

Article

Northward Expanding Variation of Neo-Chinese-Style Landscape Influenced by Bamboos in China Under Climate Change Based on MaxEnt Model

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Abstract: Bamboos, as imperative vegetations in Chinese traditional gardens, also significantly influenced the recently originated Neo-Chinese-style landscape in China, and their habitat ranges have been profoundly impacted by global climate warming. Current studies on the distribution dynamics of bamboo reveal existent gaps in assessing the suitable distribution area of Neo-Chinese-style landscapes. In this study, we calculated the habitat ranges of two widely distributed bamboo genera (*Phyllostachys* and *Bambusa*) based on the optimal MaxEnt model, predicted their future (2050s, 2070s and 2090s) distributions under different climate scenarios (SSP1-2.6 and SSP5-8.5), and assessed the suitable distribution area of the Neo-Chinese-style landscape according to the distribution union of two bamboo genera. The results showed that the optimal MaxEnt model exhibited high evaluation indices (AUC > 0.90) for the two bamboo genera. The habitat ranges of bamboo genera were significantly influenced by the minimum temperature of the coldest month and would expand northwardly in the future. The suitable distribution area of Neo-Chinese-style landscapes covered about 71.3% cities of China, which would expand 5.9%–8.7% of cities and 10%–18.7% of cities under the SSP1-2.6 climate scenario and the SSP5-8.5 climate scenario, respectively. The suitable distributions are mainly located in the southeast part of China. This study advanced our understanding of the restriction of bamboo to the distribution of the Neo-Chinese-style landscape and provided valuable insights and a scientific basis for landscape construction in different areas of China.

Keywords: Neo-Chinese-style landscape; bamboo; MaxEnt model; potential distributions; landscape construction



Academic Editor: Mark Vanderwel

Received: 20 January 2025

Revised: 22 February 2025

Accepted: 25 February 2025

Published: 26 February 2025

Citation: Zhao, Y.; Liu, J.; Zhang, Z.; Zhao, Y.; Cui, D.; Zhou, Y.; Fan, L.

Northward Expanding Variation of Neo-Chinese-Style Landscape Influenced by Bamboos in China Under Climate Change Based on MaxEnt Model. *Forests* **2025**, *16*, 428. <https://doi.org/10.3390/f16030428>

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1. Introduction

Global climate warming has profoundly impacted vegetation distributions [1–4], including many bamboo species [3,5–8]. As an important vegetation resource in China, the bamboos had abundant species and exerted enormous ecological, economic and social benefits [9,10]. In addition, the bamboos were also considered to be an ideal vegetation material in landscapes for the unique morphology and rich cultural connotation, and they have been preferred in the world-famous Chinese traditional gardens [11]. Owing to the abundant

vegetation resources, the traditional Chinese gardens enjoyed a high status in the world and perpetually aimed to pursue a natural spiritual realm [12]. The application of bamboos played an irreplaceable role in enhancing the cultural connotation and enriching the spiritual conception of the traditional Chinese gardens [13,14]. However, the ideal vegetation material of bamboo has only been planted in some southern areas of China for the limitation of their natural distributions influenced by climate and environment [15,16]. Recently, the Neo-Chinese-style landscape originated under the impetus of political, economic, and social factors and has become increasingly popular in recent years [9,10,17]. As the cultural inheritance and evolutionary form of Chinese traditional gardens, the Neo-Chinese-style landscape should pay attention to the application of bamboos [11,18]. Additionally, the vegetation applications in the current landscape usually emphasize ecological function and obey the natural distribution of species [19]. As a result, the distribution range of bamboo is a crucial factor for assessing the suitable distribution area of a Neo-Chinese-style landscape, and the distribution dynamics influenced by climate change were significantly related to the construction of Neo-Chinese-style landscapes in China.

The construction of the Neo-Chinese-style landscape was carried out in multiple places throughout the country, including residential districts, urban squares, rural landscapes, and so on [10,20]. These commonly seen Neo-Chinese-style landscapes were constructed based on human subjective preferences and broke geographical restrictions, which also displayed inconformity to the concept of respecting nature in the current landscape [19]. The extensive inclination of landscape style both hindered the development of the regional landscape and partially lost artistic conceptions in some areas [21], such as Northern China, owing to the limitation of bamboo distribution. Consequently, the appropriate distribution area of the Neo-Chinese-style landscape restricted by bamboos needs to be assessed, and the results could provide references for decision makers in selecting landscape styles in different regions. However, studies on the Neo-Chinese-style landscape were infrequent and mainly focused on the origins and development [9,10,22], artistic value [10,23], element application [10,24–26], or case analysis [27–29], which neglected evaluating the importance of bamboos. On the one hand, China possessed the richest bamboo resources in the world [30,31], and the species diversity and spatial distribution complexity increased the difficulty in studying their correlations with landscape styles. On the other hand, climate warming and human intervention have induced habitat range shifts in many species [1–4], which compelled studies to not only assess the current distributions of bamboos and their influences on the Neo-Chinese-style landscape but also predict their potential distribution dynamics in the future.

The species distribution models (SDMs) have been widely applied in assessing the impacts of climate changes on species distribution [32,33], such as the generalized linear mixed model (GLMM) [34], Genetic Algorithm for Rule-Set Prediction model (GARP) [35], the maximum entropy model (MaxEnt) [35,36], and so on. The MaxEnt, among the SDMs, has been widely favored by researchers for its user-friendly interface and stable predictions and increasingly applied to accurately assess and predict species distribution dynamics based on climatic and environmental factors [37–40], even for the species with limited occurrence records [41]. Previous studies have assessed and predicted the distribution dynamics of bamboo species under climate change, and most studies have found a northward expansion of bamboo species in China [3,5–8]. The northward expansions of bamboo species provided the vegetation supports for the constructions of the Neo-Chinese-style landscape in some northern regions of China. While these studies mainly detected the distribution dynamics of bamboo on a species level, the monospecific habitat range could not favor assessing the suitable distribution area of Neo-Chinese-style landscapes. Thus,

we focused on assessing the habitat range of bamboo on the genus level in order to cover the whole distribution area of bamboos in China.

In this study, two widely distributed bamboo genera, *Phyllostachys* and *Bambusa*, with habitat ranges covering the distribution areas of all bamboo genera in China [30,31], were used as representative materials to assess the current and future distribution of the Neo-Chinese-style landscape restricted by bamboos in China. We employed the widely used MaxEnt model to assess and predict the habitat range of above two bamboo genera. Our study aims to crystallize the following objectives: (1) identify the crucial climatic factors driving the habitats of *Phyllostachys* and *Bambusa* in China; (2) assess the currently appropriate distribution area of the Neo-Chinese-style landscape restricted by the above two bamboo genera in China; and (3) predict the potential areas of the Neo-Chinese-style landscape under different climate scenarios in the future. We hope our study compensates for the gap in appropriate area evaluations of the Neo-Chinese-style landscape restricted by bamboos, and the results are expected to provide valuable insights and a scientific basis for landscape construction in different areas of China.

2. Materials and Methods

2.1. Data Collection of Species Distribution

We compiled the occurrence records of *Phyllostachys* and *Bambusa* in China from published papers (CNKI, <https://www.cnki.net/> (accessed on 5–11 August 2024)) and the following reputable sources, including Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/> (accessed on 12 August 2024)), Plant Science Data Center (<https://www.plantplus.cn/cn> (accessed on 15 August 2024)), and the China Virtual Herbarium (CVH, <https://www.cvh.ac.cn/> (accessed on 15 August 2024)). In order to compile a comprehensive dataset on species distribution, we collected the initial records for *Phyllostachys* and *Bambusa*, which spanned from 1950 to 2023 and were filtered by several preprocessing steps to enhance the data quality. We removed records with unclear geographical information and eliminated duplicate samples from identical locations to mitigate any inaccuracies. Additionally, using a sparsification technique, we retained a single record in each grid cell (5 km × 5 km) to eliminate spatial autocorrelation. Eventually, 505 and 261 occurrence records were retained for *Phyllostachys* and *Bambusa*, respectively (Figure 1).

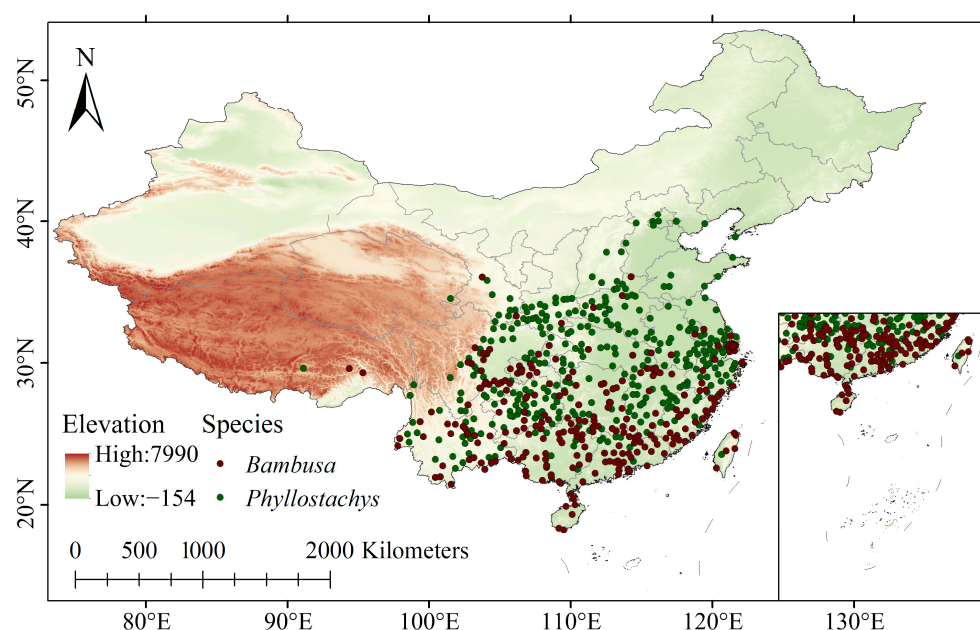


Figure 1. Occurrence records of *Phyllostachys* and *Bambusa* in China.

2.2. Environmental Variables

In this study, we employed a comprehensive set of 37 variables for assessing the habitat ranges of two bamboo genera, including 19 climate variables, 15 soil variables and 3 topography variables. The original 19 climate variables, covering the present (1970–2000) and future (2050s, 2070s and 2090s), were derived from the WorldClim database (<https://worldclim.org/> (accessed on 23 September 2024)), with a spatial resolution of 2.5° (5 km × 5 km) (Table 1). The future climate projections were employed based on the widely used climate model BCC-CSM2-MR (Beijing Climate Center-Climate System Model version 2-Medium Resolution) under the Coupled Model Intercomparison Project Phase 6 (CMIP6). The model provided future climate projections under four Shared Socio-economic Pathways (SSPs). We selected two representative Socio-economic Pathways for our analysis, including a high CO₂ emission scenario (SSP5-8.5) and a low CO₂ emission scenario (SSP1-2.6). Time spans of 2041–2060 (2050s), 2061–2080 (2070s) and 2081–2100 (2090s) were employed as the prediction periods. In order to avoid an overfitting in the model, we utilized an ENM Tools software (version 5.26) to mitigate the potential multicollinearity and autocorrelation among the 19 climate variables by excluding variables with correlations over 0.8. Eventually, 8 climate variables (bio2, bio3, bio5, bio6, bio7, bio12, bio 15 and bio19) were retained for *Phyllostachys*, and 9 climate variables (bio2, bio3, bio4, bio6, bio10, bio12, bio15, bio18 and bio19) for *Bambusa*.

Table 1. Climatic variables required for the assessment of *Phyllostachys* and *Bambusa* habitat ranges.

Abbreviation	Variable Description	Unit
Bio1	Annual mean temperature	°C
Bio2	Mean diurnal range (mean of monthly (max temp–min temp))	°C
Bio3	Isothermality (Bio2/Bio7) (×100)	/
Bio4	Temperature seasonality (standard deviation × 100)	/
Bio5	Max temperature of warmest month	°C
Bio6	Min temperature of coldest month	°C
Bio7	Temperature annual range (Bio5–Bio6)	°C
Bio8	Mean temperature of wettest quarter	°C
Bio9	Mean temperature of driest quarter	°C
Bio10	Mean temperature of warmest quarter	°C
Bio11	Mean temperature of coldest quarter	°C
Bio12	Annual precipitation	mm
Bio13	Precipitation of wettest month	mm
Bio14	Precipitation of driest month	mm
Bio15	Precipitation seasonality (coefficient of variation)	/
Bio16	Precipitation of wettest quarter	mm
Bio17	Precipitation of driest quarter	mm
Bio18	Precipitation of warmest quarter	mm
Bio19	Precipitation of coldest quarter	mm
AWC	AWC range	/
S_gravel	Soil gravel content	%vol
S_sand	Soil sand fraction	%weight
S_silt	Soil silt fraction	%weight
S_clay	Soil clay fraction	%weight
S_usda_tex_class	Soil USDA texture classification	/
S_bulk_density	Soil bulk density	kg/dm ³
S_oc	Soil organic carbon	%weight
S_ph_h2o	Soil pH (H ₂ O)	–log(H ⁺)

Table 1. Cont.

Abbreviation	Variable Description	Unit
S_cec_clay	Soil CEC (clay)	cmol/kg
S_cec_soil	Soil CEC (soil)	cmol/kg
S_Caco ₃	Subsoil calcium carbonate	%weight
S_Caso ₄	Subsoil gypsum	%weight
S_esp	Soil sodicity (ESP)	%
S_ece	Subsoil salinity	Ds/m
Ele	Elevation	m
Asp	Aspect	/
Slp	Slope	°

The soil variables were obtained from the Food and Agriculture Organization of the United Nations (FAO, <https://www.fao.org/> (accessed on 29 September 2024)) with a resolution of 1 km × 1 km. The elevation data were downloaded from the Geospatial data cloud (<http://www.gscloud.cn> (accessed on 10 October 2024)) with a resolution of 90 m × 90 m, and the aspect and slope data were derived from the elevation data by the ArcGIS 10.4 software. In addition, the soil variables and topography variables were resampled to a 5 km × 5 km resolution to ensure the consistency with the climate data format that was required by the MaxEnt model.

2.3. Model Optimization and Assessment

In this study, the MaxEnt model [36] (Version 3.4.4) was employed to assess and predict the habitat ranges of *Phyllostachys* and *Bambusa* in China. For each bamboo genus, the occurrence records were randomly divided into two groups: with 75% for the training set and 25% for validating the MaxEnt model. Additionally, 10 repetitions were performed to validate the robustness of the model. The originally obtained climate data were converted to an “asc” format recognized by the MaxEnt software through the “SDMtoolbox” in ArcGIS 10.4 software.

In order to improve the model accuracy, the ENMeval R package (version 4.2.2) [42] was performed to mitigate the risk of overfitting or underfitting. The package identified optimal parameters by different combinations of regularization multiplier (RM) values from 0.5 to 3 with an increment of 0.5 and 10 feature classes (i.e., LQ, LH, LP, LQH, LQP, LQPT, QHP, QPT, HPT and LQHPT; where L = Linear, Q = Quadratic, H = Hinge, P = Product and T = threshold). The ENMeval R package tested above parameter combinations and identified the optimal combination based on the highest test AUC scores (i.e., the area under the receiver-operating characteristic (ROC) curve) [43]. The AUC scores ranged from 0 to 1 and can be divided into <0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9 and >0.9, respectively, indicating model fitting failure, poor, fair, good, and excellent [44]. The value of the Akaike information criterion correction (AICc) was used to evaluate the fitting results of different parameter combinations, and the minimum value, that is, AICc = 0, indicated the optimal combination. Additionally, the Jackknife-cut method was used to evaluate the importance of each climatic variable in the model. Finally, we constructed response curves for the key predictor variables to illustrate the relationship between the climatic variables and species occurrence probabilities.

2.4. Suitable Area Classification and Statistics

The outputs of the MaxEnt model were used to evaluate the suitable area of the two bamboo genera and the Neo-Chinese-style landscape in China using ArcGIS 10.4 software, and the process included format conversion, reclassification, and area statistics. The current and future potential habitat ranges of two bamboo genera were grouped into four suitability levels, which were delineated by the occurrence as follows: unsuitable (probability < 0.2), low suitability (0.2–0.4), middle suitability (0.4–0.6), and high suitability (probability > 0.6) [8,45]. We assessed the distribution of the Neo-Chinese-style landscape based on the habitat ranges of *Phyllostachys* and *Bambusa* and followed the maximization principle, that is, assessing the degree of suitability based on the greater occurrence probability of two bamboo genera in the overlapped area. Then, the distributions of the Neo-Chinese-style landscape were delineated as follows: unsuitable: the occurrence probability of both bamboo genera is lower than 0.2; low suitability: the occurrence probability of either bamboo genus ranged from 0.2 to 0.4; middle suitability: the occurrence probability of either bamboo genus ranged from 0.4 to 0.6; and high suitability: the occurrence probability of either bamboo genus is higher than 0.6.

Based on the current and future distribution maps, the dynamic variations in the Neo-Chinese-style landscape were categorized as remaining unsuitable, distribution contracted, unchanged, or expanded. Then, future spatial variations in the Neo-Chinese-style landscape were predicted and calculated. In addition, we compared the distributions of Neo-Chinese-style landscape and 289 cities (including prefecture-level city and capital city) in China, and we counted the number of cities covered by the current and future Neo-Chinese-style landscape.

3. Results

3.1. Model Evaluation

We identified the optimal MaxEnt model for *Phyllostachys* was the combination of PTH feature and regularization multiplier (RM) of 0.5. For *Bambusa*, the optimal model was the LQPT feature combination, with an RM of 0.5. The AICc values for *Phyllostachys* and *Bambusa* in the optimal MaxEnt model were zero. The mean test AUC values of the optimal model for *Phyllostachys* and *Bambusa* were 0.957 and 0.980, respectively, which exceeded the default values (0.925 for *Phyllostachys* and 0.953 for *Bambusa*) (Table 2), indicating that the optimal MaxEnt model performed with excellent predictive accuracy for the above two bamboo genera.

Table 2. Comparison of test AUC values between default and optimal MaxEnt model for *Phyllostachys* and *Bambusa*.

Type	FC	RM	Test AUC
Default parameter of <i>Phyllostachys</i>	LQPHT	1	0.925
Optimal parameter of <i>Phyllostachys</i>	PTH	0.5	0.957
Default parameter of <i>Bambusa</i>	LQPHT	1	0.953
Optimal parameter of <i>Bambusa</i>	LQPT	0.5	0.980

3.2. Identification of Key Environmental Factors

We exhibited contribution proportions of the top 10 environmental variables influencing the habitat ranges of *Phyllostachys* and *Bambusa*, with cumulative proportion contributions exceeding 85%, and their permutation importance tested by the Jackknife-cut method was also exhibited (Figure 2). The MaxEnt results showed that climate variables influenced the habitat ranges of *Phyllostachys* and *Bambusa* more significantly than the topography variables and soil variables, and the min temperature of the coldest month (bio6) exhibited

the highest percent contribution for *Phyllostachys* and *Bambusa*, with percent contributions of 63% and 62.6%, respectively (Figure 2a,c). Specifically, for *Phyllostachys*, the other three variables with relatively high percent contributions were the temperature annual range (bio7), elevation, and annual precipitation (bio12) (Figure 2a). For *Bambusa*, the annual precipitation (bio12), temperature seasonality (bio4), and precipitation of the coldest quarter (bio19) were important variables following the min temperature of the coldest month (bio6) (Figure 2c). We also assessed the importance of the environmental variables for the habitat ranges of the two bamboo genera by the Jackknife-cut method, and the min temperature of the coldest month (bio6) still occupied the most importance percent, with importance values of 29.9% and 50.3% (Figure 2b,d). The other three important variables for *Phyllostachys* were the temperature annual range (bio7), annual precipitation (bio12) and elevation, with importance values of 15.8%, 15.7% and 14.8%, respectively (Figure 2b). For *Bambusa*, the other three important variables were the temperature seasonality (bio4), elevation, and precipitation of the coldest quarter (bio19), with importance values of 9.3%, 6.4% and 5.1%, respectively (Figure 2d).

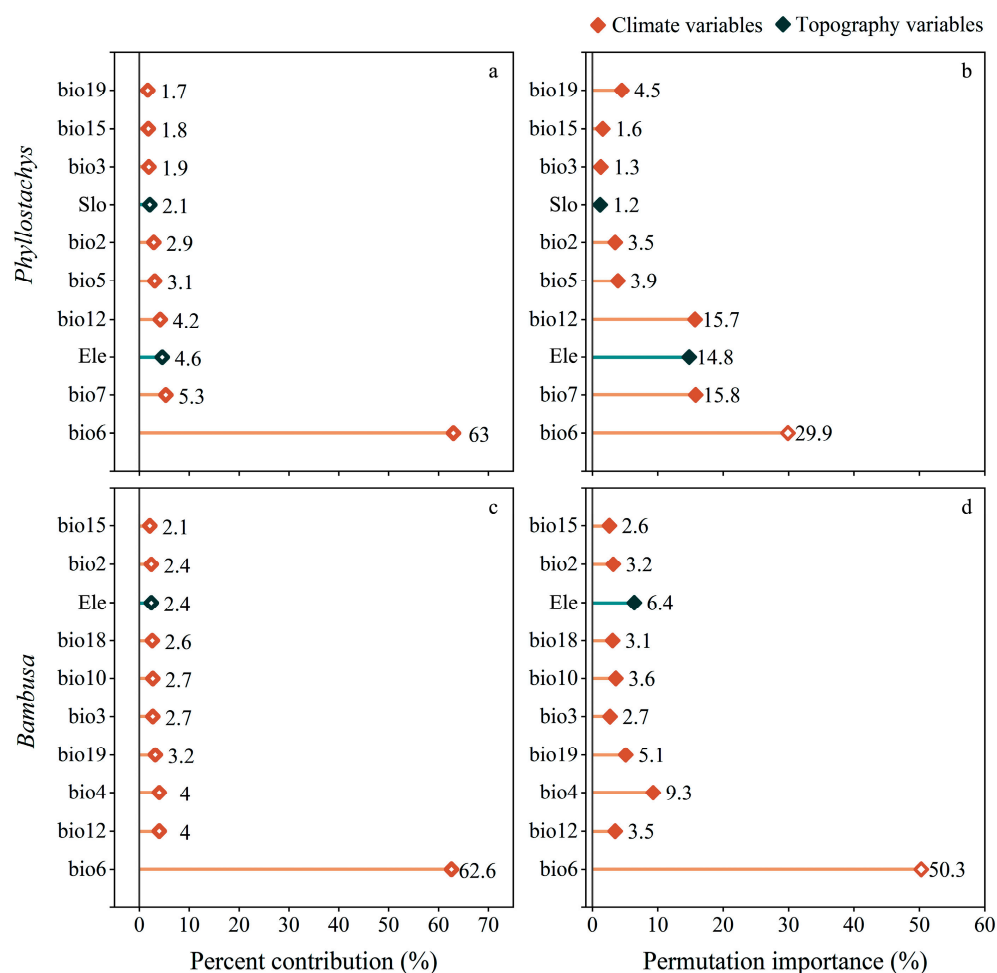


Figure 2. Percent contribution based on MaxEnt (a,c) and permutation importance tested by the Jackknife-cut method (b,d) of environmental variables for *Phyllostachys* (a,b) and *Bambusa* (c,d). Orange and grayish-green indicate the climate variables and topography variables, respectively.

To visually understand the impact of each crucial climate variable on the habitat ranges of *Phyllostachys* and *Bambusa*, we graphed the response curves for the crucial variables identified by percent contribution and the Jackknife-cut method (Figure 3). The occurrence probability of *Phyllostachys* showed a single-peak relationship with the min temperature of the coldest month (bio6), temperature annual range (bio7), and annual precipitation

(bio12) but showed a negative correlation with elevation, and *Phyllostachys* distributed with the min temperature of the coldest month ranged about -6 – 13 °C. For *Bambusa*, the occurrence probability showed positive correlations with the min temperature of the coldest month (bio6) and the precipitation of the coldest quarter (bio19), a single-peak relationship with annual precipitation (bio12), but exhibited negative correlations with temperature seasonality (bio4) and elevation. The lowest min temperature of the coldest month for *Bambusa* distribution was about -1 °C.

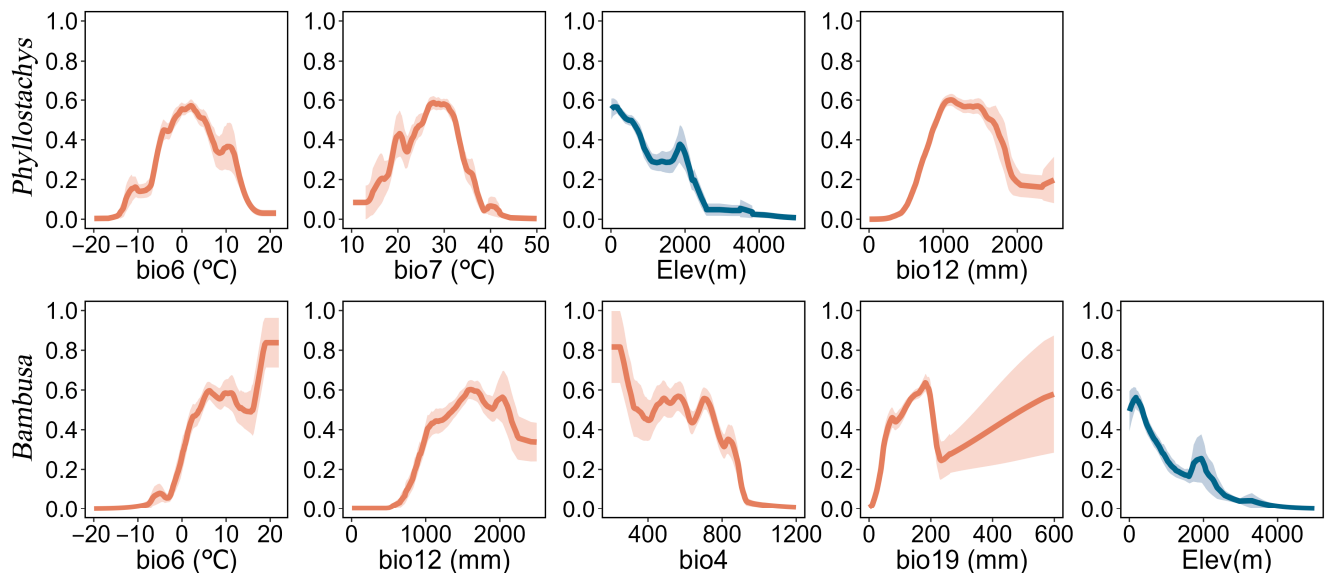


Figure 3. Response curves for crucial variables in predicting the species habitat ranges of *Phyllostachys* (top) and *Bambusa* (bottom). The horizontal and vertical coordinate represents the magnitude of variables and the occurrence probability, respectively. The colored shadow indicates the standard deviation in each subplot. Orange and blue indicate the climate variables and topography variables, respectively.

3.3. Distributions Under Current Climate

The current habitat ranges of two bamboo genera based on the MaxEnt evaluation were mainly distributed in central and Southern China, and *Phyllostachys* was more widely distributed than that of *Bambusa*, encompassing an area of approximately 255×10^4 km² and 167×10^4 km², respectively (Figure 4 and Table S1). Specifically, the highly and middle suitable area for *Phyllostachys* was approximately 49×10^4 km² and 132×10^4 km², respectively, which were predominantly distributed in the Yangtze River basin, and the low suitable area was about 75×10^4 km², with the northern boundaries of Hebei and Liaoning provinces and the western boundary of Xizang province (Figure 4a and Table S1). The *Bambusa* was predominantly distributed in the southern region of China, with a highly suitable area of 14×10^4 km² mainly in the eastern region of Sichuan province and the southern coastal provinces and identical middle and low suitable areas of 76×10^4 km² (Figure 4b and Table S1).

We outlined the suitable distribution area of the Neo-Chinese-style landscape based on the habitat ranges of *Phyllostachys* and *Bambusa* (Figure 5 and Table S1). The currently suitable distribution area of Neo-Chinese-style landscapes encompassed an area of approximately 263×10^4 km² (Table S1), and covered about 71.3% (206/289) cities of China, which comprised most provinces except Xinjiang, Qinghai, Inner Mongolia, Jilin and Heilongjiang provinces (Figure 5). The highly and middle suitable areas dominated in the Yangtze River basin and its southern region, encompassing an area of approximately 62×10^4 km² and 138×10^4 km², respectively (Figure 5 and Table S1). The low suitable area encompassed

an area of approximately $63 \times 10^4 \text{ km}^2$, with the northern boundary close to the 40° N latitude, such as Peking City and the southern part of Liaoning Province, and the western boundary near the 92° E longitude in Xizang province (Figure 5 and Table S1).

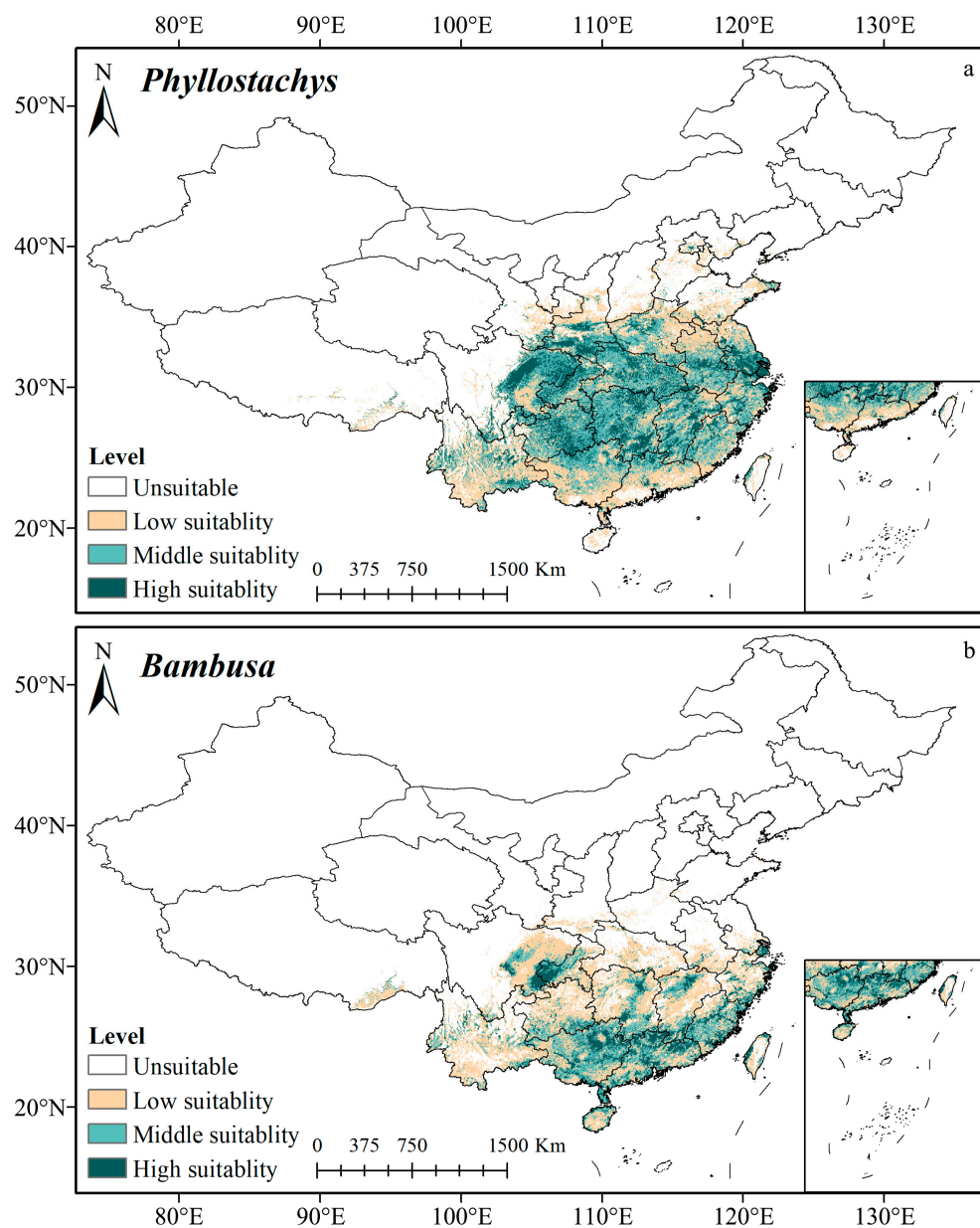


Figure 4. Current habitat ranges of *Phyllostachys* (a) and *Bambusa* (b) in China. Colors in legend represent the occurrence probability, where unsuitable: probability < 0.2 , low suitability: $0.2\text{--}0.4$, middle suitability: $0.4\text{--}0.6$, and high suitability: probability > 0.6 .

3.4. Distributions and Shifting Patterns Under Future Climate Scenarios

The habitat ranges of two bamboo genera under future climate scenarios would expand to the north and west compared with the current ones, and the details are shown in Table S1. The shifting patterns were similar in 2050s, 2070s and 2090s, but the expansion ranges were more evident under high CO_2 emission scenarios (SSP5-8.5) than that under low CO_2 emission scenarios (SSP1-2.6) (Figures 6 and S1 and Table S1), indicating a significant influence of CO_2 emission on the distributions of two bamboo genera. Especially under a high CO_2 emission scenario in 2090s, the suitable distribution area of *Phyllostachys* and *Bambusa* would, respectively, reach $358 \times 10^4 \text{ km}^2$ and $257 \times 10^4 \text{ km}^2$, with the most

significant expansion. Some northern parts of China, such as Liaoning, eastern Inner Mongolia, and western Jilin and Heilongjiang provinces, were expected to be the suitable distribution area for *Phyllostachys* (Figure S1 and Table S1). Specially, the highly suitable areas for *Phyllostachys* were projected to expand and become centralized under all future climate scenarios compared with the currently scattered habitats, which would expand significantly to the north for *Bambusa* (Figures 6 and S1, and Table S1).

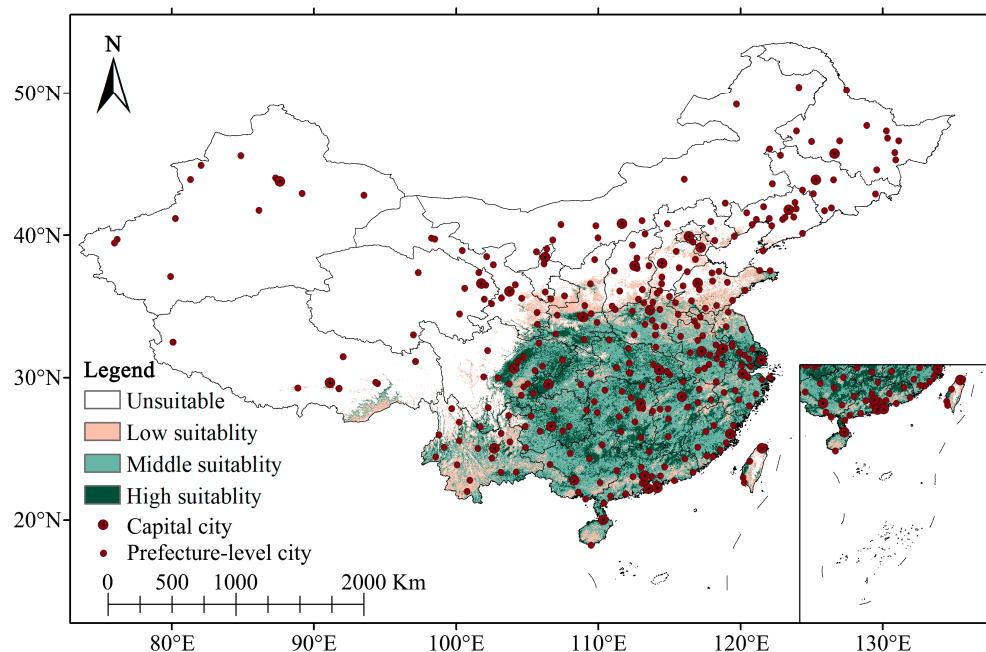


Figure 5. Current distribution area of the Neo-Chinese-style landscape influenced by the habitat ranges of *Phyllostachys* and *Bambusa* in China. Colors in legend represent the degree of suitability, where unsuitable indicates that the occurrence probability of both bamboo genera is lower than 0.2, low suitability: the occurrence probability of either bamboo genus ranged from 0.2 to 0.4, middle suitability: the occurrence probability of either bamboo genus ranged from 0.4 to 0.6, and high suitability indicates that the occurrence probability of either bamboo genus is higher than 0.6. Red dots indicate cities in China.

The suitable distribution area of the Neo-Chinese-style landscape outlined by the two bamboo genera was projected to expand, which would reach $286 \times 10^4 \text{ km}^2$ (SSP1-2.6 in 2070s) to $387 \times 10^4 \text{ km}^2$ (SSP5-8.5 in 2090s), and covered 77.1% (223/289)–85.8% (260/289) cities of China. The highly suitable areas would increase significantly under all future climate scenarios (Figure 7 and Table S1). The spatiotemporal dynamics of suitable distribution area on the Neo-Chinese-style landscape would be similar—an evidently expanded trend to the north under all future climate scenarios (Figure 8). Under low CO_2 emission scenarios, the expansion area would increase $23 \times 10^4 \text{ km}^2$ (2070s) to $35 \times 10^4 \text{ km}^2$ (2090s), which covers 5.9% (17/289)–8.7% (25/289) cities of China, including Gansu, Ningxia, Shaanxi, Shanxi, Hebei, Shandong, and Liaoning provinces (Figure 8a,c,e). Under high CO_2 emission scenarios, the future suitable distribution area of the Neo-Chinese-style landscape would almost extend to all provinces in China. The expansion areas would range from $48 \times 10^4 \text{ km}^2$ in 2050s to $124 \times 10^4 \text{ km}^2$ in 2090s and cover 10% (29/289)–18.7% (54/289) of cities of China, but the potential distributions would still mainly be located in the southeastern part of China (Figure 8b,d,f). The exploration of the above expansion areas indicated a crucial region for the bamboo introduction and cultivation and would provide valuable insights and a scientific basis for landscape construction according to different CO_2 emission scenarios.

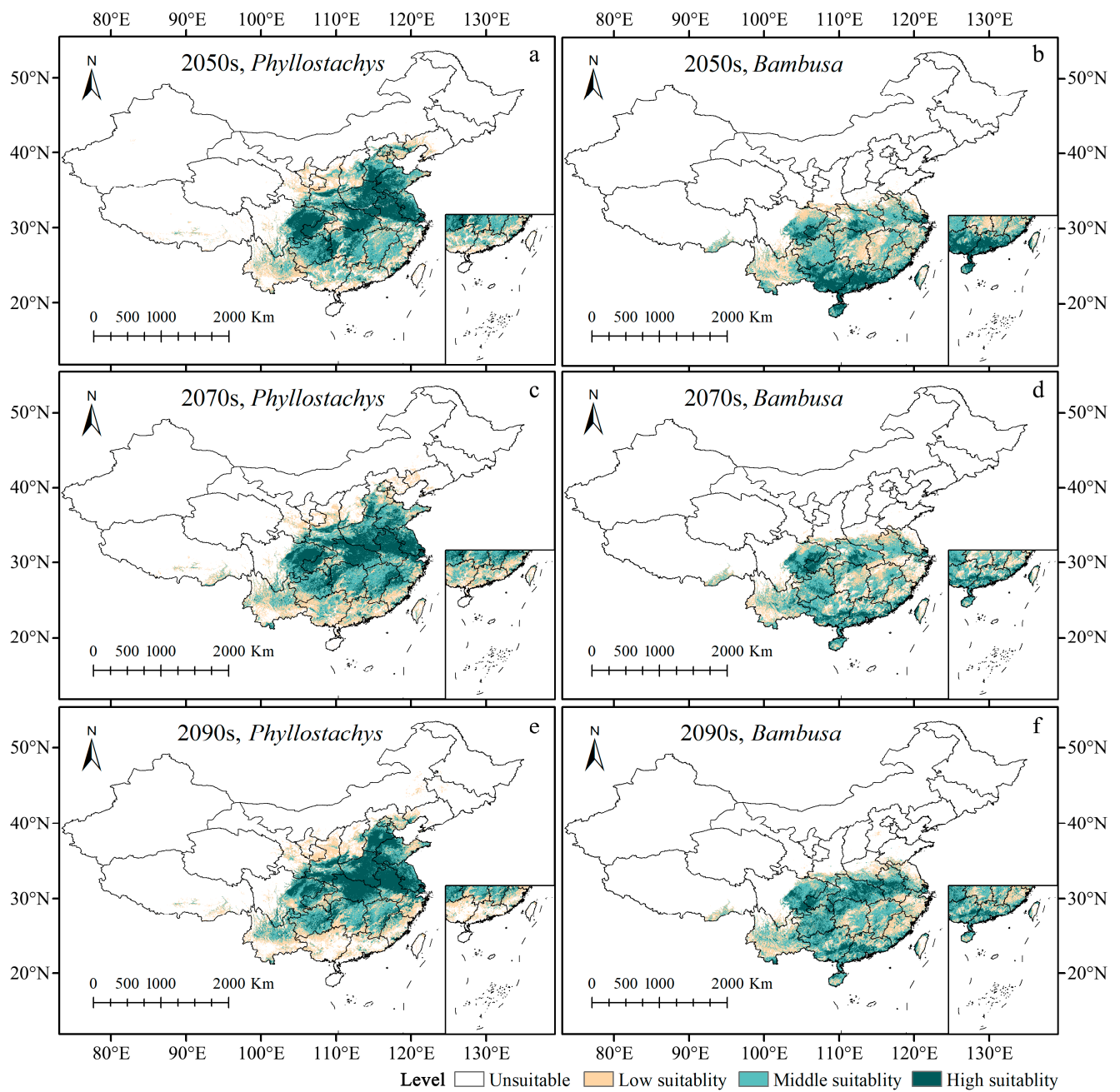


Figure 6. Potential habitat ranges of *Phyllostachys* (a,c,e) and *Bambusa* (b,d,f) in China with future predictions of 2050s, 2070s and 2090s under SSP1-2.6 scenario. Colors in legend represent the occurrence probability, which are consistent with Figure 4.

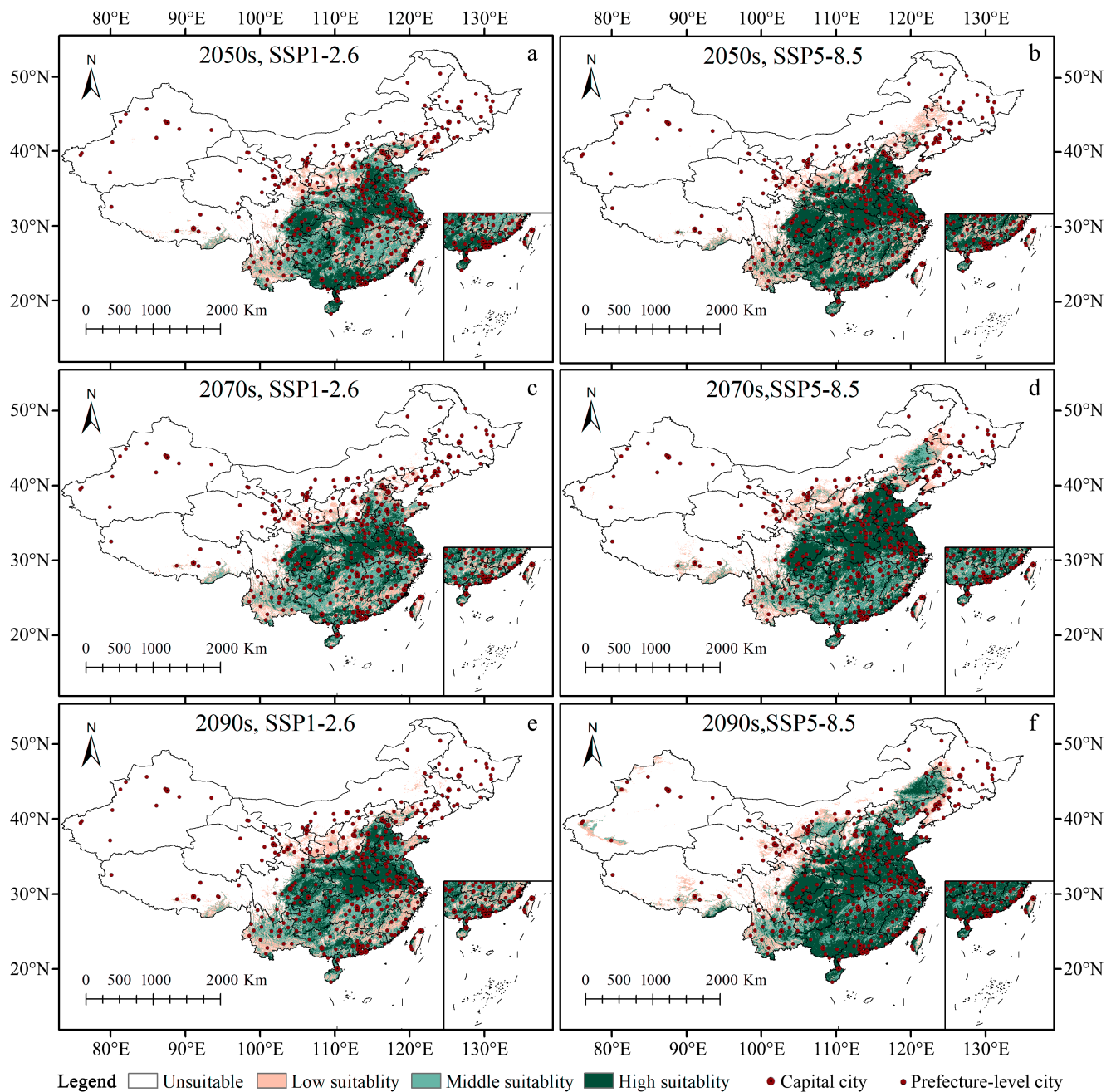


Figure 7. Potential distribution area of the Neo-Chinese-style landscape restricted by the habitat ranges of *Phyllostachys* and *Bambusa* in China with future predictions of 2050s (a,b), 2070s (c,d), and 2090s (e,f) under an SSP1-2.6 scenario (a,c,e) and SSP5-8.5 scenario (b,d,f). Red dots indicate cities in China, and colors in legend represent the degree of suitability, which are consistent with Figure 5.

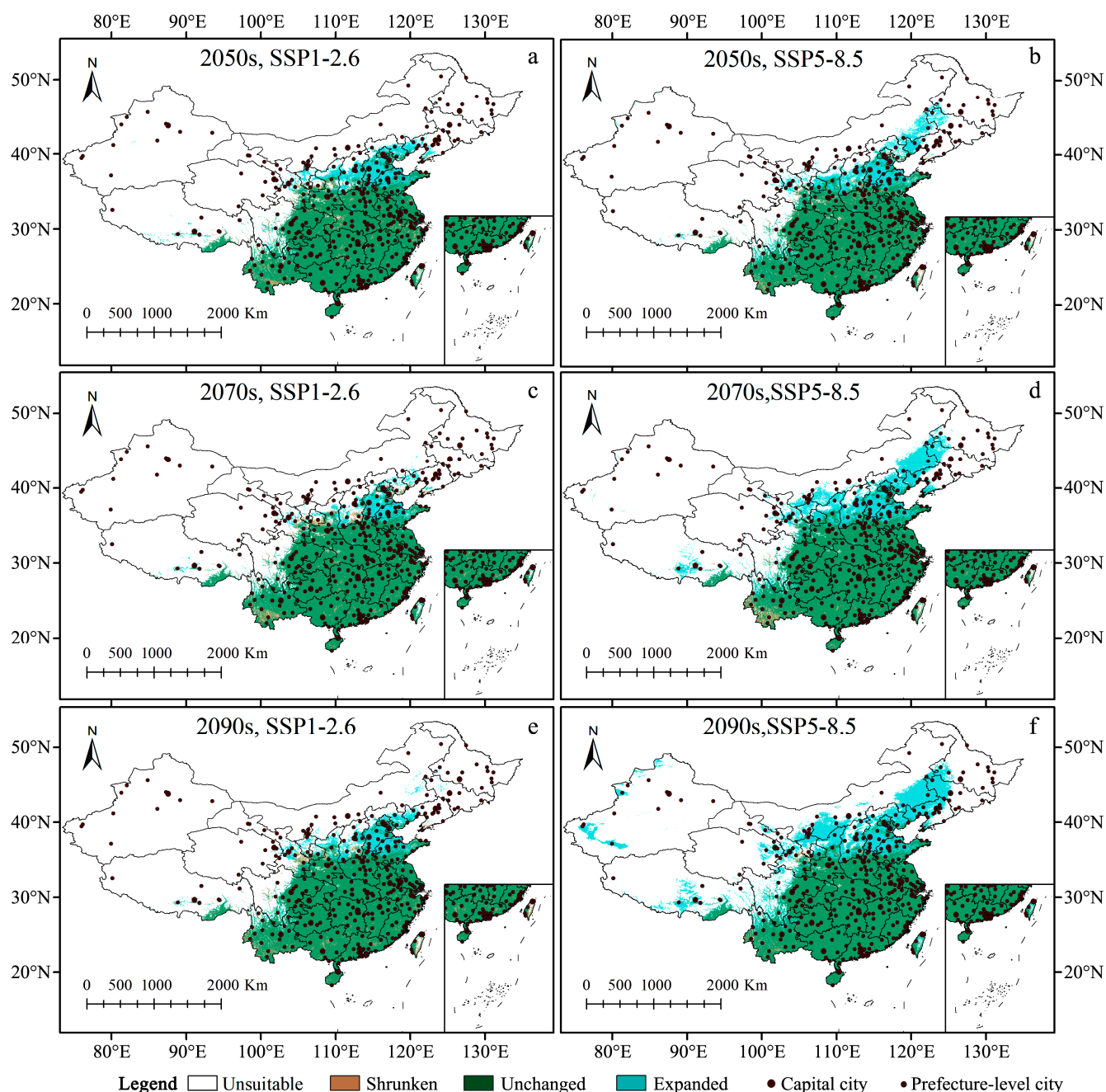


Figure 8. Distribution of dynamic variations in the Neo-Chinese-style landscape restricted by the habitat ranges of *Phyllostachys* and *Bambusa* in China with future predictions of 2050s (a,b), 2070s (c,d), and 2090s (e,f) under an SSP1-2.6 scenario (a,c,e) and SSP5-8.5 scenario (b,d,f). Colors in legend represent the potential dynamics, including the remaining unsuitable, distribution-shrunken, unchanged or expanded. Red dots indicate cities in China.

4. Discussion

4.1. Method Assessment

The MaxEnt model, among a series of species distribution models (SDMs), has been identified to predict species distribution independently and increasingly applied under global climate warming [8,38,45,46]. In this study, we employed the optimal MaxEnt model to evaluate and predict the habitat ranges of two representative bamboo genera (*Phyllostachys* and *Bambusa*). Besides the climate variables, soil variables and topography variables were also performed in the MaxEnt model, as more environmental variables

can enhance model predictions [47]. Also, we might explore more factors affecting the distribution of the two bamboo genera. Some climate variables with significant correlation coefficients were excluded to prevent an overfitting [47]. Our results revealed excellent model performances, as the output test AUC values for *Phyllostachys* and *Bambusa* exceeded 0.9, indicating high predictive accuracy and the feasibility in evaluating the habitat ranges of the above two bamboo genera. In addition, the feasibility of the MaxEnt model in predicting bamboo distribution dynamic has also been tested by its actual distribution dynamics. For example, the northward migration of bamboo predicted in earlier studies has been successfully achieved in some regions in China, including Shandong and Liaoning provinces, according to our investigation [48].

For the selection of climate data, the BCC-CSM2-MR climate model developed by the Beijing Climate Center Climate System Model has been identified to have a better ability to simulate Chinese climate events [49] and was widely used in the analysis of species distribution dynamics [5,45,46], so we employed it in assessing the habitat ranges of two bamboo genera in this study. Of course, predicting the future distributions of two bamboo genera based on the single model is insufficient, and we will provide more refined species distributions based on more climate models.

4.2. Crucial Factors and Distribution Variation

We identified the crucial climate variables influencing the habitat ranges of two bamboo genera based on percent contribution and the Jackknife-cut method and found that climate variables exert a greater influence on the habitat ranges of two bamboo genera than that of topography variables and soil variables (Figure 2). The min temperature of the coldest month (bio6) exerted an overwhelming influence in driving the habitat ranges of two bamboos, which was consistent with a previous study showing that temperature dominated the distribution of bamboo [50]. The min temperature of the coldest month showed different relationships with two bamboo genera, which might be related to their divergent distribution. As the most widely distributed bamboo genus in China [31], the *Phyllostachys* distributed in the regions with the min temperature of the coldest month ranged about -6 – 13 °C, which would be damaged by freezing when the extreme low temperature is lower than -20 °C [51]. Thus, the min temperature of the coldest month of -6 °C in our study is significantly correlated to its northern boundary and is also an important indicator for the introduction and cultivation of bamboos in Northern China. For *Bambusa*, the lowest min temperature of the coldest month for its distribution was about -1 °C, as the *Bambusa* was distributed in the southern region of China and adapted to the high temperature environment [31], which compelled the low temperature to become the main factor limiting its distribution. As a result, the habitat range of *Bambusa* would expand to the north under climate warming. Generally, the climate factors dominated the distributions of bamboos more significantly than that of soil factors and topography factors, which was consistent with previous studies [6,8,50,52]. While the assessment based on the genus level was rougher than that at species level, and our results only provided a scientific basis for the introduction and cultivation of bamboo in Northern China, especially for *Phyllostachys*.

China has the richest bamboo resources and longest history of bamboo cultivation in the world, but the bamboo is mainly distributed in the Yangtze River basin and its southern region [31], which has resulted in an unequal sharing of bamboo resources. Exploring the potential distributions of bamboo had great significance for the northern area without bamboo resources. In this study, we assessed and predicted the habitat ranges of *Phyllostachys* and *Bambusa* in China (Figures 4, 6 and S1 and Table S1), and the northward bamboo distributions are supported by previous studies [3,8]. We selected *Phyllostachys*

and *Bambusa* as representative bamboo genera for their wide distributions, and the union of their habitat ranges could cover all the bamboo distributions in China [31]. As the potential habitat ranges of *Bambusa* would still distribute in Southern China with abundant bamboo resources, we pay more attention to the influencing factors on *Phyllostachys* with significant extensions to the north of China. The habitat range union of two bamboo genera outlined an appropriate distribution area of Neo-Chinese-style landscapes (Figure 5), which approximately aligns with the characteristics of bamboo resource distribution [31]. For example, the highly and middle suitable areas dominated in the Yangtze River basin and its southern region, where most bamboo species grew [31] and were most suitable for a Neo-Chinese-style landscape. The appropriate distribution boundary of Neo-Chinese-style landscapes also aligns with our investigations in Peking City and Dalian city (the south of Liaoning Province). Furthermore, we explored significant expansions to the north and west in habitat ranges of two bamboo genera (Figures 6 and S1), which was similar to previous studies about the bamboo dynamic at species level (*Phyllostachys edulis*) [3,8]. The habitat variations reoutlined a greater distribution of Neo-Chinese-style landscapes in the future, with similar expansion directions (north and west) but different expansion ranges under high (SSP5-8.5) and low (SSP1-2.6) CO₂ emission scenarios (Figure 7). These expansion areas would cover 10% (29/289)–18.7% (54/289) of cities in China, but the potential distribution area would still mainly be located in the southeast part of China (Figure 8). Even under high CO₂ emission scenarios (SSP5-8.5) in the 2090s with the greatest expansion, the appropriate distributions of Neo-Chinese-style landscapes would be scarce in the northwest part. Fortunately, the potential distributions would be similar to the population distribution in China, i.e., covering most areas east of Hu Line.

4.3. Orientations for Landscape Study and Construction

The boom of Neo-Chinese-style landscapes was mainly because its form is inherited from traditional Chinese expressions of emotion, with inheritances and evolutions from traditions in the landscape element arrangements, such as the hills, water, and buildings, and the bamboos were always considered to be the crucial vegetation material [10,11,15,17]. The bamboos played an important role in Neo-Chinese-style landscapes mainly because of their cultural and aesthetic values [13,15,18]. On the one hand, the cultural connotation of bamboos was honorable and long-standing, which was a symbol of Eastern culture. People admired bamboo for their spirit of modesty, tenacity, and indomitability and were willing to live with them [13,15]. On the other hand, the irreplaceability of bamboos stemmed from their unique morphology, texture, and color, which generated a special beauty in landscapes [11,14]. It is difficult to find vegetations comparable to bamboos in most areas of Northern China. In addition, the application of bamboos in Neo-Chinese-style landscapes is a kind of excavation of materials representing the regional characteristics and a praise of Chinese traditional culture. Although the determination of a landscape style is mainly subjected to the decision makers, it is still necessary to consider the regional characteristics.

The landscape construction could directly reveal the physical characteristics of cities and affected the regional, ecological health and social and economic structure [53–55]. The current landscape development significantly correlated to the social economy and environment and also was the inheritance and innovation of traditional Chinese gardens [56], and the relationship between landscape forms and the regional environment or climate should always be the priority in landscape design [21]. In this study, the issue about the appropriate distribution area of Neo-Chinese-style landscapes influenced by bamboos was essentially a study of the adaptation of vegetation in landscape to the climate and environment. Our study provided an insight for landscape climatology, i.e., the adaptations of landscape elements and the related landscape style to climate. Taking the bamboos as a limiting

factor is an attempt or enlightenment in exploring the landscape style adaptation to the climate or environment. Other elements, such as buildings, also have regional characters, which should be taken into account. The appropriate distribution area of Neo-Chinese-style landscapes that we calculated in this study provided references for the planning and construction of landscapes in different cities. For example, Liaoning Province would be a priority area for Neo-Chinese-style landscape construction, and it is a potential region for bamboo distribution under any climate scenarios. The northwest region would not be suitable for the construction of a Neo-Chinese-style landscape, where one should develop the regional style landscape. The suitable distribution areas in this study complied with the natural distribution of plants and conformed to the ecological concept of modern garden development, which could also avoid the economic waste caused by the construction of Neo-Chinese-style landscapes in some unsuitable areas and indirectly make a certain contribution to the regional, social, and economic development.

Generally speaking, this study crystallized the present and predicted the future appropriate distribution areas of Neo-Chinese-style landscape influenced by bamboos in China and provided some orientations in landscape study and construction. However, our study still had limitations. The *Phyllostachys* and *Bambusa* were bamboo genera with multiple species. We assessed their spatial distribution dynamics at the genus level, and we did not propose a precise species for the future introduction and domestication. We only took the vegetation element of bamboos as limiting factors and overlooked other elements, such as the architecture, so the evaluation on the appropriate distribution area of Neo-Chinese-style landscapes might not be refined enough. This paper is only an attempt to study the adaptation of landscape style to the climate and environment under climate change, and we hope to provide a reference for subsequent studies in the future.

5. Conclusions

In this study, we utilized an optimal MaxEnt model to simulate the current and future habitat ranges of two bamboo genera, *Phyllostachys* and *Bambusa*, under climate change and assessed the suitable distribution area of Neo-Chinese-style landscapes in China. The minimum temperature of the coldest month was identified as the crucial factor influencing the habitat ranges of two bamboo genera. The current habitat ranges of two bamboo genera are predominantly distributed in the Yangtze River basin and its southern region, which would expand to north in the future. The currently suitable distribution area of Neo-Chinese-style landscapes covered about 71.3% cities of China, which would expand northward at different degrees under SSP1-2.6 climate scenario and SSP5-8.5 climate scenario in the future. The Liaoning Province would be a priority area for Neo-Chinese-style landscape construction, and it is a potential region for bamboo distribution under any climate scenarios. Our study advanced the effect of bamboos on the suitable distribution of Neo-Chinese-style landscapes and offered valuable insights in planting bamboos in some northern cities according to different climate scenarios.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/f16030428/s1>, Table S1: Current and potential habitat ranges of *Phyllostachys*, *Bambusa*, and Neo-Chinese-style landscape with current and future predictions (2050s, 2070s and 2090s) based on a low CO₂ emission scenario (SSP1-2.6) and high CO₂ emission scenario (SSP5-8.5); Figure S1: Potential habitat ranges of *Phyllostachys* (a,c,e) and *Bambusa* (b,d,f) in China with future predictions of 2050s, 2070s and 2090s under SSP5-8.5 scenario.

Author Contributions: Conceptualization, Y.Z. (Ying Zhao); methodology, Y.Z. (Ying Zhao), Z.Z. and Y.Z. (Yongbin Zhao); software, Z.Z. and D.C.; validation, D.C. and Y.Z. (Yan Zhou); formal analysis, Y.Z. (Yongbin Zhao); investigation, D.C. and Y.Z. (Yan Zhou); resources, Z.Z.; writing—original draft,

Y.Z. (Ying Zhao); writing—review and editing, L.F.; visualization, Y.Z. (Ying Zhao); supervision, J.L. and L.F.; funding acquisition, L.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Social Science Research Fund project of Liaoning Province (L23BDJ002), the Research Fund project of Liaoning Provincial Department of Education (JYTMS20231295), and the University level Research Fund project of Shenyang Agricultural University (X2022005).

Data Availability Statement: Data will be made available upon request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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