



Simulation of potential suitable distribution of original species of *Fritillariae Cirrhosae Bulbus* in China under climate change scenarios

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Abstract

Fritillariae Cirrhosae Bulbus (FCB) is a famous traditional Chinese medicine, mainly used for relieving cough and resolving phlegm. According to Chinese Pharmacopoeia (2020), the medicine comes from dried bulbs of five species and one variety in *Fritillaria*. Due to climate change and human disturbance, the wild resources have become critically endangered in recent years. Following three climate change scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) under 2050s and 2070s, geographic information technology (GIS) and maximum entropy model (MaxEnt) were used to simulate the ecological suitability of FCB, a third-grade rare and endangered medicinal plant species. The results showed that the key environmental variables affecting the distribution of FCB were altitude, human activity intensity, and mean temperature of coldest quarter. Under current climate situation, the highly suitable areas were mainly located in the east of Qinghai Tibet Plateau, including Western Sichuan, southeastern Tibet, southern Gansu, Northwestern Yunnan, and Eastern Qinghai, with a total area of 31.47×10^4 km², the area within the nature reserve was 7.13×10^4 km², indicating that there was a large protection gap. Under the future climate change scenarios, the areas of the highly and poorly suitable areas of FCB showed a decreasing trend, while the areas of the moderately and total suitable areas showed an increasing trend. The geometric center of the total suitable area of the medicine will move to the northwest. The results could provide a strategic guidance for protection, development, and utilization of FCB through its prediction of potential distribution based on the key variables of climate change.

Keywords *Fritillariae Cirrhosae Bulbus* (FCB) · Suitable area · GAP analysis · Climate change

Introduction

With the change of global climate, the frequency and intensity of extreme weather increase significantly, which has a serious impact on agriculture, forestry, animal husbandry

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and other industries (Calvin et al. 2020). As a special agricultural resource, the cultivation, growth, and distribution of traditional Chinese medicine are also affected by climate change. The change of traditional Chinese medicine resource producing areas caused by climate change will change the property of traditional Chinese medicine, and then have a potential impact on the quality, clinical efficacy, and medication safety of traditional Chinese medicine (Ma and Gao 2010). Genuine medicinal materials refer to the Chinese medicinal materials with a long history, excellent varieties, significant curative effect, obvious regional characteristics, and better quality than those from other places. However, the genuine areas of traditional Chinese medicine are not fixed, and will expand, contract, or migrate under the influence of climate change. For example, Cheng et al. (2016) found that the warming of historical temperature and excessive precipitation made the genuine area of *Astragalus membranaceus* move to the northeast. Zhou et al. (2015) showed that compared with the current distribution pattern of suitable area, the total area of suitable area of original plants of Rhei Radix et Rhizoma would be reduced in different degrees in the future. Shen et al. (2017) predicted that the increase of annual average temperature in the future will make the main distribution area of *Gentiana rhodantha* expand to higher elevation.

Parmesan and Yohe (2003) pointed out that non climatic factors dominate the short-term biological changes of plants, while climate change will affect the life system of plants. At a large scale, climate and topography are important environmental factors limiting species distribution (Brooks et al. 2006; Loarie et al. 2008; Alkemade et al. 2011). Due to the global climate change and lack of effective protection of medicinal plant resources, the geographical distribution of many medicinal plant species has shrunk sharply, or even disappeared (Zhou et al. 2015; Yang et al. 2017a, b). Traditional investigation of medicinal plant resources mainly relies on field work and manual records, which requires a large amount of work, takes a long time, and has limited evaluation ability. This method could not fully reflect the internal relationship between plants and environmental factors, especially the change of suitable area under the future climate scenario (Wang et al. 2002). How to effectively deal with climate change and human disturbances in the future is a key issue in the plant protection planning of traditional Chinese medicine. BCC-CSM2-MR is one of the most commonly used climate models developed by China National Climate Center to simulate the response of global climate to the increase of greenhouse gas concentration, especially for China (Shi et al. 2020).

The maximum entropy model (MaxEnt) was first proposed by Jaynes in 1957 (Jaynes 1982). The model can infer incomplete information and was applied to predict the potential distribution of species in 2004. Nowadays, it has been

widely used in many fields, such as ecology, biochemistry, and resource conservation (Phillips et al. 2006; Brito et al. 2009; Warren et al. 2013). Studies have shown that MaxEnt can accurately predict the potential distribution area of species even if the information of species distribution data and environmental variables in the distribution area are incomplete. Therefore, MaxEnt has been widely used in the prediction of potential distribution areas of endangered traditional Chinese medicine plants, such as *Salvia bowletana* Dunn (He et al. 2014), *Gastrodia elata* Bl. (Zhang et al. 2017), *Astragalus mongholicus* Bunge (Wang et al. 2020a, 2020b), and *Gentiana macrophylla* Pall (Tan et al. 2020).

Fritillariae Cirrhosae Bulbus (FCB), also called “Chuan-beimu,” is a kind of valuable Chinese herbal medicine with the functions of clearing heat and moistening lung, relieving cough and resolving phlegm, relieving asthma, antibacterial, and antiviral (Sun et al. 2013; Zhao et al. 2020). According to the 2020 edition of Chinese Pharmacopoeia, original species of the medicine includes *Fritillaria cirrhosa* D. Don, *F. unibracteata* Hsiao et K. C. Hsia, *F. przewalskii* Maxim., *F. delavayi* Franch., *F. taipaiensis* P. Y. Li, and *F. unibracteata* Hsiao et K.C. (Chen et al. 2019; Xiong et al. 2020). These species mostly grows in alpine meadow or shrubs with an altitude of 3200–4600m, except *F. taipaiensis* in lower regions. And growth and distributions of these species are very vulnerable to their wild habitats (Chen et al. 2003). FCB is a conventional medicine used in traditional Chinese medicine formulations, and there are more than 100 kinds of Chinese patent medicines with it as raw materials (Xiao et al. 2007; Chen et al. 2014). Due to low biological yield, few number of mature fruits, terrible germination, and survival rate of the species, wild resources are far from meeting the growing market demand. Driven by economic interests, continuous high-intensity and disordered mining result in sharply decline of the wild resources. Therefore, most of the species have been listed as the 3rd class protected plant.

At present, the research on FCB and its original species mainly focuses on the methods of physiological ecology (Chen et al. 2003; Zhang et al. 2010), chemical and pharmacological components (Cao et al. 2009; Wang et al. 2011, 2012; Pan et al. 2014), seedling breeding (Wang et al. 2010a, b), and molecular biology (Lee and Hsing 2002; Tan et al. 2011), while the research on its geographical distribution mainly focuses on specific species, lacking comprehensive research. Based on MaxEnt model, the potential distribution of FCB under current and future climate conditions was simulated by using the latest distribution information of the medicine and environmental data, the key environmental variables influencing its distribution were screened, the relationship between suitable distribution area of FCB and environmental factors was analyzed, and the population diffusion degree and suitable area change of FCB in the future were revealed. The results of this study can provide

a theoretical basis for formulating the protection strategy of the precious medicine.

Methods

Occurrence data of FCB

Firstly, the distribution data of original plants of FCB were obtained by searching GBIF (Global Biodiversity Information Facility) and related journals (Lee and Hsing 2002; Chen et al. 2003; Cao et al. 2009; Zhang et al. 2010; Wang et al. 2011). Secondly, Google Earth system was used to pick up and proofread the longitude and latitude of distribution data. Then the repeated distribution points were removed by using the data statistics function of Excel, and the longitude and latitude data were converted into decimal. Thirdly, the spatial analysis function of ArcGIS was used to calculate the distance between the distribution points and the center of the censored grid to ensure that each censored grid contains only one distribution point closest to the center, so as to reduce the impact of spatial autocorrelation (Wang et al. 2020a, 2020b). Through the above procedure, a total of 484 distribution points were obtained (Fig. 1).

Environmental variables and human activity intensity

The grid data of 19 bioclimatic variables with WGS84 coordinate system and 2.5 arc-minutes resolution were accessed through the Worldclim database (<https://www.worldclim.org/>), and the current climate data was obtained by interpolating the detailed meteorological information recorded by meteorological stations all over the world, with a time

span of 1970–2000. Beijing Climate Center Climate System Model (BCC-CSM2-MR) of the Coupled Model Intercomparison Project Phase 6 (CMIP6) was selected as the future climate model. CMIP6 Scenario Model Intercomparison Project (ScenarioMIP) comprehensively analyzed the shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs), and obtained a new prediction scenario closer to the real situation (Eyring et al. 2016). In this paper, SSP1-RCP2.6 (SSP1-2.6), SSP2-RCP4.5 (SSP2-4.5), and SSP5-RCP8.5 (SSP5-8.5) in 2050s (2041–2060) and 2070s (2061–2080) were selected as the future climate scenarios. SSP1-2.6 scenario is an upgrade of RCP2.6 scenario, which adopts a sustainable development path of low matter, low resources, and low energy, representing a low level of greenhouse gas emissions. SSP2-4.5 is an update of RCP4.5 scenario, which represents that the greenhouse gas emission is at a medium level, that is, the future socio-economic development model continues to develop along the current model. SSP5-8.5 is the updated scenario of RCP8.5, which assumes that the social economy is fully developed, but it is still based on energy intensive as the economic driver, representing a high level of greenhouse gas emissions (Eyring et al. 2016; Riahi 2017). The human activity intensity (HAI) grids or also known as Human Footprint Index (HFI) grids at a spatial resolution of ~ 1 km provided by the 2009 Human Footprint, Last of the Wild Project, Version 3, 2018 Release (LWP-3) was used as one type of environmental variables, which expressed the cumulative human pressure on the environment through eight variables (i.e., population density, built-up environments, electric power infrastructure, roads, railways, navigable waterways, crop lands, pasture lands). Its value ranges from 0 to 50 (Dong et al. 2021). We then derived the layer of distance to the human disturbance using Euclidean linear distance analysis in ArcGIS 10.5. The spatial resolution of the above data was 2.5 arc minute. Altitude data (30m) was downloaded from Geospatial Data Cloud (GDC, <http://www.gscloud.cn/>), and its resolution was unified with climate variables through Kriging interpolation (2.5 arc minute).

The 1:16 million administrative division map of China was downloaded from the website of the Ministry of natural resources of the People's Republic of China (<http://bzdt.ch.mnr.gov.cn/index.html>).

Principle and method of Geodetector

Geodetector is a spatial analysis model developed by Wang et al. (2010a, b) using Excel 2007 and R, and can be download free from the link <http://www.geodetector.cn/>. Geodetector was employed to detect the main influence factors and spatial differentiation, including risk detector, factor detector, interaction detector, and ecological detector (Wang et al. 2010a, b; Hu et al. 2011).

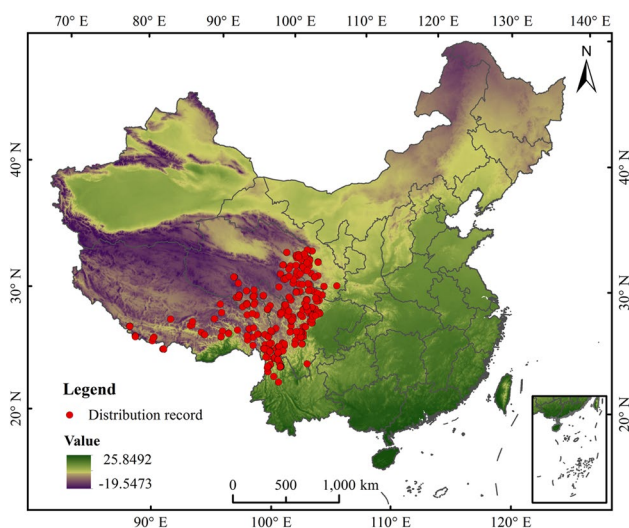


Figure 1 Species occurrence records of FCB

In this study, factor detectors were used to detect the extent to which environmental variables affect the spatial distribution of FCB. The expressions are as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} = \frac{SSB}{SST}, \quad SST = N \sigma^2$$

where q is the value to measure the correlation between environmental variables and spatial distribution of FCB, N is the sample size, and σ^2 is the variance. N_h and σ_h^2 are the sample size and variance of h layer, respectively.

The value range of q generally varied from 0 (lowest) to 1 (highest). The higher the q value, the stronger the correlation between environmental variables and spatial distribution. When $q = 1$, it indicates that the variable completely controls the spatial distribution, while when $q = 0$, it indicates that the variable has nothing to do with the spatial distribution.

Selection of environmental variables

The selection procedure of environment variables was divided into two steps (Wang et al. 2019, 2010a, b). First, all the 22 environmental variables (Table S1) and 484 distribution points (Fig. 1) of FCB were imported into the MaxEnt model, and variables with contribution rate of 0 were removed after three operations. Thereafter, the earth factor detector was used to calculate the remaining variables, and only variables with q value > 0.2 were retained. After the above program, 10 environmental variables were selected to build the final model (Table 1).

Table 1 Environmental variables used in MaxEnt model

Variable	Description
Bio1	Mean annual temperature
Bio6	Min temperature of the coldest month
Bio7	Temperature annual range(Bio5–Bio6)
Bio9	Mean temperature of the driest quarter
Bio10	Mean temperature of the warmest quarter
Bio11	Mean temperature of the coldest quarter
Bio12	Annual precipitation
Bio15	Coefficient of variation of precipitation seasonality
Slope	Slope
Altitude	Altitude
HAI	Human activity intensity

Parameter setting of MaxEnt model

Based on the selected distribution data and environmental variables, the model was established and repeated 10 times. The proportion of test data was set as “Random seed,” the replicated run type was set as “Crossvalidate,” the maximum iterations was set to 500, the importance of environmental variables was measured by “Jackknife test,” the impact of variables on the distribution of FCB was analyzed by creating response curves, the output format was logistic, and other settings were set as the default values of the software (Narouei-Khandan et al. 2016; Wang et al. 2010a, b).

Verification of model accuracy

The receiver operating characteristic (ROC) curve output by MaxEnt was one of the effective methods to evaluate the accuracy of niche model. AUC (areas under ROC curve) ≤ 0.8 indicated poor performance, $0.8 < \text{AUC} \leq 0.9$ indicated moderate performance, $0.9 < \text{AUC} \leq 0.95$ indicated good performance, and $0.95 < \text{AUC} \leq 1$ indicated excellent performance (Ortega-Huerta and Peterson 2008; López-Collado et al. 2013; Liu et al. 2021).

Division of suitable grade

In the output file, the maximum value of 10 repetitions was selected as the prediction result of this study. ArcGIS was used to convert the ASC file output by MaxEnt into raster format file. According to IPCC’s explanation of the probability (P) of species’ presence and combined with previous research results, the suitability grades were divided into four categories and displayed in different colors on the map, which were the following: highly suitable area ($P \geq 0.66$, red), moderately suitable area ($0.33 \leq P < 0.66$, orange), lowly suitable area ($0.05 \leq P < 0.33$, yellow), and unsuitable area ($P < 0.05$, white) (Remya et al. 2015; Zou et al. 2015; Wang et al. 2018).

Results

Model performance

The AUC values of training data and test data were 0.962 and 0.961 respectively (Fig. 2), and the performance level of the model was “excellent.”

Analysis of the importance of environmental variables

The results showed that the altitude (52.6%, $q = 0.45$) and the human activity intensity (29.2%, $q = 0.39$) were the two

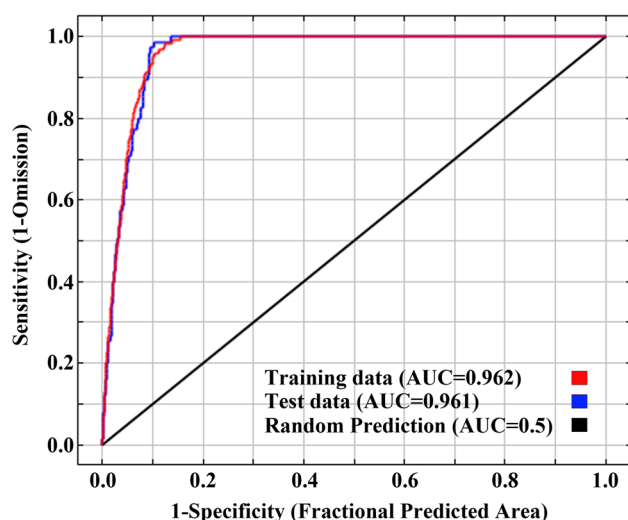


Figure 2 ROC curve and AUC values for the model

most important variables determining the distribution of FCB, which accounted for 90% of the variations (Table 2). The annual precipitation ($q = 0.37$) explained 8.7% of the contribution. The min temperature of coldest month was the variable with least impacts on FCB distribution (0.1%, $q = 0.20$).

The results of Jackknife test (Fig. 3) showed that when altitude, human activity intensity (HAI), and annual precipitation (Bio12) were used to model separately, their regularized training gains were significantly higher than other variables, which indicated that they contained unique information affecting the distribution of FCB.

Relationship between environmental variables and probability of presence

In order to clarify the relationship between key environmental variables and the probability of presence of FCB,

Table 2 Percent contribution and q value of each variable to the potential distribution of FCB defined by MaxEnt

Index	Percent contribution/%	q value
Altitude	52.6	0.45
HAI	29.2	0.39
Bio12	8.7	0.37
Bio11	4.1	0.35
Slope	1.8	0.29
Bio15	1.2	0.27
Bio1	1.1	0.26
Bio9	0.9	0.24
Bio10	0.3	0.20
Bio6	0.1	0.20

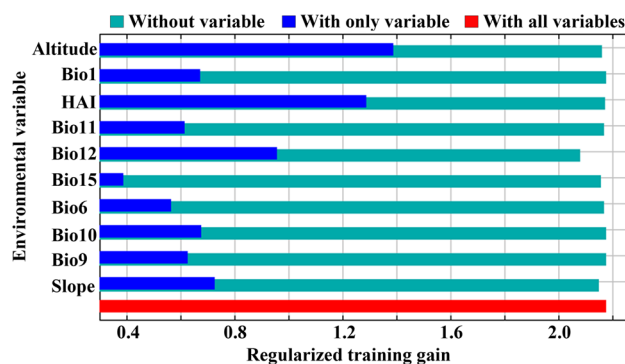


Figure 3 Importance of environmental variables to FCB by jackknife analysis. Blue bar represents the regularized training gain for models using a single variable only, while green represents the jackknife without that single variable. Red dashed lined represent the total regularized training gain using all variables

MaxEnt was used to draw the response curve using only a single environmental variable (Fig. 4). The results showed that the suitable ranges of altitude, human activity intensity, and annual precipitation were 2083.7–4081.9 m, 390.2–3825 mm, 4.8–20.1 and -7.9 – 8.0 °C, respectively.

Risk detector was also used to measure the suitable range of each variable, and the results showed that the suitable ranges of altitude, human activity intensity, annual precipitation, and mean temperature of coldest quarter were 2347–3612.7 m, 6.9–16.2, 566.0–912.9 mm, and -4.7 – 1.8 °C, respectively.

Simulation of the geographical distribution of FCB under current climate condition

Figure 5 showed the geographical distribution of FCB in China under current climate condition predicted by MaxEnt. The results showed that the highly suitable areas were mainly located in the east of Qinghai Tibet Plateau, including western Sichuan, southeastern Tibet, southern Gansu, northwestern Yunnan, and eastern Qinghai, with a total area of 31.47×10^4 km², accounting for 3.26% of China's land area. Among them, Sichuan had large areas, reaching 14.23×10^4 km². The moderately suitable areas were mainly located in eastern Tibet, southern and northwestern Sichuan, and northeastern Qinghai and southern Gansu, with a total area of 30.38×10^4 km², accounting for 3.15% of China's land area. Among them, Tibet and Sichuan had larger areas, which were 9.79×10^4 km² and 8.51×10^4 km², respectively. The lowly suitable areas were located in eastern and southern Tibet, eastern and southern Qinghai, central and eastern Gansu, northwestern Sichuan, northern Yunnan, and western Xinjiang, with a total area of 39.88×10^4 km², accounting for 4.13% of China's land area. Among them, the area of Tibet was the largest, reaching 17.69×10^4 km².

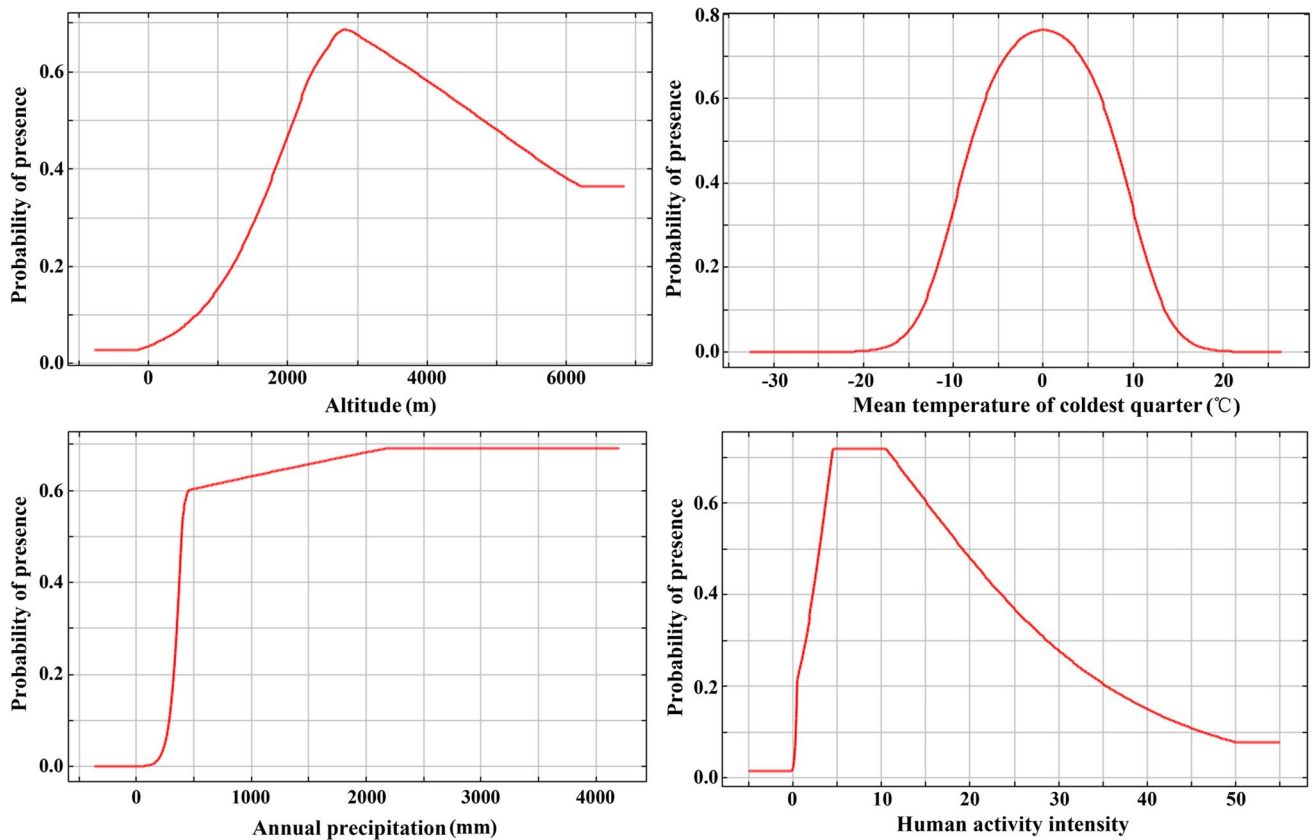


Figure 4 Response curves of presence probability of FCB to altitude, human activity intensity, mean temperature of coldest quarter, and annual precipitation

GAP analysis of FCB

In order to identify the protection gaps of FCB, the highly suitable areas and the boundaries of Natural Conservation

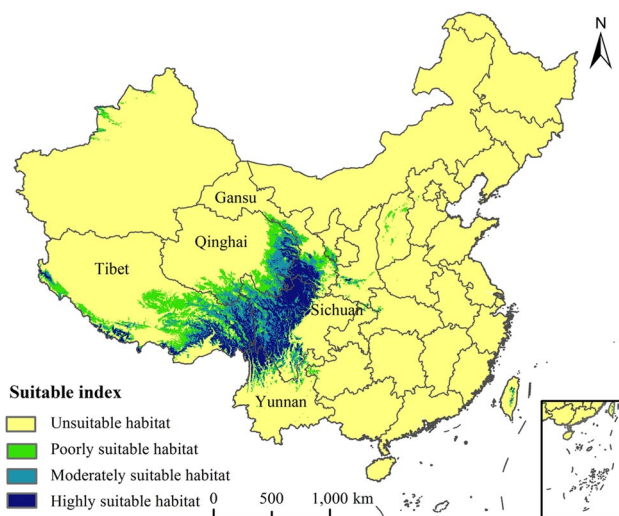


Figure 5 Simulation of the geographic distribution of FCB in China under current climate condition

Area in China were overlapped in ArcGIS. The results showed that the highly suitable area of the FCB was $31.47 \times 10^4 \text{ km}^2$, and the area within the nature reserve was $7.13 \times 10^4 \text{ km}^2$, accounting for 22% of the highly suitable area, indicating that there was a large protection gap of FCB, mainly in western Sichuan, eastern Tibet, southern Gansu, northwest Yunnan, and eastern Qinghai (Fig. 6).

Potential distribution of FCB in China under climate change scenarios

Figure 7 showed the changes of the suitable area of FCB in the future SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. Under the three climate change scenarios, the areas of the highly and poorly suitable areas of FCB showed a decreasing trend, while the areas of the moderately and total suitable areas showed an increasing trend.

By 2050s, the areas of the highly suitable areas would be reduced to $31.22 \times 10^4 \text{ km}^2$ (SSP1-2.6), $31.71 \times 10^4 \text{ km}^2$ (SSP2-4.5), and $28.88 \times 10^4 \text{ km}^2$ (SSP5-8.5), while by 2070s, the areas would be reduced to $31.81 \times 10^4 \text{ km}^2$ (SSP1-2.6), $30.59 \times 10^4 \text{ km}^2$ (SSP2-4.5), and $20.25 \times 10^4 \text{ km}^2$ (SSP5-8.5).

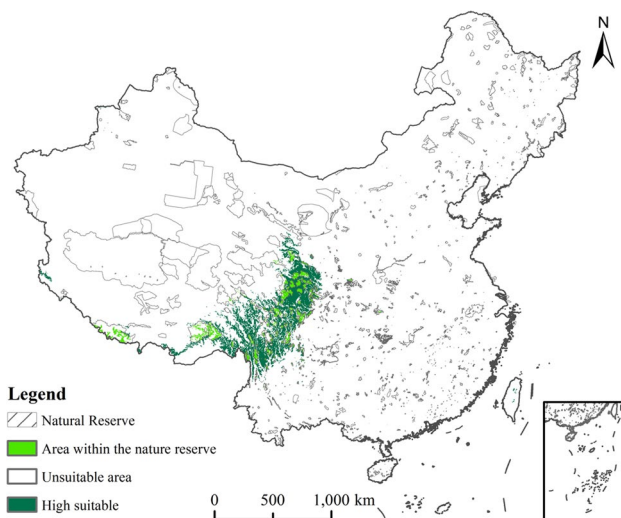


Figure 6 GAP analysis of FCB in China

By 2050s, the areas of the total suitable areas would increase to $106.3 \times 10^4 \text{ km}^2$ (SSP1-2.6), $107.75 \times 10^4 \text{ km}^2$ (SSP2-4.5), and $107.81 \times 10^4 \text{ km}^2$ (SSP5-8.5). Under SSP5-8.5 scenario, compared with the current simulation results, the increase and decrease areas were the highest, the increase areas were mainly located in eastern Tibet, southern and eastern Qinghai, and northwestern Xinjiang, and the decrease areas were mainly located in southeastern Gansu, southern Sichuan, and northern Yunnan (Fig. 8). By 2070s, the areas would increase to $106.89 \times 10^4 \text{ km}^2$ (SSP1-2.6), $106.14 \times 10^4 \text{ km}^2$ (SSP2-4.5), and $108.9 \times 10^4 \text{ km}^2$ (SSP5-8.5). Under SSP5-8.5 scenario, the areas reduced most ($10.52 \times 10^4 \text{ km}^2$), mainly distributed in Sichuan, Shandong, and Shaanxi. Under SSP5-8.5 scenario, compared with the current simulation results, the increase and decrease areas were the highest, and the increase areas were mainly located in southeastern Gansu, southwestern Sichuan, northern Yunnan, and southeastern Tibet (Fig. 8).

Variations of the geometric center of the suitable areas under climate change scenarios

Under SSP1-2.6, the geometric center of the total suitable areas of FCB would move 96.19 km from Jiangda (Current) to northwest to Yushu (2050s), then 7.02 km to northwest to Yushu (2070s). By 2070s, the center will generally displaced 101.51 km to the northwest. Under SSP2-4.5, the geometric center of the total suitable areas of the medicine would move 117.26 km from Jiangda (Current) to northwest to Yushu (2050s), then 11.12 km to northwest to Nangqian (2070 s). By 2070s, the center will generally displaced 128.04 km to the northwest. Under SSP5-8.5, the geometric center of the total suitable areas of FCB would move 133.52 km from Jiangda (Current) to northwest to Nangqian (2050s), then

37.28 km to northwest to Nangqian (2070 s). By 2070 s, the center will generally displaced 170.72 km to the northwest (Fig. 9).

Discussion

Potential distribution of FCB under current climate situation

In this study, the simulation results showed that the highly suitable areas of FCB in China were mainly located in the east of Qinghai Tibet Plateau, including western Sichuan, southeastern Tibet, southern Gansu, northwestern Yunnan, and eastern Qinghai. According to field investigation and literature review, *F. cirrhosa* is mainly produced in southern and eastern Tibet, western and southern Sichuan, and northwestern Yunnan, *F. unibracteata* is mainly produced in northern Sichuan and southern Qinghai, *F. przewalski* is mainly produced in southern Gansu, southern Qinghai and western Sichuan, *F. delavayi* is mainly produced in southern Qinghai and western Sichuan, and *F. taipaiensis* is mainly produced in southern Shaanxi and northern Chongqing (Jiang et al. 2016; Xiong et al. 2020). All the above areas were located in the suitable areas predicted here, which showed that the results were reliable. Compared with the prediction results of Jiang et al. (2016), the distribution of suitable areas in this study was more wider, which may be due to the different distribution data and environmental variables. The previous studies have suggested that the sampling range and sample size are the key factors to determine the reliability of the simulation results of species distribution model. The larger the sample size and the wider the sampling area, the more information about the relationship between species and environment will be obtained, and the higher the estimation accuracy of the species distribution model will be. In this study, we selected 484 distribution data through field survey and a large number of data, which could not only represent the habitat of its distribution area, but also avoided the deviation of simulation results due to the sample problem.

GAP analysis and protection measures of FCB

In the past decades, the importance of global climate and environmental change research in the field of scientific research has received more and more attention (Williams and Cary 2002; Carosi et al. 2020; Katragkou et al. 2020). For example, in the international well-known journal Science, there has been researches on resource reserves in recent years (Bruner et al. 2001; Curran et al. 2004; Avasthi 2005; Gerber et al. 2005). Ecologists have realized the great harm caused by the loss of biodiversity, and take ecological

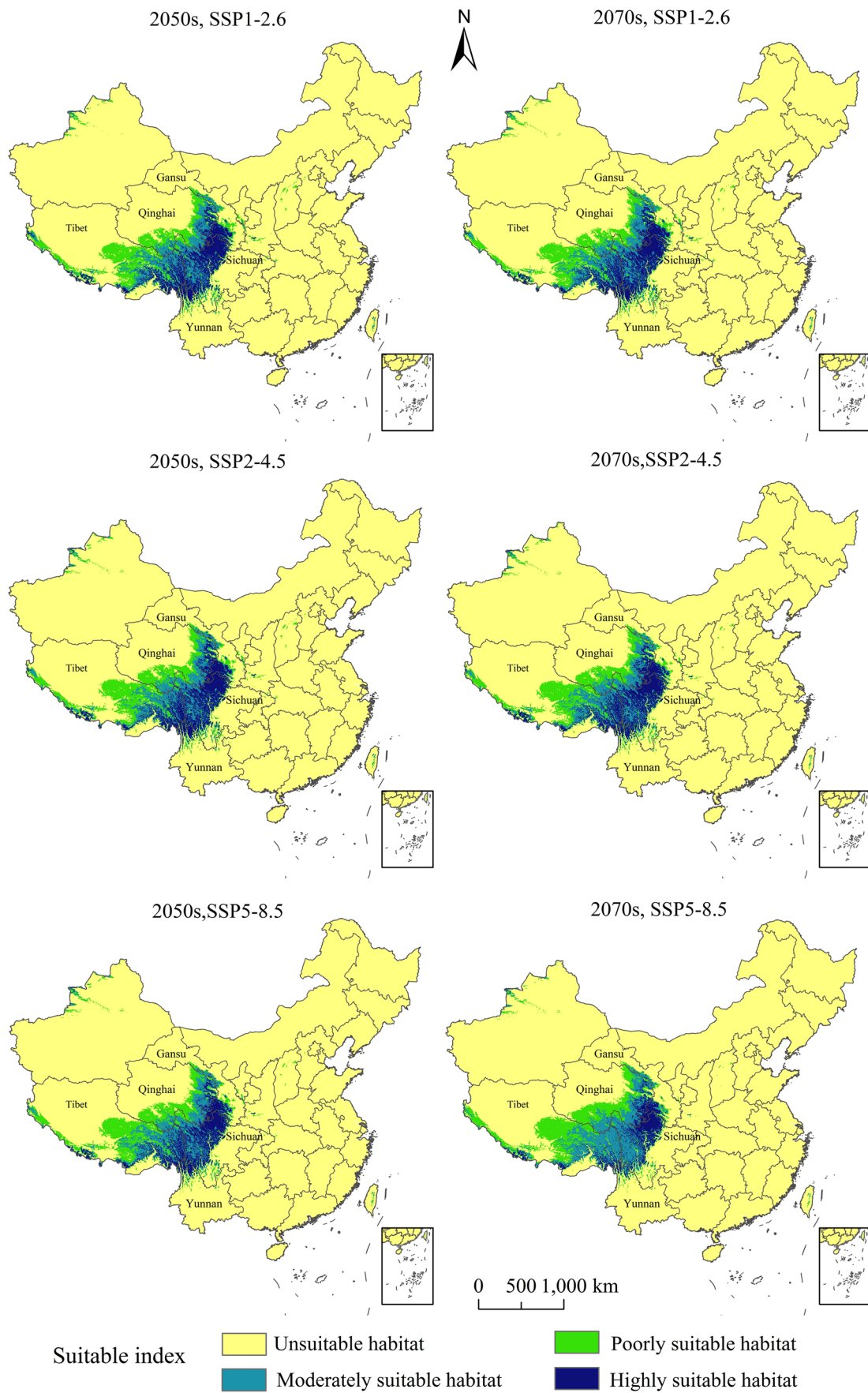


Figure 7 Potential distribution of FCB in China under climate change scenarios.

protection as a priority topic in the field of environmental research. In this paper, we conducted a GAP analysis of FCB nature reserves in China, and the results showed that there was a large protection gap in western Sichuan, eastern Tibet, southern Gansu, northwest Yunnan, and eastern Qinghai. Through years of continuous observation, it was found that the distribution area of the resources in China was generally reduced, the population was isolated, and the population quantity was rapidly reduced. In this regard, the ecological problems faced by FCB must be solved in the following ways: (1) Establishment of wildlife reserves. Wild resources protection areas should be set up in the areas where FCB are concentrated to prevent human destruction. If necessary, artificial auxiliary measures such as wild tending should be adopted to restore vegetation and population. (2) Seasonal rest grazing. In the area where wild resources of the medicine are concentrated, seasonal rest grazing should be carried out in the growing season, which is conducive to its normal growth and development, and improve the probability of bearing fruit and seed maturity. (3) It should be strictly forbidden to plant fast-growing forest in the area where FCB wild resources are concentrated, otherwise it will bring devastating damage to its existing ecological environment. (4) Establish resource collection garden or resource bank of this medicine. As FCB in the field and cultivation environment also appeared some different characters of plants, it is necessary to strengthen the protection and research, the plants in desperate need to take timely on-site protection and transplanting protection measures. (5) Take productive protection measures. The artificial cultivation technology of FCB should be vigorously developed to meet the market demand as soon as possible, fundamentally solve the situation of short supply and high market price, and solve the ecological problems caused by excessive mining.

Key climatic variables affecting the occurrence of FCB

According to specimen records, the original species of FCB are almost distributed in alpine or subalpine regions, and their growth is greatly restricted by altitude. In low altitude areas, they could not grow and reproduce normally. However, in high altitude area, the biomass of bulb and the total biomass of these species decreased with the increase of altitude. Therefore, areas with too high or too low altitude are not conducive to their normal growth. The results of this study showed that the most important environmental variable affecting the distribution of FCB was altitude, and the suitable range was 2347–3612.7 m which was basically consistent with the existing literature. FCB liked the cold and

humid climate and endures a strong cold, but was intolerant of drought and susceptible to disease especially in hot and humid conditions. It was mainly distributed in the eastern Qinghai Tibet Plateau at an altitude of about 3000 m. Due to the control and influence of southwest monsoon, westerly circulation, and Qinghai Tibet high, its main climatic characteristics are low heat, large annual rainfall, small annual temperature difference, and large daily temperature difference, which are consistent with its biological characteristics. In this study, the average temperature of the coldest quarter suitable for the existence of FCB was from -4.7 to 1.8°C , which indicated that the safe overwintering can be ensured when the temperature is not too low in winter.

Xu et al. (2019) studied the different responses of the distribution of widespread plant species and narrow-ranged plant species to human activities, and found that the impact of human activities on narrow-ranged species was negatively correlated. This study showed that the increase of human activity intensity reduces the potential probability of the species and makes its distribution area fragmented, which means that the species is very sensitive to the disturbance of human activities. Numerous studies have shown that human over harvesting, especially due to commercial interests, was one of the main reasons for endanger situation of this medicine (Konchar et al. 2011; Li et al. 2017; Cunningham et al. 2018; Wu et al. 2020; Niu et al. 2021). It was reported that the price of wild harvested FCB increased over nine-fold between 2002 and 2017, namely from the equivalent of US\$60 in 2002 to US\$560 per kg (Cunningham et al. 2018). Human disturbance not only resulted decreasing of abundance of the medicine and its size (Li et al. 2017), but also drove the color evolution of *F. delavayi* Franch, one of the original species of FCB (Niu et al. 2021). Although artificial cultivation of the medicine could supply part requirement for FCB, wild harvesting is still the most important source in the medicinal market (Fig. 10). So human activity, especially commercial harvesting, still seriously threatens survival of the original species of FCB.

Potential distribution of FCB in China under climate change scenarios

In this paper, we quantitatively analyzed and demonstrated the area changes of suitable areas of FCB in 2050s and 2070s under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The results showed that the areas of the highly and the total suitable areas would decrease in the future, and the decreasing trend would increase with the increase of SSP concentration. At the same time, the geometric center of the total suitable area of FCB would move to the northwest. Some studies have shown that under the influence of climate change in the future, the suitable areas of some traditional Chinese medicine plants will move northward

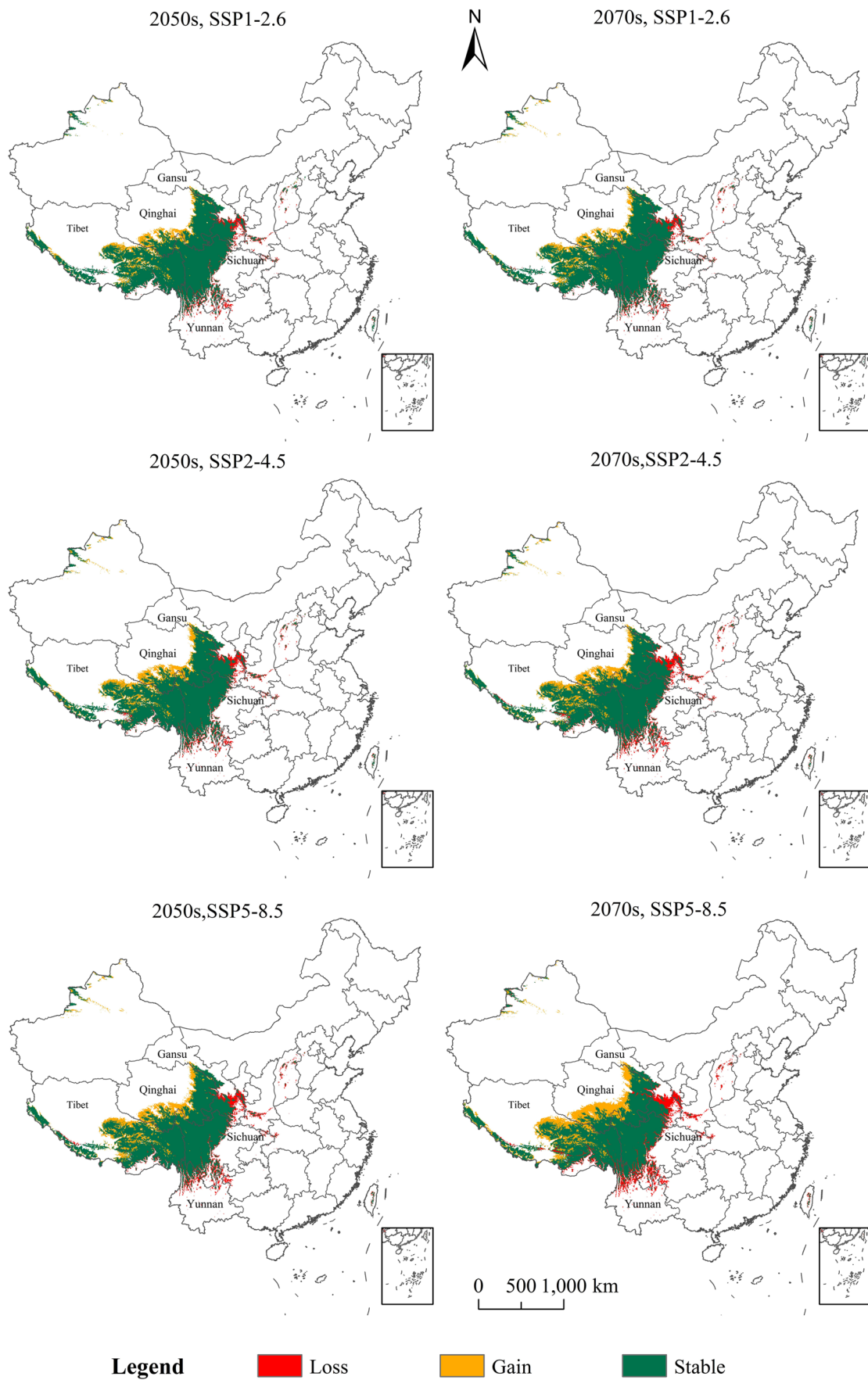


Figure 8 Changes of the total suitable areas of FCB under different climate change scenarios

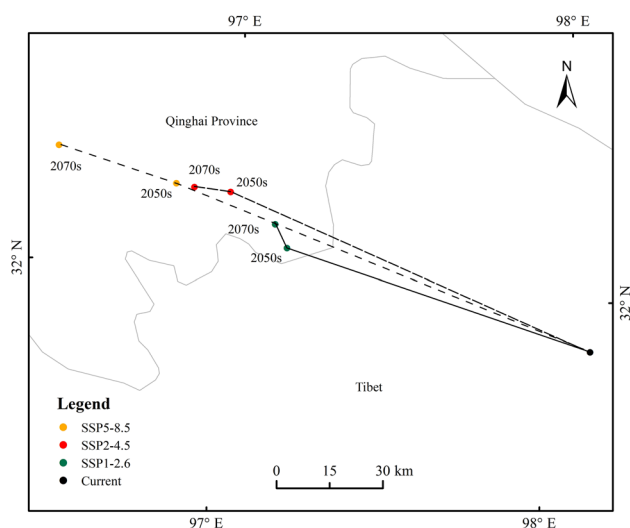


Figure 9 Variations of the centroids of the total suitable areas of FCB under climate change scenarios in the future

(Yang et al. 2017a, b; Ji et al. 2020; Tan et al. 2020). Many scholars pointed out that most of the changes in the geographical distribution of plant species caused by climate change were related to the increase of temperature and the decrease of precipitation in the growing season (Root et al. 2003; Guo et al. 2014; Zhu and Xu 2019). In the suitable area of FCB, the mean annual temperature (Bio1) would generally increase and the mean annual precipitation (Bio12) would decrease in the future. Sillmann et al. (2013) and Dyderski et al. (2018) respectively pointed out that global climate change was a trend of aridity, which is unfavorable to its growth and development in most suitable areas of western China. Therefore, it was imperative to increase the biomass per unit area of FCB, improve the utilization rate, and find reliable and feasible protection methods through science and technology under the situation that the highly suitable area was constantly broken and shrinking.

According to the results of this study, under the three climate change scenarios in the future, the stable area of the total suitable area, that was, the area less affected by climate change, accounted for a relatively high proportion



Figure 10 Commercial harvesting of FCB from wild habitats: **A** commercial harvesting of local people; **B** morphology of *Fritillaria cirrhosa* Don., one of the main original species; **C** fresh bulbous of FCB from wild habitats; **D** FCB medicine sold in medicinal market

(84.43–93.36%), which could be used as an ideal candidate for large-scale cultivation of FCB. In contrast, the remaining areas significantly affected by climate change should be the priority areas for investigation and collection of FCB wild planting resources, so as to protect this precious medicinal plant resources.

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Author contribution L. Liu and Y.J. Li planned and supervised the project. L. Liu and J.D. Zhang performed the experiments, analyzed the data, and contributed reagents/materials/analysis tools. Y. Huang, Y.Y. Zhang, Q.Y. Mou, and J.Y. Qiu, R.L. Wang contributed to data collection and evaluation. D.Q. Zhang revised the manuscript.

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

Declarations

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