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Predicting Climate Change Impacts on the Rare and Endangered *Horsfieldia tetratepala* in China

Chaonan Cai [1,2], Xiaoyan Zhang [3,4], Jianjun Zha [5], Jie Li [3] and Junmin Li [1,2,*]

1. School of Advanced Study, Taizhou University, Taizhou 318000, China; chaonancai@tzc.edu.cn
2. Zhejiang Provincial Key Laboratory of Plant Evolutionary Ecology and Conservation, Taizhou University, Taizhou 318000, China
3. Plant Phylogenetics and Conservation Group, Center for Integrative Conservation, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Kunming 650223, China; zhangxiaoyan@xtbg.ac.cn (X.Z.); jieli@xtbg.ac.cn (J.L.)
4. University of Chinese Academy of Sciences, Beijing 100049, China
5. Taizhou Research Institute, Southern University of Science and Technology, Taizhou 318000, China; jianjun_zha@126.com

* Correspondence: lijm@tzc.edu.cn

Abstract: Global climate change has become a major threat to biodiversity, posing severe challenges to species conservation. This is particularly true for species such as *Horsfieldia tetratepala* that have extremely small populations in the wild. Little is known about the species distribution of *H. tetratepala* in the current climate, as well as how that will change with potential future climates. The key environmental factors that influence its expansion, especially its habitat sustainability and its potential to adapt to climate change, are also unknown, though such information is vital for the protection of this endangered species. Based on six climate factors and 25 species distribution points, this study used the maximum entropy model (MaxEnt) to simulate the potential distribution for *H. tetratepala* in three periods (current, 2050s, and 2070s), and to investigate the changes in distribution patterns and the main environmental factors affecting species distribution. The modeling results show that the most important bioclimatic variables affecting *H. tetratepala* were precipitation of the warmest quarter (Bio_18) and temperature seasonality (Bio_4). The suitable areas for *H. tetratepala* will gradually be lost in Yunnan but will be generally offset in the northeastward direction, expanding in Hainan, Guangzhou, and Taiwan provinces under the future climate conditions. Therefore, we recommend protecting the habitats of *H. tetratepala* in Yunnan and strengthening the in-depth species investigation and monitoring in areas (Hainan, Guangzhou, and Taiwan) where no related reports of *H. tetratepala* have been reported. The results improve our understanding of this species' response under the changing climate and benefit strategies for its conservation.

Keywords: *Horsfieldia tetratepala*; maximum entropy model; species distribution; habitat suitability; shared socioeconomic pathways; endangered species

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1. Introduction

With the progress and development of human society and science and technology, the global climate is constantly changing, posing a serious threat to many endangered species and biodiversity on earth [1]. Biodiversity is vital to human well-being but has been declining throughout human history due to human disturbances, even driving the sixth mass extinction in Earth's history [2–4]. Loss of biodiversity not only affects the function of natural ecosystems but threatens the well-being of human beings [3]. Biodiversity conservation has become a global strategy, and countries are actively carrying out biodiversity conservation. The current threats to the world's species suggest that the rate of species extinction is likely to have risen fivefold over the past few years and is continuing to increase, so it is particularly important and urgent to formulate a reasonable and efficient conservation plan [3,5]. China is a recognized biodiversity hotspot and one of the main global priority conservation areas in the world, as stated by the International Biodiversity Conservation Organization [6]. Therefore, the protection of biodiversity in China is important, not only for China but also for the entire world. However, due to factors such as rapid population growth, rapid economic and sustained growth, and insufficient social awareness, biodiversity conservation in China still faces serious threats [1,7].

Rapid climate change and human-driven land-use change have become the greatest drivers threatening biodiversity [8–10]. Climate change affects the current and future distribution of many species, influencing ecosystems and biotas worldwide [11–16]. Global warming has caused significant changes in spatial and temporal environmental patterns, affecting efforts to conserve biodiversity [17–21]. Rapidly changing climates have continued to result in the serious degradation or loss of species habitats, causing declines in population sizes or even the extinction of endangered species [22–29]. Predicting the potential distribution of endangered species can alert scientists and policymakers to the potential risks that future climate change will pose on their environments to help them propose positive coping strategies to mitigate these impacts [30,31].

One of the most important challenges for the conservation of endangered species is to resolve uncertainty surrounding species distribution [32]. In recent decades, the development of species distribution models (SDMs) has contributed to solving this challenge [33]. Utilizing SDMs to predict the potential geographical distribution of species is a hotspot in biodiversity conservation research, and has great significance for developing effective biodiversity conservation strategies [14,15,34]. Based on current species occurrence data and environmental variables, SDMs have been widely used to evaluate the potential distribution of species without biodiversity observations [28,35–38]. Subsequently, many methods have been proposed for the construction of SDMs, such as random forests (RF) [39], maximum entropy models (MaxEnt) [40], and generalized linear models (GLM) [41]. Among these SDMs, MaxEnt modeling integrates machine learning and maximum entropy principles to predict the potential distribution areas of species, and have become the most powerful and extensively used models owing to their operation simplicity, faster operational capability, and high accuracy, even with minimal occurrence data points [40,42–47]. For endangered species that have few observational occurrences and live in areas where it is difficult to collect occurrence data, the MaxEnt model provides an ideal model to predict their potential distributions under global climate change [14,15,34,36].

Horsfieldia tetratepala C. Y. Wu, a plant species with extremely small populations (PSESP), belongs to the genus *Horsfieldia* of Myristicaceae [10,48]. The distribution area of *H. tetratepala* is mainly affected by the tropical monsoon climate, in which the average annual temperature is 20~25 °C and the average annual rainfall is 1500~3500 m [49]. Research has shown that the seeds of this species are mainly dispersed by frugivorous birds, mammals, some reptiles and gravity dispersal [50,51]. During a field survey in 2018, the species was found to be disappearing due to the expansion of banana and rubber cultivation and tourism development. Furthermore, *H. tetratepala* have high economic value, e.g., their trunks can be used for redwood furniture and high-end decorative woodwork, and their oily seeds are an ideal source of biodiesel [52–54]. Combined with field observations, *H. tetratepala* is growing in the tropical monsoon forest and is now scattered in the dense limestone karst forests of Yunnan and Guangxi province on latosol soils, with only a few hundred wild individuals remaining [55]. Previous studies on this plant have focused on breeding technology [56], phytochemistry [57], taxonomy [58], community characteristics [53], vegetative characteristics [59], and the genetic diversity and population structure of *H. tetratepala* [55,59]. Little information is available about the potential distribution of *H. tetratepala* in the current climate, as well as how those patterns will change in potential future climates; especially, little is known about its habitat sustainability and its potential to adapt to climate change, which is vital for the protection of this endangered species.

In this study, we used the MaxEnt 3.4.1 (American Museum of Natural History, New York, USA) model to simulate the potential distribution areas of *H. tetratepala* under different climatic backgrounds (Current, 2041–2060 and 2061–2080). This study examined what the main climatic factors affecting the distribution of *H. tetratepala* are, how the potential distribution pattern of the species changes under different climate change backgrounds, and where areas are that will be suitable for potential conservation translocations for the species in the future. Here, we will test the hypothesis that the species distribution of *H. tetratepala* would perform a northward shift to track the climatic niche in temperature and precipitation, and the suitable habitat areas will shrink under climate warming. These results could provide a robust and effective theoretical basis for the preservation, management, development, and implementation of germplasm resources for *H. tetratepala*.

2. Materials and Methods

2.1. Current Species Data

The current distribution data for *H. tetratepala* was obtained from the Global Biodiversity Information Facility (GBIF, https//www.gbif.org, accessed on 1 March 2017), National Specimen Information Infrastructure (NSII; http://www.nsii.org.cn, accessed on 1 March 2017), the Chinese Virtual Herbarium (CVH; http://www.cvh.org.cn, accessed on 1 March 2017), the Plant Photo Bank of China (PPBC; http://ppbc.iplant.cn, accessed on 1 March 2017), and from field investigations on this species around its distribution range (149 individuals, samples from Yunnan and Guangxi province) in 2018. The total records were also filtered at a resolution of 2.5 arcminutes. Records without longitude or latitude and those that were repetitive were removed [60,61]. A total of 25 distribution points for *H. tetratepala* were obtained for final analysis and were employed to generate the potential distribution based on the MaxEnt model (Figure 1; Table S1).

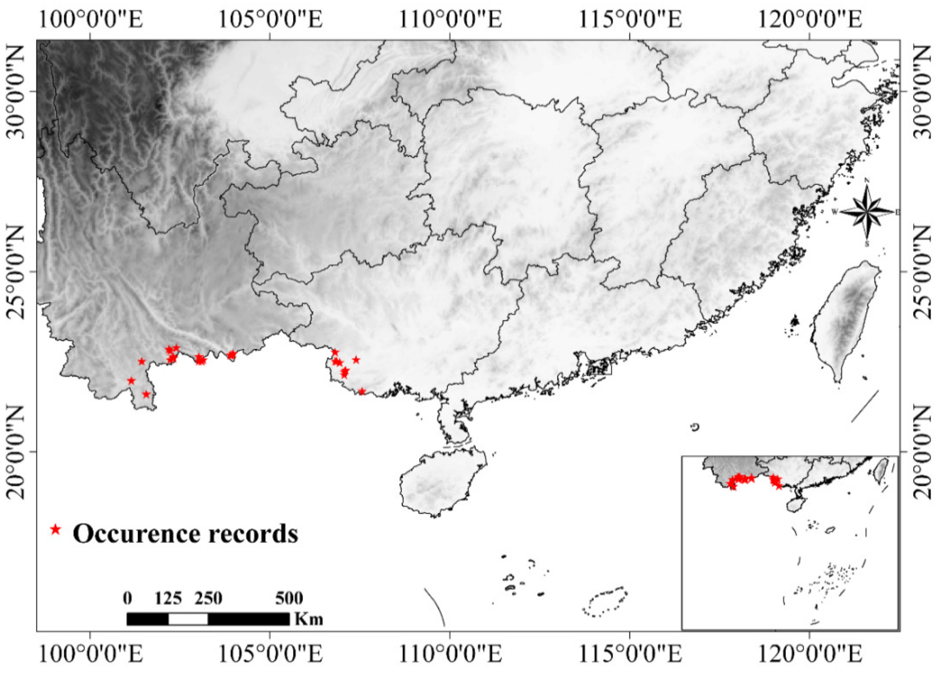

Figure 1. Map of localities where samples of the *Horsfieldia tetratepala* were employed for this study.

2.2. Environmental Variables

The 19 bioclimatic variables from the current periods were extracted from the WorldClim database (http://www.worldclim.org, accessed on 10 March 2021) with a 2.5 arcminutes resolution. To avoid overfitting the prediction results from species distribution models, the Pearson correlation coefficient was performed for the 19 bioclimatic variables in R-3.6.3 software (eliminate Pearson correlation coefficient $|r| > 0.8$ and the bioclimatic variables with low contribution, accessed on 15 March 2021) [62–64].

To predict the potential distribution of *H. tetratepala* under future climate conditions, future bioclimatic variable data (2041–2060 and 2061–2080) were downloaded from the WorldClim dataset (http://www.worldclim.org, accessed on 10 March 2021) with two global climatic models (BCC-CSM2-MR, Beijing Climate Center Climate System Model; and MIROC6, Model for Interdisciplinary Research on Climate) and four emission scenarios of the shared socioeconomic pathways (SSPs) (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) provided by the CMIP6 of the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). Four SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) represent net radiative forcing of 2.6, 4.5, 7.0, and 8.5 W/m^2 at the end of the year 2100, and represent a green development pathway, a middle development pathway, a rocky development pathway, and a high development pathway, respectively [65,66].

2.3. Habitat Suitability Modeling

MaxEnt v3.4.1 (http://Biodiversityinformatics.amnh.org/open_source/maxent/, accessed on 10 March 2021) was used with 30 replicates and the Bootstrap method to model the suitable habitat distributions of *H. tetratepala* based on occurrence records and climate variables [40,45,67,68]. The MaxEnt model was run with a convergence threshold of 10^{-5}, maximum 500 iterations, 10,000 maximum background points [42], a regularization parameter value of 1 [69], an auto-feature option, and the logistic output format. Other settings used the default values in [44]. A total of 90% of the database was used as training data, and 10% of the total database was used as test data to evaluate the accuracy and quality of the model predictions. Following this, the area under curve (AUC) of the receiver operating characteristic (ROC) as implemented in MaxEnt [37] was used to evaluate the model accuracy. The AUC can vary from 0.5 to 1, and, according to its value, the model performance can be categorized as insufficient (0.5–0.6), poor (0.6–0.7), average (0.7–0.8), good (0.8–0.9), or excellent (0.9–1) [64,70].

2.4. Predicting the Suitable Areas of Plants under Global Climate Change

ArcGIS 10.2 software (ESRI Inc., Redlands, CA, USA) with an add-in SDM toolbox [71] was used to quantify the habitat suitability of *H. tetratepala* from the MaxEnt output results. The habitat suitability maps produced by the MaxEnt model varied from 0 to 1. Jenks' Natural Breaks method available in ArcGIS layer properties was used to reclassify the potential distribution areas of the species based on 10 percentile training presence Logistic threshold (marginal value) in the MaxEnt results. Suitable areas for the species were divided into four levels: unsuitable (<marginal value), marginally suitable (marginal value—0.6), medium suitable (0.6–0.8), and optimal (0.8–1.0). The raster calculator in ArcGIS 10.2 software (ESRI Inc., Redlands, CA, USA) was then used to calculate the potential geographical distribution area of *H. tetratepala*.

3. Results

3.1. Model Performance and Contributions of the Variables

Based on the AUC values of the models developed, the accuracy of the predicted result was evaluated. The results showed that the AUC values of all climate conditions were significantly higher than 0.9, indicating a high accuracy of the MaxEnt model to predict the potential distribution of *H. tetratepala*.

Six of the bioclimatic variables used for *H. tetratepala* prediction were the mean diurnal range (Bio_2), temperature seasonality (Bio_4), mean temperature of coldest quarter (Bio_11), precipitation seasonality (Bio_15), precipitation of driest quarter (Bio_17), and precipitation of warmest quarter (Bio_18) (Table 1; Figure 2). Among them, precipitation in the warmest quarter (Bio_18) was determined to be the most important bioclimatic variable, followed by temperature seasonality (Bio_4).

Table 1. Environmental variables used for modeling and their permutation importance.

Environmental Variables	Code	Percent Contribution
Mean diurnal range	Bio_2	0.3
Temperature seasonality	Bio_4	13.4
Mean temperature of coldest quarter	Bio_11	3.2
Precipitation seasonality	Bio_15	5.9
Precipitation of driest quarter	Bio_17	3.7
Precipitation of warmest quarter	Bio_18	73.6

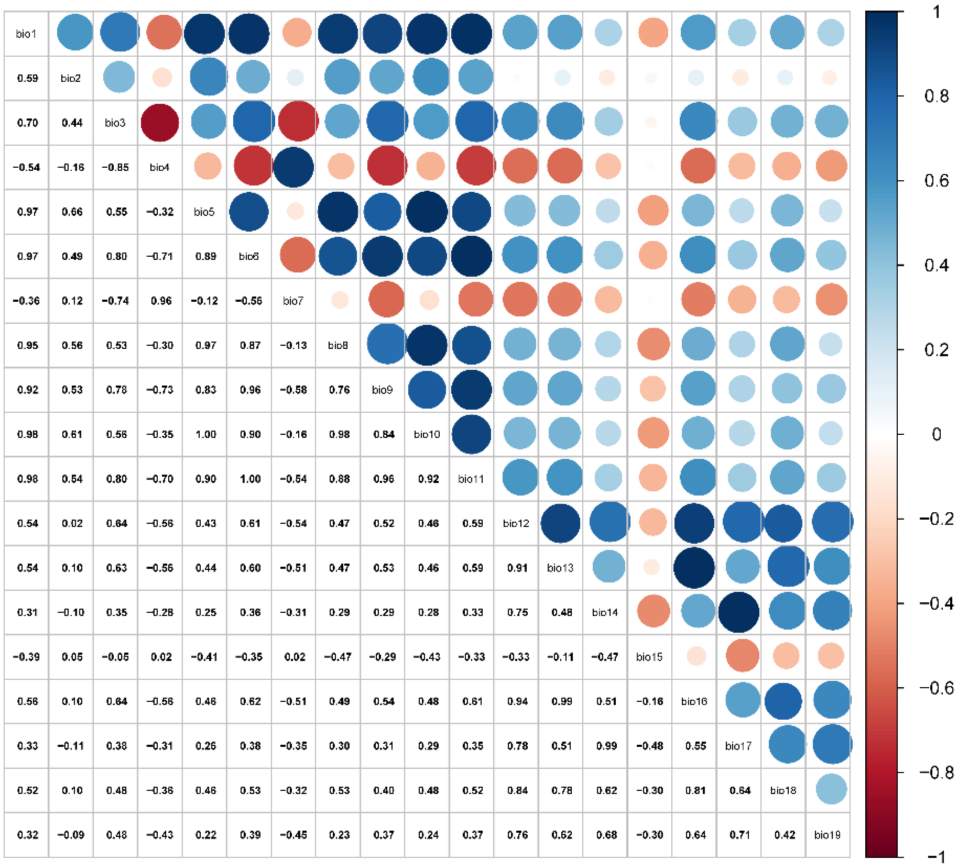

Figure 2. Pearson's correlation analysis of 19 environmental variables. Correlation coefficients ranges between −1 and 1. Positive correlations are represented in blue, while negative correlations are represented in red. The bigger and darker the circle is, the greater the correlation is.

3.2. Potential Distribution under Future Climate Conditions

The predictions of suitable areas for *H. tetratepala* in 2041–2060 (2050s) and 2061–2080 (2070s) according to BCC-CSM2-MR (Beijing Climate Center Climate System Model) and MIROC6 (Model for Interdisciplinary Research on Climate) climate data under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are shown in Figures 3–6. In the future climate conditions (2050s and 2070s), under two CMIP6 climate scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, the prediction area suitability for the distribution of *H. tetratepala* in China was basically unchanged (Figures 3–6). Compared with the high emission scenario, the global suitability of *H. tetratepala* under the low emission scenario is expected to lower. The model predicted the suitable area was the highest under the SSP5-8.5 scenario with both model and future climate conditions (Table S2).

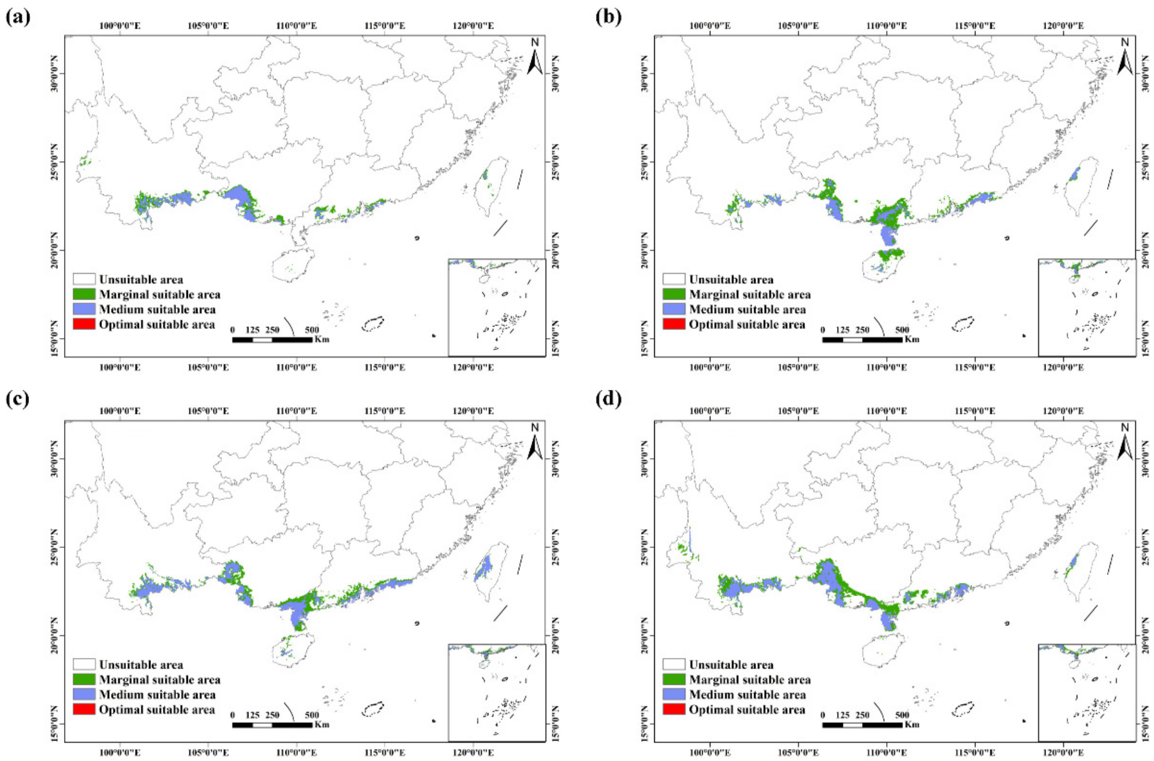

Figure 3. Projected potential distribution maps of *H. tetratepala* under future periods (2050s) in BCC-CSM2-MR models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5.

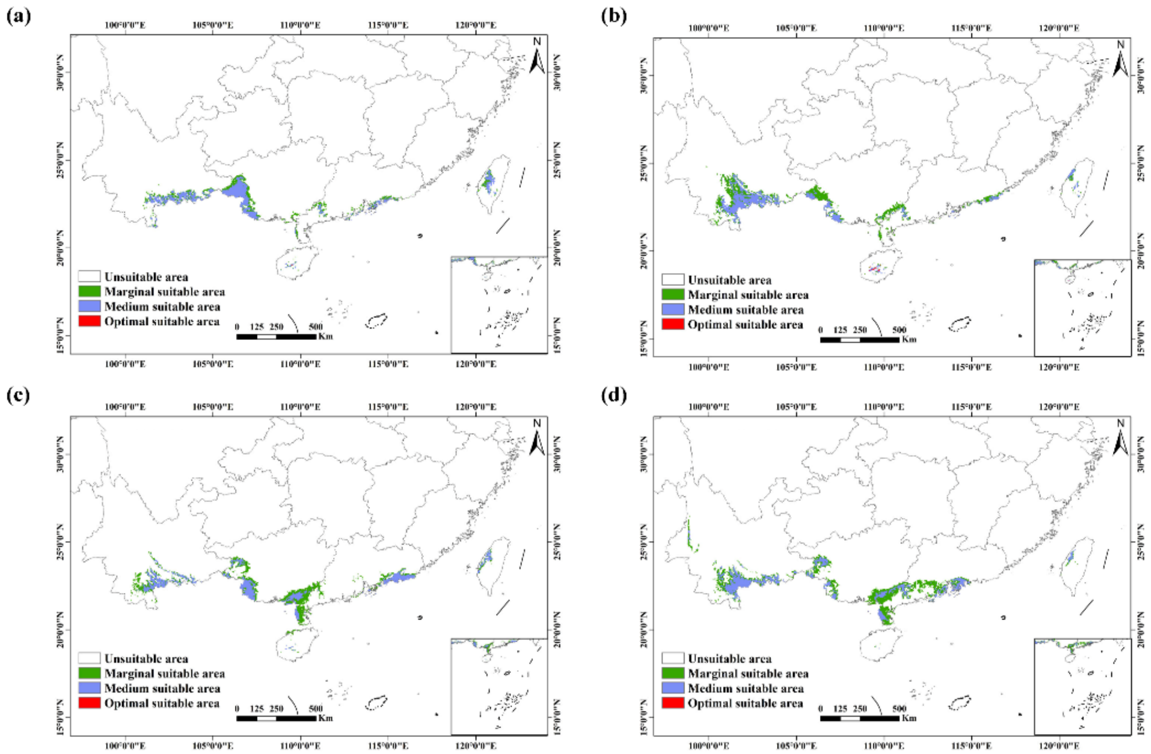

Figure 4. Projected potential distribution maps of *H. tetratepala* under future periods (2070s) in BCC-CSM2-MR models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5.

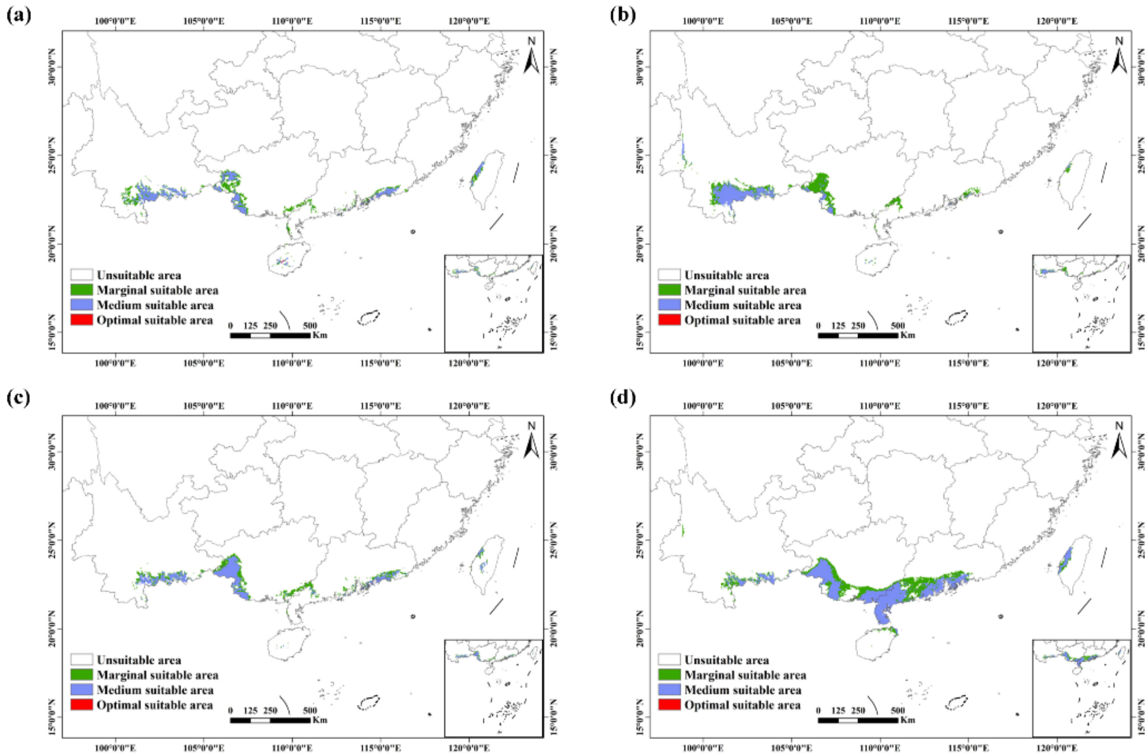

Figure 5. Projected potential distribution maps of *H. tetratepala* under future periods (2050s) in MIROC6 models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5.

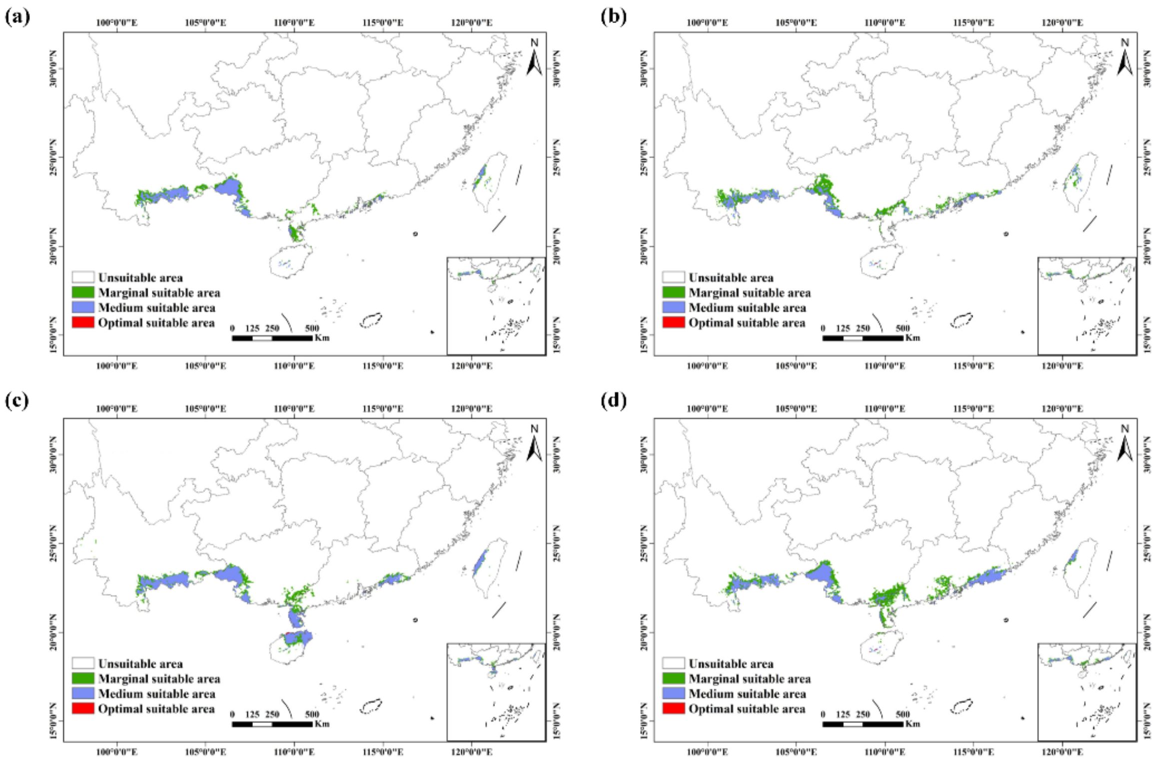

Figure 6. Projected potential distribution maps of *H. tetratepala* under future periods (2070s) in MIROC6 models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5.

An analysis of the prediction of BCC-CSM2-MR under different SSPs revealed that the maximum threshold of suitable areas was attained under SSP5-8.5, and the minimum under SSP1-2.6. Compared to the prediction of current conditions, the optimal and medium suitable areas increased dramatically under SSP2-4.5 (2070s) and SSP3-7.0 (2050s), respectively. Through observations and comparisons (Figures 3 and 4), it was found that the suitable zones were primarily located in the Yunnan, Guangxi, Guangzhou, and Hainan Provinces. Furthermore, optimal zones were significantly reduced or even disappeared in the 2050s and 2070s, except under the SSP2-4.5 (2070s), where they had an approximate increase of 350% compared to the current number of highly suitable areas.

Conversely, the prediction of the MIROC6 model under different SSPs revealed that the total suitable areas attaining a maximum under SSP2-4.5 (2050s) and SSP5-8.5 (2070s) and reaching a minimum under SSP1-2.6 (2050s and 2070s) was the same as that from the prediction of the BCC-CSM2-MR model (Table S2). Under SSP1-2.6 (2050s), the total suitable zone was the smallest, whereas the optimal zone was the largest. For the 2070s, SSP3-7.0 attained a maximum suitable area in total, and optimal areas had an approximate increase of 275.01% compared to the current highly suitable areas. Through observations and comparisons (Figures 5 and 6), it was found that the suitable zones of *H. tetratepala* under this model were the same as the prediction of the BCC-CSM2-MR model (Figures 3 and 4).

3.3. Future Changes in Suitable Habitats

Figures 7 and 8 show the future changes in suitable habitats in the 2050s and 2070s under climate scenarios of the MIROC6 models. In the 2050s, compared with current conditions, the prediction results indicated that the largest contraction of suitable habitat areas of *H. tetratepala* was under the SSP5-8.5 scenario of the MIROC6 models, (32,771.72 km^2); the gained area was also the largest (94,031.77 km^2) (Table 2). The lost area was primarily located in Yunnan, where there was a medium suitable area for *H. tetratepala* (Figure S1). The gained area was mainly concentrated in Guangxi, Guangzhou, Taiwan, as well as North Hainan, which became a medium suitable area for *H. tetratepala* (Figures 5 and 7). Furthermore, the prediction of the MIROC6 model under SSP1-2.6 showed that there were 17,589.77 km^2 of suitable areas lost and 13,762.6 km^2 gained, which was the lowest contraction of suitable habitat areas of *H. tetratepala* out of all four scenarios (Table 2).

Table 2. Habitat suitability changes from the current conditions to the future climate (2050s and 2070s) under climate scenarios in MIROC6 models: SSP 2.6, SSP 4.5, SSP 7.0, and SSP 8.5.

Periods		Area of Suitability Changes (km^2)			
		SSP 2.6	SSP 4.5	SSP 7.0	SSP 8.5
Current vs. 2050	Expansion	19,110.5	13,762.6	19,921.56	94,031.77
	Unchanged	35,027.47	45,773.96	38,651.87	30,592.01
	Contraction	28,336.26	17,589.77	24,711.85	32,771.72
Current vs. 2070	Expansion	15,334.02	22,532.14	40,679.51	44,101.15
	Unchanged	40,426.06	39,032.05	43,061.99	42,909.91
	Contraction	22,937.67	24,331.67	20,301.74	20,453.81

In the 2070s, compared with current conditions, the prediction results indicated that the largest gained area was also under the SSP5-8.5 scenario (44,101.15 km^2); the contraction area was also near the lowest value (20,453.81 km^2) (Figure 8 and Table 2). The lost area was primarily located in Yunnan, and the gained area was mainly concentrated in Guangxi, Guangzhou, and Taiwan (Figure 8). In general, this indicates that temperature increases may be beneficial to the survival of *H. tetratepala* and show a trend toward distribution moving to the northeast.

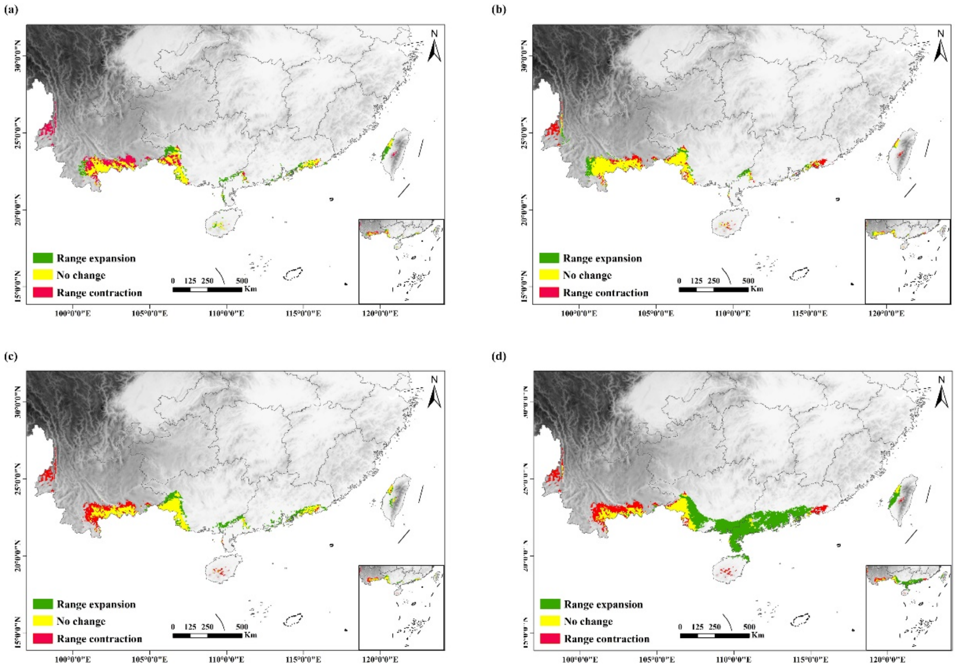

Figure 7. Habitat suitability changes from the current conditions to the future climate (2050s) under climate scenarios in MIROC6 models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5. Green area marks the total expansion of habitat suitability from unsuitable to suitable habitat. Yellow area indicates habitat suitability prediction remained the same. Red area marks the contraction of suitable habitat to unsuitable.

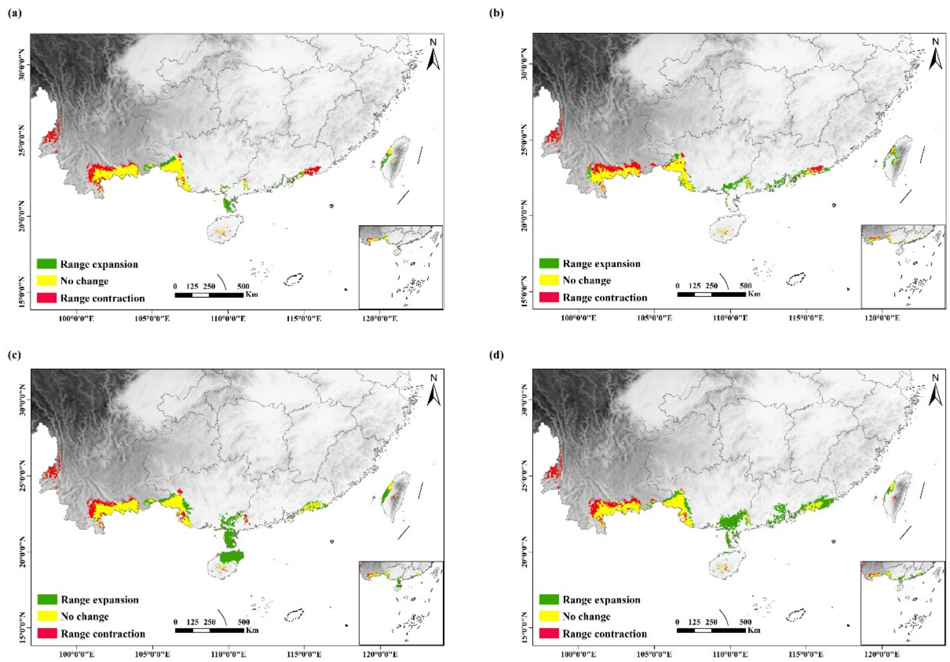

Figure 8. Habitat suitability changes from the current conditions to the future climate (2070s) under climate scenarios in MIROC6 models: (**a**) SSP 2.6, (**b**) SSP 4.5, (**c**) SSP 7.0, and (**d**) SSP 8.5. Green area marks the total expansion of habitat suitability from unsuitable to suitable habitat. Yellow area indicates habitat suitability prediction remained the same. Red area marks the contraction of suitable habitat to unsuitable.

4. Discussion

Here, the MaxEnt model was used to evaluate potentially suitable *H. tetratepala* habitat distribution based on two global future climate models. The results showed a highly effective and accurate method for predicting the potential suitable areas of *H. tetratepala*, despite the fact that the use of AUC value to estimate the predictive accuracy of the MaxEnt model is controversial [72–74]. At large spatial and temporal scales, climate was the primary determining factor in regulating species distribution [16,75]. This study revealed that the most important bioclimatic variables affecting the presence of *H. tetratepala* were precipitation during the warmest quarter (Bio_18), followed by temperature seasonality (Bio_4).

It was found that prediction results varied when analyzing the different models under the same scenario. For example, under the SSP1-2.6 scenario, the predicted results of the BCC-CSM2-MR and MIROC6 models in both the 2050s and 2070s showed that the unsuitable area for *H. tetratepala* will increase in the future, but the optimal suitable area in the 2050s increased only under MIROC6 modeling. In the SSP5-8.5 scenario, the prediction results of the two models were consistent in their predicted changes of the unsuitable area, marginally suitable area, and moderately suitable area (increase or decrease), but the optimal suitable area in the 2070s increased only under MIROC6, while in others it was predicted to absolutely disappear (Table S2). Studies have shown that the prediction of multiple models can avoid the single model's uncertainty and show trends that are more likely to be accurate [36,37,76]. In the SSP scenario with higher radiative forcing (SSP5-8.5), the increase in marginal and medium suitable areas was larger, while under the SSP scenario with lower radiative forcing (SSP1-2.6), the increased areas of unsuitable habitat was larger (Table S2). The reason behind the trend between different SSP scenarios may be due to societies with different development pathways in the future. For example, SSP1-2.6 represents the sustainable development of society with low challenges to mitigation and adaptation, whereas SSP5-8.5 represents the fossil-fueled development of society, with high challenges to mitigation and low challenges to adaptation [66].

The potential habitats of *H. tetratepala* can be concluded to be restricted to Yunnan, Guangxi, Hainan, Guangzhou, and Taiwan provinces (Figures 3–6 and S1). Currently, there are no relevant reports on *H. tetratepala* in Hainan, Guangzhou, and Taiwan provinces [10,55]; therefore, researchers need to strengthen in-depth species investigation and monitoring in those areas in the future. The model projections from this study indicated that in response to the warming climate, the suitable survival areas for *H. tetratepala* exhibited a trend of northeastward migration compared to current habitats; in the Yunnan area, its habitats appeared to be severely threatened, which is consistent with field observations. Future climate change is mainly reflected in the escalating temperature increase caused by greenhouse gases, which will promote species migration to the boreal forests [77]. At large spatial and temporal scales, climate was the primary determining factor in regulating species distribution [16,75]. This study revealed that the most important bioclimatic variables affecting the presence of *H. tetratepala* were precipitation during the warmest quarter (Bio_18), followed by temperature seasonality (Bio_4). *H. tetratepala* is a subtropical species that prefers warmth and humidity; therefore, in the highest greenhouse gas emissions scenario, high-latitude regions will provide greater space for *H. tetratepala* distribution.

Although the fast-changing climate will pose a threat to the survival of endangered species, *H. tetratepala* has been reported to be highly adaptable towards a changing climate and other environmental conditions [55]. However, owing to anthropogenic activities, the rapid expansion of agricultural/developed lands and economic development, *H. tetratepala* has been listed as an "Endangered species" and PSESP [48,78] This study provides vital information for developing viable conservation strategies for policymakers. The results indicated that *H. tetratepala* will face a high risk of habitat loss in Yunnan area in response to climate change during the 21st century, particularly under the SSP1-2.6 scenario (both in the 2050s and 2070s) based on the MIROC6 model (Figures 5 and 6; Table S2). Yunnan Province is a biodiversity hotspot in China and forms a major part of the Indo-Burma biodiversity hotspot [6]. Previous studies have revealed Yunnan lineage with the high genetic diversity of *H. tetratepala* [55], which was consistent with this study's result that the Yunnan area is a suitable distribution area for *H. tetratepala*. Combing genetic background and species distribution models of *H. tetratepala* is important to protect the shrinking habitats of *H. tetratepala* in those areas and strengthen in-depth species investigation and monitoring outside of its current known distribution.

Previous studies showed that low seed set, few seedlings and saplings, excessive human-induced disturbance, and ongoing habitat fragmentation were the main factors accounting for the endangered status of *H. tetratepala* [49,55]. Future projections from this study suggested that the *H. tetratepala* range of climate-suitable habitats would expand to Guangdong, Hainan, and Taiwan provinces. Therefore, it can potentially offer massive benefits to entire ecosystems and these regions should be examined as priority areas for species introduction and cultivation, such as through establishing protected areas and conservation botanical gardens [4,79]. Knowing that habitats in the Yunnan area are severely threatened, adaptive measures are recommended close to the in situ conservation sites to ensure that native habitats are stable and protected, including establishing protected areas, periodic scientific monitoring, and strengthening the publicity of species protection [80–82]. In summary, a combination of multiple approaches is advocated to develop effective protection and restoration management strategies for *H. tetratepala*.

5. Conclusions

In this study, the potential future suitable growth areas of *H. tetratepala* were first preliminarily predicted using the MaxEnt model based on two global climatic models under different scenarios in two future periods. Due to insufficient sample sizes, the actual distribution area of *H. tetratepala* may be smaller than the predicted results; however, maximum entropy is highly reliable despite the small sample sizes, and the model estimations matched current observations of *H. tetratepala* distribution. Because of this, we can be confident that the model correctly predicted the potential habitats of *H. tetratepala* within the context of climate warming. The results show that precipitation in the warmest quarter (Bio_18) and temperature seasonality (Bio_4) are the most important bioclimatic variables affecting *H. tetratepala*. Under the future climate conditions, the suitable areas for *H. tetratepala* are predicted to decrease continually under the SSP1-2.6 scenario and become restricted to Yunnan, Guangxi, Hainan, Guangzhou, and Taiwan provinces. In response to climate warming, the suitable survival area of *H. tetratepala* is predicted to shift considerably northeastward, with noticeable changes in the Yunnan area which contains high genetic diversity. These results will be useful for policymakers and governments to initiate appropriate strategies to protect suitable habitats for *H. tetratepala* during future global warming.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13071051/s1, Figure S1: Projected potential distribution maps of *H. tetratepala* under the current conditions; Table S1: The geographic coordinates used to generate the potential distribution models of *H. tetratepala*.; Table S2: Area of *Horsfieldia tetratepala* under different suitability classes (km^2) under current and future periods (2050s and 2070s) in MIROC6 and BCC-CSM2-MR models.

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