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ORIGINAL PAPER

Climate change impacts on *Taxus baccata* distribution and conservation

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Abstract This study looks at the impact of climate change on the future distribution of *Taxus baccata* L., a species under threat. It examines how altitudinal changes may influence distribution, projecting scenarios to 2100 using the SSPs 585 SSPs 245 scenarios in 20-year intervals. The results show a contraction in distribution in areas such as in Iceland and the United Kingdom, with certain extreme points disappearing. Simultaneously, new suitable areas are expected to emerge in select regions of Asia. The study underscores the significant changes anticipated in the distribution of *T. baccata* due to global climate change. It suggests that the threshold for addressing climate change on this particular species has been exceeded, and emphasizes the need for concerted efforts to mitigate and adapt to climate change impacts on ecosystems and organisms. As climate change affects various aspects of life, the study advocates for sector-wide plans. These would include efficient resource utilization, selecting genotypes for afforestation of this species with lower water requirements, incorporating climate change predictions into management plans, conserving biological and genetic diversity, and developing *in-situ* and *ex-situ* conservation strategies. Anticipation of future climate changes and corresponding measures in response are crucial to minimizing the impact on this species. The study recommends establishing mixed forests composed of species resilient to a range of climate scenarios, thereby enhancing forest continuity across regions with varying degrees of climate impact. Genetic diversity is an important defense mechanism important to preserving it. Global climate change will result in significant alterations in the distribution of certain species, potentially causing population declines. Intervention is required to support the adaptation of vulnerable species, necessitating forward-looking strategies that anticipate shifts in their habitat suitability. This study emphasizes the implications of climate change for *T. baccata* and underscores the urgency of targeted conservation efforts to protect its populations and ensure long-term persistence.

Keywords Global climate change · *Taxus baccata* · SSPs 245 · SSPs 585

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Introduction

Climate is a major influence on living organisms (Williams and Newbold 2020; Zhao et al. 2023). Climate, particularly temperature, critically influences the distribution of animals requiring stable body temperatures. Warm-blooded animals, which have this characteristic, have developed adaptation mechanisms like migration, hibernation, and molting to cope with climatic fluctuations (Carey et al. 2003; Beltran, 2018; Hobson et al. 2019; Deng et al. 2025).

In contrast, plants are immobile and thus at greater risk from abrupt shifts in climate, which may lead to individual, population, and species-level extinction (Gritti et al. 2006). This risk is heightened for species with long life cycles as they are particularly vulnerable to the impacts of climatic changes. Consequently, global climate change will have a profound impact on the integrity of forests, often composed of long-lived species (Iverson and Prasad 2002; Hamann and Wang 2006; Wang et al. 2013; Gajurel et al. 2014; Krishnan et al. 2019; Feng et al. 2025; Zhou et al. 2025).

Like all living organisms, the phenotypic traits of tree species are shaped by the environment within limits set by their genetic makeup (Li et al. 2020b). Hence, the impact of climate change on their distribution is unavoidable because of their limited ability to respond to climate changes. Over the Earth's estimated 4.6-billion-year history, the climate has undergone numerous changes. For instance, during the Cretaceous period, temperatures were approximately 10 °C higher than today, and atmospheric CO_2 levels were 4–8 times greater (Zachos et al. 2008; O'Brien et al. 2017).

Natural climate changes over the Earth's history have driven glaciation, sea level fluctuations, and shifts in ecosystems due to natural forces (Zachos et al. 2008; O'Brien et al. 2017). However, a concern of contemporary climate shifts is their anthropogenic origin. Rapid population growth has spurred industrial activities to meet increasing demands, resulting in significant human-induced ecological damage. The extraction and combustion of fossil fuels have led to higher concentrations of pollutants, particularly CO_2, a gas that contributes to the greenhouse effect and accelerates climate change (Zachos et al. 2008; Rosa et al. 2015; O'Brien et al. 2017). This rapid change surpasses the ability of many plant species to adapt, leading to significant losses.

The impacts of climate change on ecosystems are complex and multifaceted. Human activities to satisfy global demands—particularly housing, food production, and energy generation—have significantly elevated emissions of key greenhouse gases: methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). This increase in greenhouse gases disrupts the natural greenhouse effect, causing atmospheric warming (Bach 1981; Wuebbles and Jain 2001; Montzka et al. 2011; Manabe 2019). Pollution, urbanization, and climate change are interconnected challenges that threaten living organisms, ecosystems, and the planet's balance of energy, water, carbon, and ecosystems, and are the most critical issues of the twenty-first century (Gritti et al. 2006; McCarthy et al. 2010; Chapman et al. 2017; Afifa et al. 2024).

Significant human-induced climate alterations are a result of industrial activities underscores the severity of the upcoming changes. These global shifts will have far-reaching impacts on all living organisms and ecosystems. Global climate change is recognized as an irreversible, paramount issue requiring urgent intervention (Heller and Zavaleta 2009; Weart 2010; Rosenzweig and Neofotis 2013; Hansen and Stone 2016; Enríquez-de-Salamanca et al. 2017). Given that halting or reducing climate change is no longer feasible, it is essential to anticipate its impacts and to implement measures to mitigate its effects (Gritti et al. 2006). Sector-specific initiatives are crucial for these preventative measures and to thoroughly evaluate the impacts of climate change through a multidimensional approach (López et al. 2020).

There is a general consensus that the effects of climate change will be highly complex and uncertain. Widely accepted projections indicate that these will manifest as higher temperatures, unpredictable precipitation patterns, and increased drought (Ponce-Reyes et al. 2012; Kogan et al. 2013; Dai et al. 2018). Among living organisms, plants are particularly susceptible to these changes due to their immobility, with trees as one of the most affected (Liu et al. 2013; Wang et al. 2013; Gajurel et al. 2014; Krishnan et al. 2019; Feng et al. 2025; Zhou et al. 2025).

Forest ecosystems characterized by tree species with lengthy life cycles, will be most profoundly impacted. Consequently, there is an imperative to identify possible changes in distribution tree species. Assisting the migration mechanisms of species is essential to minimize population losses. Consequently, this study aims to determine possible altitudinal changes in the distribution of the European yew (*Taxus baccata* L.) based on various scenarios envisaged in the context of climate change.

Materials and methods

This study utilized the database of *T. baccata*, a species with widespread global distribution (EUFORGEN 2020). *Taxus* species thrive in areas of high humidity, typical of temperate oceanic climates. The species forms dense, pure stands stretching from Central Europe to the United Kingdom, often growing in moist niches as small clusters or single trees. The European yew is also found in moist areas among other tree species on north-facing slopes. Notably, these yew trees are among the longest-living organism in Europe, with some surviving up to 5,000 years. Despite their longevity, the species face significant threats, with regions of Europe and the former Soviet Union experiencing local extinctions and population decline over the past 4,000 years, a trend that continues (Linares 2013; Rounsevell 2018; Fischer et al. 2018; Rounsevell et al. 2018). This decline raises concerns about the future of the species.

The MaxEnt 3.4.1 program (Phillips and Dudík 2008; Na et al. 2018; Lissovsky et al. 2021; Zhao et al. 2023) was employed to model the potential and current distribution of *T. baccata*, and ArcGIS 10.5 (ESRI 2017) was used to prepare map representations. MaxEnt 3.4.1 operates on the principle of maximum entropy, estimating functions that correlate environmental variables with habitat suitability to analyze a species ecological and potential distribution (Phillips and Dudík 2008; Na et al. 2018; Lissovsky et al. 2021; Zhao et al. 2023). Although designed to use only available data, the MaxEnt method effectively models habitat suitability by predicting the probability of a species presence with real or representative data (Austin 2007; Miller 2010). Before carrying out species distribution modeling with WorldClim data, all bioclimatic variables relevant to *T. baccata* were tested. To best represent the current and future distribution of the species, 19 bioclimatic variables were analyzed. This study adopted a methodology commonly used in research assessing tree species suitable distribution changes due to global climate change.

Results

Model performance and contribution of environmental variables

The modeling yielded a validation value of 0.678 (AUC > 0.5) for the training data in the ROC curve and 0.677 (AUC > 0.5) for the test data, indicating a high predictive power of the model (Fig. 1). Using the Jackknife option to create a gain table for *T. baccata* in the model, it was found that the environmental variable with the most substantial impact on the species distribution in the training data was the "mean temperature of coldest quarter," followed by "minimum temperature of coldest month" and "annual mean temperature." These results underscore the significant influence of the temperature regime on the species, highlighting its sensitivity to temperature-related factors.

Future possible distribution of *Taxus baccata*

The model results for *T. baccata*'s future (2040, 2060, 2080, and 2100) are shown in Fig. 2 for the SSPs245 and SSPs 585 scenarios.

Upon examination of the maps depicting the possible future distribution of *T. baccata*, projections under the SSP2-4.5 scenario suggest a notable northward shift and expansion within parts of its native range, particularly in the United Kingdom after 2060. Additionally, the model forecasts potential climatic suitability in non-native regions such as parts of North America. Conversely, a significant decrease is projected in Iceland, with reductions and possible local extinctions at range margins. For scenario SSPs 585, an increase in distribution is foreseen for North America until 2060, followed by a decline. Additionally, substantial reductions are predicted for Iceland, habitat losses in the northern United Kingdom, and the emergence of new habitat areas in Iran and Asia. Numerical data detailing the changes in the potential altitudinal spatial distribution of *T. baccata* over time are shown in Table 1.

The results in Table 1 reveal that the area of potential distribution of *T. baccata* is primarily concentrated at lower altitudes, with a limited presence at altitudes exceeding 2000 m. Under the SSPs 245 scenario, a notable decrease is predicted in the total suitable distribution area from the present until 2040, followed by an anticipated increase. Conversely, the SSPs 585 scenario projects a substantial decrease from the year 2060, accompanied by a general upward shift in altitude. Numerical data detailing the proportional changes in the potential distribution area of *T. baccata* over time are in Table 2.

Discussion

This study highlights the likelihood of substantial altitudinal changes in the distribution of *T. baccata* due to climate change. This will result in significant habitat loss in some regions while giving rise to new habitat areas in others. Population declines are anticipated in areas experiencing habitat loss, yet the species faces challenges as natural migration to newly available areas become unfeasible. Inevitably, species and population losses are foreseen under these changing conditions.

Research has shown significant changes in the natural distribution of *Taxus* species as a result of climate change. The current habitat for *T. baccata* in Iran covers approximately 6200 km^2. Under the optimistic RCP 2.6 scenario, they projected that only 18% of these habitats would retain their suitability for the species by 2050 due to climate change. In contrast, under the pessimistic RCP 8.5 scenario, this is expected to drop to 3%. By 2070, only 12% of the present suitable habitats is expected to persist under the RCP 2.6 scenario, whereas no stable suitable habitats are anticipated under the RCP 8.5 scenario (Alavi et al. 2019; Ahmadi et al. 2020; Calvia et al. 2024).

Li et al. (2022) provide projections for potential distribution changes of *Taxus wallichiana* var. *mairei* Lemée & H. Lév. Pilg in China, forecasting a decrease of 6.5% and an increase of 23.1% by 2070 under the RCP 4.5 scenario, and a decrease of 5.5% and an increase of 19.8% under the RCP 6.0 scenario. This means *Taxus wallichiana* var. *mairei*'s overall potential distribution may shift, likely moving geographically or altitudinally, but with complex regional patterns of loss and gain. Rathore et al. (2019)

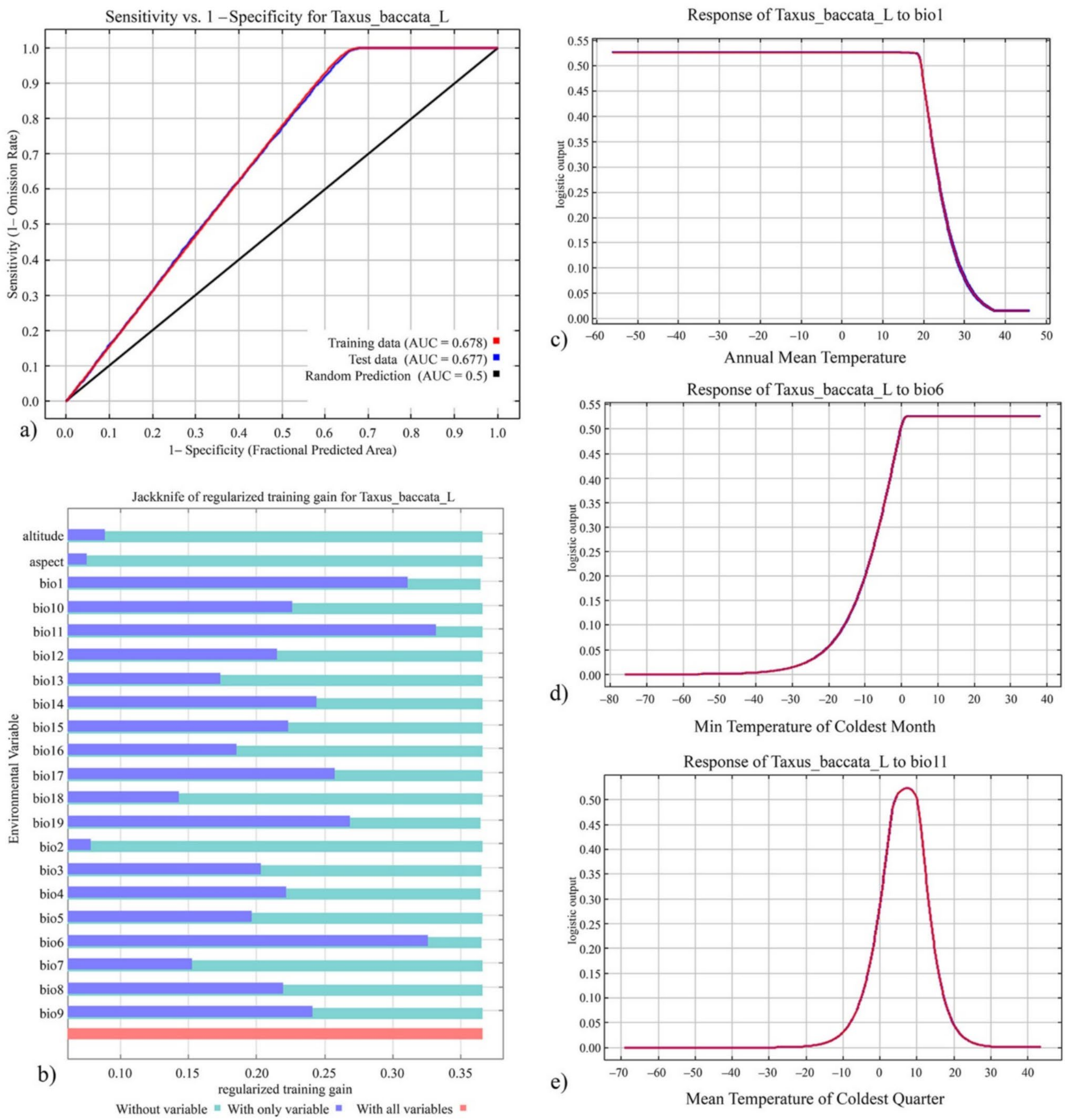

Fig. 1 **a** ROC curve-AUC the model of the value, **b** effect of variables of environmental, **c**, **d**, **e** curves of response

made projections for 2070, suggesting a distribution decrease of 22% in the Himalayas, 27% in Hindu Kush and China, and 49% in Southeast Asia under RCP 4.5, and 12% in the Himalayas, 30% in Hindu Kush and China, and 65% in Southeast Asia under RCP 8.5. Additionally, Chhetri et al. (2018) highlighted anticipated changes in the suitable distribution areas of *T. wallichiana* Zucc. Populations in Central and Eastern Nepal, with some areas of suitable habitat disappearing while new ones emerge. However, the natural migration of the species to these new areas is considered impractical and needing assisted migration mechanisms. Li et al. (2020b) estimated that areas of high suitability for *T. wallichiana* would decrease by 30–56%, and moderately suitable areas would decrease by 21–32% in the Himalaya-Hengduan Mountain region, with an

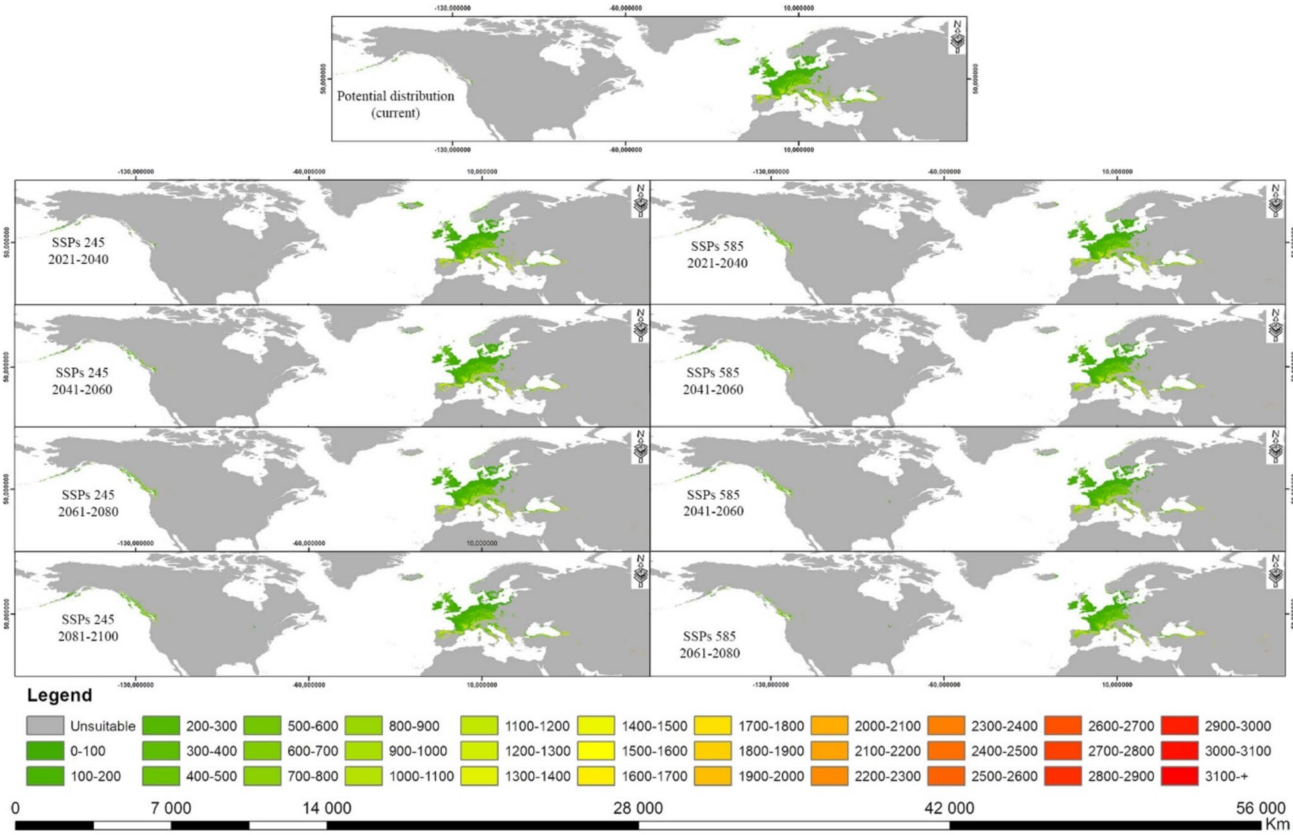

Fig. 2 Potential distribution of *Taxus baccata* (Although the legend includes multiple suitability classes, only areas with high predicted suitability (above threshold) are visible in the map due to the distribution of model output values)

Table 1 Changes of proportional area according to the model

Altitude (m)	2020 (km^2)	ssps245 (km^2)				ssps585 (km^2)			
		2040	2060	2080	2100	2040	2060	2080	2100
Unsuitable	146,946,176	147,058,828	147,011,848	146,974,647	146,972,571	146,955,186	146,955,552	147,050,269	147,357,361
0–200	980,746	936,280	991,892	1,002,808	985,556	964,630	979,940	983,419	757,944
200–400	371,849	345,270	347,931	352,070	358,773	352,363	352,241	332,682	288,791
400–600	239,686	225,890	224,706	233,741	241,615	239,344	241,225	221,311	197,919
600–800	143,651	132,589	132,052	142,380	146,007	155,982	153,284	134,653	128,096
800–1000	104,765	94,998	94,815	97,281	97,611	111,541	106,059	91,835	90,432
1000–1200	70,947	65,623	63,718	64,378	63,609	73,926	70,091	59,189	55,868
1200–1400	42,451	40,985	38,569	38,482	37,811	45,283	42,292	34,758	29,997
1400–1600	22,953	22,867	20,365	20,218	19,790	24,089	21,817	18,118	16,507
1600–1800	10,024	10,268	8925	8766	8729	10,231	9266	8192	8437
1800–2000	4261	4358	3260	3028	3455	3883	3651	2869	3578
2000–2200	1575	1526	1025	1074	1514	1599	1587	1135	1929
2200–2400	525	415	415	512	1086	855	1062	757	1135
2400–2600	171	110	269	354	879	537	855	476	805
2600–2800	74	36	183	183	610	354	574	257	635
2800–3000	134	0	49	110	379	220	354	122	452
3000+	61	0	24	12	48	24	195	0	158

Table 2 Proportional change in *Taxus baccata*'s potential distribution

Altitude (m)	2020 (%)	ssps245 (%)				ssps585 (%)			
		2040	2060	2080	2100	2040	2060	2080	2100
Unsuitable	98.66	98.74	98.71	98.68	98.68	98.67	98.67	98.73	98.94
0–200	0.65849	0.62863	0.66596	0.67329	0.66171	0.64767	0.65794	0.66028	0.50890
200–400	0.24966	0.23181	0.23360	0.23638	0.24089	0,23,658	0.23650	0.22336	0.19389
400–600	0.16093	0.15166	0.15087	0.15694	0.16223	0.16070	0.16196	0.14859	0.13288
600–800	0.09645	0.08902	0.08866	0.09560	0.09803	0.10472	0.10291	0.09041	0.08601
800–1000	0.07034	0.06378	0.06366	0.06532	0.06553	0.07489	0.07121	0.06165	0.06072
1000–1200	0.04764	0.04406	0.04279	0.04322	0.04271	0.04963	0.04706	0.03974	0.03751
1200–1400	0.02850	0.02752	0.02590	0.02584	0.02538	0.03040	0.02839	0.02334	0.02014
1400–1600	0.01541	0.01535	0.01367	0.01357	0.01329	0.01617	0.01464	0.01217	0.01108
1600–1800	0.00673	0.00690	0.00599	0.00589	0.00586	0.00687	0.00622	0.00550	0.00567
1800–2000	0.00286	0.00293	0.00219	0.00203	0.00232	0.00261	0.00246	0.00192	0.00240
2000–2200	0.00106	0.00103	0.00069	0.00072	0.00102	0.00107	0.00107	0.00076	0.00130
2200–2400	0.00035	0.00028	0.00028	0.00034	0.00073	0.00058	0.00071	0.00051	0.00076
2400–2600	0.00012	0.00007	0.00018	0.00023	0.00059	0.00036	0.00057	0.00032	0.00054
2600–2800	0.00004	0.00003	0.00012	0.00012	0.00041	0.00023	0.00039	0.00018	0.00043
2800–3000	0.00009	–	0.00003	0.00007	0.00026	0.00015	0.00024	0.00008	0.00031
3000 +	0.00004	–	0.00002	0.00001	0.00004	0.00002	0.00013	–	0.00011

upward shift in the average altitude of potentially suitable areas from 400 to 950 m.

Similar results have been observed for other tree species. Gómez-Pineda et al. (2020) indicated that habitat loss in mountainous regions of Mexico could reach 80% by 2060. Li et al. (2020a) suggested that approximately 24%–60% of trees in China would face vulnerability under universal migration by 2070. The distribution of *Fagus sylvatica* L. in Europe could decrease by up to 58% (Somogyi 2016; Cavin and Jump 2017). These studies underscore the widespread impacts of climate change on the distribution of tree species, with implications for habitat loss and increased vulnerability across different regions.

Climate is the pivotal factor influencing species adaptation, although the specific climatic parameters affecting adaptability can vary. In this study, the environmental variable most significantly influencing the distribution of *T. baccata* was the "mean temperature of the coldest quarter," followed by the "minimum temperature of the coldest month" and "annual mean temperature." Studies on related species reveal different influencing factors; for *Taxus chinensis*, the primary variable affecting its distribution is the "mean temperature of the coldest quarter," and for *Taxus mairei*, Lemée & H. Lév. SY. Hu it is "precipitation of the warmest quarter" followed by the "mean temperature of the coldest quarter" (Wu et al. 2022). In the Himalaya-Hengduan Mountain region, a study identified that the most crucial environmental variables affecting *T. wallichiana* habitats werer "isothermality," "temperature seasonality," and "annual precipitation" (Li et al. 2020b). For *T. wallichiana* var. *mairei*, Li et al. (2022) highlighted that the precipitation of the driest month accounts for 55.5% of the total variables as the most influential factor. Rathore et al. (2019) found that the mean temperature of the coldest quarter was the primary factor affecting the distribution of *T. wallichiana*.

These findings emphasize the species-specific nature of climatic variables shaping species distribution patterns. Temperature and precipitation are the pivotal factors determining the habitat of *Taxus* species. Studies indicate that the most significant changes anticipated with global climate change are expected to be temperature increases and changes in precipitation. Given this, a shift towards higher altitudes in the distribution of species seems plausible. It is well-established that for every 100-m increase in altitude, temperatures drop by 1 °C in dry air and 0.6 °C in humid air. Thus, the expected upward shift in distribution in terms of altitude aligns with these established climatic principles, as temperatures increase due to global warming.

Climate change will have multidimensional effects on ecosystems, functioning within a complex framework. Beyond alterations in temperature and precipitation regimes, changes in climatic parameters are expected to introduce stressors, including increases in UV-B radiation (Strid et al. 1994; Huttunen et al. 1998; Liu et al. 2013; Qian et al. 2021; Bernal-Escobar et al. 2025). These will trigger plant stress mechanisms, leading to reductions in biomass growth, partial withering, yield loss, and other impacts that hinder plant development (Abramoff et al. 2023; Yuan et al. 2024; Oliva et al. 2025). The interconnected nature of these effects highlights the intricate challenges posed by global climate change to plant ecosystem health, development, and sustainability.

Conclusion

The findings of this study underscore the potential for changes in distribution of *T. baccata* due to the impacts of climate change. Previous research has indicated that the point of no return for climate change has already been passed. Consequently, in addition efforts to halt or at least slow this process, measures must be taken to mitigate the effects on living organisms and ecosystems. Global climate change is anticipated to impact every facet of life and will require comprehensive planning and precautions across all sectors. In forestry, some of these precautions will include the efficient utilization of natural resources, the selection of genotypes with lower water requirements, the incorporation of climate change predictions into management plans, the conservation of biological and genetic diversity, and the development and implementation of *in-situ* and *ex-situ* conservation strategies for endangered and potentially endangered species. These strategies are essential for mitigating the detrimental impacts of global climate change on forest ecosystems.

To minimize the impact of climate change on species, anticipation of future changes and corresponding measures are vital. Predicting potential alterations in species distributions and implementing appropriate measures are essential. For example, establishing mixed stands composed of species capable of adapting to both current and projected climate conditions is advisable. This strategy can help conserve some species despite potential losses and improve ecosystem resilience to environmental stressors. This approach may ensure the conservation of certain species even with some species loss and also enhances resilience to various environmental factors. The significant variation in species resistance to external factors underscores the importance of intraspecific genetic diversity. Preserving genetic diversity in forest stands is one of the most crucial defense mechanisms to unforeseeable threats. Therefore, most of the attention should be directed towards the conservation of genetic diversity of tree species as part of comprehensive strategies to mitigate the effects of climate change.

The emphasis on climate change underscores the predicted alterations in species distribution. However, the inability of species to naturally migrate to new suitable areas may lead to potential species and population losses over extensive regions. Acknowledging these possibilities, intervention to assist species to adapt is imperative. Comprehensive action plans should be developed and implemented to ensure the continuity of species and forest ecosystems, and pluralistic approaches adopted in planning that consider potential changes in the distribution of other tree species. The recognition for intervention underscores the urgency of proactive strategies to address the ecological consequences of climate change and foster the resilience of forest ecosystems.

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Data availability The datasets used and/or analyzed during the study are available from the corresponding author on reasonable request.

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