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Effects of Climate Change and Environmental Factors on Bamboo (*Ferrocalamus strictus*), a PSESP Unique to China

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Abstract: Bamboo is a plant that may replace plastics and wood as a new green environmental protection material that can be developed. *Ferrocalamus strictus* is a very special and rare bamboo which is a plant species with extremely small populations (PSESP) endemic to Yunnan, China, and it is listed as a China key national first-class protected wild plant. To explore the effects of extreme climate and environmental changes on this PSESP, we conducted a case study on the response of *F. strictus* to climate under two extreme future emission scenarios. We combined 29 environmental variables, including the temperature, precipitation, altitude, slope, aspect, soil pH, soil organic carbon content, and mean UV-B radiation of the highest month, to analyze the important environmental factors limiting the distribution of *F. strictus* and identified the priority conservation areas (PCAs) of *F. strictus*. Under the two future extreme climate scenarios, the core potential suitable distribution area of *F. strictus* would decrease by 26%–34% in 2040, 44%–46% in 2060, and 23%–58% in 2080, respectively. Bio18 (precipitation in the warmest quarter) and Bio3 (isotherm) were the two key factors limiting the geographical distribution of *F. strictus* (the contribution rates were 40.1% and 18.45%, respectively). The results of this study show that *F. strictus* is in urgent need of protection and PSESPs require more attention.

Keywords: *Ferrocalamus strictus*; species distribution modelling; endangered; priority protected areas; climate change

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1. Introduction

China is very rich in plant diversity [1], but there are still many plants that are threatened or that have even gone extinct [2], e.g., plant species with extremely small populations (PSESP). PSESPs are priority species for conservation in China due to their narrow distribution, habitat disturbance, and high extinction risk [3–6], and they have attracted international attention in recent years [7–10].

Climate change is an important factor affecting plant survival [11,12]. Climate affects forests by influencing plant phenology, plant pests and diseases, and the characteristics of forest ecosystems [13,14], which in turn have strong influences on soil properties [15,16]. These effects threaten plants in many ways [17–19], especially species with a narrow habitat distribution [20]. Continuing climate change will shift the distribution of species [21] and reduce the quality of habitats [21], which will increase the risk of extinction. According to the 2022 intergovernmental panel on climate change (IPCC) sixth assessment (AR6) (https://www.ipcc.ch/assessment-report/ar6/ (accessed on 27 November 2022)), the impact of human activities is intensifying, regional climate change is significant, and extreme weather events are more frequent.

Under climate change, protecting the extremely small populations of PSESPs is urgent. Many PSESPs are relict species dating back hundreds of years. The conservation of PSESPs

is of great significance to the conservation of global biodiversity [22–24]. At the same time, the impact of climate change on PSESPs should be considered when implementing protection plans [25–28].

In order to estimate the potential impact of climate on species habitat and evaluate the habitat distribution characteristics and environmental factors affecting habitat suitability, various distribution models have been used to predict ecological environments and distribution areas [29,30]. Priority conservation areas (Pca) were established with the help of the model [31–34]. The MaxEnt (maximum entropy) model is widely used as a niche simulation method to predict the impact of future climate change on an area of suitable habitat for a species [35–38]. The MaxEnt model can predict the distribution range of a small number of species, which is very suitable for the prediction of some endangered plants, and it can achieve a high level of accuracy [39–41].

Bamboo is one of the fastest growing plants in the world and has an irreplaceable place in biodiversity. Bamboo is crucial to environmental protection and biodiversity conservation, which are beneficial to the environment and to economies [42,43]. Bamboo has a very important conservation value. It is a new type of green material with a high development value, for example, it may replace plastics, and "bamboo instead of plastic", "bamboo instead of wood", "bamboo instead of cotton", "bamboo instead of steel and concrete building materials", and other innovations reduce global plastic pollution and help to build a green and low-carbon environment.

F. strictus is a rare bamboo species in China, and there have been few reports on it [44]. *Ferrocalamus strictus* belongs to Poaceae *Ferrocalamus*. It has been listed as a key national first-class protected wild plant species in China and a PSESP unique to China. *F. strictus* is a fast-growing bamboo, and only three bamboo species, including *F. rimosivaginus* and *F. fibrillosus*, are members of *Ferrocalamus* throughout the world [45,46]. *F. strictus* is a special type of bamboo with branches that are nearly as thick as culms. Its longest section can reach up to 121 cm, which is one of the longest sections of bamboo reported in the world. It has great development potential as a green environmental protection material. With global plastic and carbon pollution rising, it is increasingly urgent to promote green materials to develop a carbon-neutral economy. *F. strictus* has great significance in ecological protection.

The natural distribution area of *F. strictus* is very narrow, and its habitat is seriously fragmented. As a typical PSESP within its narrow geographical range, *F. strictus* is vulnerable to rapid environmental changes caused by natural or human interference. The analysis of the species distribution and habitat is the basis and premise for its effective protection [47]. However, thus far, limited information is available regarding the habitat suitability of its habitat distribution characteristics and the major ecological environmental factors affecting its suitability, especially under climate change scenarios. Understanding its habitat suitability and risk factors are the first steps in conserving these PSESPs.

In this paper, the effects of climate on PSESPs were investigated using *F. strictus* as an example. On the basis of extensive field investigation, we used climate models to study the potential suitable habitat and spatial variation in the geographical distribution of *F. strictus* in China. We sought to (1) investigate the population distribution and habitat status of *F. strictus*. (2) predict the potential geographic distribution of *F. strictus* under two future climate change scenarios and analyze the key environmental variables that would limit the distribution of *F. strictus*, and (3) determine the priority protection area of *F. strictus* and put forward some suggestions for its protection. The results of this study will help to guide the conservation of *F. strictus* and provide reference for the conservation of other PESP habitats on an international scale.

2. Materials and Methods

2.1. Distribution of F. strictus

The distribution information of *F. strictus* was obtained from the literature and data records, e.g., *Flora of China*, *Flora of Yunnan*, the flora of various places, and the specimen records collected by the herbarium of the Southwest Forestry University. From October

2020 to March 2021, we conducted extensive field surveys and GPS positioning of all of the distribution areas of *F. strictus* documented in China, and we confirmed all of the distribution points of *F. strictus* in China through field investigations. According to the literature and our field investigations, the distribution of *F. strictus* was recorded only in the south of Yunnan Province. In order to prevent model overfitting, we used ArcGIS software to screen the distribution points and we selected only one distribution point in a "30 × 30" grid. Finally, we selected 25 distribution points from the field investigations which covered almost all of its distribution range.

2.2. Environment Variables

Several environmental factors were used in this study, including 19 climate factors and 3 topographic factors (altitude, slope, and aspect) from the World Climate website (https://www.worldclim.org/ (accessed on 27 November 2022)), 4 UV-B variables from the Global UV-B Radiation Database [48], and 2 soil factors (soil pH and organic carbon content) from the Harmonized world soil database v1.2 [49]. In the MaxEnt (version 3.4.3, https://biodiversityinformatics.amnh.org/open_source/MaxEnt/ (accessed on 27 November 2022)) model, the contribution rate of 28 environmental factors was tested by jackknife to rank their importance. In order to prevent mutual influences among the variables, we conducted a correlation coefficient analysis to eliminate variables with correlation coefficients greater than 0.75. Combined with the jackknife of the MaxEnt model, we finally selected 5 climate factors, 3 topographic factors, 2 soil factors, and 1 UV-B factor (Table 1). Each variable has a uniform resolution of 2.5 arc-minutes and was in the coordinate system CGS_WGS_1984. The maps we used in this article are from the China geographic information system network and were provided on the basis of a 1:4,000,000 map of China and the administrative zoning map of China. We selected two shared socioeconomic pathways (SSP 1-2.6 and SSP 5-8.5) from the BCC CSM2-MR climate system model [50].

Table 1. The environmental factors used in the model and their contributions in predicting the current and future distributions of *Ferrocalamus strictus* in China.

Variables	Description	Percent Contribution (%)						
		Current	SSP [c] 1-2.6			SSP5-8.5		
			1 [d]	2	3	1	2	3
bio1 (°C) [a]	Annual mean temperature	0.1	0.8	0.1	0.1	0.1	0.1	0.1
bio2 (°C) [b]	Mean diurnal range (mean of monthly (max temp–min temp)	-	-	-	-	-	-	-
bio3	Isothermality (bio2/bio7) (×100)	31.8	34	27.3	26.2	17	22.5	24.8
bio4	Temperature seasonality (standard deviation × 100)	1.9	1.8	4.1	3.8	5.7	3.3	4.1
bio5 (°C)	Maximum temperature of warmest month	-	-	-	-	-	-	-
bio6 (°C)	Minimum temperature of coldest month	-	-	-	-	-	-	-
bio7 (°C)	Temperature annual range (bio5-bio6) × 10	-	-	-	-	-	-	-
bio8 (°C)	Mean temperature of wettest quarter	-	-	-	-	-	-	-
bio9 (°C)	Mean temperature of driest quarter × 10	-	-	-	-	-	-	-
bio10 (°C)	Mean temperature of warmest quarter	-	-	-	-	-	-	-
bio11 (°C)	Mean temperature of coldest quarter	-	-	-	-	-	-	-
bio12 (mm)	Annual precipitation	-	-	-	-	-	-	-
bio13 (mm)	Precipitation of wettest month	-	-	-	-	-	-	-
bio14 (mm)	Precipitation of driest month	10.2	3.5	3.5	6.6	2.5	4.9	4.1
bio15 (mm)	Precipitation seasonality (coefficient of variation)	-	-	-	-	-	-	-
bio16 (mm)	Precipitation of wettest quarter	-	-	-	-	-	-	-
bio17 (mm)	Precipitation of driest quarter	-	-	-	-	-	-	-
bio18 (mm)	Precipitation of warmest quarter	31.5	34	35.5	36.3	45.8	38.3	37
bio19 (mm)	Precipitation of coldest quarter	-	-	-	-	-	-	-
aspect	(Uphill height/horizontal distance) × 100%	3.2	2.5	3.7	3.6	3.5	3.8	3.4
slope	(height difference/distance) × 100%	10.5	12.4	13.6	12.3	11.2	13.7	12.9
elev (m)	Elevation	0.7	1.6	2.7	2.5	6	3.1	2.5
T-ph	Soil pH	1.1	2.3	1.8	1.6	2	2.1	2.2
T-oc	Organic carbon (g/kg × 100%)	8.3	7.4	6.3	5.8	5.5	6.7	7.1
Uvb3 (J/m^2/d)	Mean UV-B radiation of highest month	0.6	2.1	1.3	1.2	0.8	1.6	1.6

[a] Bioclimatic variable from the WorldClim database (worldclim.org). [b] The variables in bold were used in the maximum entropy model. The current distribution based on the historical bioclimatic data was averaged for 1970–2000. [c] SSP 1-2.6 represents the climate change scenario of +2.6 W m^{-2} radiative forcing under an SSP1 assumption, and SSP 5–8.5 represents the climate change scenario of +8.5 W m^{-2} radiative forcing under an SSP5 assumption. [d] 1, 2, and 3 represent the periods 2021–2040, 2041–2060, and 2061–2080, respectively.

2.3. MaxEnt Model Accuracy

MaxEnt was chosen because it only requires the presence of data and can provide accurate predictions, even with a small sample size [40,51]. Distribution data and environmental data were imported into MaxEnt and 25% of the distribution records were randomly selected for model testing, with the remaining 75% used as training data sets. Because of the small sample size, we used the ENMeval package (http://cran.r-project.org/web/packages/ENMeval/index.html (accessed on 27 November 2022)) to optimize the regularization multipliers and feature combinations to improve the model's performance and avoid overfitting the results [52,53]. Setting regularization multiplier = 2 and feature combination = LQHPT [54]. Spatial filtering of the raw data with ARGIS software's SDMtoolbox tool was used to avoid model performance exaggeration [55,56]. Model setup iterations run 10,000 times [51].

The jackknife cutting method was selected to analyze the importance of the environmental factors. The prediction accuracy test of MaxEnt was evaluated by the receiver operating characteristic curve (ROC) and the "continuous Boyce index" package (adamlilith/enmSdm source: R/contBoyce.r (rdrr.Io)), because AUC is not enough to fully evaluate model performance [57]. Therefore, AUC and CBI (continuous Boyce index) were adopted to evaluate the model together. The CBI is suitable for evaluating the performance of models with small sample sizes [58]. The values of the Aucs ranged from 0 to 1, and the prediction effects were divided into poor (<0.7) and good (>0.9) [59]. The outputs from MaxEnt were transferred into ArcGIS10.5 and the reclassification tool of ArcGIS10.5 was used to classify the suitable areas as follows: very highly suitable area (1–0.8), highly suitable area (0.8–0.6), moderately suitable area (0.6–0.4), lowly suitable area (0.4–0.2), and unsuitable area (Mt < 0.2) [60]. The very highly suitable area was the core distribution region. We used the centroid of its core distribution region to detect the change spatial distribution pattern of *F. strictus* for different periods [61].

3. Results

3.1. Population Status of F. strictus

According to the literature and our field investigations, *F. strictus* was only distributioned in Honghe and Puer in Yunnan (Figure 1). And Honghe County of Honghe Prefecture is a new county distribution point we found. The longitude range of *F. strictus* in the field was 101°42′53.57″–103°03′13.435″, and the latitude range was 23°27′24.549″–22°29′37.366″. The altitude range was ~750–1985 m. The actual distribution area of *F. strictus* was only approximately 5.92 km^2, which was very narrow and patchy. The distribution area showed a decreasing trend. After our field investigations, we found that the distribution area was suffering from serious human disturbance (Figure 2). Local residents had been cutting it down to make fences and sheds and using its leaves to make traditional Chinese rice pudding. According to the rules of the IUCN Red List of Threatened Species, *F. strictus* can be classified as endangered (B1a+B1bi). However, *F. strictus* is not listed on the IUCN Red List of Threatened Species, and it is recommended that *F. Strictus* be added to the IUCN Red List of Threatened Species.

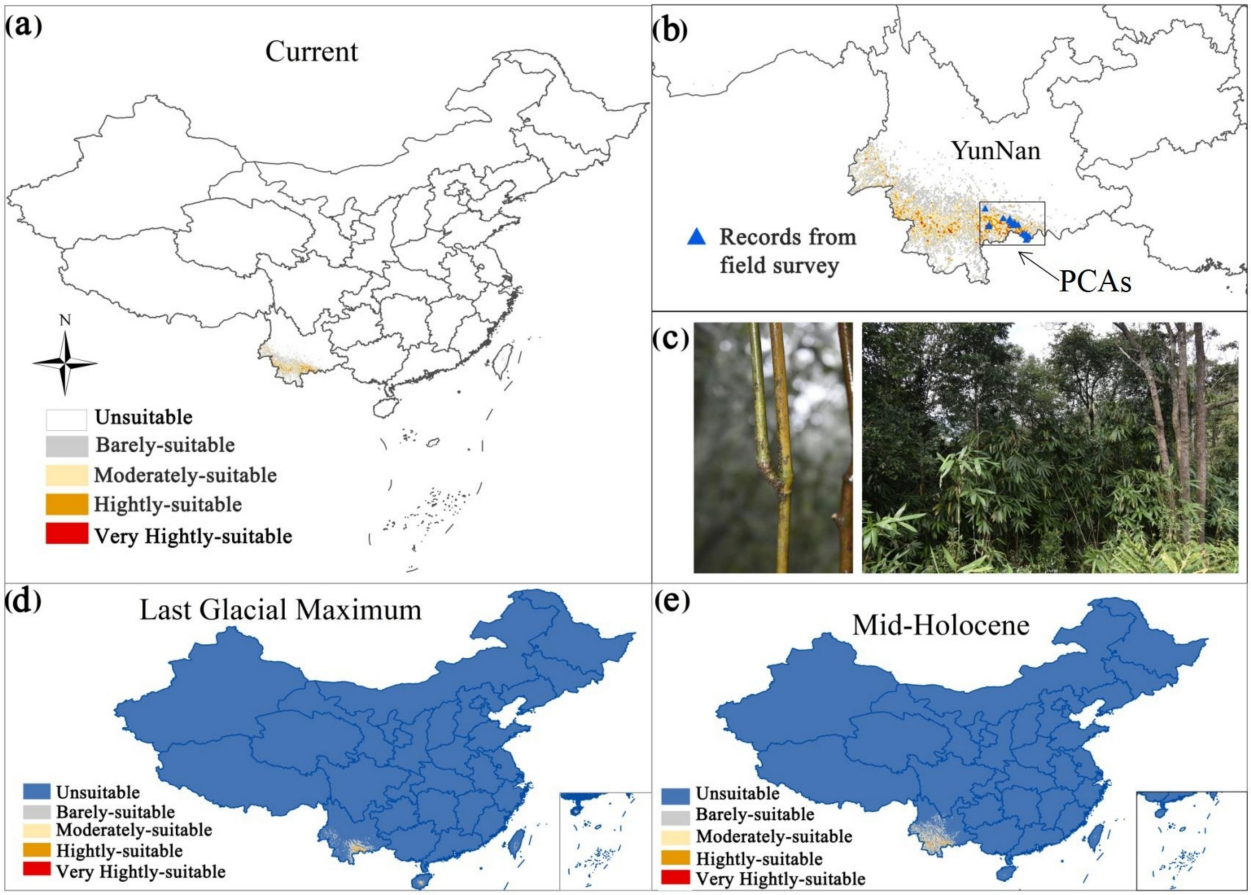


Figure 1. Current distribution of the potential suitable areas for *Ferrocalamus strictus* (**a**). The current distribution and priority conservation areas of *Ferrocalamus strictus* (**b**). A picture of a whole *F. strictus* specimen (**c**). Potential distribution area of *Ferrocalamus strictus* in the mid-Holocene (approximately 6 kya) (**d**) and Last Glacial Maximum (approximately 21 kya) (**e**) periods.

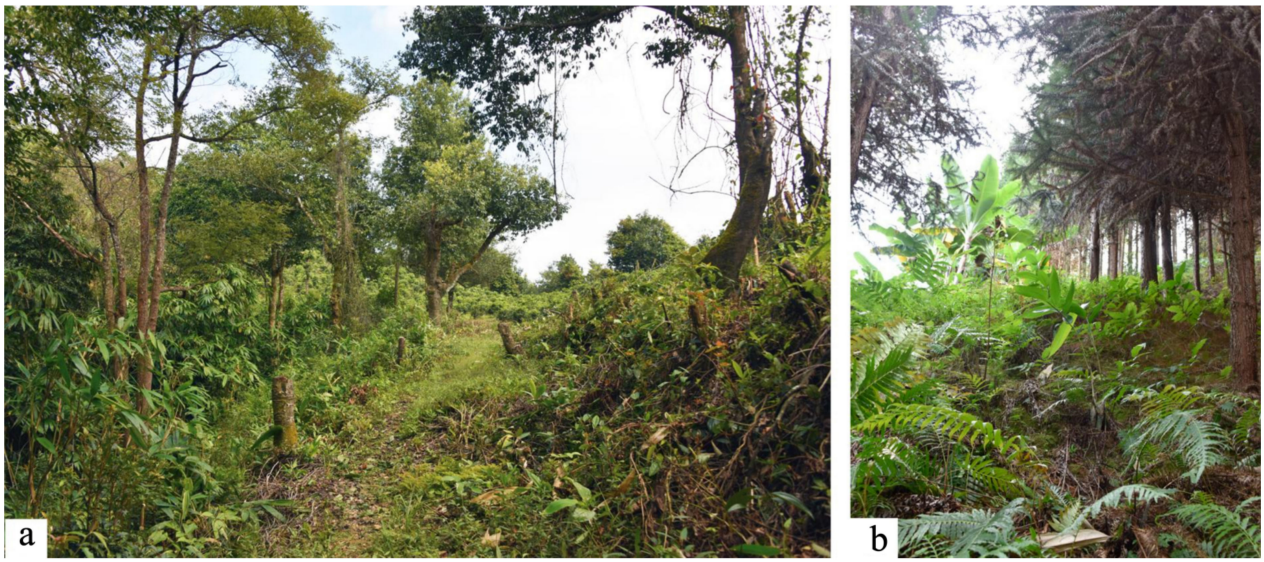


Figure 2. Remnants of *F. strictus* and tea forests (**a**). The remaining *F. strictus* forest, sand forest, and banana forest (**b**).

3.2. The Restriction of Environmental Factors on the Geographical Distribution of F. strictus

The AUC value reached 0.997 (Figure 3) and the CBI value reached 0.975 (Figure 4), indicating that the prediction results were accurate. Based on the MaxEnt model, the current total suitable area for *F. strictus* in China is ~63,883 km^2, accounting for 0.99% of the total area of China. Of the total area in China, 99.01% is unsuitable for *F. strictus* growth (Figure 1). The potential suitable areas are concentrated in Southwest Yunnan, and partial suitable areas in Hainan. The very highly suitable area of *F. strictus* is ~1162 km^2, the highly suitable area is 8586 km^2, the moderately suitable area is ~18,906 km^2, and the barely suitable area is ~35,228 km^2.

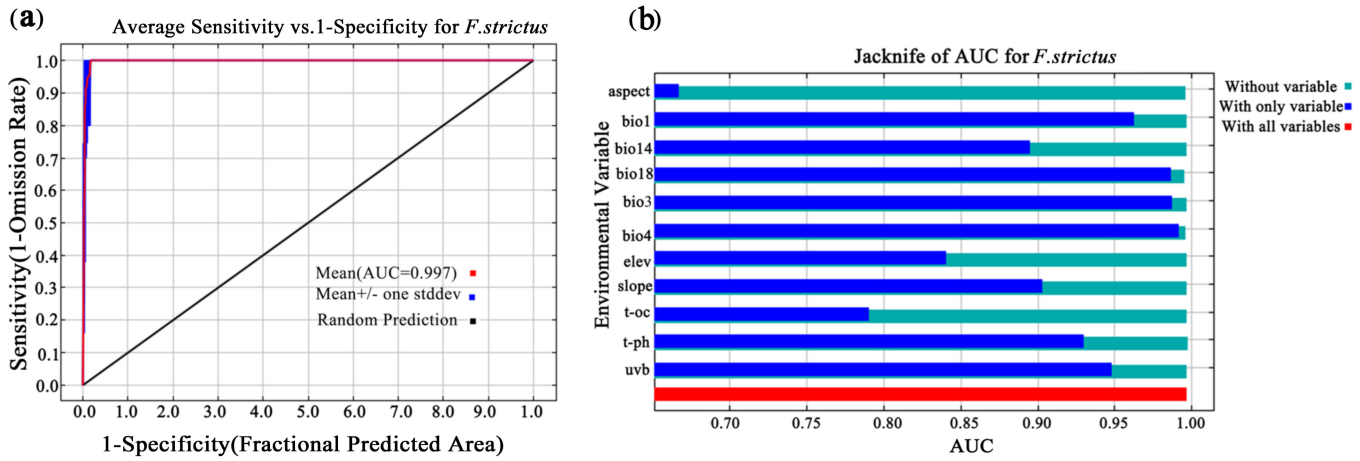


Figure 3. Prediction of the ROC in the MaxEnt model. The model accuracy reached 0.997 (**a**). The jackknife of the AUC for *F. strictus* (**b**).

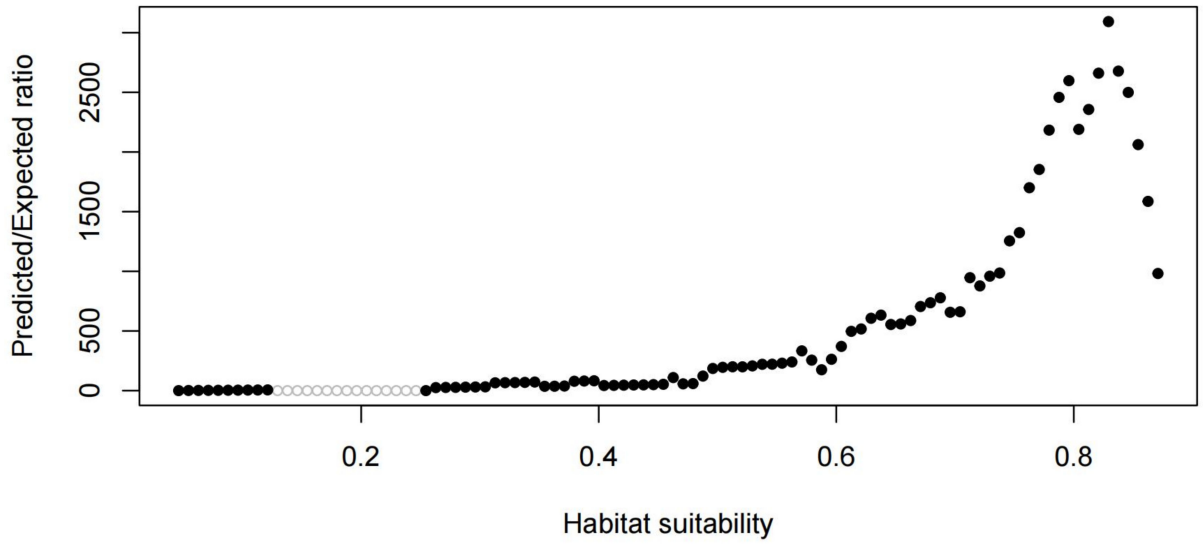


Figure 4. CBI = 0.975. CBI is used as a reliable performance measure.

Based on the contribution rate (Table 1) and the AUC results based on the model, the precipitation in the warmest quarter (bio18), isotherm (bio3), slope, precipitation in the driest month (bio14), and temperature seasonality (standard deviation × 100) (bio4) were important to the distribution of *F. strictus*. The precipitation of the warmest quarter (bio18) and the isotherm (bio3) were the key factors affecting the distribution of *F. strictus* (their cumulative contribution reached 63.3%). When 702 mm < bio18 < 1124 mm, or 42 °C < Bio3 < 54.6 °C, the area was suitable for the growth of *F. strictus* (Figure 5). This was consistent with our field observations. We have observed in the wild that *F. strictus* preferred a humid and hot habitat and preferred to grow in a gully with water.

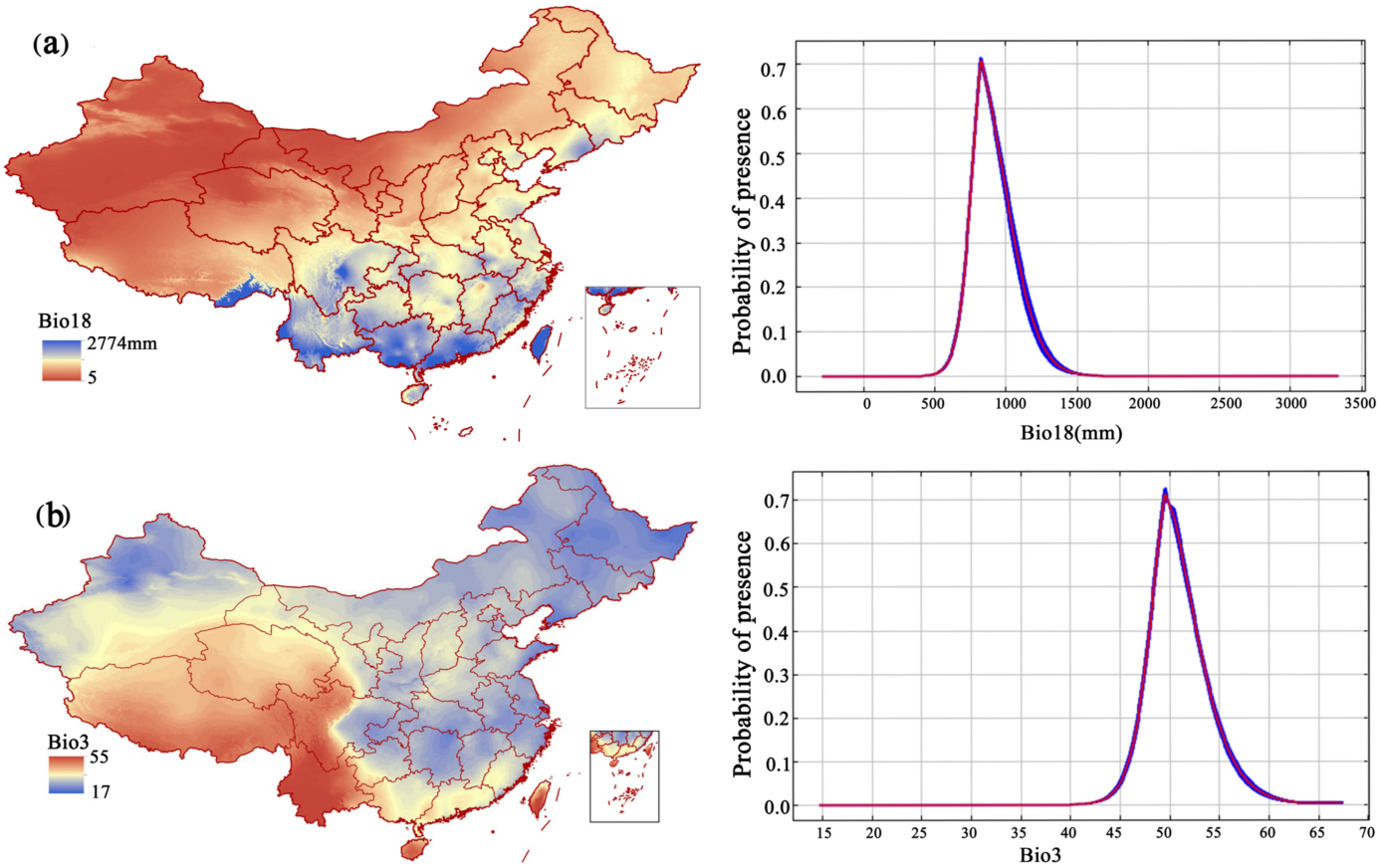


Figure 5. Response curves of the major environmental factors affecting *F. strictus* (**a**,**b**).

3.3. Changes in the Potential Distribution of F. strictus under Climate Change

Figure 4 shows the change in suitable habitat for three different periods in the future (2021–2040, 2041–2060, and 2061–2080) based on two different climate scenarios (Figure 6). The current total ecologically suitable area for *F. strictus* increased ~21.6%, ~19.9%, and ~21.1%, respectively, compared with the future SSP1-2.6 climate scenario, and the current total ecologically suitable area for *F. strictus* increased ~34%, ~26%, and ~30.9%, respectively, compared with the future SSP5-5.8 climate scenario (Table 2). The potentially suitable area for *F. strictus* in the high emission scenario increased faster than that of the low emission scenario. This indicates that the scenario for high concentration emissions was conducive to the expansion of the suitable area for *F. strictus*.

During the Last Glacial Maximum and the mid-Holocene periods, the distribution center of *F. strictus* migrated northward (Figure 7). According to the dynamic distribution and location of the center of the mass of *F. strictus* from the present to the future, the distribution direction of *F. strictus* is first east and then north in the low emission scenario. In the high emission scenario, the distribution direction of *F. strictus* shifts eastward.

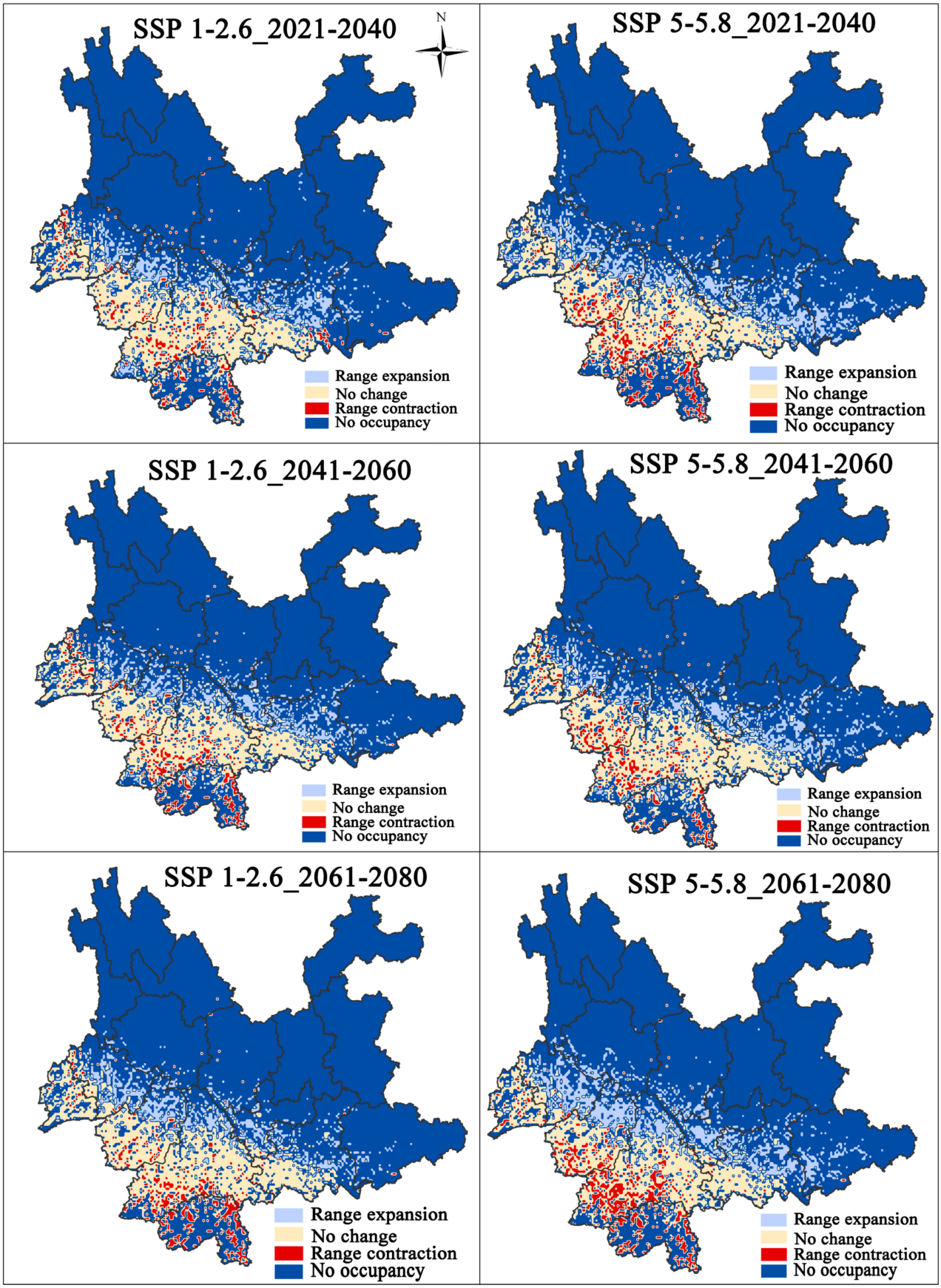


Figure 6. Distribution of potential suitable change for *F. strictus* under future climate change. The change of the suitable area compared to the present.

Table 2. The distribution area of *F. strictus* under climate change.

Area	Last Glacial Maximum	Mid-Holocene	Current	SSP 1-2.6			SSP 5-5.8		
				2021–2040	2041–2060	2061–2080	2021–2040	2041–2060	2061–2080
Barely suitable [a]	−28% [b]	+63%	3.5229 (km^2)	+34%	+28%	+23%	+40%	+43%	+48%
Moderately suitable	−51%	+32%	1.8907 (km^2)	+17%	+21%	+24%	+35%	+16%	+25%
Highly suitable	−41%	+18%	8586 (km^2) [c]	−12.8%	−8.19%	+11.6%	+14.3%	−15%	−16.4%
Very highly suitable	+377%	+42%	1162 (km^2)	−34%	−46%	−23%	−26%	−44%	−58%
Total suitable	−37%	+47%	6.3883 (km^2)	+21.6%	+19.9%	+21.1%	+34%	+26%	+30.9%

[a] The values of the MaxEnt logistic outputs were divided into five classes, i.e., unsuitable (0–0.2), barely suitable (0.2–0.4), moderately suitable (0.4–0.6), highly suitable (>0.6), and very highly suitable (0.8–1). [b] −/+ represents the percentage of the potential distribution area that decreased or increased in each period compared with the current potential distribution. [c] represents the current potential distribution area for *F. strictus*.

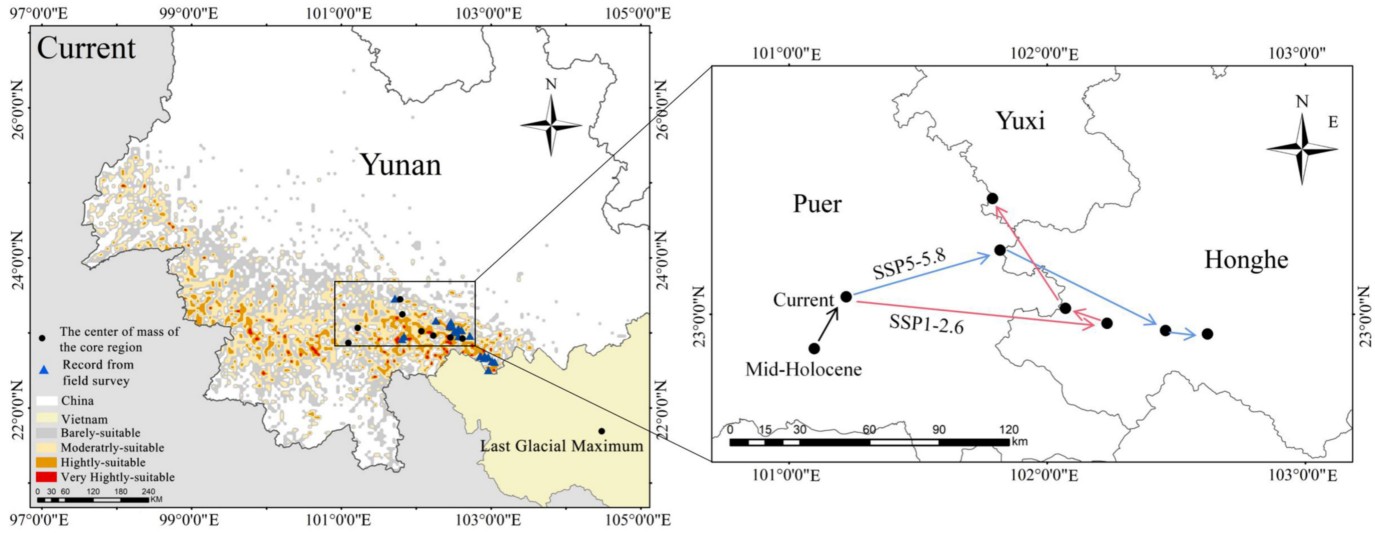


Figure 7. Spatial variation patterns of the potential geographical distribution for *F. strictus* in different periods. Pca is the priority conservation area for *F. strictus*.

3.4. Priority Conservation Areas

Considering the distribution of suitable areas in the Last Glacial Maximum period, the mid-Holocene period, and the future, the core area of *F. strictus* in each period was near south Yunnan. Combined with the modern distribution of *F. strictus*, it is suggested to establish priority conservation areas for in situ and ex situ protection in Yunnan Honghe Jinping Fenshuiling Provincial Nature Reserve and Pu'er Mojiang Xiqisuoluo Provincial Nature Reserve (Figure 1). *F. strictus* is found in both reserves.

4. Discussion and Conclusions

4.1. The Effect of Climate on Distribution

The potential distribution of *F. strictus* during the Last Glacial Maximum period decreased by ~37% compared to the current period, but it increased by ~47% during the mid-Holocene period. This shows that the climate of the mid-Holocene period was more suitable for the growth of *F. strictus*. This is likely because the climate began to warm from the Last Glacial Maximum to the mid-Holocene period. As the ice age receded and temperatures rose, the potential distribution areas of barely suitable, moderately suitable, and highly suitable were increasing, and the total potential distribution area of *F. strictus* reached its maximum in the middle of the mid-Holocene period.

Under climate change, many species tend to expand northward [62]. The reason that *F. strictus* does not migrate northward in the high-emission scenario may be that precipitation decreases due to the future's increased temperatures, which would limit its distribution. Temperature and precipitation play vital roles in plant survival and distribution [63–65]. Most of the actual distribution points of *F. strictus* are in the Ailao Mountain area of southern Yunnan Province, China. This is likely because the mountain

barrier is conducive to the formation of a stable microclimate environment, which also provides more suitable conditions for the survival of *F. strictus* [66]. In combination with the present geographical distribution and future climate responses, *F. strictus* is sensitive to moisture and temperature, which is likely the main reason for its narrow distribution. Further continuous field monitoring is needed to identify the predictions for *F. strictus*, which are crucial for the survival of the population.

4.2. Refuge

During the Quaternary glacial period, many species were affected by the glacial climate and moved to areas where they could survive. These areas are called refuges. Refuges are also the starting point for post-glacial redevelopment and the dispersal of species. Studies have shown that southwest China and northern Vietnam were sanctuaries for many plants during the ice age [67]. According to the potential suitable habitat during the Last Glacial Maximum period, the refuge for *F. strictus* during the glacial period may have been located in Southwest China and Northern Vietnam (Figure 1). However, in the plant survey records of China and Vietnam, there are no records of *F. strictus* in Vietnam. More evidence is needed to determine whether *F. strictus* ever survived in Vietnam during the Last Glacial Maximum period. At present, the core area of the model analysis is very close to the actual distribution of *F. strictus*. Thus, iron bamboo responds very sensitively to the climate. It also shows that the future unstable climate will be a significant challenge for the survival of *F. strictus*. Before we understand why *F. strictus* is endangered, we should first protect it. In our field investigations, we found that the anthropogenic influence of *F. strictus* greatly aggravated its degree of endangerment. It has been found in many places that *F. strictus* has been cut down, and many specimen-recording sites could not find any trace of it. It is important to identify their priority conservation areas (PCAs) [34], which are essential for providing the in situ and ex situ conservation management of plant populations and habitats.

4.3. Limitations and Prospects

With the increasing application of species distribution models, many studies have shown that the combination model is more suitable for rare species with fewer distribution points [68]. There may be limitations in predicting the results of species in this study using a single model [69]. The human activity factor [70] and spread of species [71,72] was not taken into account in this study, which is also the point that future research needs to address. In this paper, only the relationship between environmental factors and the distribution has been preliminarily explored as the cause of the endangerment of iron bamboo, but there are limitations. In order to better protect iron bamboo, we should study its biological characteristics, ecological adaptability, genetic diversity, and reproductive biology in the future to find out the mechanisms of its endangerment.

4.4. Recommendations for Protection

As a typical PSESP and a rare bamboo species, *F. strictus* is of great value and should be protected. *F. strictus* is under great threat, and the threat continues to expand. We need to take measures to protect this rare resource, and herein, we provide suggestions for protecting the natural distribution of *F. strictus*: (1) establishing priority conservation areas to protect existing population habitats and implementing cultivation and breeding programs; (2) monitoring the growth dynamics of *F. strictus* to carry out scientific research on its biological characteristics and exploring its endangered mechanisms; (3) planning for the effects of climate change on iron bamboo and developing conservation plans; and (4) strengthening iron bamboo protection publicity and popularizing science work to reduce human interference.

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