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Original Research

Predicting the Potential Distribution of the Endangered Plant *Magnolia wilsonii* Using MaxEnt under Climate Change in China

Jing-Tian Yang[1#], Xue Jiang[2#], Hao Chen[2], Pan Jiang[3], Mei Liu[1], Yi Huang[2]*

[1]Ecological Security and Protection Key Laboratory of Sichuan Province, Mianyang Normal University, Mianyang 621000, Sichuan, China
[2]Engineering Research Center for Forest and Grassland Disaster Prevention and Reduction, Mianyang Normal University, Mianyang 621000, Sichuan, China
[3]College of Environment and Resources, Southwest University of Science and Technology, Mianyang Sichuan 621010, China

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Abstract

Changes in future climate will have a great impact on biodiversity. *Magnolia wilsonii,* an endangered tree native to China, has important scientific and medicinal value occurring in western Sichuan, northern Yunnan and western Guizhou. And it has severely declined and become critically endangered in the last years due to habitat loss and fragmentation. In this study, we modeled the current and future distributions of *M. wilsonii* under three representative concentration pathways (SSP1-2.6, SSP2-4.5 and SSP5-8.5). The results showed that the AUC values of all simulations were greater than 0.940. The key environmental variables affecting the potential distribution of *M. wilsonii* were the annual precipitation (573-1671 mm), the min temperature of coldest month (10.1ºC-16.2ºC), the coefficient of variation in precipitation seasonality (11.5-160.9), and the standard deviation of temperature seasonality (404.7-1765.6). The area of the highly suitable habitat was 29.66×10^4 km², mainly concentrated in Yunnan, Sichuan, Guizhou and Guangxi. Yunnan had the largest suitable habitat, occupying 13.23×10^4 km², accounting for 44.6% of the highly suitable area. Under the three climate change scenarios, the areas of the suitable habitat of *M. wilsonii* showed increasing trends, the geometric center of the highly suitable habitat would move to the northeast. Our results can provide a scientific basis for the protection, cultivation, management and sustainable use of *M. wilsonii*.

Keywords: MaxEnt, climate change, habitat suitability, species distribution pattern, *Magnolia wilsonii*

# These Authors equally contributed to the work.
*e-mail: hyhy1232021@163.com

Introduction

Environmental factors (e.g., temperature, water, soil and surface moisture) have significant effects on the distribution of species [1]. For decades, researchers have focused on plant-environment interactions and their effects on plant growth [2-3]. Many studies have found that the interaction relationship between species will be weakened at large scale, and non biological factors will become the main driving factors for the growth, reproduction and distribution pattern of the species [4-5]. At present, it is generally accepted by scholars at home and abroad that climate is one of the main environmental factors that determine species distribution on a macro scale [6-9]. Global climate change is occurring at an unprecedented rate, with the average temperature rising by 0.85ºC over the last century, and is expected to continue to increase by at least 0.3-1.7ºC, with a maximum increase of 2.6-4.8ºC during this century [10-11]. Many studies have found that the geographical distribution of plants is very sensitive to climate change. For example, Penuelas and Boada found that the cold temperate ecosystem in parts of Spain was gradually replaced by the Mediterranean ecosystem [12]. Walther et al. showed that the distribution range of palm trees expanded and drifted northward due to the influence of winter temperature [13]. Studying and understanding the impact of climate and other environmental variables on the geographical distribution of plants can provide a lot of information for protecting species diversity and making natural resource management plans.

Biodiversity is the basis of human survival, and there are differences in species diversity in different regions [14]. The response modes of plant diversity to climate change are species extinction, adaptive evolution and change of distribution pattern [15-16]. Climate change directly or indirectly changes the plant-environment adaptation relationship and the plant-plant competition relationship [1]. Studying the spatial pattern and causes of species diversity can not only deepen the understanding of important biogeographic processes such as geological history, environmental change, biological evolution and migration in different regions, but also help to improve people's ability to protect species diversity and resources [17].

MaxEnt is a geographic scale spatial model software of species built by Phillips et al. based on Java platform, which is mainly used to simulate and predict the potential distribution of species [18]. Nowadays, it has been widely used in many fields, such as ecology, biochemistry, resource conservation and so on [19-20]. Compared with other common niche models, such as GARP (the genetic algorithm for rule set prediction), Bioclim (the biological prediction system), Domain (the domain model) and ENFA (ecological niche factor analysis), MaxEnt is more accurate [1, 21]. 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 [21-22] Therefore, it has been widely used in the prediction of potential distribution areas of many tree species, such as *Bretschneidera sinensis* [23], *Broussonetia papyrifera* [24], *Canacomyrica monticola* [25], *Cunninghamia lanceolata* [26], *Blumea balsamifera* [27], etc.

*Magnolia wilsonii*a is a tree belonging to the genus Oyama and family Magnoliaceae [28], it blooms after the danger of frosts, has pristine white 12 centimeter wide flowers with brilliant crimson-red stamens that hang like bright lanterns, has an elegant rich fragrance, doesn't get too big (Fig. 1). *M. wilsonii*, an endangered and endemic species in China, is mainly distributed in central and western Sichuan, northern Yunnan, and Guizhou (China Digital Science and Technology Museum). As a relatively primitive species of the Magnolia genus, it has important scientific value to study the geographical distribution of *M. wilsonii* (China Digital Science and Technology Museum). Moreover, *M. wilsonii* is classified as the national second-grade protection of China [29]. Because the bark of *M. wilsonii* has medicinal value and is a substitute of Magnolia officinalis, its market demand has increased rapidly in recent years. At the same time, *M. wilsonii* is usually considered as the excellent ornamental tree species due to the large, white and fragrant blooms [30]. *M. wilsonii* has a strong cold resistance, it can tolerate –20ºC. Hence, *M. wilsonii* is introduced and cultivated in Europe and North America. However, few researchers have focused on *M. wilsonii*, except for Ling and Zhang reported that the complete chloroplast genome of *M. wilsonii* [31]. In addition, the natural resources of *M. wilsonii* have been seriously damaged due to global warming, deforestation, habitat deterioration and its weak reproductive capacity [32-34]. Therefore, the main significance of this study was 1).understanding the potential distribution of *M. wilsonii* in China, 2) obtaining the main variables affecting the distribution of *M. wilsonii* and their suitable range, 3) simulating the change trend of suitable habitat of *M. wilsonii* under climate change scenarios, 4) providing a scientific

Fig. 1. *M. wilsonii* photographed from wild habitat.

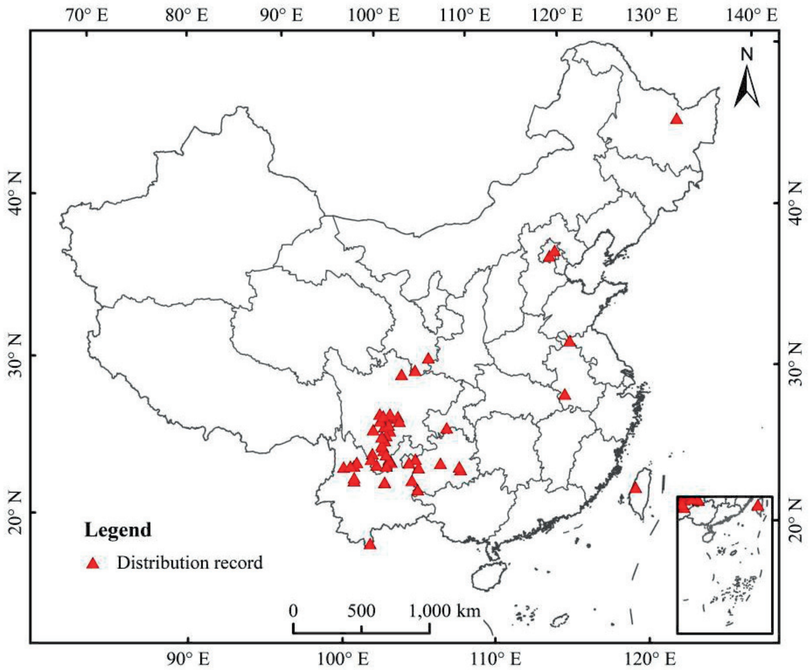

Fig. 2. Distribution point data for *M. wilsonii* in China.

basis for the protection, cultivation, management and sustainable use of *M. wilsonii*.

Materials and Methods

Occurrence Data of *M. wilsonii*

In this study, we obtained the occurrence data of *M. wilsonii* by field investigation and searching database, including Chinese Digital Herbarium (CVH) http://www.cvh.ac.cn/), the Global Biodiversity Information Platform (http://www.gbif.org), the Living Plant Distribution Database and the Pedagogical Specimen Resource Sharing Platform (http://mnh.scu.edu.cn/main.aspx) to obtain the occurrence data of *M. wilsonii*. To identify and screen the geographical coordinates of the specimens, distribution points that were not specific enough and were not within the study area were removed. Finally, 107 distribution points for *M. wilsonii* were collected (Fig. 2). All records were imported into Microsoft Excel and saved in the "CSV" format [35].

Environmental Variables

The World Climate Database (http://www.world-clim.org//) was used to obtain data for 19 environmental variables with datums of WGS84 and grid sizes of 2.5’. The database includes detailed meteorological information recorded by weather stations around the world from 1970 to 2000. Future climate data was modeled using the Beijing Climate Center Climate System Model (BCC-CSM2-MR) climate systems that were developed at the National Climate Center and include three emissions scenarios (shared socioeconomic pathway (SSP5-8.5, SSP2-4.5, and SSP1-2.6). Compared with the scenarios used in previous studies, SSP scenarios more scientifically describe future climate change projections [36-37].

Because there is a certain correlation between environmental variables, it is necessary to analyze the correlation between environmental variables before they are used in the MaxEnt model. The selection of environmental variables was divided into two steps. Firstly, all environmental variables were imported into the MaxEnt model operation, and the variables with contribution rates of 0 were deleted. Secondly, the Spearman correlation coefficient between the remaining

Table 1. Environmental variables in the MaxEnt model.

Index	Description
Bio3	Isothermality
Bio4	Standard deviation of temperature seasonality
Bio6	Min temperature of coldest month
Bio10	Mean temperature of warmest quarter
Bio12	Annual precipitation
Bio15	Coefficient of variation in precipitation seasonality
Altitude	Altitude
Slope	Slope
Aspect	Aspect

variables was calculated. When the correlation coefficient of two environmental variables was ≥0.8, the variables with small contribution rates were removed, and 9 environmental factors were finally selected (Table 1) [38].

MaxEnt Model Parameters

The distribution data and environmental variables were imported into MaxEnt software, and the parameters were set as follows: 25% of the distribution points was set as test data, 75% of the distribution points was set as training data, the importance of variables was tested by the jackknife method, the receiver operating characteristic (ROC) curve was selected to measure the model performance, and the other options were set by model default [39]. The above model was repeated 10 times, and the group with the largest area under the curve (AUC) value was selected as the final prediction result.

Model Accuracy Verification

The application of subject work characteristics (ROC) and the AUC were used to evaluate the prediction accuracy of the model. An AUC value closer to 1 indicates that the model prediction effect is better. The evaluation criteria for model prediction accuracy were divided into four grades: poor (AUC≤0.80), general (0.80<AUC≤0.90), good (0.90 AUC≤0.95) and best (0.95) [18, 40].

Division of Suitable Grade

In the output file, a maximum of 10 repetitions was selected as the prediction result of this study. The result was based on the existence the probability logic value (P) of the species to generate the ASCII grid graph layer. The P range was 0~1, and a larger P value indicated a greater likelihood of species being present. ArcGIS10.2 software was used to convert predictions into raster formats to grade and visualize the suitable areas. Based on P values, the natural discontinuous point method was used to divide the suitable area into 4 grades. They were highly suitable (0.5≤P≤1.0), moderately suitable (0.3≤P≤0.5), minimally suitable (0.1≤P≤0.3) and unsuitable (0.0) [41]. The grid number of each grade was counted, and the proportion of suitable area for each grade in different time periods was calculated.

Results and Discussion

Model Performance

The potential geographical distribution of *M. wilsonii* in China was simulated and predicted using the MaxEnt model based on 107 distribution records, and the AUC values of training and test data were 0.953 and 0.940, respectively, which indicated that the results were good (Fig. 3).

Importance of Environmental Variables

Among the 9 environmental variables, the percent contribution of annual precipitation (Bio12) was 41%, standard deviation of temperature seasonality (Bio4) was 18.4%, and min temperature of coldest month (Bio6) was 12.9%. The cumulative percent contribution of the above three variables was 72.3%. By comparing the permutation importance, annual precipitation

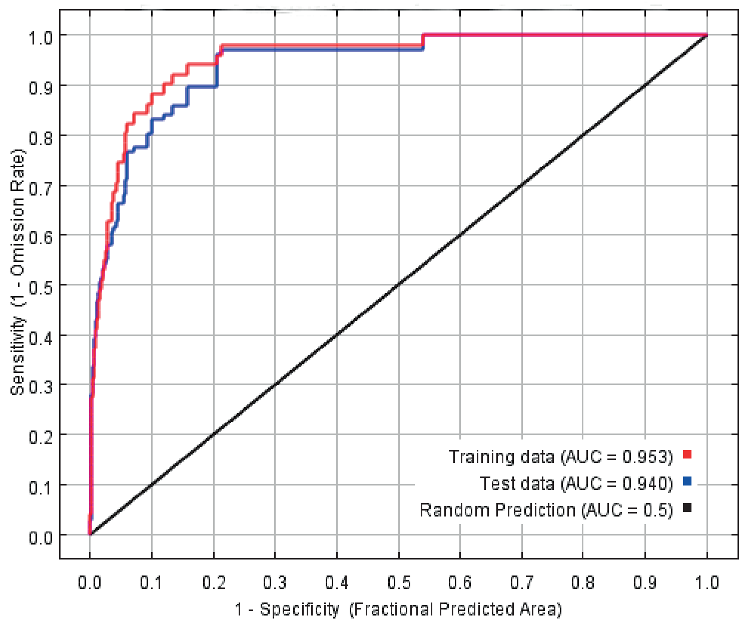

Fig. 3. ROC curve of the Maxent model of *M. wilsonii*.

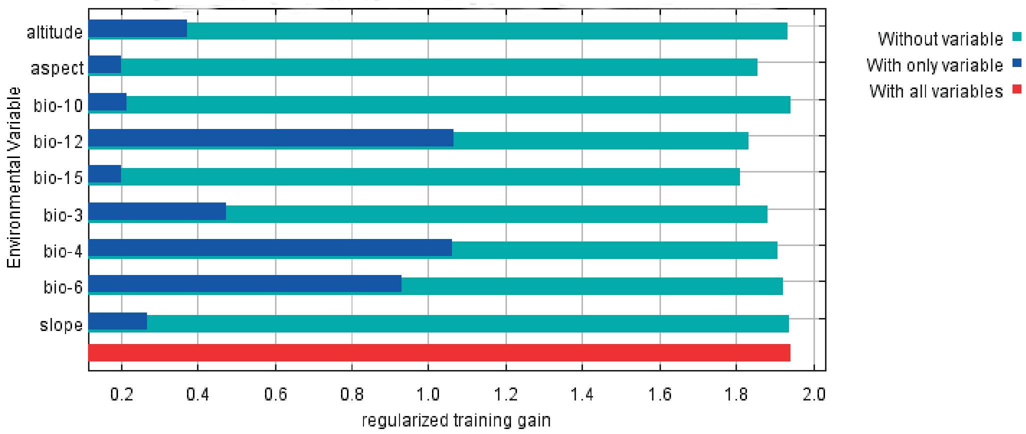

Fig. 4. Results of importance of environmental variable to *M. wilsonii* by jackknife test.

(Bio12, 41%), min temperature of coldest month (Bio6, 30.2%) and coefficient of variation in precipitation seasonality (Bio15, 9.8%) were the three important variables, with a cumulative rate of 81%. According to the results of the jackknife test (Fig. 4) when a single environmental variable was used, the regularization training gain of annual precipitation (Bio12), standard deviation of temperature seasonality (Bio4) and min temperature of coldest month (Bio6) were significantly higher than other variables, which indicated that these three variables contained unique information affecting the distribution of *M. wilsonii*.

The relationship between the probability of occurrence of *M. wilsonii* and the environmental variables was determined according to the response curves of the environmental variables (Fig. 5). When the probability was greater than 0.5, the corresponding environmental variable value was beneficial to the growth of *M. wilsonii*. According to this standard, the suitable range of dominant environmental variables was obtained. The annual precipitation (Bio12) was 573-1671 mm, the min temperature of coldest month (Bio6) was 10.1ºC-16.2ºC, the coefficient of variation in precipitation seasonality (Bio15) was 11.5-160.9, and the standard deviation of temperature seasonality (Bio4) was 404.7-1765.6.

Water condition is not only the leading factor to determine the level of forest productivity in most areas

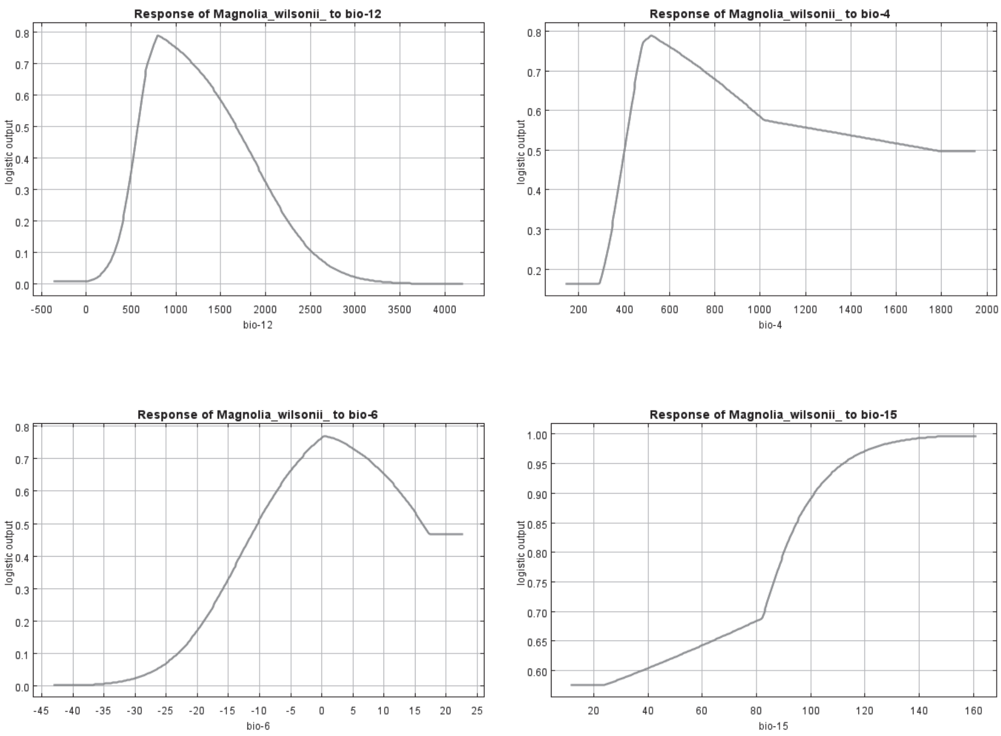

Fig. 5. Response curves of the probability of occurrence to the dominant variables.

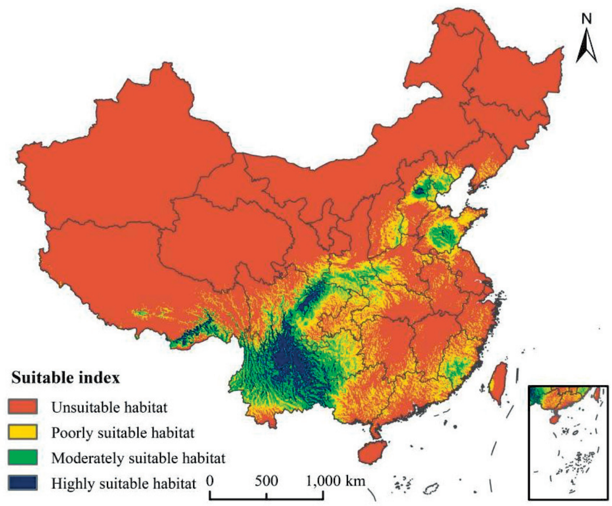

Fig. 6. Potential suitable habitat for *M. wilsonii* under current climate condition.

Table 2. Percent contribution and permutation importance of each variable to the potential distribution of M. wilsonii defined by MaxEnt.

Code	Percent contribution/%	Permutation importance/%
Bio12	41	41.7
Bio4	18.4	2
Bio6	12.9	30.2
Bio15	10.8	9.8
Altitude	9.2	3.4
Aspect	4.7	4
Bio3	2.8	8.3
Slope	0.2	0.5
Bio10	0.1	0.1

of China, but also the decisive factor to determine the formation and growth of trees. In this study, we used MaxEnt to explore the effects of climatic variables on the distribution pattern of *M. wilsonii*. The results showed that the annual precipitation had the highest percent contribution (41%) and permutation important (41.7%) to the simulation, which was the key variable affecting its distribution. When the annual precipitation was 573-1671 mm, the probability of *M. wilsonii* was higher, indicating that there was a greater demand for water in its growth process. According to our investigation, *M. wilsonii* is mainly distributed in subalpine areas in Sichuan, with an average annual precipitation of 1247.8 mm. The resource distribution characteristics of *M. wilsonii* in Guizhou, and found that the annual precipitation was significantly related to its growth and development [38]. All the above results indicated that water factor plays an important role in the geographical distribution of *M. wilsonii*, which was important for understanding its habitat preference. Studies have shown that the extreme value and variation range of temperature were closely related to the large-scale landscape geographical distribution of tree species. Our results showed that the percent contribution rate of the min temperature of coldest month (Bio6) and the standard deviation of temperature seasonality (Bio4) were 12.9% and 18.4%, respectively, which confirmed the importance of temperature factor to the distribution of *M. wilsonii* in large-scale.

Projections of Potential Suitable Habitats for *M.wilsonii* under Current Climatic Conditions

Fig. 6. showed that the area of the highly suitable habitat was 29.66×10^4 km^2 and mainly distributed in Yunnan, Sichuan, Guizhou, and Guangxi. The area of the moderately suitable habitat was 37.61×10^4 km^2 and mainly distributed in Yunnan, Sichuan, Guizhou, Shandong, Tibet, Shaanxi, Guangxi, Fujian, and Hebei. The area of poorly suitable habitat was 110.18×10^4 km^2 and mainly distributed in Sichuan, Guangxi, Guizhou, Yunnan, Hubei, Shandong, Fujian, Shaanxi, Guangdong, Hebei, Tibet, Chongqing, Hunan, and Shanxi.

A full understanding of the potential suitable area of *M. wilsonii* will be helpful for its collection of germplasm resources, protection of genetic diversity and genetic improvement [42]. The simulation results showed that the highly suitable habitat were mainly distributed in Yunnan, Sichuan, Guizhou, and Guangxi, with an area of 29.66×10^4 km^2. According to literature review [43], *M. wilsonii* is a second-class protected wild plant in China, which is distributed in central and Western Sichuan, Northern Yunnan, and Guizhou. This areas were located in the suitable areas predicted in this paper, which showed that the results were reliable. Studies have found that human activities are the primary factor causing endangered species, and reducing human activities is one of the key measures to protect wild resources of *M. wilsonii*. The establishment of nature reserves can effectively reduce the interference of human activities and provide space for species recovery. However, the environmental variables selected in this paper only include climate factors, which may affect the prediction results. In the next step, human activities, soil types, vegetation types and other variables should be selected to make the prediction results more accurate.

Potential Habitat for *M. wilsonii* under Climate Change Scenarios

Under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, the area of the total suitable habitat increased significantly in Northeast China in the 2070s (Table 3), mainly in Beijing, Tianjin, Hebei, Shanxi and Shandong (Fig. 7). Compared to the current condition, by 2050s,

Table 3. Potential suitable habitat area for *Magnolia wilsonii* (10^4 km^2).

Period	Scenario	Highly suitable	Moderately suitable	Poorly suitable	Total suitable
Current		29.66	37.61	110.18	177.45
2050s	SSP1-2.6	41.40	46.74	123.30	211.44
	SSP2-4.5	38.69	51.73	135.82	226.24
	SSP5-8.5	42.31	44.32	138.66	225.29
2070s	SSP1-2.6	42.95	43.69	119.07	205.71
	SSP2-4.5	42.76	51.44	138.71	232.91
	SSP5-8.5	44.73	51.72	140.38	236.83

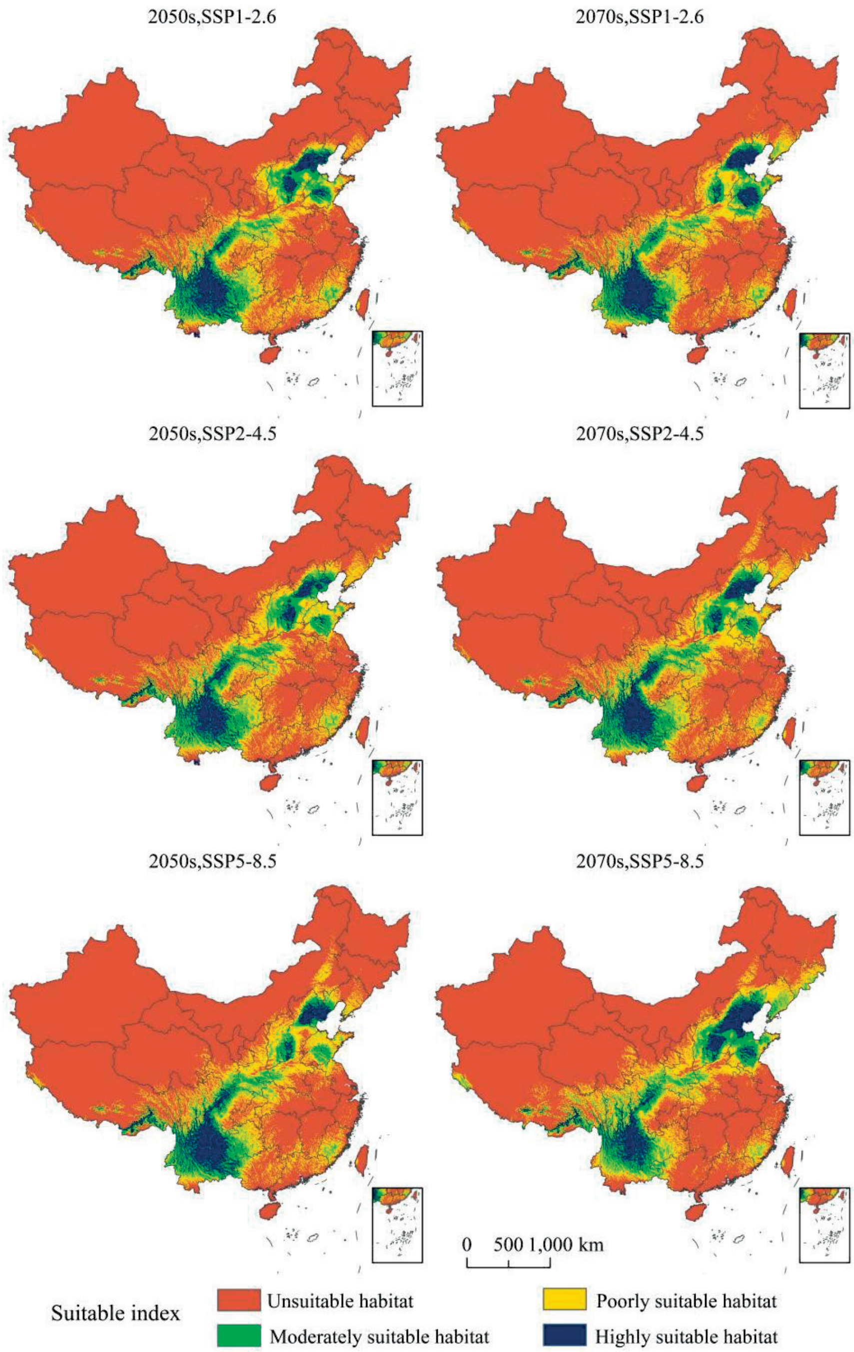

Fig. 7. Potential suitable habitat for *M. wilsonii* under climate change scenarios.

the total suitable habitat area under the three SSPs will increase by 19.15%, 27.50% and 27.00% respectively, the area of the highly suitable habitat will increase by 39.58%, 30.45% and 42.65% respectively, and the area of the poorly habitat will increase by 24.28%, 37.54% and 17.84% respectively (Table 3).

Under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, compared with the current situation, by 2070s, the area of the total suitable habitat will increase by 15.93%, 31.25% and 33.46% respectively, the area of the highly suitable habitat will increase by 44.81%, 44.17% and 50.81% respectively, and area of the poorly suitable habitat will increase by 8.07%, 25.89% and 27.41% respectively (Table 3).

We quantitatively analyzed the area changes of suitable areas of *M. wilsonii* in 2050s and 2070s under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. The results showed that the areas of the suitable areas would increase. The impact of climate change on the distribution pattern of different species is different. Different species have different responses to climate change. The habitat of some species will be threatened by climate warming, which will make them endangered [44-46]. On the contrary, because climate change is conducive to the improvement of some species' habitats, their habitats will expand. According to our results, *M. wilsonii* obviously belongs to the latter case. Scholars pointed out that most of the changes in the geographical distribution of plant species caused by climate change are related to the change of temperature and precipitation in the growing season [47-48]. Previous studies have shown that under the influence of climate change in the future, the suitable areas of many trees would move northward [40, 49, 50]. In the present study, we found that the geometric center of the highly suitable area of *M. wilsonii* would move to the northwest, which was consistent with the above conclusions.

Our prediction shows that the potential suitable climate distribution of *Magnolia wilsonii* will be expanded under all future climate scenarios (2070s>2050s>current), which means that more suitable habitat areas will be available for both cultivated and wild *M. wilsonii* in the future. The increasing trend of highly suitable habitat in Beijing, Tianjin, Hebei, Shanxi, Shandong confirms that climate change will improve the living environment of *M. wilsonii*. The results from the different scenarios did not show the same trend, which may be due to several factors. First, human activities and climate change may promote the adaptation of plant species to new climatic conditions in nonlocal contexts, leading to climate niche differences between local and invasive ranges [51]. Second, the selection of environmental factors in models may also be a source of uncertainty, as there may be overfitting of results [52]. Third, studies shown that, throughblockage and adsorption, vegetation can positively remove atmospheric particulates, whereas the retention of excessive particulates can negatively affect plant growth. Bhatti et al. confirmed the use of the model to predict PM2.5 feasibility of concentration change [53], and their other studies further showed that

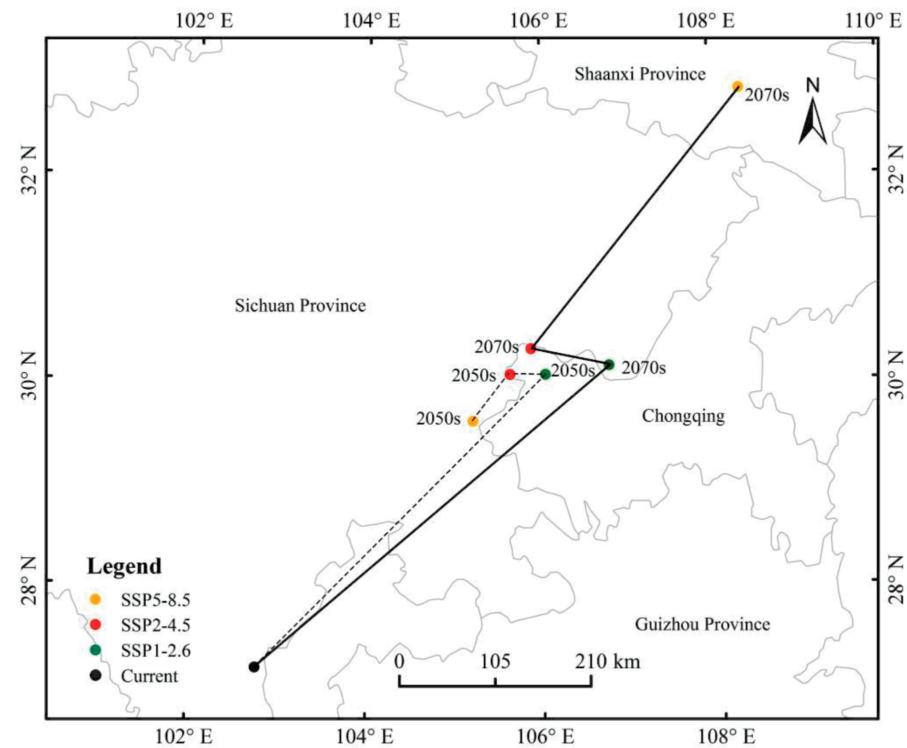

Fig. 8. Variations of the geometric center of the highly suitable habitat of *M. wilsonii* under climate change scenarios in the future.

the distribution pattern of ambient air quality patterns was obviously different pre-to post-COVID-19 [54]. Therefore, whether climate variables and pollution variables can be comprehensively considered in the future needs to be further discussed. Finally, the Intergovernmental Panel on Climate Change (IPCC)'s global climate model clearly notes that the warming trend will continue [55], but its range and speed are uncertain [56].

Variations of the Geometric Center of the Highly Suitable Habitat of *M. wilsonii* under Climate Change Scenarios in the Future

From now on to 2070s, the geometric center of the suitable habitat of *M. wilsonii* generally will move to the northeast. Under SSP1-2.6 scenario, the geometric center will essentially continue moving to the northeast, and the migration distance from current to 2050s was farther than that from 2050s to 2070s. Under SSP2-4.5 scenario, the geometric center essentially continue moving to the northeast. Under SSP5-8.5 scenario, the geometric center essentially continue moving to the northeast, and the migration distance from current to 2050s was shorter than that from 2050s to 2070s (Fig. 8).

Conclusions

Based on MaxEnt model and species distribution data, we concluded that the highly suitable areas of *M. wilsonii* were mainly located in Yunnan, Sichuan, Guizhou, and Guangxi. The key environmental variables affecting the potential distribution of *M. wilsonii* were the annual precipitation (573-1671 mm), the min temperature of coldest month (10.1ºC-16.2ºC), the coefficient of variation in precipitation seasonality (11.5-160.9), and the standard deviation of temperature seasonality (404.7-1765.6). Under the three climate change scenarios, the areas of the suitable habitat of *M. wilsonii* showed increasing trends, the geometric center of the highly suitable habitat would move to the northeast. Our results can provide a scientific basis for the protection, cultivation, management and sustainable use of *M. wilsonii*.

In this paper, we analyzed the geographical distribution of *M. wilsonii* in China, and the results showed that there was a large protection gap in western Sichuan. Through years of continuous observation, it was found that the distribution area of the resources in China was generally reduced. In this regard, the ecological problems faced by *M. wilsonii* must be solved in the following ways: (1) Establishment of wildlife reserves. Wild resources protection areas should be set up in the areas where *M. wilsonii* are concentrated to prevent human destruction. If necessary, artifcial auxiliary measures such as wild tending should be adopted to restore vegetation and population. (2) The government restricted the cutting of *M. wilsonii*. In the area where wild resources of *M. wilsonii*, Limit felling 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 *M. wilsonii* 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 *M. wilsonii* in the field and cultivation environment also appeared some diferent 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 artifcial cultivation technology of *M. wilsonii* 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.

Author Contributions

J.-T.Y. planned and supervised the project. X.J. performed the experiments, analyzed the data, contributed reagents/materials/analysis tools. H.C., P.J. and L.M. contributed to data collection and evaluation. Y.H. revised the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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