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Global Warming and Landscape Fragmentation Drive the Adaptive Distribution of *Phyllostachys edulis* in China

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Abstract: Global warming and landscape fragmentation significantly affect the spatial distribution pattern of bamboo forests. This study used high-resolution data and an optimized MaxEnt model to predict the distribution of *Phyllostachys edulis* in China under current and future climatic conditions in three climate scenarios (SSP126, SSP370, SSP585), and analyzed its land use landscape fragmentation using landscape indices. The results indicate that *Phyllostachys edulis* currently has potentially suitable habitats majorly distributed in East China, Southwest China, and Central South China. The precipitation of the driest month (BIO14) and the precipitation seasonality (BIO15) are the key environmental factors affecting the distribution of *Phyllostachys edulis*. In the next three scenarios, the adaptive distribution area of *Phyllostachys edulis* is generally expanding. With an increase in CO_2 concentration, the adaptive distribution of *Phyllostachys edulis* in the 2050s migrates towards the southeast direction, and in the 2070s, the suitable habitat of *Phyllostachys edulis* migrates northward. In the suitable habitat area of *Phyllostachys edulis*, cropland and forests are the main land use types. With the passage of time, the proportion of forest area in the landscape pattern of the high-suitability area for *Phyllostachys edulis* continues to increase. Under SSP370 and SSP585 scenarios, the cropland in the *Phyllostachys edulis* high-suitability area gradually becomes fragmented, leading to a decrease in the distribution of cropland. In addition, it is expected that the landscape of high-suitability areas will become more fragmented and the quality of the landscape will decline in the future. This research provides a scientific basis for understanding the response of *Phyllostachys edulis* to climate change, and also provides theoretical guidance and data support for the management and planning of bamboo forest ecosystems, which will help in managing bamboo forest resources rationally and balancing carbon sequestration and biodiversity conservation.

Keywords: *Phyllostachys edulis*; global warming; landscape fragmentation; optimized MaxEnt model; adaptive distribution

Citation: Zhang, H.; Liu, P.; Zhang, Y.; Wang, Z.; Liu, Z. Global Warming and Landscape Fragmentation Drive the Adaptive Distribution of *Phyllostachys edulis* in China. *Forests* **2024**, *15*, 2231. https://doi.org/10.3390/f15122231

Received: 25 November 2024
Revised: 15 December 2024
Accepted: 16 December 2024
Published: 18 December 2024

1. Introduction

Global warming has a great influence on the geographical distribution patterns of vegetation [1]. The global mean temperature has increased by 0.85 °C in the past century, and China's warming rate is even higher than the global average [2,3]. Climate change and changes in precipitation patterns may cause changes in the distribution areas of certain species, habitat fragmentation, and rapid decline in global biodiversity [4–8]. In addition, these changes may have a significant impact on the ability of China's terrestrial ecosystems to absorb and store carbon, and may even lead to the conversion of carbon sinks into carbon sources, further accelerating global warming [9–11]. Therefore, predicting the adaptive distribution of plant species to climate change and their future migration trends can provide a scientific basis for planning future plant introduction, ecological protection, and management strategies [12].

Phyllostachys edulis, an important type of forest in southern China, has a long lifecycle, grows rapidly, and has a strong carbon sequestration ability, which can effectively mitigate climate change and is becoming more and more important for achieving the national goal of carbon neutrality [13–16]. The carbon sequestration capacity of *Phyllostachys edulis* forests far exceeds that of ordinary trees, and it is 1.46 times that of spruce forests and 1.33 times that of tropical rainforests [17]. In the past thirty years, the area of *Phyllostachys edulis* forest has grown rapidly, with an average growth rate of 3% per year [18]. This means that *Phyllostachys edulis* is playing an increasingly important role in growing national and global forest carbon sinks [19]. However, the expansion of *Phyllostachys edulis* can also lead to a loss of biodiversity [20], and studying its fragmentation is beneficial for balancing biodiversity conservation and improving forest carbon sinks. At present, research on *Phyllostachys edulis* mainly centers on the influence of its invasion on the structure and function of forest ecosystems under climate change [21–23]. There is relatively little research on the influence of global change and landscape fragmentation on the distribution of *Phyllostachys edulis*. Therefore, conducting research on the distribution of *Phyllostachys edulis* driven by global warming and landscape fragmentation can provide a theoretical understanding of the optimal control of *Phyllostachys edulis* ecosystems and achieve national carbon neutrality goals.

In recent years, species distribution models (SDMs) have played a key role in exploring species distribution patterns; they use known species distribution data and environmental factors to simulate the geographic distribution of species and their response to climate change through specific algorithms [3,24]. Among the SDMs, the MaxEnt model proposed by Phillips and constructed based on the maximum entropy principle has been widely adopted and applied in ecological research both domestically and internationally due to its effectiveness and practicality [25–29]. The advantage of this method is its high prediction accuracy, making it one of the most representative species distribution models. Even when the sample size is small, it can still achieve good prediction results [30].

Based on existing research, the MaxEnt model usually predicts under the default parameters of the model, often neglecting the optimization of model parameters. The MaxEnt model, which uses default parameters, is relatively complex and has some fitting bias, which may cause overfitting and make the results difficult to explain [2,25,31–34]. To solve this problem, Muscarella et al. [35] exploited the R package ENMeval to optimize model parameters in 2014. This matter regulates the two parameters of the model, regularization multiplier (RM) and feature combination (FC), compares the complexity of models generated by different parameter combinations, and selects the parameter combinations that can achieve the same prediction effect with lower complexity to construct the model. This method effectively alleviates the overfitting problem of using default parameter models and improves the exactitude of the model.

This research integrated the distribution and influencing factors of *Phyllostachys edulis* in China using an optimized MaxEnt model based on the geographic distribution of vegetation, utilizing data on climate, terrain, soil, and human activities. Then, using the theory of landscape patterns, we refined the suitable habitat area of *Phyllostachys edulis* and analyzed the changes in landscape pattern fragmentation. The purpose of this research was to (1) identify and analyze the main environmental factors limiting the distribution of *Phyllostachys edulis*, (2) simulate and predict the adaptive distribution and centroid transfer of *Phyllostachys edulis* under different periods and scenarios, and (3) evaluate the land landscape patterns and the effects of landscape fragmentation on the distribution patterns of *Phyllostachys edulis'* adaptive distribution in different scenarios and periods, both current and future. This research provides a scientific basis for understanding the response of *Phyllostachys edulis* to climate change, and also provides theoretical guidance and data support for the management and planning of bamboo forest ecosystems, which helps in achieving the sustainable utilization of bamboo forest resources.

2. Materials and Methods

2.1. Data Screening and Processing

The boundary data of the Chinese base map used in this research were from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (RESDC, https://www.resdc.cn, accessed on 5 May 2024). The species point data were sourced from the "Vegetation Atlas of China (1:1,000,000)" published by Science Press in 2001. Firstly, ArcGIS 10.8 was used to perform a series of spatial registration, vectorization, and rasterization processes on the dataset, generating latitude and longitude data for *Phyllostachys edulis* with a resolution of 1 km × 1 km. Secondly, the R software package 'devtools' was used to randomly grid the latitude and longitude information, retaining only one distribution point every 5 km × 5 km (approximately 2.5′) area. The sample points were evenly distributed, minimizing spatial autocorrelation of sample points, and reducing errors in the model results. Finally, 2665 sample points were retained (Figure 1). To construct the MaxEnt model, the species distribution point data were input into Excel according to "the species name, longitude, latitude" and kept in "*. CSV" format.

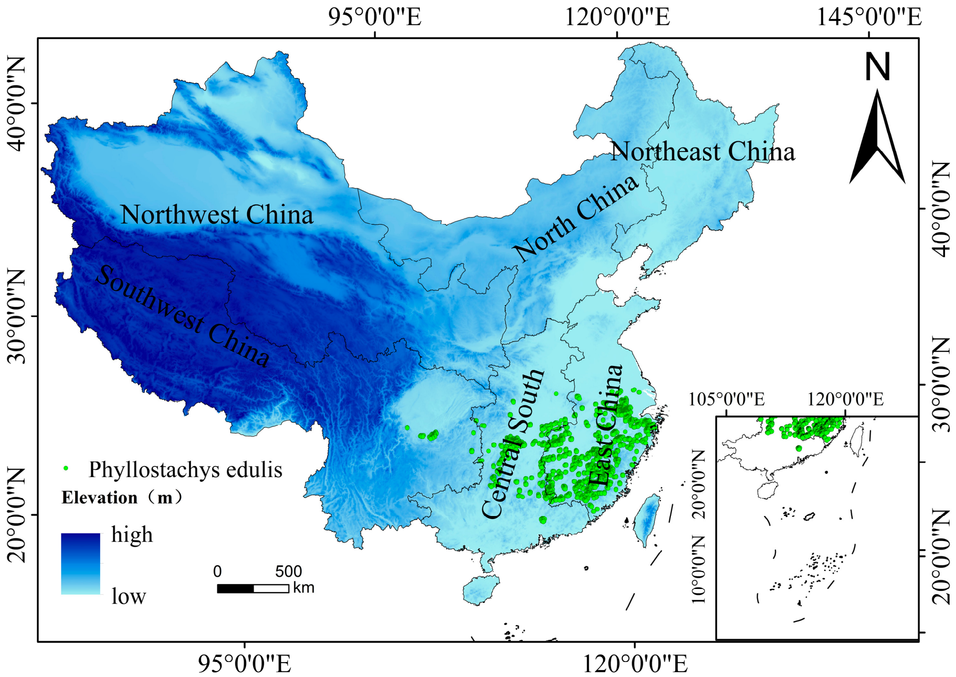

Figure 1. Distribution of occurrence points of *Phyllostachys edulis* in China.

This study selected 32 environmental factors (including 19 bioclimatic factors, 8 soil factors, 3 terrain factors, and 2 human activity factors) as initial environmental variables (Table S1). Data on the 19 bioclimatic and elevation factors were sourced from WordClim (https//wordclim.org, accessed on 5 May 2024), including current (1970–2000) and future (2050s: 2041–2060; 2070s: 2061–2080) bioclimatic data with a spatial resolution of 2.5′ (approximately 5 km). Slope and aspect data were extracted from elevation data using the 3D analysis tool ArcGis10.8.2, with a spatial resolution of 2.5′. Data on the 8 soil factors were sourced from the Harmonized World Soil Database (HWSD1.2) (HWSD, http://www.iiasa.ac.at/web/home/research/researchPrograms/water/HWSD.html, accessed on 5 May 2024) constructed by the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA), with a spatial resolution of 1 km.

Land use data were sourced from the article by Zhang et al. [36], including current (2020) and future (2050 and 2070) land use data, with a spatial resolution of 1 km. This study selected simulated land use data from three shared socio-economic pathways (SSP126, SSP370, and SSP585) in the future (2050 and 2070) for research. Human activity data came from socio-economic data and application centers (SEDAC, https//sedac.ciesin.columbia.edu, accessed on 5 May 2024), with a spatial resolution of 1 km.

Future climate model selection: Beijing Climate Center Climate System Model Second Edition (BCC-CSM2-MR) with CMIP6. The BCC-CSM2-MR model has shown high accuracy and reliability in simulating extreme temperature indices and their trends in China [37]. This study selected three shared socio-economic pathways (SSP126, SSP370, and SSP585) simulated by the BCC-CSM2-MR model for research. Among them, SSP126 refers to a future development scenario where greenhouse gas emissions are low and climate warming is relatively mild; SSP370 refers to a future development scenario where greenhouse gas emissions are high, leading to severe climate warming; SSP585 refers to a future development scenario characterized by high energy consumption, rapid economic development, strong radiative forcing, and extremely high greenhouse gas emissions [31]. These three scenarios have been extensively used in the study of species distribution in suitable habitats [38,39]. These scenarios represent different greenhouse gas emissions and social development paths, providing diverse perspectives on future climate change and socio-economic changes.

This study uses ArcGis10.8.2 software to extract, crop, resample, and project all environmental factors into masks, matches their resolution with the resolution of species point data, and unifies them to 5 km × 5 km (approximately 2.5′) and a unified projection coordinate of WGS1984-UTM_Zone50N for subsequent analysis and modeling. In this work, considering climate change scenarios, we anticipate that the impact of these factors will be very limited. Therefore, we assume that terrain and soil conditions will remain stable and unchanged over the next 100 years.

The multicollinearity between variables can lead to overfitting of species distribution models [40]. Therefore, before predicting species-suitable habitats, it is essential to conduct a correlation analysis on various environmental factors to avoid the problem of multicollinearity among environmental factors. Firstly, 32 environmental variable data are screened, and the screening process is divided into two steps: (1) Incorporate 32 environmental variables and species distribution data into the MaxEnt model and run it, removing environmental variables with a contribution rate less than 0.5% from the running results. (2) Perform Pearson correlation analysis on the remaining environmental variables using SPSS 27 software. If the correlation between two environmental variables is very strong (with an absolute correlation coefficient greater than 0.85), we choose to remove the environmental variable with a lower contribution rate. Ultimately, 8 environmental factors involved in modeling are determined (Table S1).

2.2. Application of the MaxEnt Model

In order to select appropriate model parameters to simulate the potential habitable zone of *Phyllostachys edulis*, this study first used a partitioning method to divide 2665 *Phyllostachys edulis* data into 4 equal groups, with 3 groups for training and 1 group for testing [34]. Next, we set the RM values to range from 0.5 to 4, increasing in increments of 0.5, resulting in 8 different RM parameters in all [41]. At the same time, this research considered five aspects of feature combination (FC) parameters, namely linear (L), hinge (H), product (P), quadratic (Q), and threshold (T). Based on these features, this study constructed six different feature combinations: L, LQ, H, LQH, LQHP, and LQHPT [41]. Then, this study used the ENMeval software package to test the 48 parameter combinations mentioned above. The Akaike information criterion (AICc) was used to evaluate the complexity of the MaxEnt model and its fit to the data, with priority given to the model with the smallest AICc value [35]. Ultimately, we found that the AICc value is minimized when the modulation multiplier (RM) is 0.5 and the feature combination (FC) is LQHPT. This indicated that the parameter settings of RM = 0.5 and FC of LQHPT provide the optimal fitting effect for the model (Figure S1A).

Then, we imported species distribution data and environmental factors into the MaxEnt model with RM = 0.5 and FC as LQHPT. In total, 75% of the samples were randomly selected from the species distribution point data for validation, while the remaining 25% were used for testing. We set the default parameters and repeated the calculation 10 times using the cross-validating method. The number of iterations and background points was set to 500 and 10,000, respectively, the jackknife test option was used to obtain the percentage contribution of each environmental variable, and response curves were obtained to analyze the range of environmental variables suitable for *Phyllostachys edulis* growth. Universally, when the probability value of an environmental variable reaches 0.5 or above, it indicates that the environmental conditions are suitable for the growth of *Phyllostachys edulis* [42]. The relative importance of each variable was evaluated using the jackknife test, percentage contribution rate, and permutation importance. The model evaluation used the receiver operating characteristic (ROC) curve and the area enclosed by the x-axis (AUC value) to assess the goodness of fit of the model. If the AUC value of the model is below 0.5, it is considered that the predictive ability of the model is insufficient. When the predicted value of the model reaches 0.75, it indicates that the model begins to have predictive ability. If the predicted value of the model exceeds 0.78, it indicates that the predictive performance of the model is good [43].

2.3. Classification of Adaptive Distribution and Calculation of Centroid Migration

At the beginning, it is necessary to import the result file of the MaxEnt model into ArcGIS 10.8.2, and use the reclassification tool in the spatial analysis tool to classify the simulation results using the Jenks natural breakpoint classification method. The model simulation results were classified into four classes (unsuitable habitat (0–0.1), poorly suitable habitat (0.1–0.3), moderately suitable habitat (0.3–0.5) and highly suitable habitat (0.5–1)) to obtain the possible geographical distribution areas of *Phyllostachys edulis* in China. Then, a grid calculator was used to calculate the number of grids for each category and determine the suitable habitat for different climates within each category. Then, the centroid of the species' suitable areas was obtained using the SDM module of ArcGis10.8.2 software, and the migration distance and direction of the centroid of the species' suitable areas under future climate scenarios were calculated.

2.4. Calculation of Landscape Fragmentation

Firstly, we used land use data from three scenarios (SSP126, SSP370, and SSP585) in 2020, 2050, and 2070 to superimpose the adaptive distribution data of *Phyllostachys edulis* onto the three scenarios (SSP126, SSP370, and SSP585) of the present, 2050s, and 2070s, respectively, to obtain the landscape patterns of current (1970–2000) and future (2050s and 2070s) land use, so as to understand the concentration and connectivity of suitable habitats for *Phyllostachys edulis*, and to specify the distribution of climate-suitable habitats for *Phyllostachys edulis*. The landscape pattern index also explains the process of fragmentation and degradation in local areas. Then, FragStats4.2 software was used to calculate the landscape pattern index of *Phyllostachys edulis'* climate-adaptive distribution [44], and comprehensively considered five indicators to analyze the fragmentation of the land use landscape of *Phyllostachys edulis'* suitable habitats, including the total (class) area (CA), number of patches (NP), patch density (PD), aggregation (AI), and the percentage of landscape (PLAND). We analyzed the changes in the land use landscape fragmentation of poorly, moderately, and highly suitable habitats for *Phyllostachys edulis* in three scenarios of the present, 2050s, and 2070s. In landscape fragmentation analysis, CA was a measure of landscape composition, NP represented the number of patches, and an increase in the number of patches indicated a greater degree of landscape fragmentation. PD reflected the patch density and to some extent, the degree of fragmentation. The larger the PD value, the higher the degree of fragmentation. AI represented the degree of aggregation, and the higher the AI value, the lower the degree of fragmentation. PLAND quantifies the proportional abundance of each patch type in the landscape. These indicators can effectively reflect the landscape pattern, showcasing its structural and spatial distribution characteristics. These analyses helped us explain the process of local fragmentation and loss in *Phyllostachys edulis*.

3. Results

3.1. Adaptive Distribution and Driving Factors

Phyllostachys edulis currently has potential suitable habitats primarily distributed in East China, Southwest China, and Central South China, with a total suitable habitat area accounting for 10.36% of the entire study area (Figure 2). Under current climate conditions, the centroid of suitable habitats of *Phyllostachys edulis* is situated in the western part of East China, west of the Gan River (Figure 2). The highly suitable habitats are primarily concentrated in the areas south of the Yangtze River in Eastern and Central Southern China. They account for 4.96% of the entire study area and 47.86% of the overall adaptive distribution. The moderately suitable habitats are mainly concentrated in the eastern part of Southwest China and the eastern of Central South China, with a small distribution in the southern and central parts of Central South China, and the central and southern parts of East China. They occupy 2.00% of the total research area and 19.30% of the suitable habitat. The poorly suitable habitats are mainly concentrated in the eastern part of Southwest China, the central northern parts of Central South China, and a small part of the central northern parts of East China. They occupy 3.40% of the entire research area and 32.84% of the total suitable habitat (Figure 2).

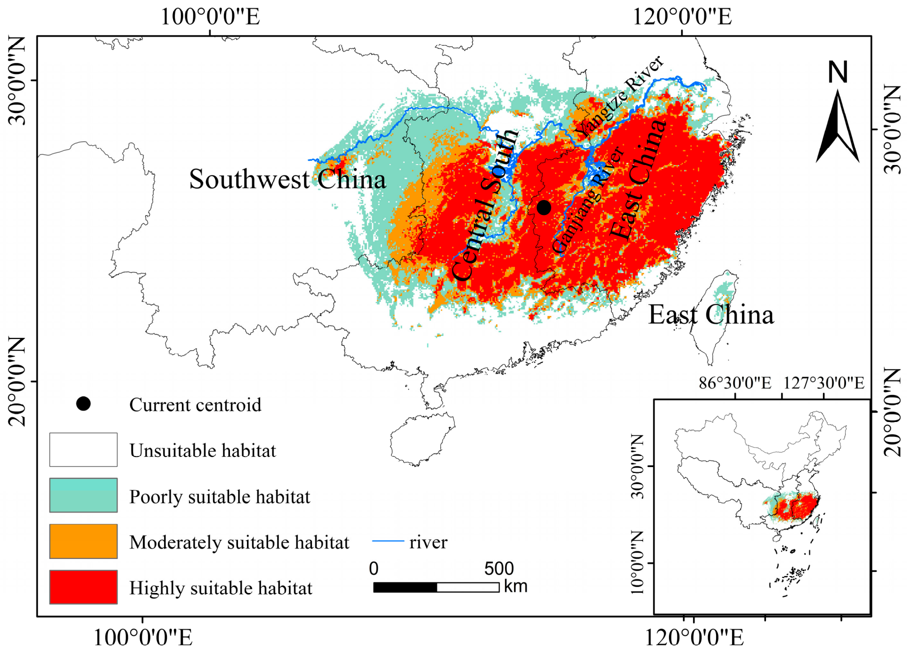

Figure 2. Adaptive distribution and current centroid of *Phyllostachys edulis* under current climate conditions based on the MaxEnt model.

Among the eight environmental factors that influence the distribution of *Phyllostachys edulis*, the precipitation of the driest month (BIO14) is the major limiting factor for the potential distribution of *Phyllostachys edulis*, with a single factor contribution rate of 70.6% (Figure 3A), followed by precipitation seasonality (BIO15), mean diurnal range (BIO2), annual mean temperature (BIO1), and precipitation of the warmest quarter (BIO18), with a contribution rate of 95.8% for the five environmental factors. The cumulative permutation importance is 74.1% (Figure 3A). Based on the jackknife test (Figure 3B) using a single environment variable, precipitation of the driest month (BIO14) ranked highest in terms of the regularized training gain. Next are the precipitation seasonality (BIO15), mean diurnal range (BIO2), precipitation of the warmest quarter (BIO18), and annual mean temperature (BIO1). Comprehensive jackknife testing and percent contribution analysis show that the precipitation of the driest month (BIO14), precipitation seasonality (BIO15), mean diurnal range (BIO2), annual mean temperature (BIO1), and precipitation of warmest quarter (BIO18) are the dominant environmental factors affecting the distribution of *Phyllostachys edulis* under current climate conditions. Based on the above analysis, it can be concluded that precipitation factors have the greatest influence on the distribution of *Phyllostachys edulis*, followed by the mean diurnal range (BIO2) and annual mean temperature (BIO1). In contrast, soil and terrain factors, as well as human activities, have little impact on the distribution of *Phyllostachys edulis*.

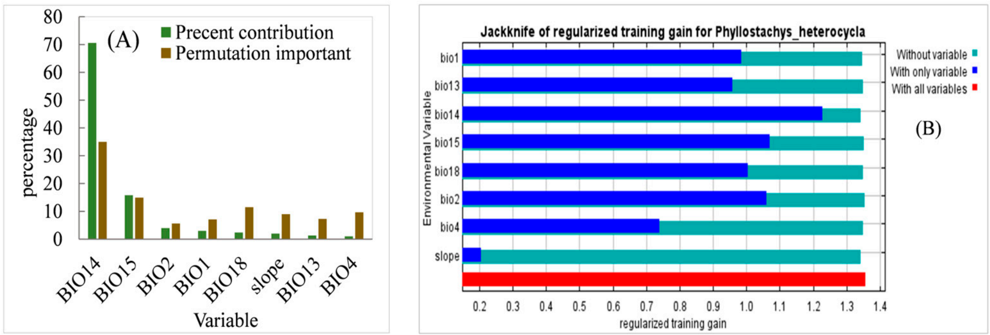

Figure 3. (**A**) Percentage contribution and permutation importance of environmental factors; (**B**) jackknife test for a single environmental variable.

In order to gain a deeper understanding of the adaptability of *Phyllostachys edulis* to climate conditions and predict which regions may be suitable for *Phyllostachys edulis* growth under the current climate background, we conducted an in-depth analysis of the impact of five key environmental factors on the distribution of *Phyllostachys edulis* and plotted response curves between these factors and the *Phyllostachys edulis* distribution (Figure 4). Research has found that the suitable range for annual mean temperature (BIO1) is 12.56–19.19 °C (Figure 4A), the suitable range for mean diurnal range (BIO2) is 7.18–8.90 °C (Figure 4B), the suitable range for precipitation of the driest month (BIO14) is 32.20–52.70 mm (Figure 4C), the suitable range for precipitation seasonality (BIO15) is 44.54–62.73 mm (Figure 4D), and the suitable range for precipitation of the warmest quarter (BIO18) is 449.95–678.18 mm (Figure 4E).

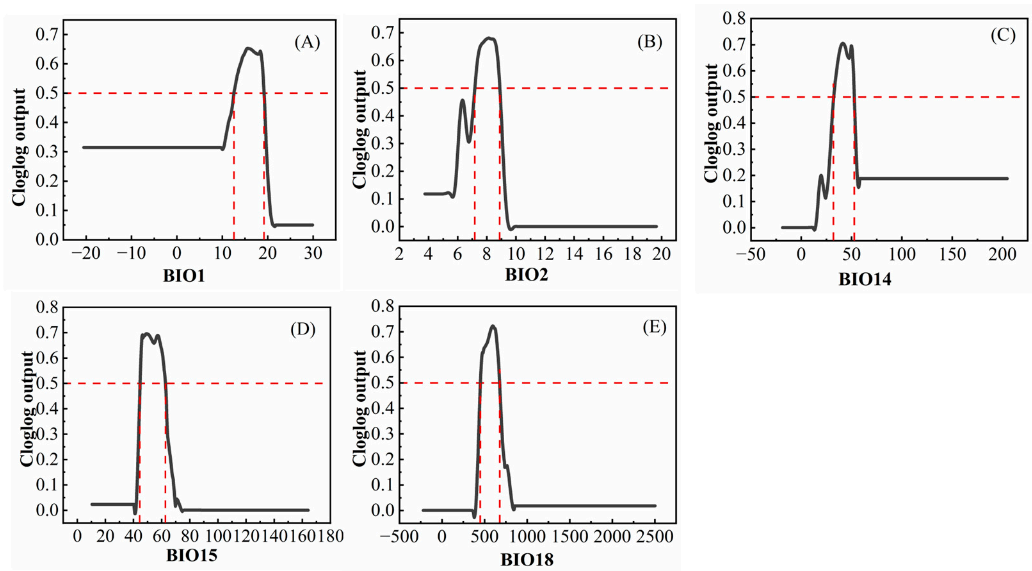

Figure 4. Response curve of the main environmental factors (**A**–**E**).

3.2. Adaptive Distribution and Centroid Migration Driven by Global Warming

The overall pattern of the adaptive distribution for *Phyllostachys edulis* in the future is relatively consistent in spatial distribution with the current period, with slight differences in different scenarios (Figures 2 and 5A–F). The overall distribution area of *Phyllostachys edulis* will expand in the future (Table S2). With an increase in CO_2 concentration, the total suitable habitats of *Phyllostachys edulis* continue to increase. With an increase in CO_2 concentration, the suitable habitats of *Phyllostachys edulis* in the 2050s migrate towards the southeast direction, and in the 2070s, the suitable habitats of *Phyllostachys edulis* migrate northward (Figure 5A–F). The change area is located at the edge of the predicted suitable growth area, which means that in the area south of the boundary line, the distribution of *Phyllostachys edulis* is more fixed and less susceptible to environmental changes. The new ranges are mainly spreading out from the current ranges into the surrounding areas, with the abruptly emerging ranges being smaller in size. They gradually move towards higher latitudes in the SSP370 and SSP585 scenarios. Most of the lost ranges are located in the eastern part of Southwest China, and the central north and southern parts of Central South China (Figure 5A–F and Table S2). With the passage of time, the amplitude of total habitable areas under the SSP126 and SSP370 scenarios continues to increase, while the amplitude of total habitable areas under the SSP585 scenario decreases. In the 2050s, the comparison of the area of highly suitable habitats under various scenarios is as follows: SSP126 > SSP370 > SSP585. Based on the SSP585 scenario, the total suitable habitats show the largest increase of 16.92%. In the 2070s, the area of highly suitable habitats based on the SSP585 scenario is the largest, and the increase in total suitable areas is the greatest. The change in the area of the moderately suitable areas based on the SSP370 scenario is the largest among all scenarios, accounting for 64.31% (Table S3).

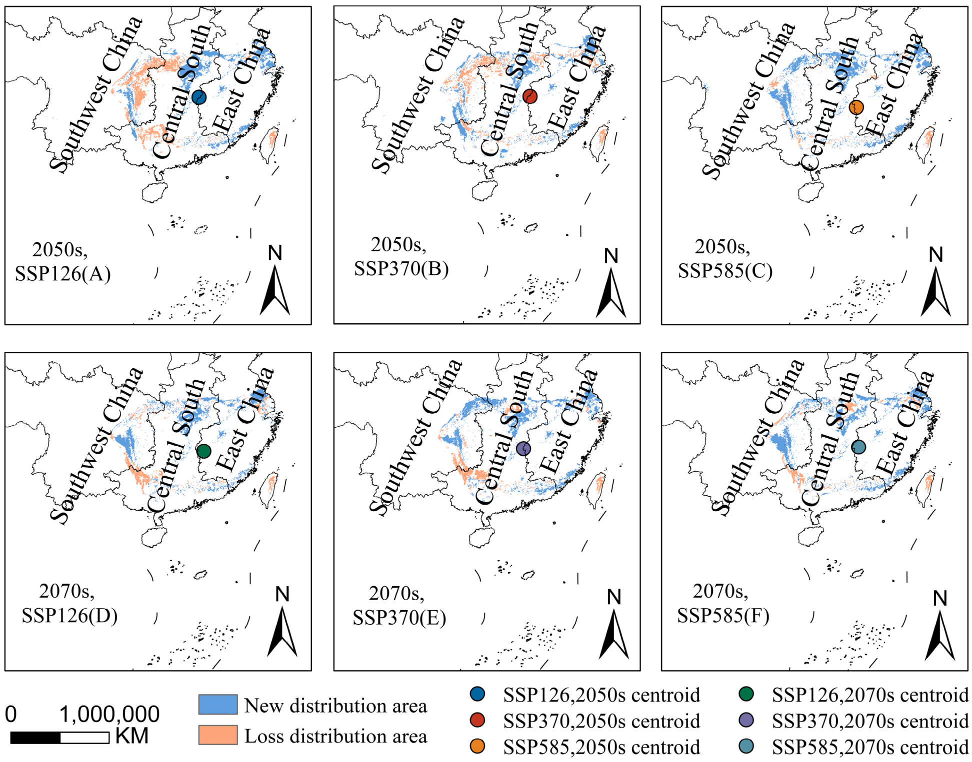

Figure 5. Change in distribution area and migration of centroid in the adaptive distribution of *Phyllostachys edulis* (**A**–**F**).

The future pattern changes of *Phyllostachys edulis* are closely related to the precipitation of the driest month (BIO14) and the precipitation seasonality (BIO15). The precipitation of the driest month (BIO14) and the precipitation seasonality (BIO15) are important climate variables that affect the potential distribution of suitable areas for *Phyllostachys edulis* in the 2050s and 2070s. The two variables have the highest contribution rates to the distribution of suitable areas for *Phyllostachys edulis* in the future: both are above 85% (Figure 6A). The contribution rates of other climate factors vary greatly under different scenarios in different periods. In order to intuitively reflect the differences in the contribution rates of climate factors under different scenarios in different periods, we removed the two factors with the highest contribution rates and found that the contribution rates of the mean diurnal range (BIO2) and annual mean temperature (BIO1) are higher in the SSP585 scenario in the 2050s than in other scenarios during other periods. The contribution rate of temperature seasonality (BIO4) is higher in the SSP126 scenario in the 2050s than in other scenarios. The contribution rate of the precipitation of the warmest quarter (BIO18) is higher in the SSP126 scenario in the 2070s than in other scenarios, and the contribution rate of the precipitation of the wettest month (BIO13) is higher in the SSP370 scenario in the 2050s than in other scenarios (Figure 6B).

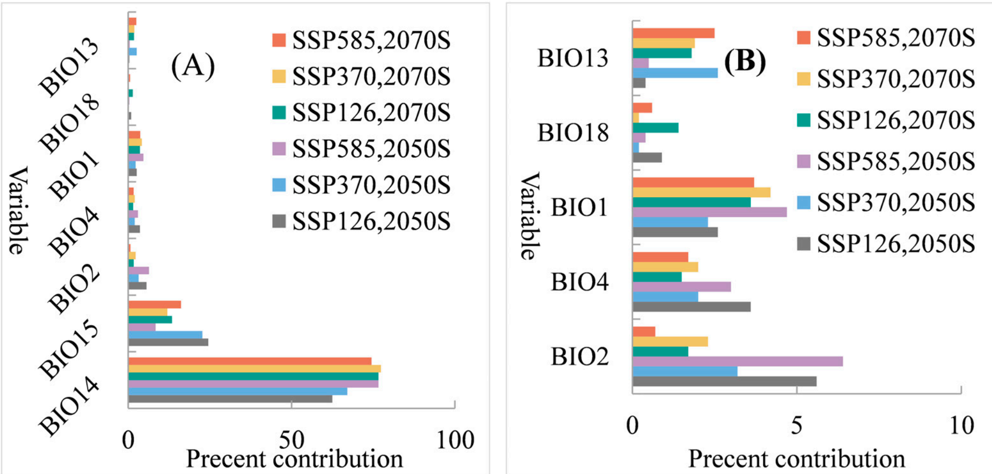

Figure 6. (**A**) Comparison chart of climate factor contribution rates; (**B**) Comparison of contribution rates after removing the two environmental factors with the highest contribution rates.

3.3. The Impact of Landscape Fragmentation on the Adaptive Distribution

Among the land use areas suitable for *Phyllostachys edulis* habitat, cropland and forests account for the largest proportion (Figure 7A–C). The proportion of cropland and forest area in the poorly and moderately suitable areas of *Phyllostachys edulis* is mostly cropland > forest (Figure 7A), while the proportion of cropland and forest area in the highly suitable areas is forest > cropland (Figure 7B). In the SSP370 and SSP585 scenarios of the present and the 2070s, as the suitable habitat for *Phyllostachys edulis* increases, the distribution of forests gradually expands, while the distribution of cropland gradually decreases. In other periods and scenarios, as the suitable habitat for *Phyllostachys edulis* increases, the distribution of forests first shrinks and then expands, and the distribution of cultivated land first expands and then shrinks (Figure 7A–C). The land use area of the suitable habitat for the disappearance of bamboo is forest > cultivated land, indicating that most of the disappeared bamboo is in the forest (Figure 8A–F). The proportion of newly added suitable land use types for bamboo is cultivated land > forest (Figure 8G–L). The area of suitable habitat for bamboo in the newly added forest is larger than the area of disappearing suitable habitat.

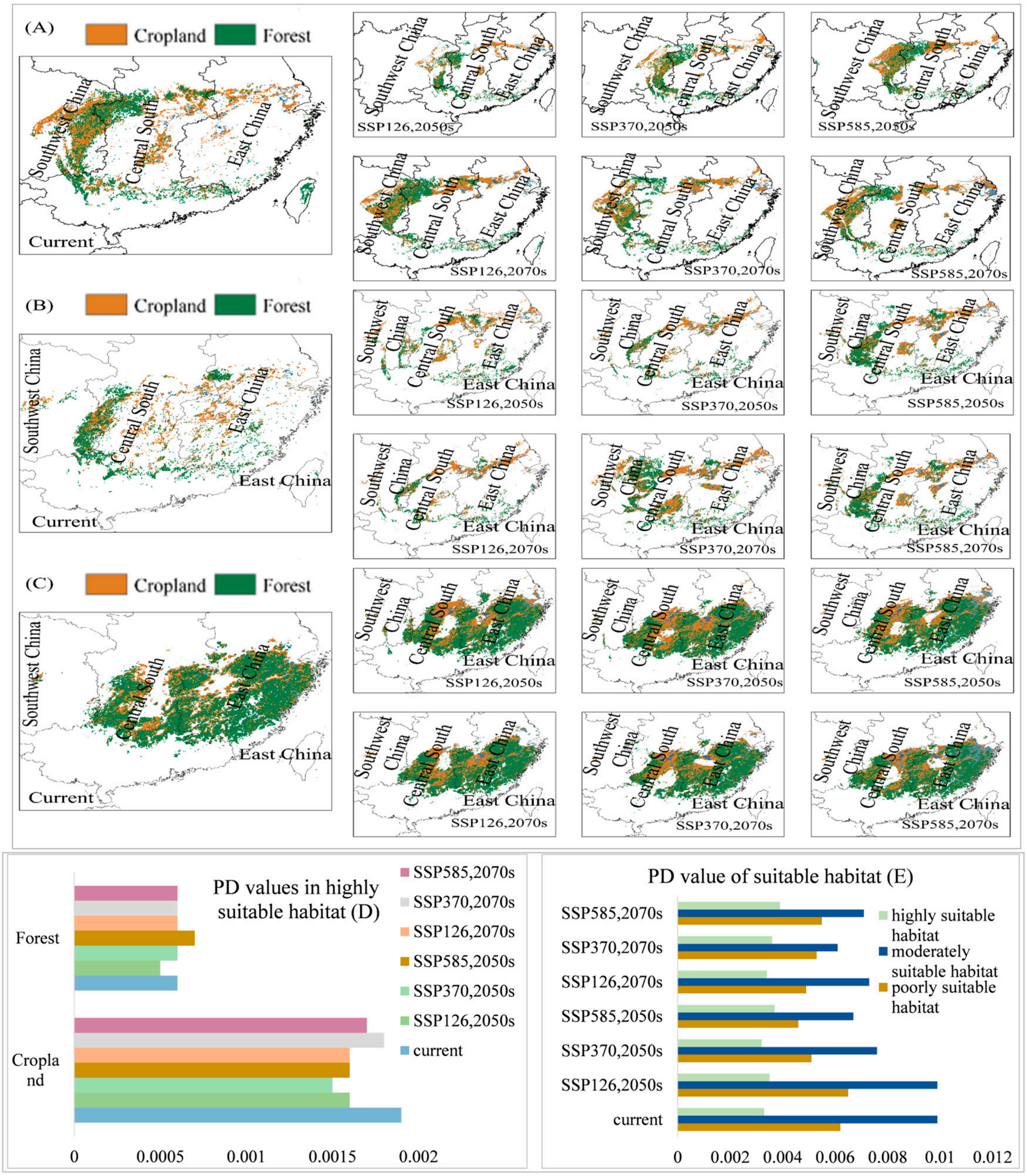

Figure 7. Analysis results of land use landscape pattern (current, 2050s, 2070s) in different climate-suitable areas for *Phyllostachys edulis*: (**A**) poorly suitable habitat; (**B**) moderately suitable habitat; (**C**) highly suitable habitat; (**D**) PD values in highly suitable habitat; (**E**) PD value of suitable habitat.

In the 2050s and 2070s, the total NP and PD values in the low- and moderate-suitability areas decrease, while the corresponding values in the high-suitability areas increase (Figure S2(A4,B5,C5)). This indicates that the fragmentation of *Phyllostachys edulis'* high-suitability areas will continue to intensify in the future, leading to a decline in overall landscape quality. In the 2050s, with an increase in CO_2 content in the air, the PD value of forests in highly suitable areas of *Phyllostachys edulis* will continue to rise, while the AI value will continue to decrease (Figure 7D). This change indicates that with an increase in CO_2

content, the degree of forest fragmentation and aggregation in the highly suitable area of *Phyllostachys edulis* is significantly reduced, further leading to a decline in forest landscape quality. With the passage of time, under the SSP370 and SSP585 scenarios, the PD value of cultivated land in the highly suitable area of *Phyllostachys edulis* continues to increase, while the AI value continues to decrease, indicating that under these two scenarios, the cropland in the highly suitable area of *Phyllostachys edulis* gradually becomes fragmented, leading to a decrease in the distribution of cropland (Figures 7E and S2(A1)).

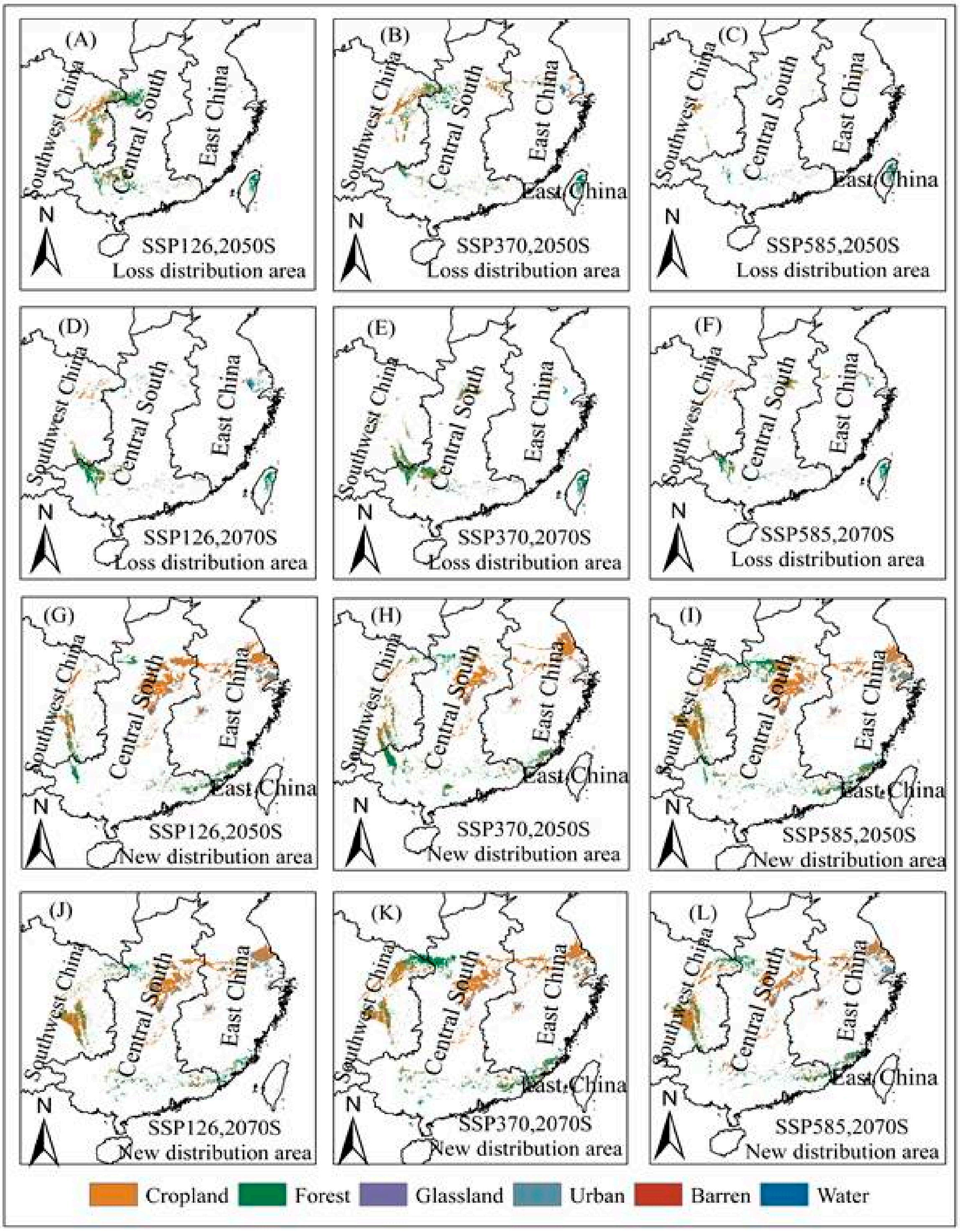

Figure 8. (**A**–**F**) Land use types in suitable habitats for the disappearance of *Phyllostachys edulis* and (**G**–**L**) newly added land use types suitable for *Phyllostachys edulis* growing areas.

4. Discussion

Previous studies have mostly used preset parameters in MaxEnt models, which may cause overfitting and sampling bias issues, ultimately reducing the transferability of species prediction results [45]. For the study of a species, adjusting the model settings for a specific species yields more accurate results than using default settings [46]. In this study, the ENMeval software package optimized the complexity of the MaxEnt model by integrating multiple parameters, and compared to other software packages, it demonstrated more advantages [47,48]. The optimization results show that when the RM was adjusted from 4 to 0.5 and the FC was changed from LQHP to LQHPT, the AICc decreased from 1288.062 to 0, indicating that the transferability of the default model is relatively low [49]. Moreover, under fine-tuning settings, the response curve is smoother and the AUC value is higher, at 0.887 ± 0.004 (>0.78). The fine-tuning model more reasonably reflects the response of bamboo to environmental factors and accurately predicts the adaptive distribution of *Phyllostachys edulis* [50].

Bamboo forest, with an important and unique role in forest ecosystems, is widely distributed in tropical, subtropical, and warm temperature regions between 46°N and 47°S, as it grows better in warm and humid climates [13]. *Phyllostachys edulis* is the most representative bamboo in southern China [51]. It reproduces asexually through its well-developed underground rhizome system and expands its population by sprouting new shoots from these rhizomes. However, the variation range of annual precipitation has a significant impact on the growth and community development of plant seedlings. Therefore, bamboo shoots can grow into adult bamboo plants, and the biomass produced by these plants primarily depends on the mean rainfall and the extent of its variation over the growing season [52,53].

But it is generally believed that temperature, precipitation, altitude, and soil factors all have significant impacts on the distribution of bamboo [54–57]. The results of this study particularly emphasize that precipitation and temperature are the main factors affecting the distribution of *Phyllostachys edulis*. A recent study suggests that precipitation plays a more important role in limiting the distribution of *Phyllostachys edulis* than temperature [51]. With sufficient precipitation, temperature becomes a more important and limiting environmental factor for the distribution of bamboo. However, in the central and northern regions of China, due to the common occurrence of drought, precipitation has a more critical impact on the distribution of *Phyllostachys edulis* than temperature. This means that in these regions, the growth and distribution of *Phyllostachys edulis* are more limited by precipitation conditions rather than temperature conditions [51]. These studies demonstrate the importance of precipitation in the distribution of *Phyllostachys edulis*, which is consistent with our research findings.

According to research estimates, the carbon sequestration of bamboo forest ecosystems in China accounts for approximately 5.1% of the total forest carbon storage in the country [58]. Especially the *Phyllostachys edulis* forest, its annual fixed carbon content exceeds the national average of forest vegetation [59,60]. This indicates that bamboo forests have a greater potential for carbon sequestration than other forest species. There are also studies indicating that with an increase in carbon dioxide concentration, the physiology and growth patterns of bamboo, being a C3 plant, will change, not only because of the improvement of water use efficiency but also because the fertilization effect significantly enhances photosynthesis [61]. A study has found that with an increase in CO_2 concentration, the threat posed by climate change to bamboo decreases, as elevated CO_2 increases the climate adaptability of bamboo by 15%, which may lead to an increase in its potential distribution area. In the RCP4.5 and RCP8.5 scenarios, the potential change trend of bamboo moves towards higher latitudes [62]. These findings are consistent with the results of this study, which show that as CO_2 concentration increases, the suitable habitat for *Phyllostachys edulis* continues to expand. With an increase in CO_2 concentration, the suitable habitat of *Phyllostachys edulis* in the 2050s migrates towards the southeast direction, and in the 2070s, the suitable habitat of *Phyllostachys edulis* migrates northward. In the 2070s, the area of high-suitability areas based on the SSP585 scenario is the largest, and the increase in overall suitable areas is the greatest.

However, our research shows that with an increase in CO_2 content, the degree of forest fragmentation and aggregation in the highly suitable area of *Phyllostachys edulis* is significantly reduced. With the passage of time, under the SSP370 and SSP585 scenarios, cropland in high-suitability areas for *Phyllostachys edulis* is gradually fragmented. Research has found that during the decade from 2010 to 2020, the area of *Phyllostachys edulis* forests in China rapidly increased. However, this expansion led to an increase in the discontinuity of *Phyllostachys edulis* distribution and degradation of the overall *Phyllostachys edulis* landscape, manifested as a decrease in landscape connectivity and ecological value [63]. This agrees with the results of this research. *Phyllostachys edulis* has a powerful root system that can rapidly grow and invade surrounding forests through asexual reproduction, leading to continuous expansion of its area [64]. Therefore, the proportion of forest area in the *Phyllostachys edulis* landscape pattern continues to increase and the area of newly suitable habitat for bamboo in the forest is larger than the area of disappearing suitable habitat. In addition, the high nutrient output and low nutrient input of *Phyllostachys edulis* forests may lead to unsustainable long-term productivity levels [65,66]. This may cause the fragmentation of the highly suitable habitat landscape for *Phyllostachys edulis*, resulting in a decline in its landscape quality. However, it should be noted that the expansion of bamboo forests can also cause the loss of forest plant diversity [20]. Therefore, balancing the protection of biodiversity is a significant issue in the management of bamboo forests.

5. Conclusions

Phyllostachys edulis is one of the most significant forest resources with strong carbon sequestration ability, which can effectively mitigate climate change. This research used the adaptive distribution of an optimized MaxEnt model to predict influencing factors and the centroid shift of *Phyllostachys edulis* in China under three current and future scenarios (SSP126, SSP370, SSP585). Then, landscape indices were used to analyze the changes in its landscape pattern. The results indicate the following: (1) *Phyllostachys edulis* currently has potentially suitable habitats majorly distributed in East China, Southwest China, and Central South China. Precipitation is a key factor affecting the distribution of *Phyllostachys edulis*, with the precipitation of the driest month (BIO14) and precipitation seasonality (BIO15) being the two most critical factors affecting the current and future distribution of *Phyllostachys edulis*. (2) In the next three scenarios, the overall trend of *Phyllostachys edulis*′ suitable habitat is expanding. With an increase in CO_2 concentration, the suitable habitat of *Phyllostachys edulis* in the 2050s migrates towards the southeast direction, and in the 2070s, the suitable habitat of *Phyllostachys edulis* migrates northward. (3) In the future, the high-suitability areas of *Phyllostachys edulis* will become more fragmented and the overall landscape quality will decline. Among the land use areas suitable for *Phyllostachys edulis*, cropland and forests account for the largest proportion. With the passage of time, the proportion of forest area in the landscape pattern of highly suitable areas for *Phyllostachys edulis* continues to increase, and with an increase in CO_2 content, the degree of forest fragmentation in highly suitable areas for *Phyllostachys edulis* is significant. Over time, the cropland in *Phyllostachys edulis*′ high-suitability area under the SSP370 and SSP585 scenarios gradually becomes fragmented, leading to a decrease in the distribution of cropland. *Phyllostachys edulis* forests play a significant role in carbon sequestration and mitigating climate change. The results of this study provide theoretical support for future rational planning of *Phyllostachys edulis* and balanced biodiversity conservation. Therefore, further efforts should be made to curb the rampant expansion of *Phyllostachys edulis* forests in order to balance carbon storage and food security, as well as protect biodiversity.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15122231/s1, Figure S1: Delta.AICc of MaxEnt model under different parameter combinations generated by ENMeval and AUC result of MaxEnt modeling. Legend represents different categories of elements (L = linear, Q = quadratic, H = hinge, P = product and T = threshold); Figure S2: Fragmentation of *Phyllostachys edulis* land use landscape in different climate suitable areas (A1–A4, poorly suitable habitat; B1–B5, moderately suitable habitat; C1–C5, highly suitable habitat); Table S1: List of environmental variables used in the model development; Table S2: Direction and distance of centroid migration in the suitable habitat area of *Phyllostachys edulis*; Table S3: The area and changes in the suitable habitat for *Phyllostachys edulis* under different current and future scenarios.

Author Contributions: Conceptualization, H.Z.; methodology, H.Z.; software, P.L.; validation, H.Z., Y.Z. and Z.W.; formal analysis, P.L.; investigation, H.Z. and P.L.; resource, H.Z.; data curation, P.L.; writing—original draft preparation, H.Z. and P.L.; writing—review and editing, H.Z., P.L., Y.Z., Z.W. and Z.L.; visualization, P.L.; supervision, H.Z.; project administration, H.Z. and Z.L.; funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Water Pollution Control and Treatment Science and Technology Major Project (2017ZX07101) and the Discipline Construction Program of Huayong Zhang, Distinguished Professor of Shandong University, School of Life Sciences (61200082363001).

Data Availability Statement: All links to input data are reported in the manuscript and all output data are available upon request to the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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