

Article

Predicting the Potential Habitat of Three Endangered Species of *Carpinus* Genus under Climate Change and Human Activity

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Abstract: The impact of climate change and human activities on endangered plants has been a serious concern in forest ecology. Some *Carpinus* plants have become extinct. Thus, we need to pay more attention to the *Carpinus* plants that are not yet extinct but are endangered. Here, we employed the species distribution model (SDM) considering different climate change scenarios and human footprint to test the potential habitat changes of three *Carpinus* species (*C. oblongifolia*, *C. tientaiensis*, and *C. purpurinervis*) in the future. Our results showed that the mean diurnal range of temperature (MDRT), isothermality, mean temperature of wettest quarter, and human footprint were the most influential factors determining the distribution of *C. oblongifolia*. Precipitation seasonality (coefficient of variation), MDRT, and precipitation of driest quarter were the most important climatic factors affecting *C. tientaiensis*. The minimum temperature of the coldest month was the most important factor in the distribution of *C. purpurinervis*. Our results also showed that the three species had different adaptability and habitat change trends under the future climate change scenarios, although they belong to the same genus. The potential habitats of *C. oblongifolia* would expand in the future, while the potential habitats of *C. tientaiensis* and *C. purpurinervis* would decrease for the same period. The predicted changes of these three endangered species on temporal and spatial patterns could provide a theoretical basis for their conservation strategies.

Keywords: *Carpinus*; human footprint; MaxEnt; habitat suitability; niche modeling



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1. Introduction

Accelerating global climate change is accompanied by more frequent extreme climate events that threaten biodiversity [1,2]. Global climate change has put about one-fifth of plant species on the brink of extinction [3]. Previous studies have shown that studying the habitat of endangered species is one of the most effective measures to promote the restoration of endangered species [4].

Multiple studies on the relationship between endangered species and the environment only considered climatic variables, which may overestimate or underestimate the potential distribution of tree species [5,6]. Climatic variables alone may not fully explain the distribution of endangered species patterns [7]. Other environmental variables, such as human footprint, also play an important role in species distribution modeling (SDM) [8]. The human footprint includes multiple human activities that affect the natural ecosystems directly or indirectly [2,9]. It largely affects the habitat distribution pattern of many endangered species [10,11]. However, few studies have considered human activity factors

as an environmental factor in developing SDMs and applied them to endangered species studies. Therefore, we propose considering climate conditions and human footprint to incorporate into the SDM for predicting potential habitats of endangered species.

Species distribution models (SDMs) are useful tools for studying the impact of climate change on endangered species and formulating effective forest resources management [12,13]. Maximum entropy (MaxEnt) is a SDM with good simulation accuracy [14]. It has been widely used to predict habitats for endangered species, invasive species, and marine animals [15–18].

Carpinus genus has more than 30 species that occur across much of the temperate regions of the northern hemisphere, with the greatest number of species in East Asia, particularly China [19]. Some *Carpinus* plants have become extinct, such as *C. symmetrica* L. Xue & L.B. Jia, *C. asymmetrica* L. Xue & L.B. Jia, and *C. sp. 1* [20]. *Carpinus putoensis* Cheng has only one natural individual tree globally, and it has become the most endangered plant in the world [21]. Therefore, we need to pay more attention to the *Carpinus* plants that are not yet extinct but are endangered.

Carpinus tientaiensis Cheng is an endemic species in Zhejiang province. Only 21 mature individuals were identified in the wild [22]. It is a national secondary key protected plant [23] and listed as a critically endangered species in the IUCN red list of threatened species [24,25]. Due to severe habitat fragmentation and weak reproductive capacity, *C. tientaiensis* is on the verge of extinction [26] and susceptible to stochastic events. *Carpinus oblongifolia* (Hu) Hu & W. C. Cheng is a specialty species of *Carpinus* genus in Jiangsu Province [27]. It was listed as critically endangered (CR) by the “Red List of Biodiversity in China-Higher Plant Volume” [28]. *Carpinus purpurinervis* Hu is distributed in Guangxi, southern China. Only 11 points were founded in the Chinese Virtual Herbarium (CVH) database, indicating that the current population of *C. purpurinervis* is worrying. However, these studies did not consider the impact of climate change on suitable habitats and productivity of these three *Carpinus* species. At present, it is urgent to assess the potential impact of climate change on these three species in order to formulate follow-up protection strategies.

This study aimed to determine the effects of climate change on the distribution of three *Carpinus* species. The results of this study could be used for selective protection and restoration of the endangered species *Carpinus* in potentially suitable habitats. We used the human footprint data combined with climate data for our niche modeling. We hypothesized that: (i) suitable habitats of three *Carpinus* species would follow different trends in future climates, and (ii) the responses of suitable habitats to global climate change would differ among different future climate scenarios.

2. Materials and Methods

2.1. Data Collection

We collected 17, 35, and 11 occurrence points for *C. oblongifolia*, *C. tientaiensis*, and *C. purpurinervis*, respectively (Figure 1). These occurrence data were collected from many sources, including two global databases (Global Biodiversity Information Facility, GBIF, <https://www.gbif.org>, accessed on 6 September 2021) [29–31] and Web of Science (<http://apps.webofknowledge.com/>, accessed on 8 October 2020) [32], and three Chinese databases: (1) the National Specimen Information Infrastructure (<http://www.nsii.org.cn>, accessed on 8 October 2020) [33], (2) the Chinese Virtual Herbarium (<http://www.cvh.ac.cn>, accessed on 8 October 2020) [34], and (3) China National Knowledge Infrastructure (<https://www.cnki.net/>, accessed on 8 October 2020) [35].

Environmental variables for our niche modeling included 19 climate variables and a human footprint index (Table 1). The climatic variables were from the WorldClim Global Climate Data (<http://www.worldclim.org/bioclim>, accessed on 8 October 2020) [36]. We used the Community Climate System Model version 4 (CCSM4) of the two climate change scenarios RCP2.6 and RCP8.5 included in a global climate model for this study [37]. The current climatic data were the average from the years 1970–2000. The future climate data were from 2041 to 2060. The human footprint index was collected from the Cen-

ter for International Earth Science Information Network (CIESIN, <http://www.ciesin.org/>, accessed on 8 October 2020) to reflect the degree of human activities. The human foot (HF) index data were developed from: (1) built environments; (2) population density; (3) electric infrastructure; (4) croplands; (5) pasture lands; (6) roads; (7) railways; and (8) navigable waterways [38].

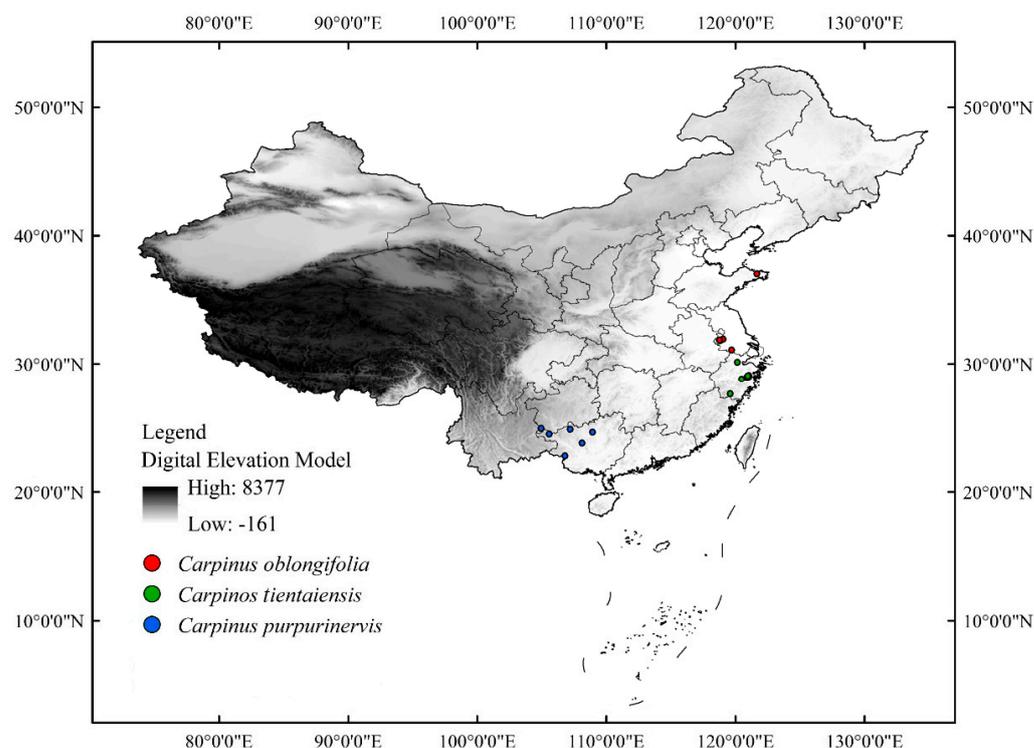


Figure 1. Distribution of observed occurrences of the three *Carpinus* species.

Table 1. Climate variables and a human footprint index that used for developing the MaxEnt models.

Variable Abbreviation	Variables Description
AMT	Annual Mean Temperature
MDRT	Mean Diurnal Range of Temperature (Mean of monthly (max temp–min temp))
ISO	Isothermality (MDR/TAR)
TS	Temperature Seasonality
MTWM	Max Temperature of Warmest Month
MTCM	Min Temperature of Coldest Month
TAR	Temperature Annual Range (MTWM–MTCM)
MTWTQ	Mean Temperature of Wettest Quarter
MTDQ	Mean Temperature of Driest Quarter
MTWRQ	Mean Temperature of Warmest Quarter
MTCQ	Mean Temperature of Coldest Quarter
AP	Annual Precipitation
PWM	Precipitation of Wettest Month
PDM	Precipitation of Driest Month
PS	Precipitation Seasonality (Coefficient of Variation)
PWTQ	Precipitation of Wettest Quarter
PDQ	Precipitation of Driest Quarter
PWRQ	Precipitation of Warmest Quarter
PCQ	Precipitation of Coldest Quarter
HF	Human footprint index

2.2. Model Setting

We used the MaxEnt model version 3.4.1 [39] with 19 climatic variables and a Human footprint index as predictors and the species occurrence as the dependent variable. The regions without occurrence points were taken as the “control”, and the species distribution model was predicted as “experimental diagnosis” [14,40]. We randomly selected 25% of

data points for model validation and used the remaining 75% data points to build the model. To consider the uncertainty introduced by splitting the training and validation sets, we repeated the operation 15 times. The model employed a set of four possibility features, namely logistic regression, bioclimatic rules, range rules, and negated range rules [11]. We selected logistic regression to explain the habitat suitability of these three species [40]. As the outputs of the MaxEnt were the cumulative probability for each pixel on the scale of 0–1 or suitability index value (probability of presence) [41], we classified habitat suitability using four classes of the suitability index value: 0.5–1 = high-suitability area, 0.3–0.5 = medium-suitability area, 0.1–0.3 = low-suitability area, 0–0.1 = non-suitable area [11].

We used all the 20 environmental variables to pre-build the model in MaxEnt three times in succession and discarded the variables with no contribution (contribution = 0). Then, we calculated the Pearson correlation coefficient between each pair of the climatic variables. To avoid the multicollinearity of environmental, if two climatic variables were strongly correlated at $r > 0.8$, only one variable with a higher contribution rate was selected for model input [7].

2.3. Model Evaluation

We utilized the receiver operating characteristic curve (ROC) built in the MaxEnt software to check the accuracy of our simulations. The area under the curve (AUC) is the area under the ROC. AUC value ranges from 0 and 1 [6]. The closer the AUC value is 1, the greater the distance from the random distribution, the stronger the correlation between environmental variables and the geographical distribution of predicted species [14].

2.4. Model Prediction

In order to evaluate the response of the suitable habitats of these three species to climate change, we simulated the suitable habitats under the current and two future scenarios of RCP2.6 and RCP8.5. Since there are no future human activity data (also difficult to project), we assumed that the human activity is constant from the current to the future and apply the current human activity data in the future projections. We mapped the future changes of medium and high suitable (logistic output > 0.3) areas in ArcGIS, and displayed them in three modalities: “loss”, “stability”, and “expansion”.

3. Results

3.1. Model Performance and Contributing Variables

AUC values were considered excellent as they were larger than 0.9 in the training data and testing data [11]. The AUC values of three *Carpinus* spp. in the training data and testing data were greater than 0.95 in the current climate condition (Table 2). Therefore, our simulation results were highly reliable and could be used for further analysis.

Table 2. AUCs under the current climate of three *Carpinus* spp. for mean values of 15 times simulations.

Species	AUC
<i>C. oblongifolia</i>	0.983
<i>C. tiantaiensis</i>	0.995
<i>C. purpurinervis</i>	0.951

MDRT (33.9%) had the largest contribution rate in the model of *C. oblongifolia*, followed by ISO (24.2%), MTWTQ (22.8%), and HF (9.3%) (Table 3), which accumulatively explained 90.2% of the modeling variations. The top contributing variables for *C. tiantaiensis* were PS (57.2%), MDRT (10.8%), PDQ (10.7%), and PDM (10%), which cumulatively interpreted 88.7%. For *C. purpurinervis*, MTCM had a dominant contribution rate of 88.5%, followed by MDRT (3.7%) and TAR (2.5%).

Table 3. Contributions of the most influencing environmental variables to each model.

Species	Variable	Contribution (%)
<i>C. oblongifolia</i>	MDRT	33.9
	ISO	24.2
	MTWTQ	22.8
	HF	9.3
<i>C. tientaiensis</i>	PS	57.2
	MDRT	10.8
	PDQ	10.7
<i>C. purpurinervis</i>	MTCM	88.5
	MDRT	3.7
	TAR	2.5

The response curves of two major environmental variables of each of the three species were shown in Figure 2. The optimal environmental ranges for *C. oblongifolia* were 4–8 °C in MDRT, 15–25 in ISO. The optimal environmental ranges for *C. tientaiensis* were 20–60 mm in PS, 4–8 °C in MDRT. The optimal environmental ranges for *C. purpurinervis* were 5–15 °C in MTCM, 4–8 °C in MDRT.

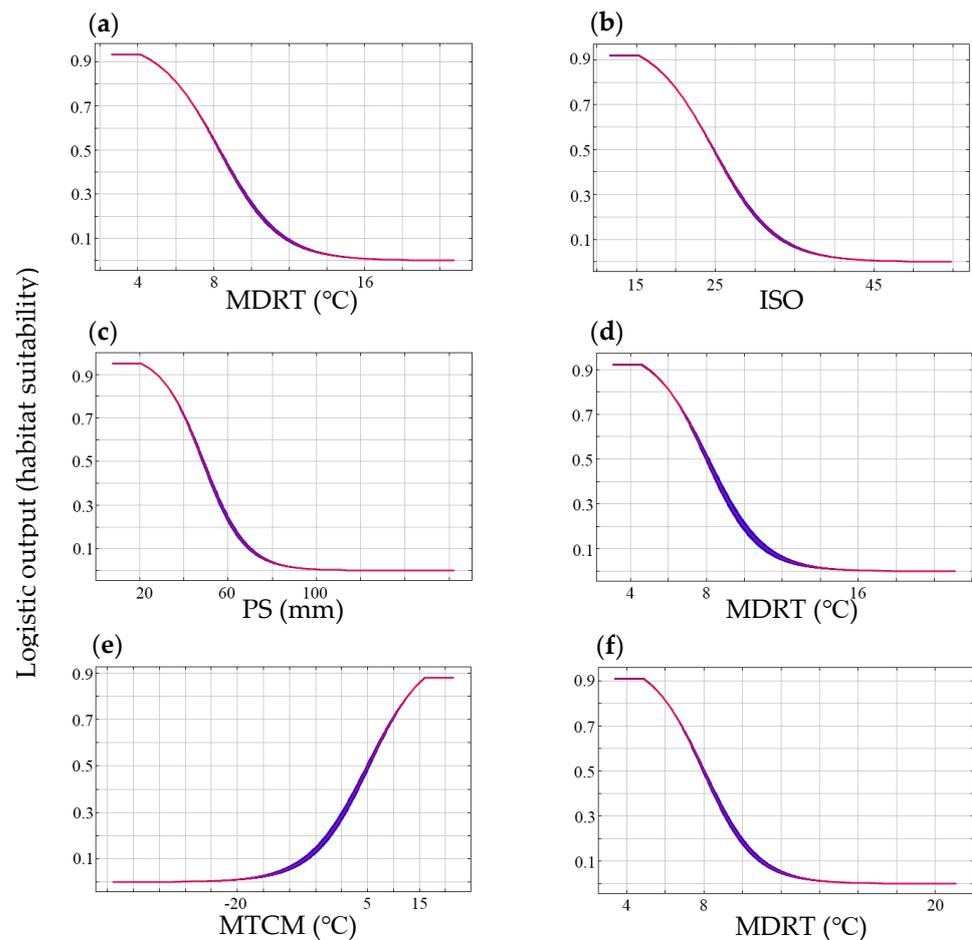


Figure 2. The response curves of species occurrence to the top two influencing variables for *C. oblongifolia* (a,b), *C. tientaiensis* (c,d), and *C. purpurinervis* (e,f), respectively. The response curves of species occurrence to the top two influencing variables for *C. oblongifolia* (a,b), *C. tientaiensis* (c,d), and *C. purpurinervis* (e,f), respectively. The logistic output of SDM (also known as habitat suitability) is represented by the vertical Y-axis and the environmental variable by the horizontal X-axis. When

the logistic output value is greater than 0.5, the probability of species presence under this condition is higher than that under a ‘typical’ condition, which indicates that the condition is highly suitable for the tree species. The red curves were the averages over 15 replicate runs; blue margins showed ± 1 standard deviation (SD) calculated over 15 replicates.

3.2. Predicted Suitable Habitats for the Current

Distributions of the climate suitability of the three *Carpinus* species habitats under the current climate conditions in China were shown in Figure 3. The high suitable habitats for *C. oblongifolia* were mainly distributed between 28 and 35° N and covering 182.2×10^3 km². Medium suitable habitats (261.1×10^3 km²) were distributed around high suitable habitats. The areas of low suitable habitats were relatively large, reaching 858.1×10^3 km² (Figure 3a).

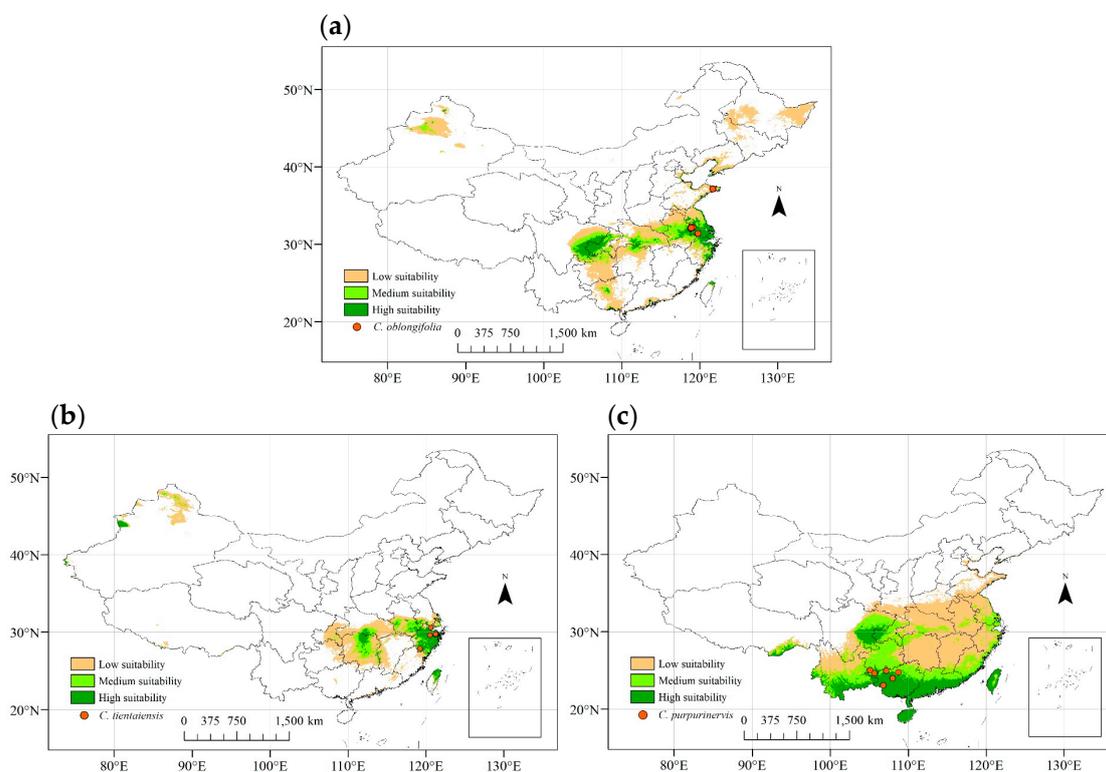


Figure 3. Potential distributions of the current (1970–2000) suitable habitats of three *Carpinus* species in China: (a) *C. oblongifolia* habitats; (b) *C. tientaiensis* habitats; (c) *C. purpurinervis* habitats.

High suitable habitats for *C. tientaiensis* were mainly distributed in Zhejiang, the junction of Hunan and Hubei, and northern Taiwan, covering 123.3×10^3 km². The area of suitable medium habitats was larger than that of high suitable habitats, covering 152.4×10^3 km². The area of low suitable habitats was the largest, covering 486.5×10^3 km² (Figure 3b).

The distribution range of *C. purpurinervis* was wider than that of *C. oblongifolia* and *C. tientaiensis*. The latitude of high suitable habitats was low, mainly distributed between 15 and 25° N, covering 459.2×10^3 km². The medium suitable habitats presented as stripes with a total area of 700.7×10^3 km². Low suitable habitats were distributed around suitable medium habitats, covering 1257.3×10^3 km² (Figure 3c).

3.3. Potential Distribution under Different Climate Change Scenarios

Compared with the current distribution (Figure 3a), the suitable habitats of *C. oblongifolia* expanded under both RCP2.6 (expansion of 404.0×10^3 km²) and RCP8.5 (expansion of 305.7×10^3 km²) in the future (Table 4). The main expanded area was distributed between

28 and 32° N, including the surrounding areas of Hubei, Hunan, and Shandong coastal areas (Figure 4).

Table 4. Predicted changes in the climatically suitable habitats area (km²) of three *Carpinus* species under different climate change scenarios (RCP2.6 and RCP8.5 in the years 2041–2060).

Species	Future Scenarios	Stable Area (×10 ³ km ²)	Loss Area (×10 ³ km ²)	Expanded Area (×10 ³ km ²)
<i>C. oblongifolia</i>	RCP2.6	371.8	71.6	404.0
	RCP8.5	355.2	88.1	305.8
<i>C. tientaiensis</i>	RCP2.6	104.3	171.3	16.9
	RCP8.5	72.4	203.2	2.4
<i>C. purpurinervis</i>	RCP2.6	831.8	328.0	72.3
	RCP8.5	755.6	404.3	82.7

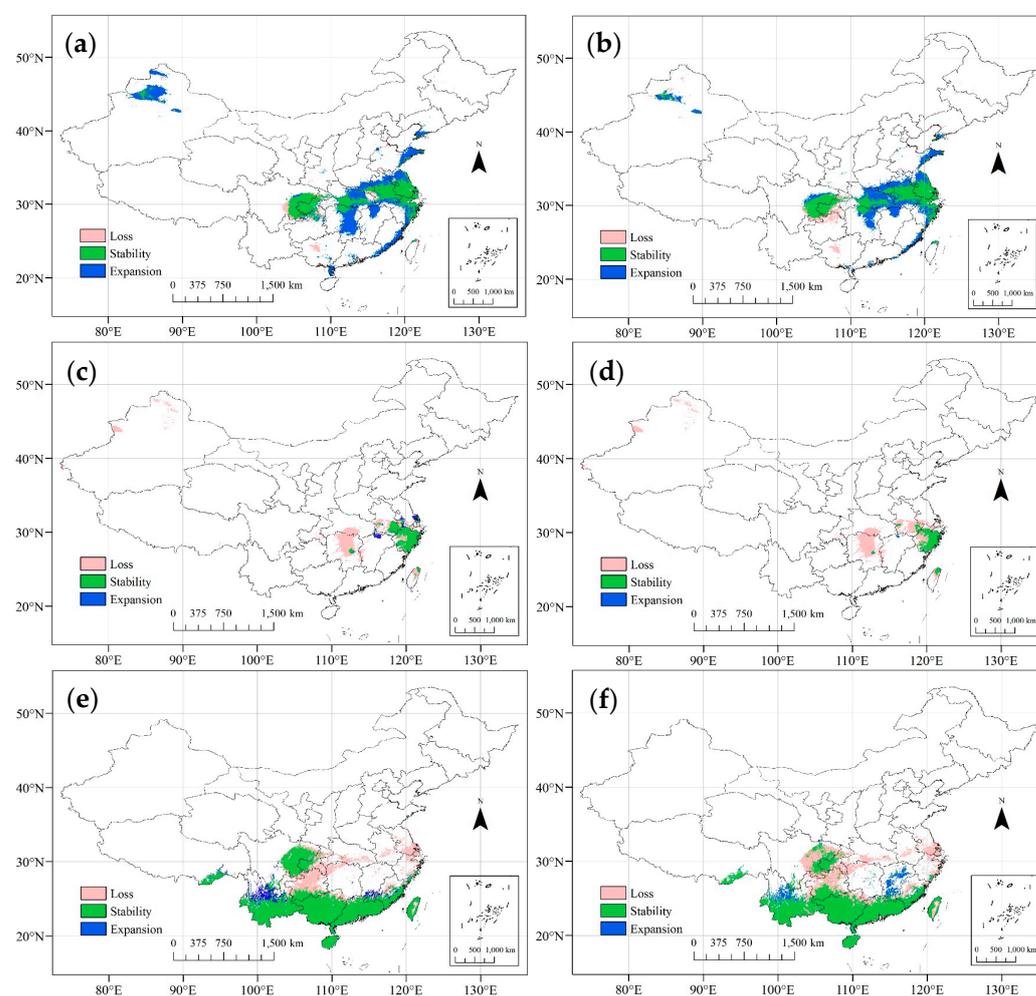


Figure 4. Predicted changes in the climatically suitable habitat area of three *Carpinus* species under different climate change scenarios. *C. oblongifolia* suitable habitats (a,b), *C. tientaiensis* suitable habitats (c,d), and *C. purpurinervis* suitable habitats (e,f) in the 2040–2061 under the RCP2.6 (left) and RCP8.5 (right), respectively.

In contrast, suitable habitats for *C. tientaiensis* and *C. purpurinervis* were partially lost in the future. By 2041–2060, the suitable habitats area of *C. tientaiensis* decreased $171.3 \times 10^3 \text{ km}^2$ and $203.2 \times 10^3 \text{ km}^2$ under RCP2.6 and RCP8.5, respectively (Table 4). Chongqing, Hunan, and Hubei were no longer be suitable in the future. The suitable habitats area of the junction of Hunan and Hubei decreased significantly (Figure 4). The

suitable habitats of *C. purpurinervis* decreased by 328.0×10^3 km² under RCP2.6 and decreased by 404.3×10^3 km² under RCP8.5.

4. Discussion

4.1. Key Climate Factors Contributing *Carpinus* Distribution

Multiple simulation studies have shown the importance of climate variables on tree species distribution [42,43]. We found that most three contributing factors of *C. oblongifolia* were all temperature-related factors (MDRT, ISO, and MTWTQ), suggesting that the growth of *C. oblongifolia* is sensitive to temperature variation. This fills in the gaps in previous understanding of the characteristics of *C. oblongifolia* population [27]. We found that for *C. tientaiensis* the most contributing factor was precipitation seasonality, indicating the growth of *C. oblongifolia* trees is sensitive to water conditions. Excessive precipitation seasonality may also be accompanied by seasonal drought or excessive precipitation, which is not conducive to growth. A previous study has shown that frequent rainfall hinders the normal pollination process and even causes flower drop, leading to a high rate of empty seed, therefore, making it difficult for reproduction [44]. The temperature variable MTCM (88.5%) had the highest contribution rate to the *C. purpurinervis*. This might be because the low temperature in the coldest month was not conducive to the release of dormancy in plants and even led to chilling injury [45].

4.2. Implications for *Carpinus* Conservation

Many studies have shown that biological trends are consistent with climate change predictions [46]. Therefore, understanding the potentially suitable habitats of species under future climate conditions and proposing corresponding conservation priority methods could identify the priority to restore plants' natural habitat for more effective conservation and restoration [47,48].

Our predictions showed that *C. oblongifolia* would benefit from climate change in the future. These findings were similar to the change trends of some other species [7,49]. Tree species would benefit from climate change if the temperature rise were within their physiological tolerance range [49,50]. This species does not occupy a dominant position in their communities due to its small number of young seedlings. Further, the population was difficult to maintain stably [27]. For this situation, we recommend combining in-situ protection and ex-situ protection measures. Native habitats protection, reintroduction, and restoration nearly native populations should be considered as priorities. Second, northern Jiangsu, northern Anhui, and Shandong provinces could be considered as priority ex-situ living areas.

The existing *C. tientaiensis* were rare, relatively concentrated, and the habitat range was narrow [51,52]. Changes in the native environment in the future may significantly impact the growth of existing plants and the natural regeneration of the population [51]. Therefore, we recommend focusing on expanding ex-situ conservation, giving priority to the Yangtze River in Jiangsu, Anhui, and Hubei junction as the introduction and cultivation area. Precipitation seasonality (Coefficient of variation) should also be considered when afforestation.

C. purpurinervis was currently mainly distributed in sparse mountain forests or the shrubbery on top of rocks at 1000 m a.s.l., such as Guangxi, Xingyi, and Dushan in Guizhou. The minimum temperature of the coldest month was the most influencing/driving factor to the distribution pattern of *C. purpurinervis*, which means this species was sensitive to low temperature and intolerant to winter freeze-thaw. Similarly, a previous study reported that the minimum temperature of the coldest quarter was the driving/influencing factor to the suitability of *P. deltooides* populations [48]. We found that a substantial proportion of the currently existing habitat of *C. purpurinervis* would be lost in the future (Figures 1 and 4e,f). Therefore, it is urgent to protect it in-situ. In order to prevent the extinction risk of this species caused by climate change, we should also establish a seed bank to preserving seed resources.

5. Conclusions

In this study, we conducted simulations (AUC > 0.9) using a SDM to predict the impact of climate change on the potentially suitable habitats for three endangered *Carpinus* species. We identified the major environmental variables that affect the distribution of the three endangered *Carpinus* species and predicted suitable habitats for them under future climate conditions. Our results showed that the suitable habitats of three species would change to different degrees in the future. Among them, the suitable habitat of *C. oblongifolia* would expand in the future, but the suitable habitat of *C. tientaiensis* and *C. purpurinervis* would decrease in the future. We recommended specific protection measures for each of the three species. Our results are essential for endangered plants to formulate adaptation strategies and management plans. Although the lack of occurrence data could limit and bias results, our work is still significant for biodiversity conservation, flora, and phytogeography research.

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