 selected environmental variables (Fig. 3). It indicates that the prediction results of MaxEnt model are accurate and usable with high predictability.

3.2 Ecological suitability zoning in the current environment

Under the current environmental model, the *Ephedra sinica* Habitat zone is mainly distributed to varying degrees along and north of the Qinling-Huaihe River line in China (Fig. 4). The total habitable area is 42.24×10^5 km^2. The low, medium, and high habitable areas account for 22.7%, 50.1%, and 27.2% of the total habitable area, respectively. From the distribution of provinces, the high Habitat zone is concentrated in Gansu, Ningxia, Shaanxi, Shanxi, Hebei, Liaoning, and other provincial administrative regions from east to west. It has a scattered distribution in Xinjiang and Jilin. The middle Habitat zone not only surrounds the high Habitat zone but also expands in size compared to the high Habitat zone. The low Habitat zone is mainly located in the northwest and surrounds the middle and high Habitat zones from both east and west.

3.3 Zoning of ecological suitability under future climate

The future area of suitable area for *Ephedra sinica* increased compared to that of the current period (Table 4), indicating that the future environmental conditions are favorable for *Ephedra sinica* (Fig. 5). The distribution center generally shifted northward from Shaanxi Province to Ordos City in Inner Mongolia Autonomous Region (Fig. 6).

In the SSPs1-2.6 emission scenario, the center of mass is shifted from Yulin City, Shaanxi Province, to Ordos City, Inner Mongolia, with the center of mass is shifted northward as a whole. The area of suitable area will increase by 2.4×10^5 km^2 and 2.64×10^5 km^2 in 2050 and 2070, respectively. *Ephedra sinica* may expand its distribution in Xinjiang and Northeast China while reducing the suitable area in Qinghai Province. Therefore, the appropriate distribution area of *Ephedra sinica* under SSPs1-2.6 emission scenarios gradually expanded over time and migrated in a northern direction overall.

The center of mass of distribution in 2050 and 2070 under SSPs2-4.5 emission scenario are both located in Dalat Banner, Erdos City, Inner Mongolia, and migrate to the northeast and northwest, respectively. under the SSPs3-7.0 emission scenario, the area of suitable habitat increases by 2.59×10^5 km^2 and 2.58×10^5 km^2 in 2050 and 2070, respectively. The SSPs5-8.5 emission scenario shifts the center of mass northward and increases the area of *Ephedra sinica* suitable area in 2050 and 2070 compared to the suitable area in the current climate scenario.

Table 4
The change of the suitable area for *Ephedra sinica* under different climate change scenarios (10^5 km^2)

Period	range expansion	no change	range contraction
2050s, SSPs1-2.6	3.6	10.3	1.2
2050s, SSPs2-4.5	4.07	10.39	1.08
2050s, SSPs3-7.0	3.56	10.5	0.97
2050s, SSPs5-8.5	3.87	10.45	1
2070s, SSPs1-2.6	3.73	10.37	1.09
2070s, SSPs2-4.5	3.73	10.35	1.11
2070s, SSPs3-7.0	3.56	10.49	0.98
2070s, SSPs5-8.5	3.84	10.24	1.23

3.4 Ecological characteristics of distribution zones

Environmental factors significantly influencing the distribution range of *Ephedra sinica* (Fig. 7): Elevation contribution was 20.8%; wettest monthly precipitation (bio13) was 18.2%; temperature seasonality (bio4) was 15.2%; driest quarterly average temperature (bio9) and driest quarterly precipitation (bio17) were both 12.1%. None of the remaining factors contribute more than 10%. The results of the knife-cut test showed (Fig. 8) that the three environmental factors that had the greatest effect on the gain of formalized training when using only the individual variables were, respectively, mean annual temperature (bio1), wettest monthly precipitation (bio13), and water vapor pressure.

Figure 9 shows the relationship between the presence probability of *Ephedra sinica* and environmental factors. It is generally accepted that when the survival probability is more significant than 0.6, the corresponding environmental factors are favorable for the growth of *Ephedra sinica*. According to the ecological factor response curve simulation, the altitude suitable for the growth of *Ephedra sinica* is 1258 ~ 1738 m, the wettest monthly precipitation is 83 ~ 117 mm, the temperature seasonality is 1038 ~ 1202, and the average temperature of the driest quarter is -7.5~ -4.8℃. When the probability of survival of *Ephedra sinica* was maximum, the corresponding elevation, wettest monthly precipitation, temperature seasonality, and driest quarterly mean temperature were 1382 m, 100 mm, 1120, and − 5.5°C, respectively.

3.5 Establishment of resistance surfaces and ecological corridors

Although the future environment is favorable for *Ephedra sinica*, there is still a need for further protection of *Ephedra sinica*. By selecting ecological source sites, the study area was determined to cover seven municipalities northwest of the Chinese capital Beijing, with Steeper terrain in the study area. The environmental source sites are scattered in different geographies, further verifying the wide range of suitability of *Ephedra sinica*. The minimum resistance surface of *Ephedra sinica* diffusion was first generated (Fig. 10), and then 11 ecological source sites were established with a maximum distance of 275 km between environmental sources. The source area is at a high altitude and often has mountain ranges. Finally, 19 optimal solutions were obtained as ecological corridors for the dispersal of *Ephedra sinica* in the study area (Fig. 11); among them, seven long-distance corridors and 12 short-distance corridors. All passages are far from the artificial surface, mostly near high-altitude sites. The ecological corridors are spatially scattered, unevenly distributed, and often separated by high-altitude mountains, which can only be spread through the vicinity of the mountains. In addition, the minimum cost distance has good continuity in Ulanqab, realizing the connection between Huiteng Xil grassland in the northwestern part of Ulanqab city and Sumu Mountain Forest Park in the southwestern part with good habitat, thus constructing a biological corridor with a total length of 430.2 km in Ulanqab. With the restoration of habitat quality, this corridor can be further extended to the biological corridor within Zhangjiakou City, Hebei Province.

4. Discussion

4.1 Current distribution area of Ephedra sinica

The ecological niche distribution model is based on the geospatial information of species and environmental spatial details to simulate the predicted survival space of species. In contrast, the actual distribution of species is part of the potential distribution area of the prediction result (Farahat et al., 2021). The more constraints the MaxEnt model establishes, the higher its prediction accuracy (Ensslin et al., 2015). The AUC value simulated in this study reached 0.915, which is much larger than the mean (AUC = 0.5), indicating a high predictive result (Fig. 3).

According to the prediction of the MaxEnt model, the potential distribution area of *Ephedra sinica* in China is vast, with a total suitable area of 42.24×10^5 km^2 (Fig. 4). The suitable areas are mainly distributed in the central and western regions of China and a few in the southern regions, which may be due to the difference in climatic conditions in the north and south of China (Remya et al., 2015). Areas with more significant suitability indices than 70% were distributed in Gansu, Ningxia, Shaanxi, Shanxi, Hebei, and Liaoning, with scattered distribution in Xinjiang and Jilin. The distribution area is influenced by both temperate continental climate and typical temperate monsoonal climate, which is in accordance with the biological characteristics of *Ephedra sinica* that prefer mild and cool climate and are more cold tolerant (Mao et al., 2021).

4.2 Future distribution area of Ephedra sinica

Under future climatic conditions, the average annual precipitation in China will increase by 20%, especially in the north and northwest, and the surface temperature in China will also increase by 2.7–2.9°C (Kong et al., 2021). The results of this study suggest that the potential suitable zone for *Ephedra sinica* will expand under the climatic conditions in the next 40 years (Fig. 5). It is hypothesized that the future increase in rainfall and temperature will positively affect the survival of *Ephedra sinica*, which is consistent with the results of this study (Fig. 6).

4.3 Ecological characteristics of the distribution area of Ephedra sinica

Environmental factors play a determining role in the spatial distribution of most species on Earth (Fig. 7). The most obvious and direct response to environmental factors is changes in species distribution patterns (Stevens et al., 2014). In this study, the critical environmental factor affecting the distribution of *Ephedra sinica* was the altitude (Fig. 8), followed by precipitation and temperature (Fig. 9). Zhang et al. (2014) studied the distribution of rare and endangered plants in northwest China under climate change. They found that altitude was the number one factor affecting the distribution of rare plants. This is because environmental factors such as water, heat, and light likewise changed significantly with elevation, which could provide a more diverse survival environment for rare and endangered plants (Tu et al., 2021). Yi et al. (2010) found that elevation and precipitation factors had a more significant influence on endangered species, which is consistent with the results of this study. The suitable range of ephedra expanded under all four emission patterns, suggesting that future climatic conditions will be favorable for the survival of *Ephedra sinica*. A study by Erasmus et al. (2016) showed that 78% of the species distribution in South Africa decreased, but 17% expanded under climate change, and there were differences in the response of different species to climate change. Several studies have suggested that the effects of global climate change will lead to a trend of migration of many species to higher latitudes and altitudes (Gebrewahid et al., 2020), which is consistent with the results of the present study.

4.4 Construction of Ephedra sinica Ecological Corridor

Ecological corridors can improve ecosystem services by breaking up the isolated distribution of organisms (Fig. 10), providing opportunities for the genetic exchange of populations, and eliminating the effects of habitat fragmentation on biodiversity (Rich et al., 2010). Rushdi et al. found that habitats connected by corridors retained more native species than isolated patches, an effect that increased over time and was essential for maintaining local biodiversity diversity (Rushdi et al., 2015). The 19 ecological corridors screened in this study showed (Fig. 11) that most corridors were not unduly disturbed by environmental factors such as topography, slope, and aspect. The corridor paths were far from people's residential areas. In addition, the ecological corridors selected in this study were divided into short-range and long-range. Since *Ephedra sinica* is a plant with minimal mobility, short-range corridors should be given priority, and long-range corridors can be selected secondarily. It is recommended to improve the quality and stability of these corridors as much as possible in future habitat management and to restore further and reconstruct suitable habitats to perform their proper ecological functions.

5. Conclusion

This study analyzed that the current distribution status and future trends of *Ephedra sinica*, a rare and endangered species in China. The results showed that *Ephedra sinica* is mainly distributed in China's northwestern and northern regions. Among them, Gansu, Ningxia, Shaanxi, Shanxi, Hebei, and Liaoning are very suitable for the growth of *Ephedra sinica*. Under the future climate change, the distribution area of *Ephedra sinica* will be expanded year by year. Elevation of 1258 ~ 1738 m, wettest monthly precipitation of 83 ~ 117 mm, the seasonal temperature of 1038 ~ 1202, and the driest quarterly average temperature of -7.5~-4.8°C are the most suitable meteorological conditions for the growth of *Ephedra sinica*. The 19 ecological corridors constructed using the MCR model will also provide considerable importance for the survival of *Ephedra sinica* on a longer time scale in the future.

Declarations

Compliance with Ethical Standards

Competing Interests

All the authors do not have any possible conflicts of interest.

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Ethical Approval

The manuscript does not involve human participants, human data or human tissue.

Consent to Participate

The manuscript does not report on or involve the use of any animal or human data or tissue.

Consent for Publish

The manuscript does not contain any individual person’s data (including any individual details, images or videos).

Corresponding author information

Minxia Liu, Professor, College of Geography and Environment Science, Northwest Normal University, Lanzhou, China. **Email address: liumx@nwnu.edu.cn.**

Authors Contributions

Minxia Liu: Funding acquisition, Writing – review & editing. Le Li: Conceptualization, Methodology, Software, Writing – original draft. Data collection and analysis were performed by Siyuan Wang, Shirui Xiao and Jiale Mi. Final approval of the version to be submitted- all named authors should approve the paper prior to submission.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

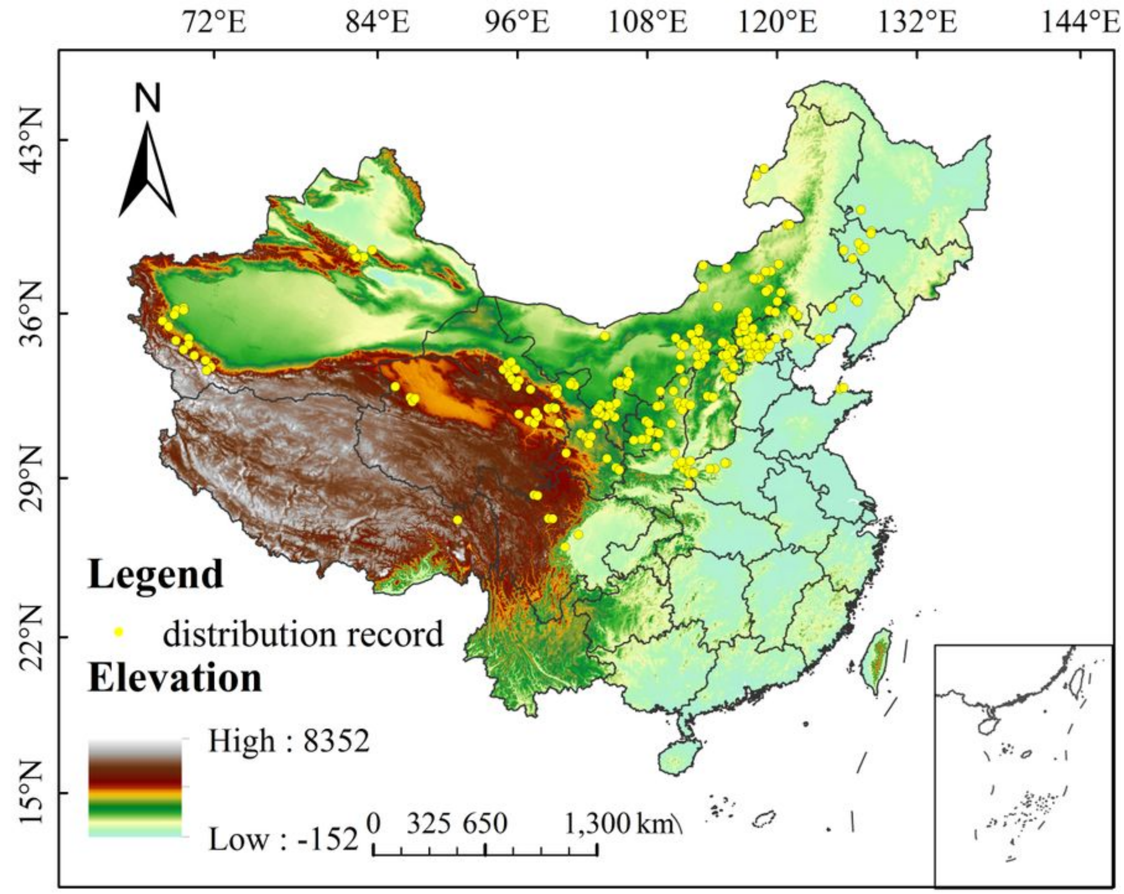

Figure 1

Locations of occurrence records of *Ephedra sinica* in China

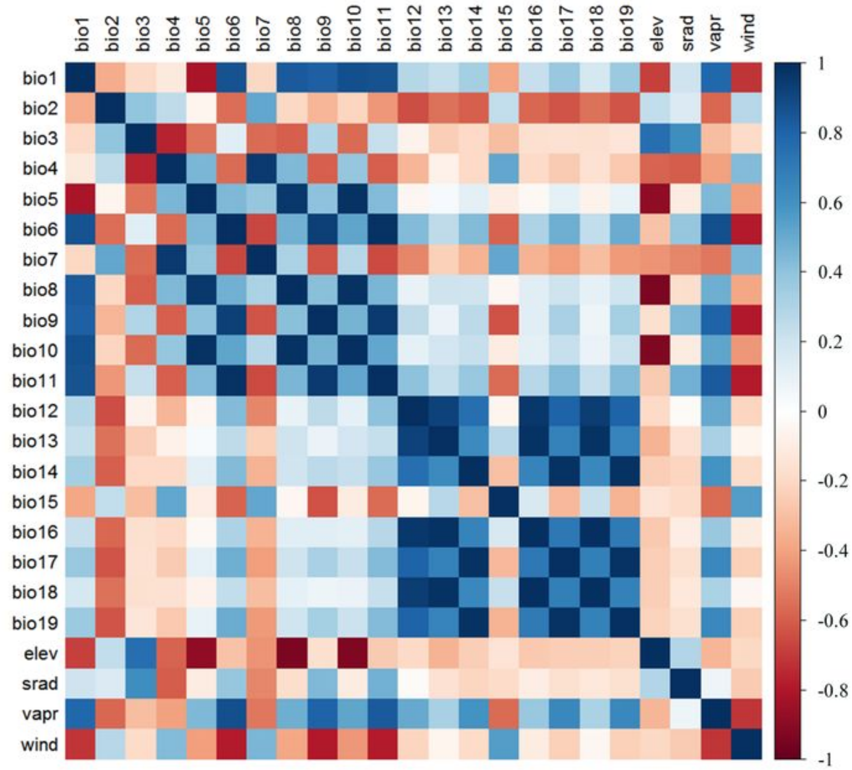

Figure 2

Correlation coefficient of bioclimatic factors

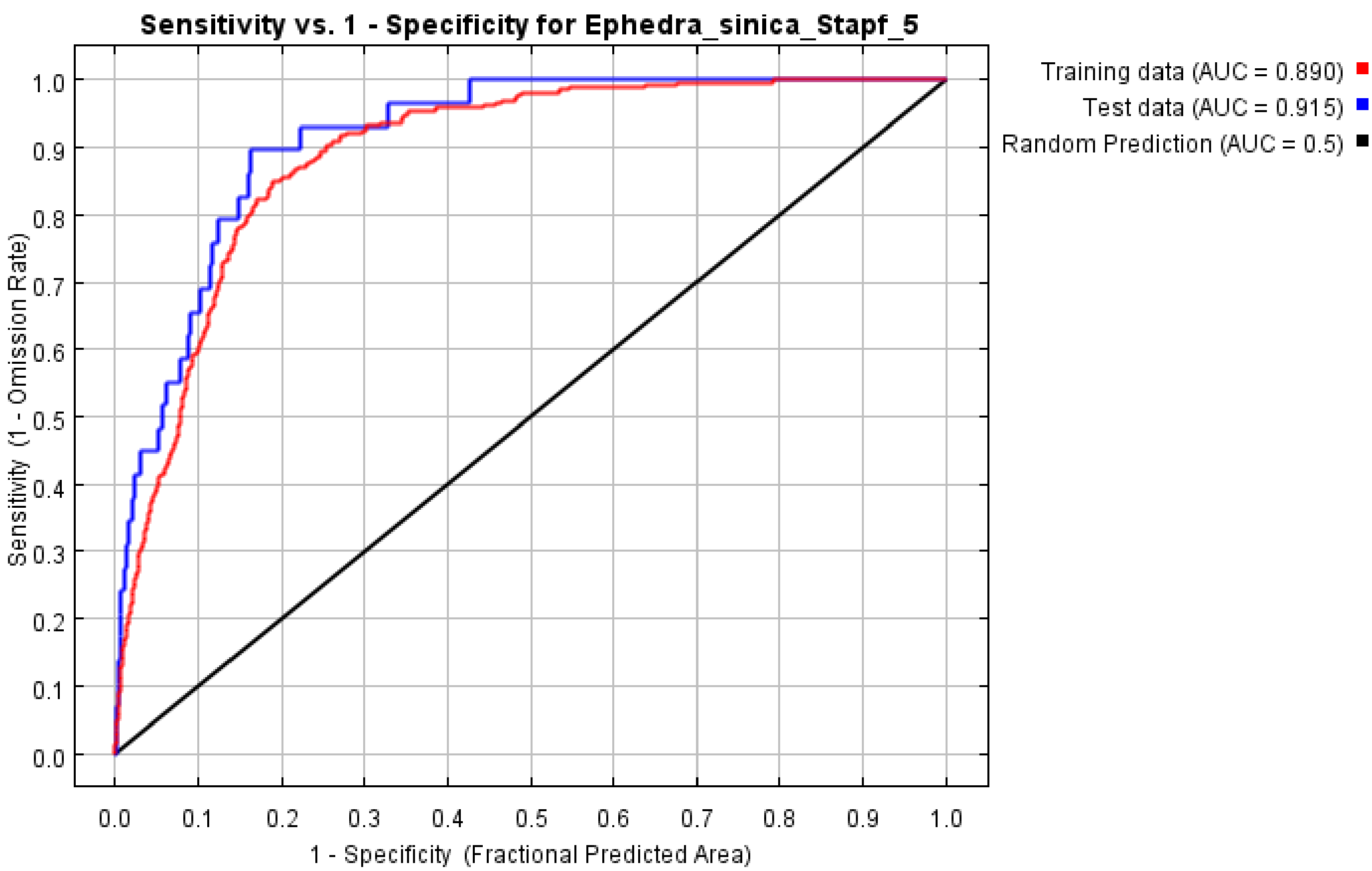

Figure 3

Reliability test of the distribution model created for *Ephedra sinica*

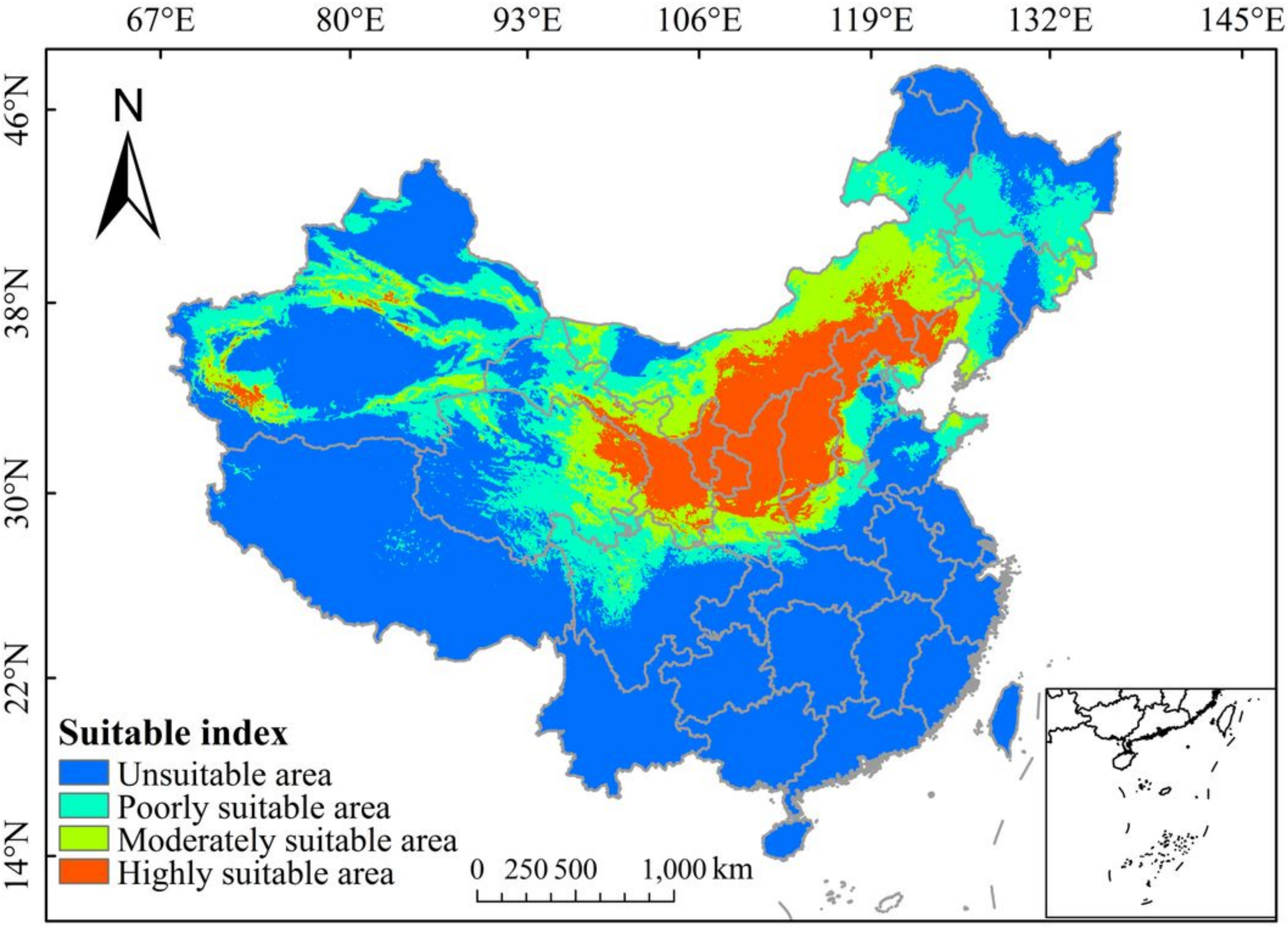

Figure 4

Potential current and suitable habitat for *Ephedra sinica* in China.

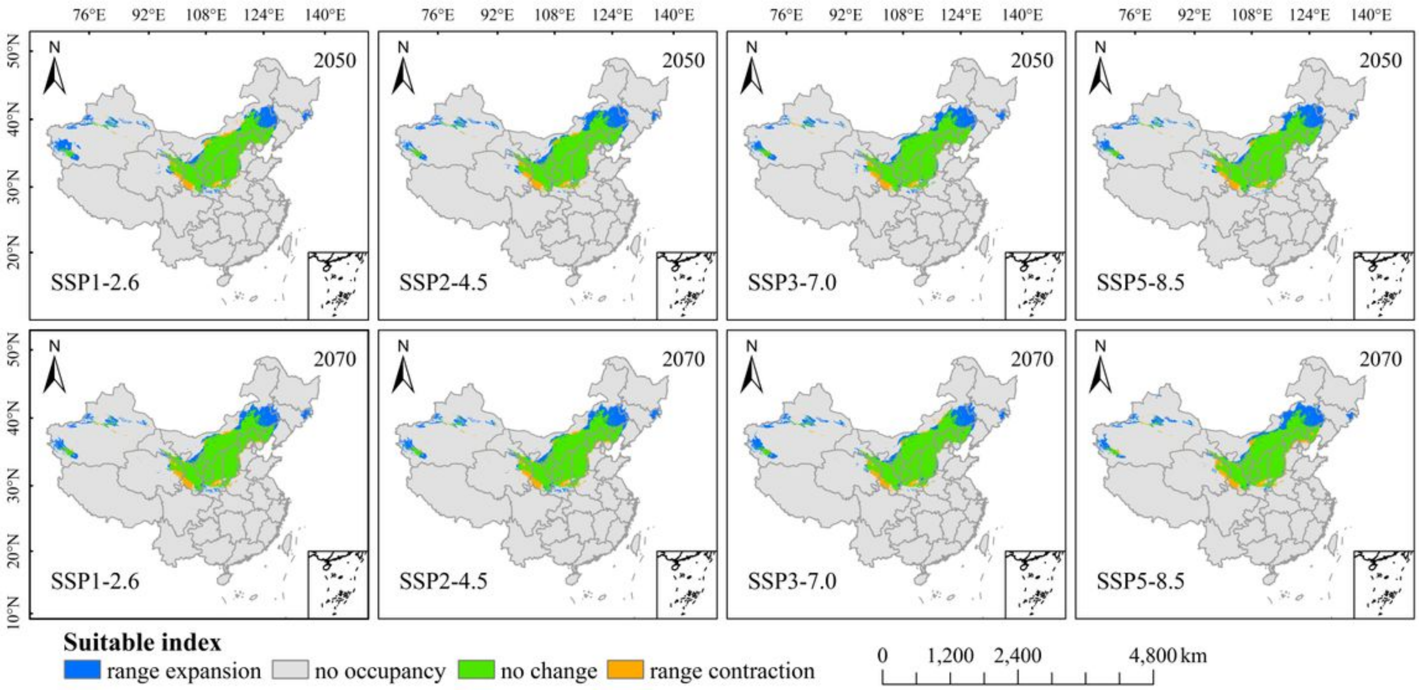

Figure 5

Changes in the potential geographical distribution of *Ephedra sinica* under climate change scenarios.

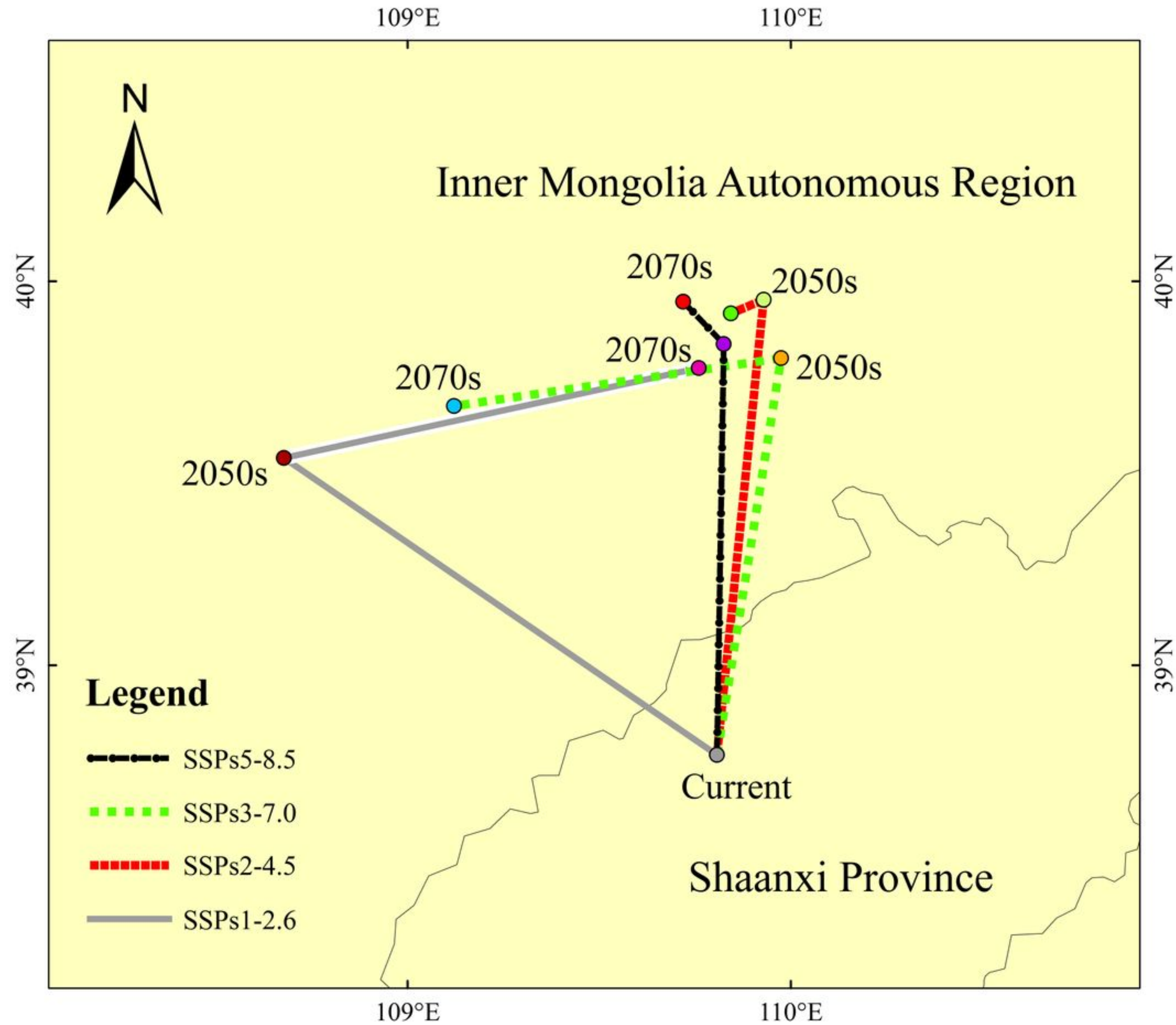

Figure 6

Highly suitable area centroid distributional shifts under climate change for *Ephedra sinica*.

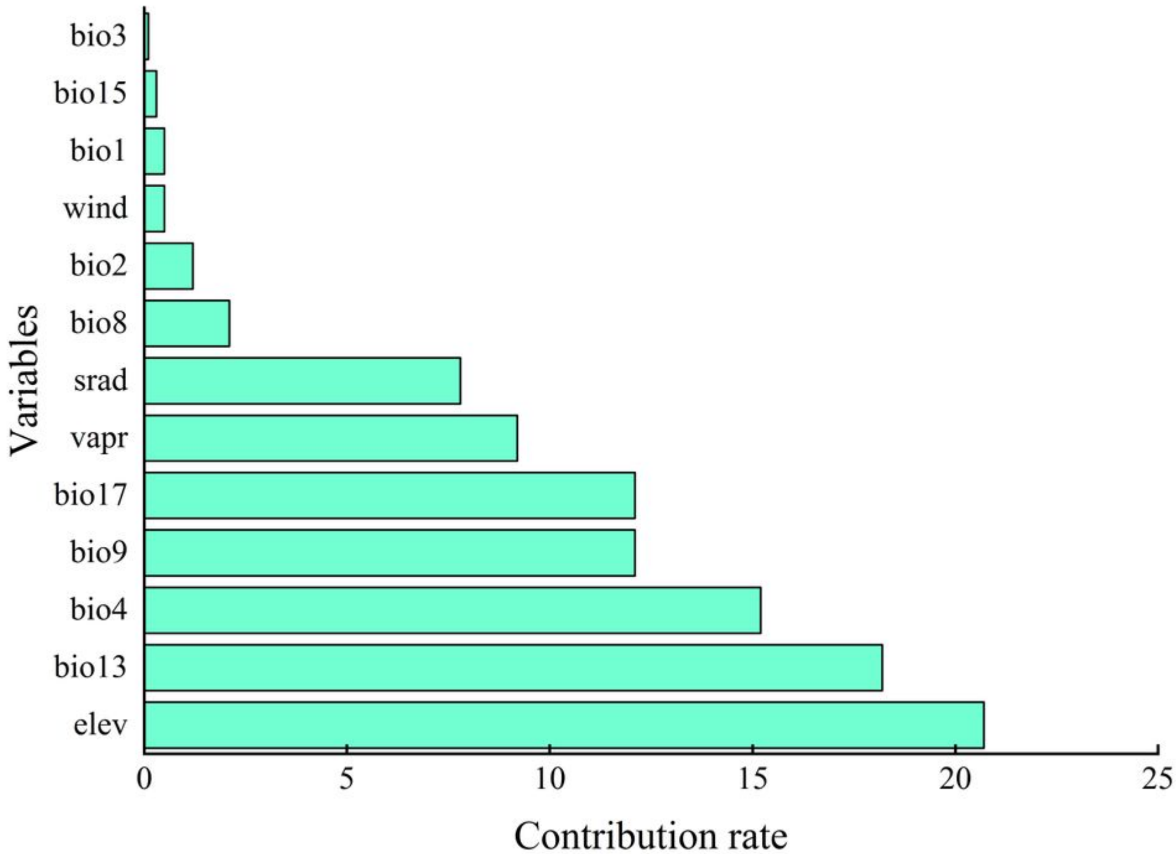

Figure 7

Permutation importance of variables for modeling.

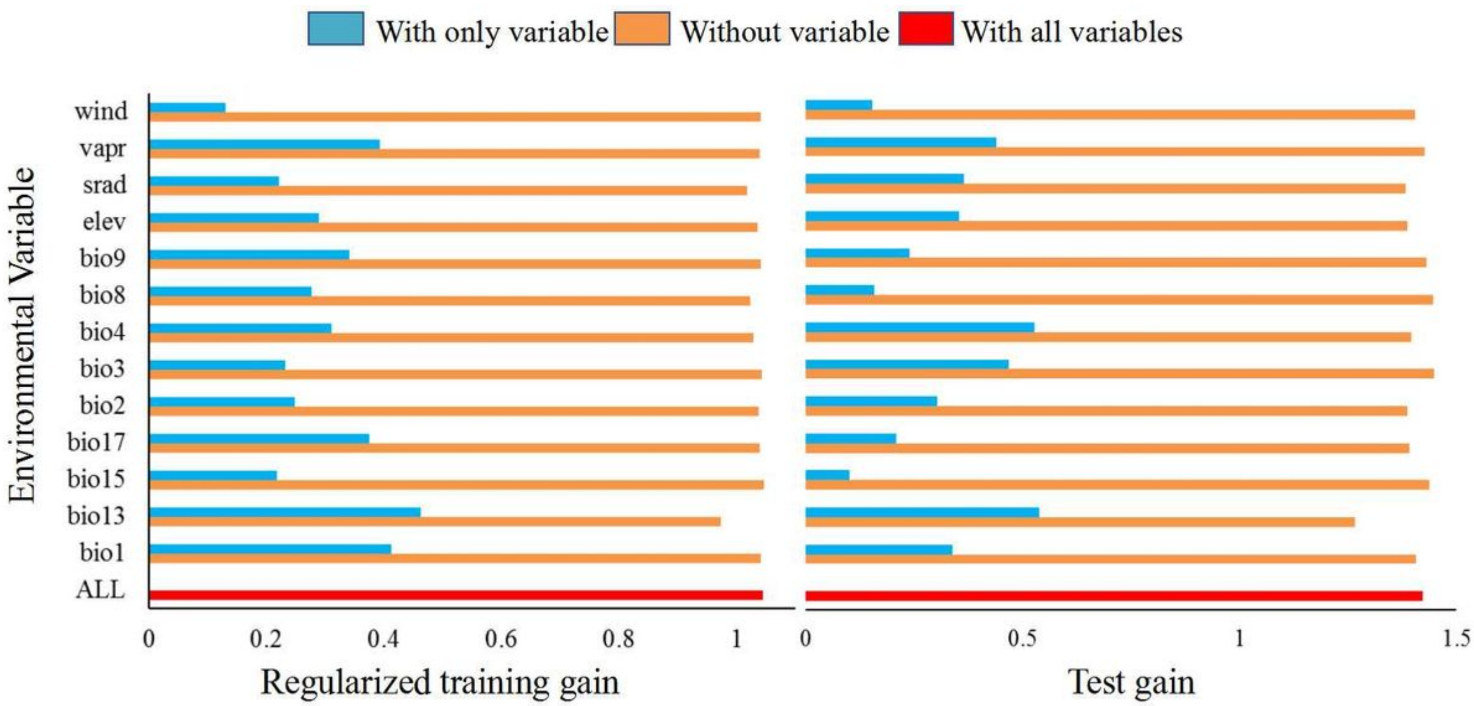

Figure 8

The jackknife test result of the environmental factor for *Ephedra sinica*.

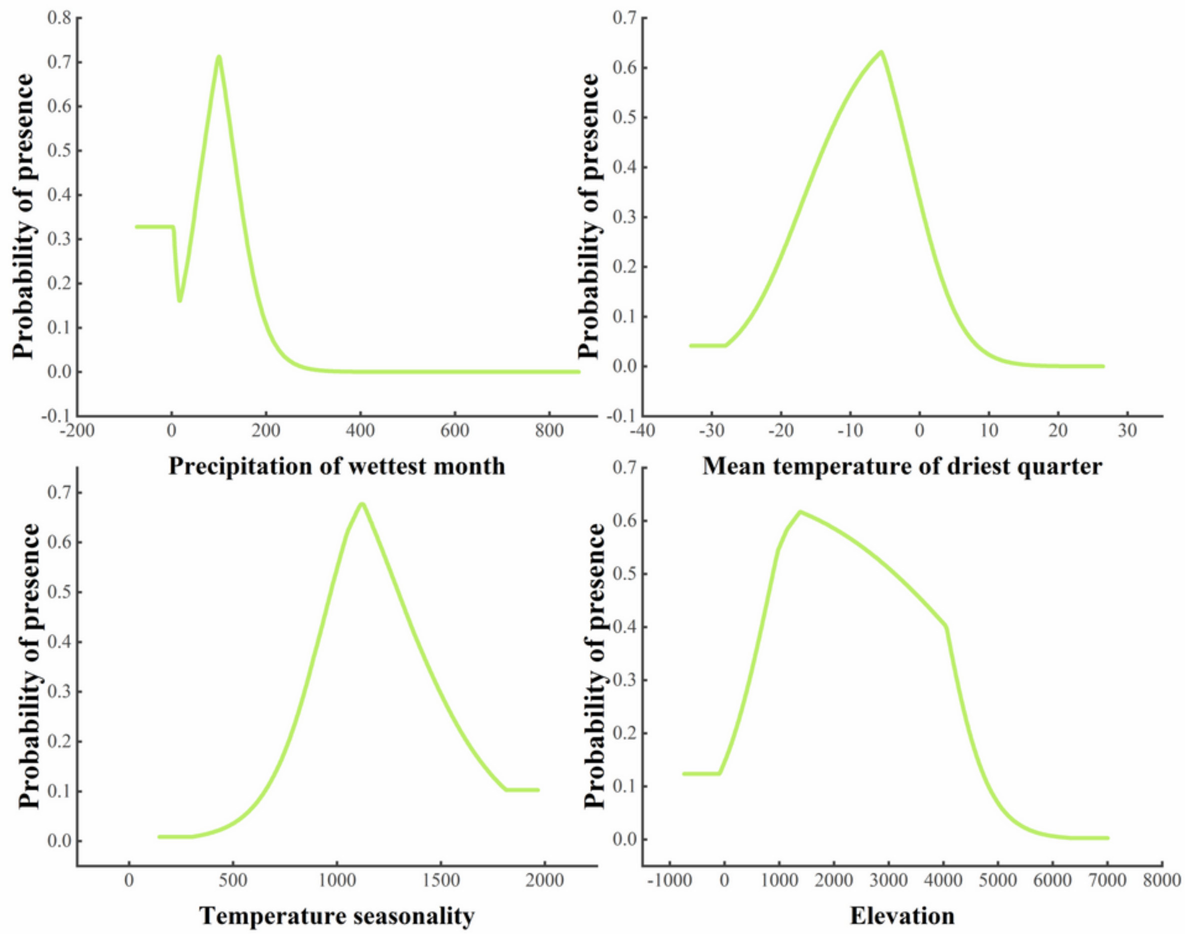

Figure 9

Response curves of a probability of presence for *Ephedra sinica*.

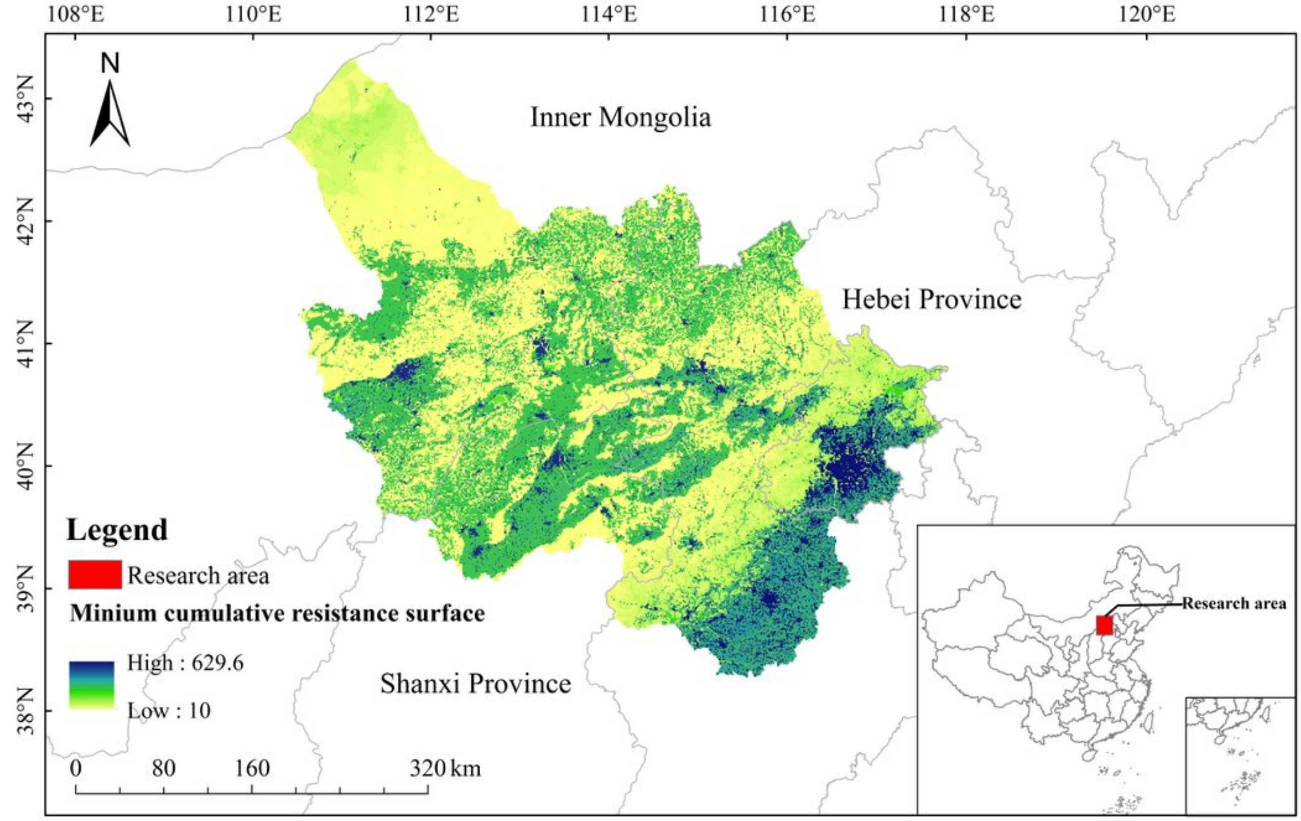

Figure 10

Minimum cumulative resistance surface for *Ephedra sinica*.

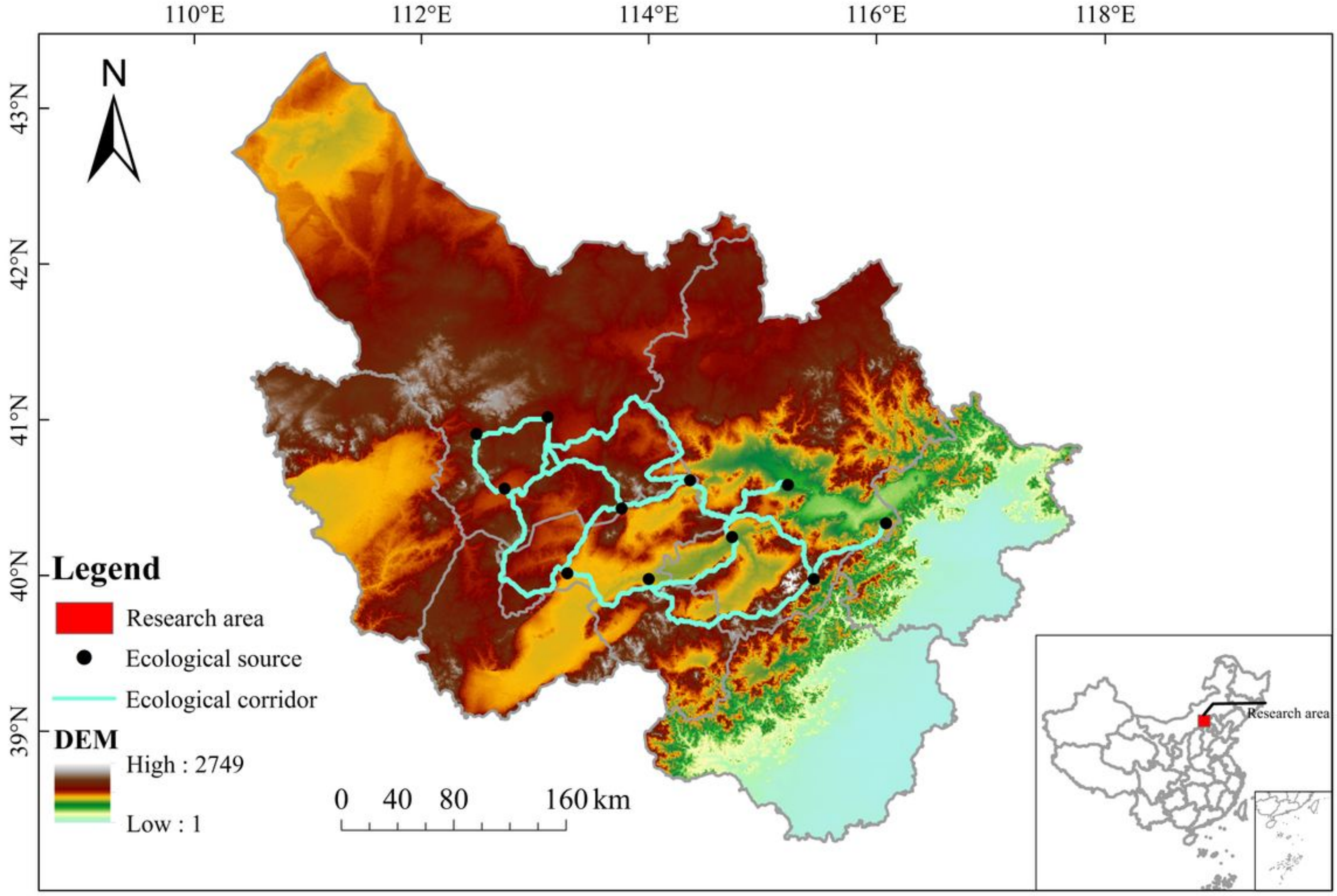

Figure 11

Relationship between ecological corridors and topography.

Supplementary Files

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