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Predicting the potential distribution of *Taxus cuspidata* in northeastern China based on the ensemble model

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Abstract

Climate change is poised to exert a significant impact on species distribution in the future, and *Taxus cuspidata* as an endangered species is no exception. Predicting the potential distribution of *T. cuspidata* is essential for decision-makers to develop conservation policies and explicitly implement conservation measures. In this study, a combined model was employed to predict potentially suitable habitats for *T. cuspidata* based on extant data of *T. cuspidata* distributions in northeastern China. Our findings suggest that mean diurnal range (bio2) and isothermality (bio3) were identified as dominant factors influencing *T. cuspidata* distribution. Under future climate scenarios, suitable habitat areas increased only in the SSP126 scenario in the 2070s, declining in all other scenarios. In all climate scenarios, the centroid of suitable habitats ultimately shows a trend in northward movement. Decreases in suitable habitat predominantly occurred in Yanbian Korean Autonomous Prefecture, Baishan city, and Tonghua city. Overall, this study highlights a projected habitat reduction due to climate change. Recommendations entail the strategic establishment of nature reserves and the implementation of initiatives aimed at population replenishment.

Baoliang Chang and Chen Huang contributed equally to the work reported here.

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KEYWORDS
Biomod2, endangered plants, nature reserves, population status, species distribution model, *Taxus cuspidata*

INTRODUCTION

At present, the looming problem of global climate change is a matter of grave concern. Climate change has significantly emerged as a predominant abiotic factor exerting influence on biodiversity and the distribution of various species (Gao et al., 2023). The consensus among climate scholars is that global warming is an inevitability in forthcoming climate scenarios, with a pronounced impact expected in high-altitude regions (Ansari, 2023; Hamid et al., 2019). The ramifications of climate change are multifaceted, altering the course, frequency, and intensity of species interactions. This poses a substantial threat to species distribution, culminating in a worrisome decline in species diversity—a matter now considered one of the foremost ecological quandaries worldwide (Blois et al., 2013; McQuillan & Rice, 2015; Rosenberg et al., 2019). Furthermore, the vitality of certain species, especially those of economic significance, has been adversely affected by human activities such as logging and harvesting, leading to a stark reduction in their populations and the degradation of their habitats (Pan et al., 2022; Zhan et al., 2022). The confluence of climate warming and intensified human interventions is progressively causing suitable habitats for numerous species to shift toward higher latitudes and elevations (Wani et al., 2023; Zhao et al., 2021). Alarming statistics reveal that approximately one-quarter of the world's plant species currently face extinction risks, with this number continuing to escalate (Yang et al., 2021). As a result, safeguarding endangered species and preserving the quality of their habitats has unequivocally emerged as a paramount priority in the realm of biodiversity conservation, with particular emphasis on species bearing high ecological and economic value (Ansari, 2023; Cahyaningsih et al., 2021).

Taxus cuspidata, an evergreen tree classified within the Taxus genus and Taxaceae family, bears red fruit (Figure 1c). Recognized as a tertiary relict and often referred to as a botanical living fossil, *T. cuspidata* exhibits stringent environmental requirements and exhibits a scarcity of natural, undisturbed forest habitats. Its natural distribution primarily spans the northeastern regions of China. Renowned for its profound

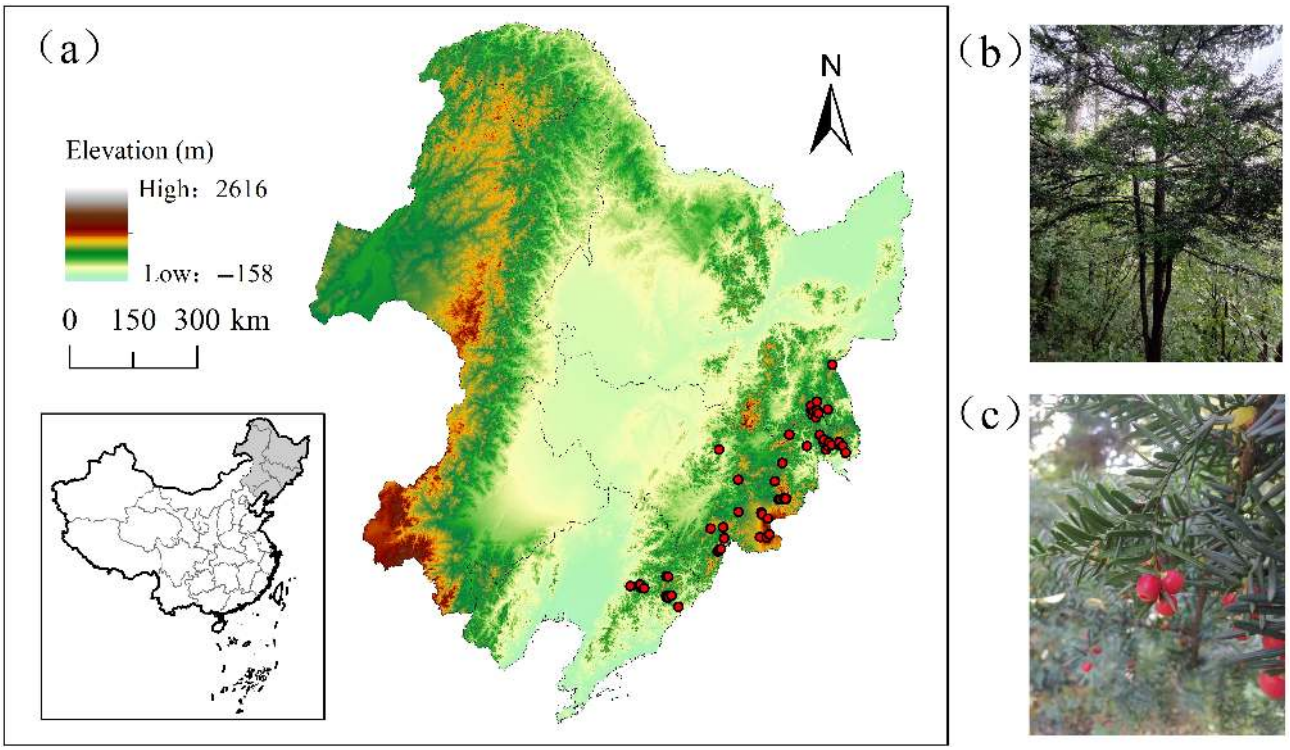


FIGURE 1 (a) Study area and distribution points of *Taxus cuspidata* (b) trees (c) and fruits. Photo credit: Yanqing Huang.

medicinal value, *T. cuspidata* is particularly celebrated for its paclitaxel-based antitumor properties (Cheng et al., 2015). Nevertheless, the current production of paclitaxel falls considerably short of demand, and the intricate mechanisms underpinning paclitaxel biosynthesis remain predominantly enigmatic (Kuang et al., 2019). In recent decades, human disturbances, logging, and environmental degradation have precipitated a perilous decline in *T. cuspidata*'s wild resources, exacerbating the precarious state of its natural populations (Zhang & Wenming, 2010). *T. cuspidata* is one of the endangered plants in the "Threatened Species List of China's Higher Plants" (Qin et al., 2017). The natural products, associated genes, and population status of *T. cuspidata* were the main areas of interest in early studies (Kan et al., 2020; Long et al., 2021; Zhou et al., 2019). However, with the increasing negative impact of climate change on species diversity, the protection of its suitable habitats has become the focus of current research. In the future, its suitable habitat may be more sensitive to climate change, so understanding the current and future changes in its suitable habitat is essential for the protection of its population.

Species distribution modeling (SDM) is an effective method to study the relationship between species distribution and environmental factors, which mainly utilizes species distribution data and relevant environmental data to predict the potential distribution of species (Ardestani et al., 2021; Guo et al., 2023). Because of its advantages such as low difficulty of data acquisition and good prediction effect, many algorithmic models have been developed and widely used in recent years (Chen et al., 2022). For example, the most commonly used include maximum entropy model (MaxEnt), generalized linear model (GLM), generalized additive model (GAM), multivariate adaptive regression splines (MARS), random forest (RF), and artificial neural network (ANN). However, the selection of a single model for simulation studies may lead to large differences in simulation results and increase uncertainty in species distributions (Subedi et al., 2024). This problem can be remedied by the ensemble model (EM), which integrates the results of multiple models and improves the accuracy of predictions (Ardestani & Ghahfarrokhi, 2021).

The establishment of nature reserves is a fundamental strategy for the conservation of endangered plants in the wild (de Souza & Prevedello, 2020). Nature reserves can provide suitable conditions for the normal growth and development of endangered species and effectively prevent the loss of suitable habitats for species. It has been demonstrated that species richness is much higher inside nature reserves than outside (Gray et al., 2016). However, under climate change, it is still unknown whether the reserve is facing the risk of loss of suitable habitat for *T. cuspidata* and whether the current reserve can meet the needs of protecting *T. cuspidata*. Therefore, the comprehensive analysis of species-suitable habitat changes and nature reserves can better provide guidance for conservation management.

This study used EM to simulate the potential distribution of *T. cuspidata* under climate changes. The overall objectives of the study include the following: (1) to predict current and future changes in the spatial distribution of suitable habitat for *T. cuspidata*; (2) to identify key environment variables that influence the distribution of its suitable habitat; (3) to provide a scientific basis for the conservation and management of *T. cuspidata*.

MATERIALS AND METHODS

Study area

The study area is located in northeastern China (Figure 1). This area comprises Liaoning, Jilin, Heilongjiang, and three cities within the Inner Mongolia Autonomous Region. Notably, this geographical expanse constitutes the principal natural habitat of the Northeastern Red Bean Pine in China, bounded by the Changbai Mountains to the east, the Daxinganling region to the west, and the Xiaoxinganling region to the north.

Model data

The distribution data of *T. cuspidata* in northeast China were collected from the field distribution point data recorded in the Digital Herbarium of China (http://www.cvh.ac.cn) and the Global Biodiversity Information Network (http://www.gbif.org/). In addition, we obtained point data for *T. cuspidata* through field surveys and review of the relevant literature (Long et al., 2021). A total of 69 data were finally obtained after removing duplicates. In order to consider the spatial autocorrelation between the coordinate points, one of the two points with a distance of less than 1 km was removed, and finally 61 valid data were obtained.

The bioclimatic data selected for this study were obtained from the World Climate Database version 2.1 (http://www.worldclim.org/), which consists of 19 climate variables at a resolution of 1 km. Future climate data from the World Climate Database BCC-CSM2-MR model projections for the period 2061–2080, driven by different socioeconomic assumptions, with projected scenarios of how humans will emit greenhouse gases, also known as the Shared Socio-Economic Pathway (SSP): SSP126

(low-impact scenario), SSP245 (medium-impact scenario), SSP245 (medium- to high-impact scenario), and SSP485 (high-impact scenario). The elevation data were obtained from Geospatial Data Cloud (https://www.gscloud.cn/), and the data were used to generate slope and aspect in ArcGIS 10.8. Soil data were obtained through the World Soil Database (HWSD). There are 28 environmental factors in three categories (Appendix S1: Table S1).

In order to prevent multicollinearity among climate environment variables from affecting the prediction results, the environment variables were first analyzed for correlation. These environmental correlations were calculated from the values of all environment variables in the study area. For two variables with correlation coefficients greater than 0.8, preserve the one with greater of contributivity and ensure that the variance inflation factor (VIF) is <10 between factors (Werkowska et al., 2017). Five climatic environment indicators, three topographic indicators, and five soil indicators were finalized (Table 1). The same five climate environment indicators were selected for the four future climate scenarios to ensure comparability of the models. The data on the boundaries of the nature reserves come from the geographic information database of the China Nature Reserve Specimen Resource Sharing Platform (http://www.papc.cn/).

Species distribution modeling

Species distribution models are widely used for the prediction of suitable habitats for species, among which MaxEnt model (Du et al., 2021; Yu et al., 2019), random forest (Zhang, Wei, Zhang, et al., 2020; Zhang, Wei, Zhao, et al., 2020), and other models are more widely used. With the development of the model, the composite model that integrates multiple models often has more advantages (Hao et al., 2020; Yusup et al., 2022). This is because a single model may produce overfitting, whereas an EM may reduce uncertainty in model fitting (Battini et al., 2019; He et al., 2023). In order to more accurately simulate and predict the distribution of *T. cuspidata* in northeast China, this study used "biomod2" in R4.1.2 for simulation and prediction (Thuiller et al., 2021). Biomod2 is a collection package for SDM, including 10 models (Appendix S1: Table S2). In the process of SDM, it is difficult to obtain accurate absence point data. Therefore, we adopted the method of randomly generating 1000 pseudo-absences in the study area. In addition, we performed three operations to eliminate the bias in the sample generated during the pseudo-absence generation process (Rather et al., 2022). During the modeling process, 75% of the distribution data samples were randomly selected as training data, and 25% of the samples were used as testing data. According to the parameter setting, the model is run 10 times repeatedly to reduce the spatial deviation. Normally, true skill statistic (TSS) and the area under the relative operating characteristic curve (AUC) are used as evaluation indicators for model accuracy. The closer the values of the two indicators are to 1, the better the simulation results of the model. The models with excellent assessment results were selected as the base models to be combined, and the combined model results for current and future simulations were obtained after weighting with AUC values.

The suitable habitat value range of the EM output is 0–1000, and we use ArcGIS 10.6 to visualize the simulation results. We first divide the study area into unsuitable habitat (0–500) and suitable habitat (500–1000). The suitable habitat was divided into low suitable habitat (500–600) and high suitable habitat (600–1000) (Hamid et al., 2019; Leng et al., 2008). Finally, the area of suitable and highly suitable habitat was counted to determine the spatial variation in suitable habitat for *T. cuspidata*.

TABLE 1 Environment variables used in the model.

Variable type	Variable name	Code
Climatic variables	Annual mean temperature	bio1
	Mean diurnal range	bio2
	Isothermality	bio3
	Annual precipitation	bio12
	Precipitation seasonality (coefficient of variation)	bio15
Terrain variables	Digital elevation model	dem
	Shope	shope
	Aspect	aspect
Soil variables	Topsoil silt fraction	t_silt
	Topsoil clay fraction	t_clay
	Topsoil pH	t_ph
	Topsoil organic carbon	t_oc
	Topsoil reference bulk density	t_bulk

Geospatial analysis

We used the tool of "Distribution Changes Between Binary SDMs" in the SDMtoolbox version 2.4 tool kit of the ArcMap 10.8 software to calculate the changes in suitable habitats in the future. Then, we analyzed the spatial distribution of expansion and contraction areas in different scenarios in the future, and obtained the distribution map of stable and contraction areas in 2090s.

Finally, the spatial distribution of nature reserves was analyzed in relation to the spatial distribution of areas of loss of suitable habitat.

RESULTS

Model evaluation and contribution of environment variables

We used AUC > 0.95 and TSS > 0.9 as the screening criteria, and the excellent models screened out were MaxEnt, GLM, Flexible Discriminant Analysis Model (FDA), and MARS. The combined model after performing the combination has an AUC value of 0.996 and a TSS value of 0.974, giving excellent model performance. These results affirm the exceptional predictive capabilities of the combined model, which demonstrated heightened accuracy in simulating the suitable habitat distribution for *T. cuspidata* in the northeastern region.

In general, climatic factors exerted a substantial influence on the distribution of suitable habitats for *T. cuspidata*, whereas topographical and soil-related factors exhibited comparably minor effects. Among the contributing variables in the comprehensive model, bio2 and bio3 emerged as the most significant. The preferred environmental range for *T. cuspidata* can be defined as follows: mean daily range of 6–12.3°C; isothermality of 24.5–31; annual precipitation of 590–1100 mm; and precipitation seasonality (coefficient of variation) of 64–107 mm (Figure 2).

Distribution of suitable habitats for *T. cuspidata*

The current suitable habitat for *T. cuspidata* primarily exists in the eastern portion of the northeastern region, predominantly concentrated within the Changbai Mountain Range, which constitutes the primary natural habitat for *T. cuspidata* (Figure 3). Currently, the total area of suitable habitat encompasses 69,868 km^2, with 22.81% classified as merely suitable habitat and the remaining 77.19% designated as highly suitable habitat. Notably, suitable habitat predominantly encircles areas characterized as highly suitable habitat. Looking ahead to potential climate scenarios, under the SSP126 scenario, an expansion of suitable habitat is projected in the 2070s, followed by a reduction in suitable habitat area in the 2090s. Under scenarios SSP245, SSP370, and SSP585, total suitable habitat area for *T. cuspidata* decreases significantly, with losses of 12,095, 7976, and 4864 km^2 in the 2070s, respectively. It lost 7787, 9130 and 10,717 km^2 in the 2090s, respectively.

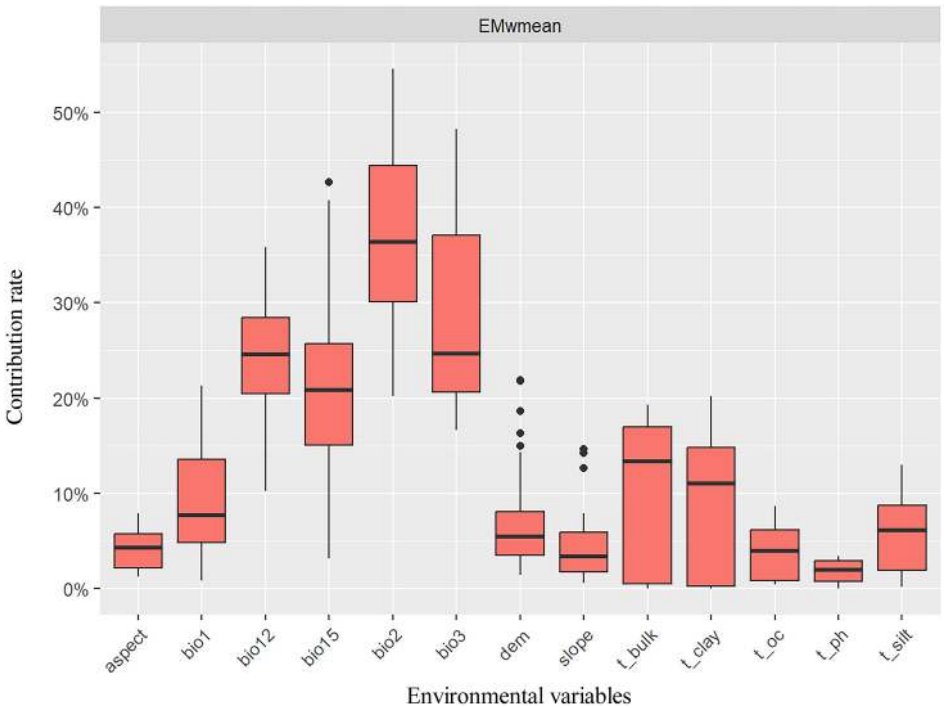


FIGURE 2 Contribution of environment variables. The lower and upper ends of each box represent the 25th and 75th quartiles, the bold lines within the boxes represent medians, whiskers represent no more than 1.5 times the interquartile range, and solid circles represent outliers. See Table 1 for an explanation of variable codes.

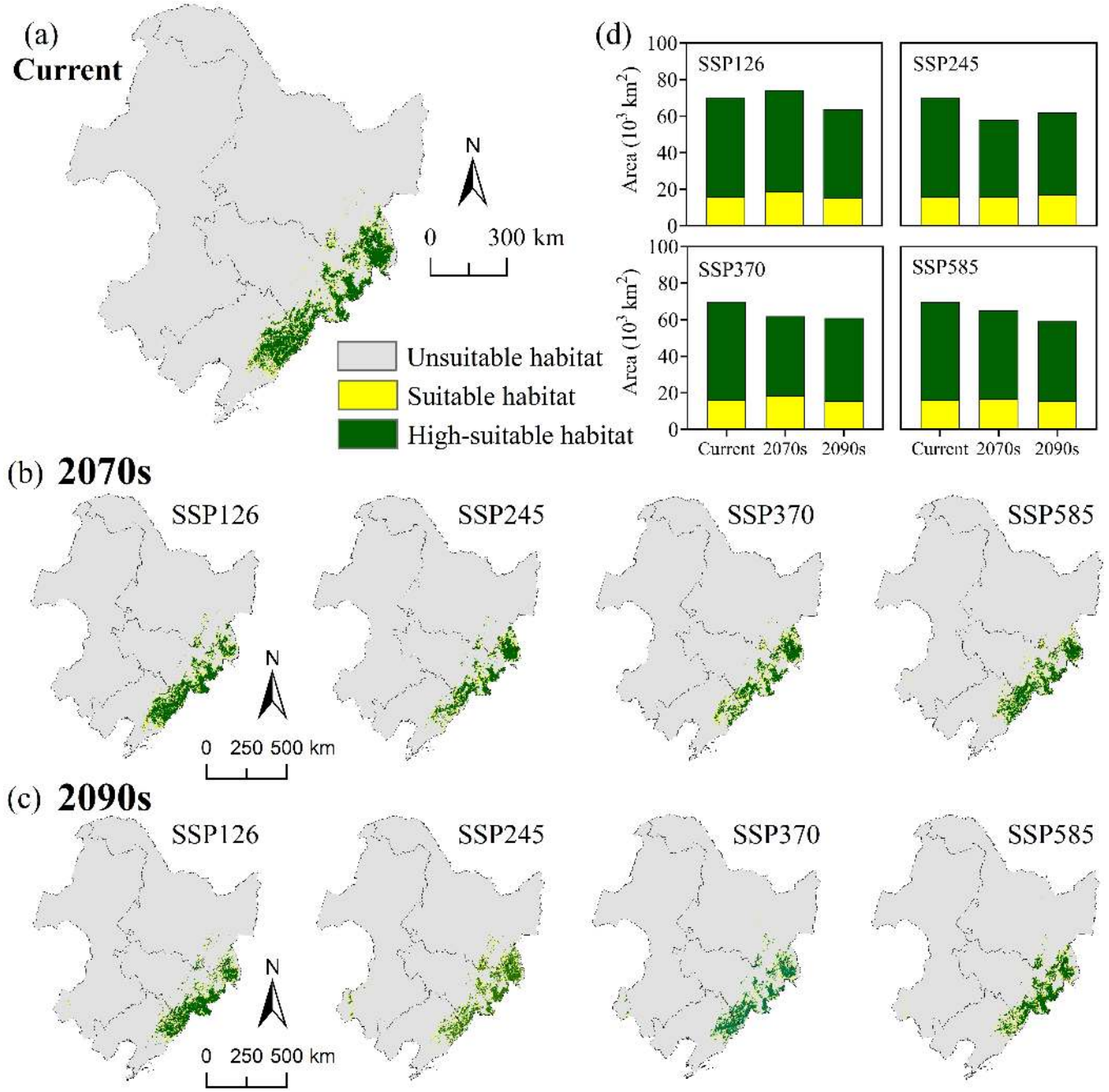


FIGURE 3 (a) Current suitable habitat of *Taxus cuspidata*. (b) Suitable habitats for *T. cuspidata* under different climate scenarios in 2070s. (c) Suitable habitats for *T. cuspidata* under different climate scenarios in 2090s. (d) Area of suitable habitat.

Dynamics of suitable habitat under different climatic scenarios

Figure 4 shows the spatial variation in suitable habitat under different climate scenarios in the 2090s. In the SSP126 scenario, significant habitat contraction occurred mainly at the southern and northern ends of the total suitable habitat. In contrast, the SSP126 scenario exhibited a greater area of habitat expansion than that of contraction, mainly within the central Jilin Province. In contrast, the other three climatic scenarios demonstrate prominent habitat contraction primarily within the southern portion of the total suitable habitat, concentrated within Liaoning Province. Across all three climate scenarios, the expansion of suitable habitat is consistently surpassed by contraction, leading to an overall habitat reduction. Notably, the population distribution patterns of *T. cuspidata* indicate a clear trend in migration to higher elevations.

From the final results, the area of suitable habitat for *T. cuspidata* will decrease in the 2090s. Under the SSP126

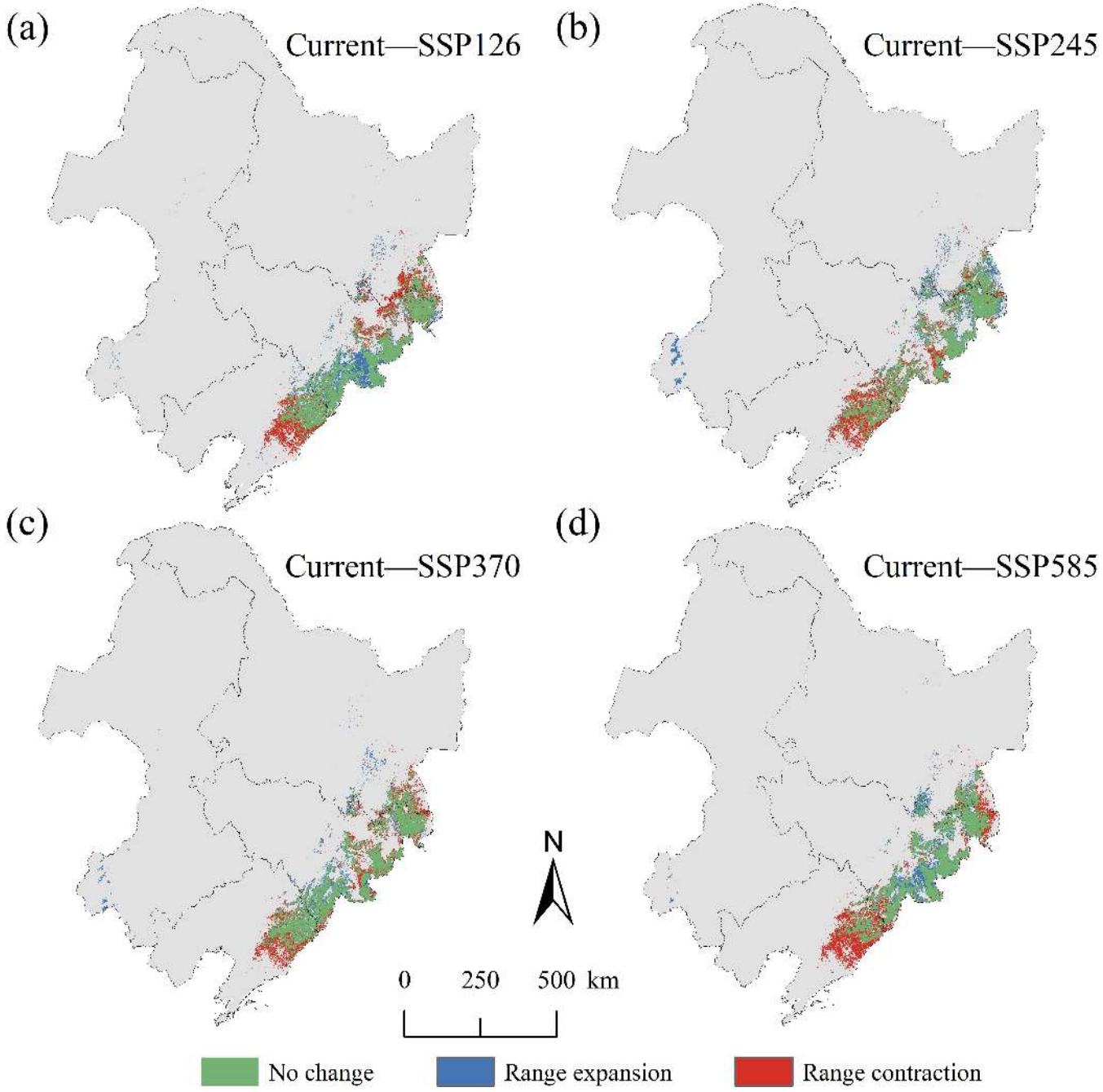


FIGURE 4 Spatial changes in *Taxus cuspidata* under different climatic scenarios in 2090s: (a) SSP126; (b) SSP245; (c) SSP370; (d) SSP585.

climate scenario, *T. cuspidata* had the smallest shrinkage in total suitable habitat, with a decrease of 8.95%. As climate change pressures increase, the shrinking area of suitable habitat increases. Under the three climate scenarios, the shrinkage rates of suitable habitat area were 11.08%, 13.11%, and 15.35%, respectively (Table 2).

In terms of spatial pattern, the centroid of total suitable habitat was located within the city of Baishan, Jilin Province, in both the current and future four periods (Figure 5). In the SSP126 scenario, the centroid has the shortest final migration distance. Overall, the centroid has a tendency to migrate northward. The centroid of current suitable habitat is located in Fusong County, Baishan City (127°23′56.4″ E, 42.19′33.6″ N).

The areas where suitable habitat stabilizes or disappears under all four future climate scenarios are the areas of key concern for future conservation efforts (Figure 6). Specifically, the suitable habitat areas that disappeared under different climate scenarios in 2070s and 2090s were 2073 and 2061 km^2, respectively. It is mainly located in

TABLE 2 Change in suitable habitat area under different climate scenarios in 2090s (in square kilometers).

Future climate scenarios	Total suitable habitat	Range expansion	Range contraction	No change	Total change
SSP126	63,510	15,166	21,410	48,344	−6244
SSP245	62,023	13,304	21,035	48,719	−7731
SSP370	60,612	10,183	19,325	50,429	−9142
SSP585	59,050	11,784	22,488	47,266	−10,704

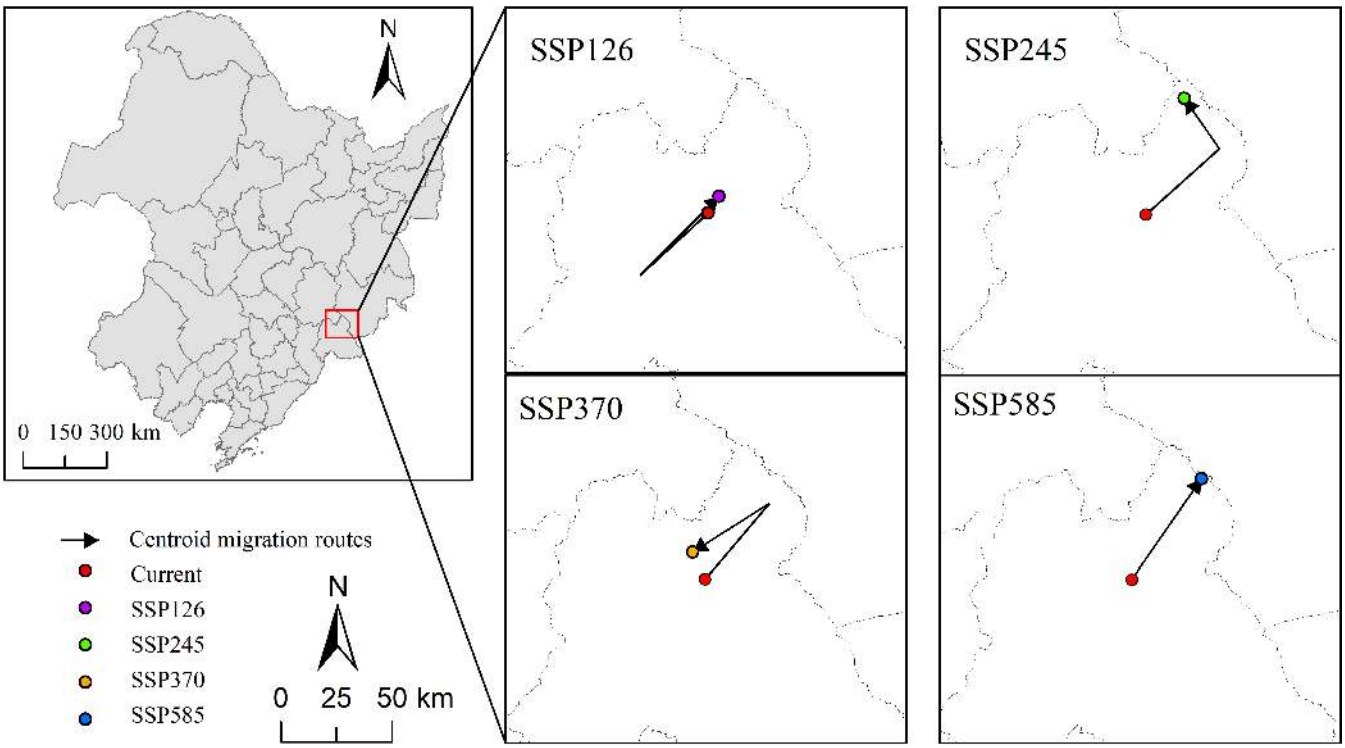


FIGURE 5 Centroid migration of suitable habitats.

Yanbian Korean Autonomous Prefecture, Baishan City, and Tonghua City. It is worth noting that contraction of suitable habitat exists in established nature reserves. At the same time, the areas of suitable habitat under all four climate scenarios in the 2070s and 2090s were 37,833 and 32,071 km^2, respectively. This is a naturally updated stable region of *T. cuspidata*.

DISCUSSION

Suitable habitat impact factors and conservation status

Climate, topography, and soil factors exert significant influences on the growth and development of plants, particularly for endangered wild species like *T. cuspidata* (Bhat et al., 2023). *T. cuspidata* thrives within the altitude range of 500–1000 m above sea level, with temperature being the predominant factor governing its survival. Our modeling results underscored that daily mean temperature and isothermality emerged as pivotal environmental factors dictating the distribution of *T. cuspidata*. Additionally, annual precipitation and the seasonality of precipitation wielded considerable influence over *T. cuspidata*'s distribution in the northeastern region of China. Notably, these bioclimatic variables also hold significance in shaping the distribution patterns of other plant species in the same northeastern context. This phenomenon can be attributed to the region's pronounced temperature fluctuations and the concentration of precipitation during the summer months (Liu et al., 2021; Wang, Liu, Shuai, et al., 2023). Predominantly, the suitable habitat for *T. cuspidata* is concentrated in the

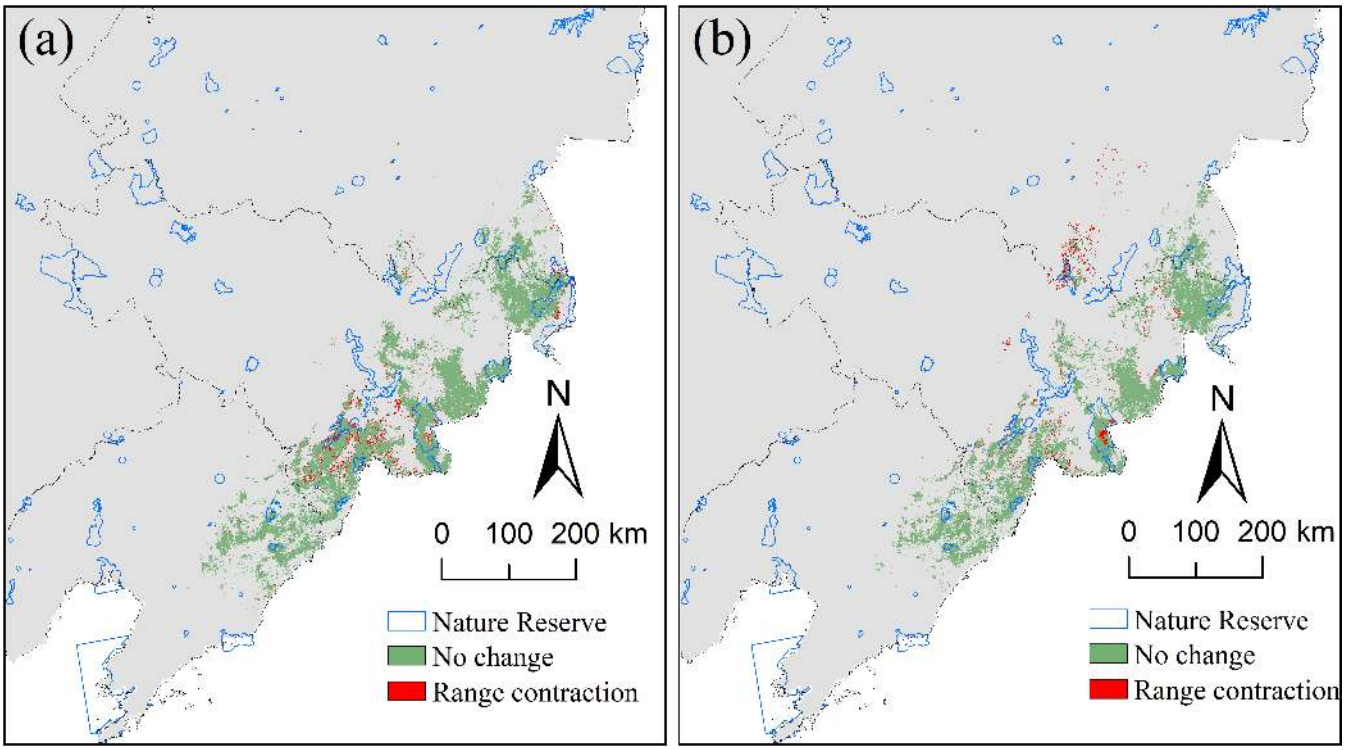


FIGURE 6 Range contraction and unchanged areas in different scenarios: (a) 2070s; (b) 2090s.

Changbai Mountain area. Projections under future climate scenarios suggest a conspicuous reduction in suitable habitat at lower altitudes, a pattern akin to many other species' habitat changes (Abdelaal et al., 2019; Prevey et al., 2020).

By comparing the extent of suitable habitat for *T. cuspidata* with the extent of the current nature reserve, it is possible to speculate whether the current reserve area meets the conservation requirements (Hu et al., 2020; Wan et al., 2015). Notably, the degree of overlap between current nature reserves and *T. cuspidata*'s suitable habitat remains limited, both in the current context and under projected future climate scenarios (Figure 6). This shortfall suggests that the existing nature reserves may fall short in safeguarding suitable habitat under future climatic conditions, thus highlighting a conservation deficit (Amarasinghe et al., 2021; Zhang et al., 2022). Consequently, the identification of stable and suitable habitats as priority zones for protection is imperative, with a primary focus on establishing future nature reserves within these prioritized areas (Han et al., 2019). Our research has found that some lost suitable habitats are located within nature reserves (Figure 6). This tells us that some areas in the nature reserves may also be affected by climate change and need special attention from the protection department. These research outcomes hold substantial significance for the delineation of priority conservation zones for *T. cuspidata* in northeast China and the formulation of effective conservation strategies. Furthermore, the study's findings offer valuable scientific guidance for facilitating the population recovery of *T. cuspidata*.

Implications and pathways for the conservation of *T. cuspidata*

Our results suggest that the suitable habitat for *T. cuspidata* faces imminent threats under future climate change scenarios. We propose two primary conservation strategies for *T. cuspidata*. Firstly, progressive establishment of nature reserves in areas where suitable habitats are stabilized under different climate scenarios. The current area of the reserve does not meet the demand for *T. cuspidata* protection. These nature reserves play a crucial role in managing shifts in the population structure of endangered species, thereby reducing the risk of natural extinction (Geldmann et al., 2018; Yu et al., 2014). By implementing a carefully planned zoning strategy, the nature reserves can form a coherent system or network to achieve the purpose of protection (Song et al., 2021; Wan et al., 2016). At the same time, nature reserves are able to maintain existing environmental conditions of suitable habitat and prevent further loss of their suitable habitat area (Guo et al., 2019). Second, relocation conservation and species return. Relocation conservation measures

can be implemented for plants located in areas where suitable habitat is shrinking under different climate scenarios. There have been successful cases of stable regenerating populations of *Taxus wallichiana* in the wild through translocation conservation (Li et al., 2021). In addition, the number of *T. cuspidata* can be gradually increased in areas where suitable habitat is stabilized under different climatic scenarios. This is mainly due to the dispersed nature of wild populations and the fragmentation of habitats that hinders self-propagation and population renewal (Wang, Liu, Liu, et al., 2023). It is important to note that raw plant material from different populations can be collected, which can lead to higher genetic diversity in the returned populations (Niu et al., 2021; Wan et al., 2014).

Limitations

For species distribution models, uncertainty in species point locations inevitably increases the uncertainty in the prediction results. Although species distribution models can give desirable predictions with a small sample size, species distribution models will have higher accuracy as the sample size increases. This study used 61 species distribution data, and extensive surveys should be conducted in the future to obtain more sample data. In addition to species sample data, environment variables can also affect prediction results. For example, in our prediction process, we did not consider the potential impact of land use factors. This may exaggerate the suitable habitat area for *T. cuspidata*. But with the continuous improvement in people's awareness of conservation, the impact of land use change on species is gradually decreasing. Currently, the change in suitable habitats for organisms is mainly caused by climate change (Pant et al., 2021). In the future, predicting suitable habitats for species using species distribution models can comprehensively consider the quantity of species location data and related environmental factors.

CONCLUSION

In this study, we used ensemble modeling analysis to evaluate the current and future planning areas for the preserve. Our results revealed that daily mean temperature and isothermality are the primary drivers influencing the distribution of *T. cuspidata*, highlighting the pronounced impact of temperature-related variables over precipitation-related ones on species distribution. The predictions under different climate scenarios in the future indicate that suitable habitat of *T. cuspidata* is shrinking and there is an overall trend in northward movement. We suggest that ex situ protection and in situ protection measures should be carried out in different regions according to the changes in suitable habitats. At the same time, the planning and expansion of nature reserves, especially for *T. cuspidata*, should be strengthened. Furthermore, management and conservation strategies within these reserves should be improved to foster the healthy development of wild populations of this endangered species.

AUTHOR CONTRIBUTIONS

Baoliang Chang and Chen Huang conceived the project and drafted the manuscript. Bingming Chen and Ziwen Wang performed the main analyses. Xingyuan He, Wei Chen, Yanqing Huang, and Yue Zhang collated and digitized data. Shuai Yu led the writing of the manuscript.

FUNDING INFORMATION

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The distribution data for *Taxus cuspidata* were obtained from The Global Biodiversity Information Network Database (GBIF; https://www.gbif.org), Chinese Virtual Herbarium (CVH; https://www.cvh.ac.cn), and China National Specimen Information Infrastructure (NSII; http://www.nsii.org.cn/), and from a previous study (Long et al., 2021). Bioclimatic variables and soil data were obtained from WorldClim (https://www.worldclim.org/) and Harmonized World Soil Database version 1.23 (HWSD; http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonizedworld-soil-database-v12/en/). Query details for retrieving the relevant data are as follows: For species distribution data, we obtained coordinates of longitude and latitude from the above databases and literature, identified and eliminated invalid and duplicate records, and used ArcGIS to refine the coordinates of longitude and latitude to no more than 1 per km, ultimately obtaining the distribution point data of species. The bioclimatic variables and soil data obtained from the WorldClim and HWSD databases were obtained at the global scale, and we used the mask extraction tool in ArcGIS to extract data from northeastern China for this study.

REFERENCES

Abdelaal, M., M. Fois, G. Fenu, and G. Bacchetta. 2019. "Using MaxEnt Modeling to Predict the Potential Distribution of the Endemic Plant *Rosa arabica* Crep. in Egypt." *Ecological Informatics* 50: 68–75. https://doi.org/10.1016/j.ecoinf.2019.01.003.

Amarasinghe, P., N. Barve, H. Kathriarachchi, B. Loiselle, and N. Cellinese. 2021. "Niche Dynamics of Memecylon in Sri Lanka: Distribution Patterns, Climate Change Effects, and Conservation Priorities." *Ecology and Evolution* 11(24): 18196–215. https://doi.org/10.1002/ece3.8415.

Ansari, A. 2023. "Prediction of Climate Change Effects on Siberian Crane (*Grus leucogeranus*) Habitat Suitability by Using Ensemble Modeling in Asia Wetlands." *Wetlands* 43(1): 4. https://doi.org/10.1007/s13157-022-01646-3.

Ardestani, E. G., and Z. H. Ghahfarrokhi. 2021. "Ensembpecies Distribution Modeling of *Salvia hydrangea* under Future Climate Change Scenarios in Central Zagros Mountains, Iran." *Global Ecology and Conservation* 26: e01488. https://doi.org/10.1016/j.gecco.2021.e01488.

Ardestani, E. G., H. Rigi, and A. Honarbakhsh. 2021. "Predicting Optimal Habitats of *Haloxylon persicum* for Ecosystem Restoration Using Ensemble Ecological Niche Modeling under Climate Change in Southeast Iran." *Restoration Ecology* 29(6): e13492. https://doi.org/10.1111/rec.13492.

Battini, N., N. Farias, C. B. Giachetti, E. Schwindt, and A. Bortolus. 2019. "Staying Ahead of Invaders: Using Species Distribution Modeling to Predict Alien Species' Potential Niche Shifts." *Marine Ecology Progress Series* 612: 127–140. https://doi.org/10.3354/meps12878.

Bhat, I. A., M. Fayaz, S. Roof-ul-Qadir, S. Rafiq, K. Guleria, J. A. Qadir, T. A. Wani, and Z. Kaloo. 2023. "Predicting Potential Distribution and Range Dynamics of *Aquilegia fragrans* under Climate Change: Insights from Ensemble Species Distribution Modelling." *Environmental Monitoring and Assessment* 195(5): 623. https://doi.org/10.1007/s10661-023-11245-2.

Blois, J. L., P. L. Zarnetske, M. C. Fitzpatrick, and S. Finnegan. 2013. "Climate Change and the Past, Present, and Future of Biotic Interactions." *Science* 341(6145): 499–504. https://doi.org/10.1126/science.1237184.

Cahyaningsih, R., J. Phillips, J. M. Brehm, H. Gaisberger, and N. Maxted. 2021. "Climate Change Impact on Medicinal Plants in Indonesia." *Global Ecology and Conservation* 30: e01752. https://doi.org/10.1016/j.gecco.2021.e01752.

Chen, C., X. J. Zhang, J. Z. Wan, F. F. Gao, S. S. Yuan, T. T. Sun, Z. D. Ni, and J. H. Yu. 2022. "Predicting the Distribution of Plant Associations under Climate Change: A Case Study on *Larix gmelinii* in China." *Ecology and Evolution* 12(10): e9374. https://doi.org/10.1002/ece3.9374.

Cheng, B.-B., Y.-Q. Zheng, and Q.-W. Sun. 2015. "Genetic Diversity and Population Structure of *Taxus cuspidata* in the Changbai Mountains Assessed by Chloroplast DNA Sequences and Microsatellite Markers." *Biochemical Systematics and Ecology* 63: 157–164. https://doi.org/10.1016/j.bse.2015.10.009.

de Souza, A. C., and J. A. Prevedello. 2020. "The Importance of Protected Areas for Overexploited Plants: Evidence from a Biodiversity Hotspot." *Biological Conservation* 243: 108482. https://doi.org/10.1016/j.biocon.2020.108482.

Du, Z., Y. He, H. Wang, C. Wang, and Y. Duan. 2021. "Potential Geographical Distribution and Habitat Shift of the Genus *Ammopiptanthus* in China under Current and Future Climate Change Based on the MaxEnt Model." *Journal of Arid Environments* 184: 104328. https://doi.org/10.1016/j.jaridenv.2020.104328.

Gao, M., G. Zhao, S. Zhang, Z. Wang, X. Wen, L. Liu, C. Zhang, N. Tie, and R. Sa. 2023. "Priority Conservation Area of *Larix gmelinii* under Climate Change: Application of an Ensemble Modeling." *Frontiers in Plant Science* 14: 1177307. https://doi.org/10.3389/fpls.2023.1177307.

Geldmann, J., L. Coad, M. D. Barnes, I. D. Craigie, S. Woodley, A. Balmford, T. M. Brooks, et al. 2018. "A Global Analysis of Management Capacity and Ecological Outcomes in Terrestrial Protected Areas." *Conservation Letters* 11: 3. https://doi.org/10.1111/conl.12434.

Gray, C. L., S. L. L. Hill, T. Newbold, L. N. Hudson, L. Borger, S. Contu, A. J. Hoskins, S. Ferrier, A. Purvis, and J. P. W. Scharlemann. 2016. "Local Biodiversity Is Higher inside than outside Terrestrial Protected Areas Worldwide." *Nature Communications* 7: 12306. https://doi.org/10.1038/ncomms12306.

Guo, L., Y. Gao, P. He, Y. He, and F. Meng. 2023. "Modeling for Predicting the Potential Geographical Distribution of Three Ephedra Herbs in China." *Plants-Basel* 12(4): 787. https://doi.org/10.3390/plants12040787.

Guo, Z., G. Cui, M. Zhang, and X. Li. 2019. "Analysis of the Contribution to Conservation and Effectiveness of the Wetland Reserve Network in China Based on Wildlife Diversity." *Global Ecology and Conservation* 20: e00684. https://doi.org/10.1016/j.gecco.2019.e00684.

Hamid, M., A. A. Khuroo, B. Charles, R. Ahmad, C. P. Singh, and N. A. Aravind. 2019. "Impact of Climate Change on the Distribution Range and Niche Dynamics of Himalayan Birch, a Typical Treeline Species in Himalayas." *Biodiversity and Conservation* 28(8–9): 2345–70. https://doi.org/10.1007/s10531-018-1641-8.

Han, Y., S. Dong, W. Xiaoyu, S. Liu, S. Xukun, Y. Zhang, H. Zhao, X. Zhang, and D. Swift. 2019. "Integrated Modeling to Identify Priority Areas for the Conservation of the Endangered Plant Species in Headwater Areas of Asia." *Ecological Indicators* 105: 47–56. https://doi.org/10.1016/j.ecolind.2019.05.064.

Hao, T., J. Elith, J. J. Lahoz-Monfort, and G. Guillera-Arroita. 2020. "Testing whether Ensemble Modelling Is Advantageous for Maximising Predictive Performance of Species Distribution Models." *Ecography* 43(4): 549–558. https://doi.org/10.1111/ecog.04890.

He, X.-H., J.-H. Si, L. Zhu, D.-M. Zhou, C.-Y. Zhao, B. Jia, C.-L. Wang, J. Qin, and X.-L. Zhu. 2023. "Modeling Habitat Suitability of *Hippophae rhamnoides* L. Using MaxEnt under Climate Change in China: A Case Study of *H. r. sinensis* and *H. r. turkestanica*." *Frontiers in Forests and Global Change* 5: 1095784. https://doi.org/10.3389/ffgc.2022.1095784.

Hu, W., Y. Wang, P. Dong, D. Zhang, Y. Weiwei, Z. Ma, G. Chen, et al. 2020. "Predicting Potential Mangrove Distributions at the Global Northern Distribution Margin Using an Ecological Niche Model: Determining Conservation and Reforestation Involvement." *Forest Ecology and Management* 478: 118517. https://doi.org/10.1016/j.foreco.2020.118517.

Kan, S.-L., T.-T. Shen, P. Gong, J.-H. Ran, and X.-Q. Wang. 2020. "The Complete Mitochondrial Genome of *Taxus cuspidata* (Taxaceae): Eight Protein-Coding Genes Have Transferred to the Nuclear Genome." *BMC Evolutionary Biology* 20(1): 10. https://doi.org/10.1186/s12862-020-1582-1.

Kuang, X., S. Sun, J. Wei, Y. Li, and C. Sun. 2019. "Iso-Seq Analysis of the *Taxus cuspidata* Transcriptome Reveals the Complexity of Taxol Biosynthesis." *BMC Plant Biology* 19: 210. https://doi.org/10.1186/s12870-019-1809-8.

Leng, W., H. S. He, B. Rencang, L. Dai, H. Yuanman, and X. Wang. 2008. "Predicting the Distributions of Suitable Habitat for Three Larch Species under Climate Warming in Northeastern China." *Forest Ecology and Management* 254(3): 420–28. https://doi.org/10.1016/j.foreco.2007.08.031.

Li, K., G. Zhang, Y. Zhang, and M. Patrick Griffith. 2021. "A Noteworthy Case of Rewilding Chinese Yew from a Garden Population in Eastern China." *PeerJ* 9: e12341. https://doi.org/10.7717/peerj.12341.

Liu, H., H. Jacquemyn, X. He, W. Chen, Y. Huang, Y. Shuai, L. Yupeng, and Y. Zhang. 2021. "The Impact of Human Pressure and Climate Change on the Habitat Availability and Protection of Cypripedium (Orchidaceae) in Northeast China." *Plants-Basel* 10(1): 84. https://doi.org/10.3390/plants10010084.

Long, T., W. Xinlei, Y. Wang, J. Chen, X. Chao, J. Li, J. Li, and R. Zang. 2021. "The Population Status and Threats of *Taxus cuspidata*, a Plant Species with Extremely Small Populations in China." *Global Ecology and Conservation* 26: e01495. https://doi.org/10.1016/j.gecco.2021.e01495.

McQuillan, M. A., and A. M. Rice. 2015. "Differential Effects of Climate and Species Interactions on Range Limits at a Hybrid Zone: Potential Direct and Indirect Impacts of Climate Change." *Ecology and Evolution* 5(21): 5120–37. https://doi.org/10.1002/ece3.1774.

Niu, Y., A. Bhatt, Y. Peng, W. Chen, Y. Gao, X. Zhan, Z. Zhang, H. Wan, M. Song, and Y. Zhijun. 2021. "Genetic Diversity and Population Structure Analysis of *Emmenopterys henryi* Oliv., an Endangered Relic Species Endemic to China." *Genetic Resources and Crop Evolution* 68(3): 1135–48. https://doi.org/10.1007/s10722-020-01054-8.

Pan, C., S. Chen, Z. Chen, Y. Li, Y. Liu, Z. Zhang, X. Yani, et al. 2022. "Assessing the Geographical Distribution of 76 *Dendrobium* Species and Impacts of Climate Change on Their Potential Suitable Distribution Area in China." *Environmental Science and Pollution Research* 29(14): 20571–92. https://doi.org/10.1007/s11356-021-15788-0.

Pant, G., T. Maraseni, A. Apan, and B. L. Allen. 2021. "Predicted Declines in Suitable Habitat for Greater One-Horned Rhinoceros (*Rhinoceros unicornis*) under Future Climate and Land Use Change Scenarios." *Ecology and Evolution* 11(24): 18288–304. https://doi.org/10.1002/ece3.8421.

Prevey, J. S., L. E. Parker, C. A. Harrington, C. T. Lamb, and M. F. Proctor. 2020. "Climate Change Shifts in Habitat Suitability and Phenology of Huckleberry (*Vaccinium membranaceum*)." *Agricultural and Forest Meteorology* 280: 107803. https://doi.org/10.1016/j.agrformet.2019.107803.

Qin, H., Y. Yang, S. Dong, Y. Qiang He, L. Z. Jia, Y. Shengxiang, L. Huiyuan, et al. 2017. "Threatened Species List of China's Higher Plants." *Biodiversity Science* 25(7): 696–744.

Rather, Z. A., R. Ahmad, T.-U.-H. Dar, and A. A. Khuroo. 2022. "Ensemble Modelling Enables Identification of Suitable Sites for Habitat Restoration of Threatened Biodiversity under Climate Change: A Case Study of Himalayan Trillium." *Ecological Engineering* 176: 106534. https://doi.org/10.1016/j.ecoleng.2021.106534.

Rosenberg, K. V., A. M. Dokter, P. J. Blancher, J. R. Sauer, A. C. Smith, P. A. Smith, J. C. Stanton, et al. 2019. "Decline of the North American Avifauna." *Science* 366(6461): 120–24. https://doi.org/10.1126/science.aaw1313.

Song, K., C.-R. Mi, Y.-Z. Zhao, N. Yang, Y.-H. Sun, and X. Ji-Liang. 2021. "Zonation of Nature Reserve According to the Habitat Requirement of Conservation Target: A Case Study on the Endangered Brown Eared-Pheasant at Baihuashan Nature Reserve." *Global Ecology and Conservation* 32: e01941. https://doi.org/10.1016/j.gecco.2021.e01941.

Subedi, S. C., S. Drake, B. Adhikari, and M. V. Coggeshall. 2024. "Climate-Change Habitat Shifts for the Vulnerable Endemic Oak Species (*Quercus arkansana* Sarg.)." *Journal of Forestry Research* 35(1): 23. https://doi.org/10.1007/s11676-023-01673-8.

Thuiller, W., D. Georges, M. Gueguen, R. Engler, and F. Breiner. 2021. "Biomod2: Ensemble Platform for Species Distribution Modeling, Version 3.5.1." https://cran.r-project.org/package=biomod2.

Wan, J. Z., C. J. Wang, J. H. Yu, S. M. Nie, S. J. Han, J. Z. Liu, Y. G. Zu, and Q. G. Wang. 2016. "Developing Conservation Strategies for *Pinus koraiensis* and *Eleutherococcus senticosus* by Using Model-Based Geographic Distributions." *Journal of Forestry Research* 27(2): 389–400. https://doi.org/10.1007/s11676-015-0170-5.

Wan, J. Z., C. J. Wang, J. H. Yu, S. M. Nie, S. J. Han, L. H. Wang, J. Z. Liu, and Y. G. Zul. 2015. "Model-Based Assessment of Priority Protected Areas: A Case Study on *Fraxinus mandshurica* in China." *Polish Journal of Environmental Studies* 24(2): 725–733.

Wan, J. Z., C. J. Wang, J. H. Yu, S. M. Nie, S. J. Han, Y. G. Zu, C. M. Chen, S. S. Yuan, and Q. G. Wang. 2014. "Model-Based Conservation Planning of the Genetic Diversity of *Phellodendron amurense* Rupr Due to Climate Change." *Ecology and Evolution* 4(14): 2884–2900. https://doi.org/10.1002/ece3.1133.

Wang, L., J. Liu, J. Liu, H. Wei, Y. Fang, D. Wang, R. Chen, and G. Wei. 2023. "Revealing the Long-Term Trend of the Global-Scale Ginkgo Biloba Distribution and the Impact of Future Climate Change Based on the Ensemble Modeling." *Biodiversity and Conservation* 32: 2077–2100. https://doi.org/10.1007/s10531-023-02593-z.

Wang, Y., H. Liu, Y. Shuai, Y. Huang, Y. Zhang, X. He, and W. Chen. 2023. "Potential Distribution of the Spring Ephemeral Plant *Adonis amurensis* in Northeast China under Future Climate Change." *Ecosphere* 14(5): e4519. https://doi.org/10.1002/ecs2.4519.

Wani, B. A., S. A. Wani, J. A. Magray, R. Ahmad, A. H. Ganie, and I. A. Nawchoo. 2023. "Habitat Suitability, Range Dynamics, and Threat Assessment of *Swertia petiolata* D. Don: A Himalayan Endemic Medicinally Important Plant under Climate Change." *Environmental Monitoring and Assessment* 195(1): 214. https://doi.org/10.1007/s10661-022-10773-7.

Werkowska, W., A. L. Márquez, R. Real, and P. Acevedo. 2017. "A Practical Overview of Transferability in Species Distribution Modeling." *Environmental Reviews* 25(1): 127–133. https://doi.org/10.1139/er-2016-0045.

Yang, Z., Y. Bai, J. M. Alatalo, Z. Huang, F. Yang, P. Xiaoyan, R. Wang, W. Yang, and X. Guo. 2021. "Spatio-Temporal Variation in Potential Habitats for Rare and Endangered Plants and Habitat Conservation Based on the Maximum Entropy Model." *Science of the Total Environment* 784: 147080. https://doi.org/10.1016/j.scitotenv.2021.147080.

Yu, F., T. Wang, T. A. Groen, A. K. Skidmore, X. Yang, K. Ma, and W. Zhifeng. 2019. "Climate and Land Use Changes Will Degrade the Distribution of Rhododendrons in China." *Science of the Total Environment* 659: 515–528. https://doi.org/10.1016/j.scitotenv.2018.12.223.

Yu, J. H., C. J. Wang, J. Z. Wan, S. J. Han, Q. G. Wang, and S. M. Nie. 2014. "A Model-Based Method to Evaluate the Ability of Nature Reserves to Protect Endangered Tree Species in the Context of Climate Change." *Forest Ecology and Management* 327: 48–54. https://doi.org/10.1016/j.foreco.2014.04.020.

Yusup, A., U. Halik, A. Abliz, T. Aishan, M. Keyimu, and J. Wei. 2022. "Population Structure and Spatial Distribution Pattern of *Populus euphratica* Riparian Forest under Environmental Heterogeneity along the Tarim River, Northwest China." *Frontiers in Plant Science* 13: 844819. https://doi.org/10.3389/fpls.2022.844819.

Zhan, P., F. Wang, P. Xia, G. Zhao, M. Wei, F. Wei, and R. Han. 2022. "Assessment of Suitable Cultivation Region for *Panax notoginseng* under Different Climatic Conditions Using MaxEnt Model and High-Performance Liquid Chromatography in China." *Industrial Crops and Products* 176: 114416. https://doi.org/10.1016/j.indcrop.2021.114416.

Zhang, F.-X., L.-H. Yang, C.-J. Wang, C.-H. Zhang, and J.-Z. Wan. 2022. "Distribution and Conservation of Plants in the Northeastern Qinghai-Tibet Plateau under Climate Change." *Diversity-Basel* 14(11): 956. https://doi.org/10.3390/d14110956.

Zhang, J.-T., and R. Wenming. 2010. "Population Characteristics of Endangered Species *Taxus chinensis* var. *mairei* and Its Conservation Strategy in Shanxi, China." *Population Ecology* 52(3): 407–416. https://doi.org/10.1007/s10144-009-0192-y.

Zhang, X., H. Wei, X. Zhang, J. Liu, Q. Zhang, and G. Wei. 2020. "Non-Pessimistic Predictions of the Distributions and Suitability of *Metasequoia glyptostroboides* under Climate Change Using a Random Forest Model." *Forests* 11(1): 62. https://doi.org/10.3390/f11010062.

Zhang, X., H. Wei, Z. Zhao, J. Liu, Q. Zhang, X. Zhang, and G. Wei. 2020. "The Global Potential Distribution of Invasive Plants: *Anredera cordifolia* under Climate Change and Human Activity Based on Random Forest Models." *Sustainability* 12(4): 1491. https://doi.org/10.3390/su12041491.

Zhao, G., X. Cui, J. Sun, T. Li, Q. Wang, X. Ye, and B. Fan. 2021. "Analysis of the Distribution Pattern of Chinese *Ziziphus jujuba* under Climate Change Based on Optimized biomod2 and MaxEnt Models." *Ecological Indicators* 132: 108256. https://doi.org/10.1016/j.ecolind.2021.108256.

Zhou, T., X. Luo, Y. Chunna, C. Zhang, L. Zhang, Y.-B. Song, M. Dong, and C. Shen. 2019. "Transcriptome Analyses Provide Insights into the Expression Pattern and Sequence Similarity of Several Taxol Biosynthesis-Related Genes in Three Taxus Species." *BMC Plant Biology* 19: 33. https://doi.org/10.1186/s12870-019-1645-x.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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