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ORIGINAL PAPER

Modeling potential habitat distribution of scots pine under climate change scenarios

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Abstract Global climate change is impacting organisms and ecosystems on a wide scale, with increasingly visible effects. This ongoing process is anticipated to significantly threaten species and populations, especially plants that lack mobility, potentially causing large-scale losses in the near future. To mitigate these impacts, it is essential to understand how long-lived forest trees will respond to climate shifts and to facilitate necessary migration mechanisms through human intervention. This study aims to model the suitable habitat distribution of Scots pine (*Pinus sylvestris*), a crucial forest tree species in Türkiye, under two climate scenarios (SSP245 and SSP585) for the present and future years (2040, 2060, 2080, and 2100) using the Maxent entropy model, with mapping support from ArcGIS software. Habitat suitability was analyzed with 21 parameters (19 bioclimatic and 2 topographic). Jackknife test results indicated that Mean Temperature of the Driest Quarter (Bio9) and Mean Temperature of the Warmest Quarter (Bio10) were the most influential parameters on the species' distribution. The findings showed that under the SSP245 scenario, the suitable habitat for Scots pine is projected to decline to 83.63% of its current range by 2060, then increase to 106.02% by 2100. For the SSP585 scenario, the area is projected to decrease to 81.89% by 2060 and reach 96.13% by 2100. Populations in Türkiye's southern and Marmara regions face high risks of near-total loss. To sustain Scots pine in new suitable habitats, adjustments to current forest management plans and silvicultural practices are needed to align with climate change projections.

Keywords Scots pine · Climate change · Maxent · Habitat suitability · Bioclimatic factors

Introduction

The global population has nearly reached 8 billion, marking a historic peak and intensifying the challenges of resource management and environmental sustainability (Pimentel and

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Pimentel 2006). Industrial progress has accelerated urbanization, causing significant shifts in population distribution and increasing the strain on urban areas (Luo et al. 2020; Kalayci et al. 2025). The demand for raw materials has driven extensive mineral extraction, contributing to irreversible heavy metal pollution in both terrestrial and aquatic ecosystems (Lu et al. 2015; Sun et al. 2018; Cetin et al. 2023, 2025). As a result, the interlinked issues of urban expansion and atmospheric pollution have emerged as critical global concerns. These problems alter atmospheric composition, accelerating climate change, a process now regarded as a major, possibly irreversible threat to biodiversity and ecosystem stability (Omann et al. 2009; Liang et al. 2019; Saxena 2025).

Current research indicates that global climate change is an ongoing process that humanity must accept and adapt to in order to mitigate its most severe impacts (Adger et al. 2003). Monitoring these climatic shifts and developing adaptive strategies has become imperative, particularly as their effects intensify year after year (Khan and Roberts 2013). Climate, as the primary environmental determinant, shapes the phenotypic traits of all organisms, thus even minor shifts can have substantial effects on biodiversity (Przybylo et al. 2000; Chapin 2003; Bijlsma and Loeschcke 2005; Somero 2010; Steudel et al. 2012). Plants, in particular, face unique vulnerabilities due to their limited ability to migrate. Though plants possess natural migratory mechanisms, the rapid pace of anthropogenic climate change outpaces their adaptive capacity. This mismatch suggests that without human intervention, many plant species may face extinction, as their natural mechanisms cannot keep up with current climate shifts. Assisting plant migration could help mitigate the projected losses in biodiversity.

Forests are among the ecosystems most at risk, due to their long-life cycles and sensitivity to environmental changes. Addressing the impact of climate change on forests involves assessing the effects on key tree species and implementing strategies to aid their distribution shifts. Scots pine (*Pinus sylvestris* L.), a critical species in the Northern Hemisphere and Türkiye, represents one such species requiring careful study. This research aims to evaluate the potential impact of climate change on the distribution of Scots pine, highlighting the importance of proactive management in forest ecosystems.

Materials and methods

Scots pine (*P. sylvestris*) has a broad distribution across Eurasia (Fig. 1) and is highly adaptable, thriving in diverse climates and ecological habitats. This species, which has several varieties, holds considerable economic value, particularly in northern Europe, where its easily processed wood is widely used in construction, furniture, and the pulp

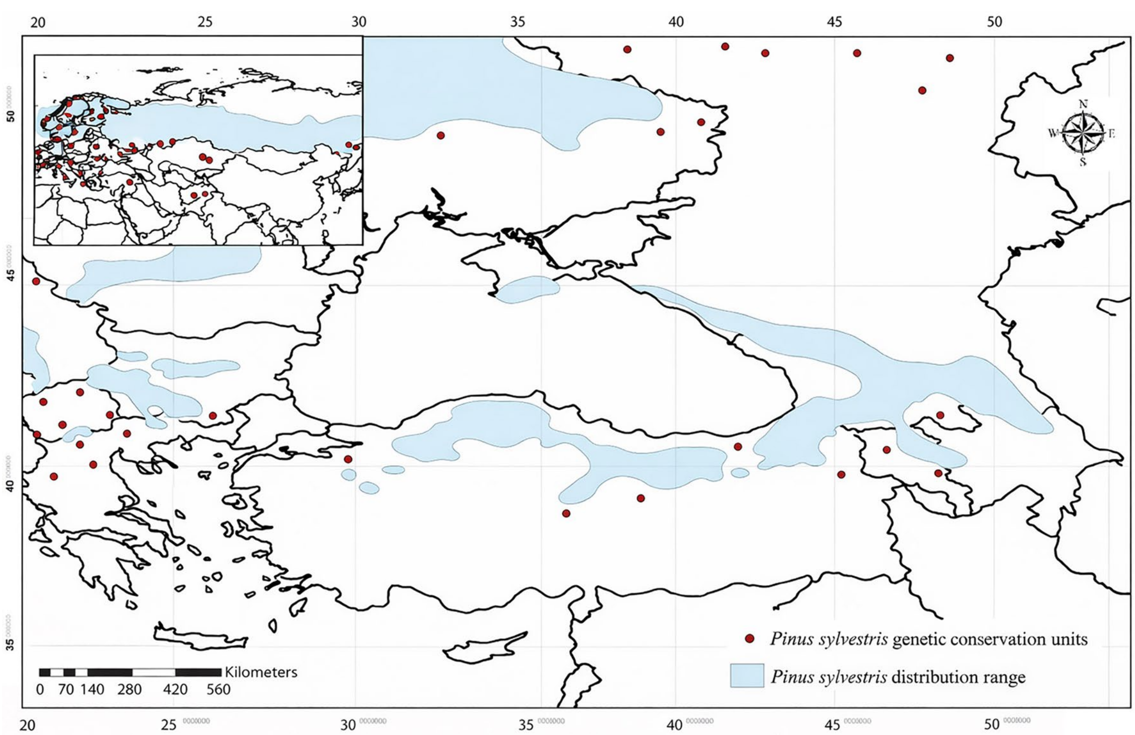

Fig. 1 Global and Türkiye distribution of Scots pine (*Pinus sylvestris* L.)

Table 1 Bioclimatic variables used in the model

Code	Bioclimatic variable	Unit
B1	An Mean Temp	°C
B2	Mean Diurnal Range (Monthly Mean of [Max Temp – Min Temp])	°C
B3	Isothermality (B2/B7 * 100)	–
B4	Temp. Seasonality (Standard Dev. * 100)	Coefficient of variation, °C
B5	Max Temp. of Warmest Month	°C
B6	Min Temp. of Coldest Month	°C
B7	Temp. Ann Range (B5 – B6)	°C
B8	Mean Temp. of Wettest Quar	°C
B9	Mean Temp. of Driest Quar	°C
B0	Mean Temp. of Warmest Quar	°C
B11	Mean Temp. of Coldest Quar	°C
B12	Ann Precip	mm
B13	Precip of Wettest Month	mm
B14	Precip of Driest Month	mm
B15	Precip of Seasonality (Coeff of Var)	Percent
B16	Precip of Wettest Quar	mm
B17	Precip of Driest Quar	mm
B18	Precip of Warmest Quar	mm
B19	Precip of Coldest Quar	mm
Q	Emberger Climate Class	–

and paper industries. Scots pine is also employed in stabilizing sandy soils due to its tolerance for poor soils, drought, and frost. Known as a pioneering species, it can colonize nutrient-deficient soils in degraded areas. Scots pine grows at altitudes up to 2600 m (Euforgen 2023) and typically ranges from 1000 to 2500 m in Türkiye.

This research evaluates the potential impact of global climate change on the distribution of Scots pine (*P. sylvestris* L.), a significant species for Türkiye. The distribution modeling was carried out using Maximum Entropy (MaxEnt) software, incorporating 19 bioclimatic variables (Table 1) alongside two topographic factors, elevation and aspect. Projections were based on Shared Socioeconomic Pathways (SSPs) 245 and 585, outlined in the IPCC's Sixth Assessment Report (2021), and were made for the years 2040, 2060, 2080, and 2100 using WorldClim data. MaxEnt was selected for its strength in modeling species distributions under climate pressure, especially with limited occurrence data, and its capability to assess the significance of environmental variables while predicting shifts in species distribution (Elith et al. 2011).

The accuracy of the species distribution models was validated using Receiver Operating Characteristic (ROC) curve analysis, Area Under the Curve (AUC) metrics, and the Jackknife test, which helped determine the influence of each environmental variable on model performance (Phillips and Dudík 2008; Merow et al. 2013; Phillips et al. 2017; Ayugi et al. 2021; Feyissa et al. 2023).

The SSP framework includes five major scenarios—SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5—which project different pathways of societal development and greenhouse gas emissions (O'Neill et al. 2017). This study utilized SSP2-4.5 and SSP5-8.5 to assess potential environmental impacts. These scenarios, consistent with the IPCC's Sixth Assessment Report, offer projections of greenhouse gas levels based on different levels of human-induced emissions (IPCC 2021).

Additionally, the study employed the CNRM-CM6-1 climate model from the Centre National de Recherches Météorologiques, which provides detailed atmospheric data, including stratocumulus cloud representation, at a spatial resolution of 2.5 min (Voldoire et al. 2019). Model effectiveness was evaluated using ROC and AUC analyses, with variable importance assessed through Jackknife testing (Mouton et al. 2010; Jiménez-Valverde 2012).

Results

The ROC curve validation value for the training data was 0.919 (AUC > 0.5), while for the test data it was 0.899 (AUC > 0.5), indicating that the model had a high predictive accuracy (Fig. 2a).

According to the Jackknife test results, five variables significantly contributed to the distribution of the species, with Mean Temperature of Driest Quarter [Bio9] and Mean Temperature of Warmest Quarter [Bio10] providing the highest contributions (> 45%) (Fig. 2b). These were followed by Annual Mean Temperature [Bio1], Precipitation Seasonality [Bio15], and Max Temperature of Warmest Month [Bio5]. The effects of these five variables on habitat suitability for *P. sylvestris* are displayed in Fig. 2c–g. Response curves illustrating the relationship between environmental factors and species occurrence (Abolmaali et al. 2018) show that *P. sylvestris* favors habitats where the annual mean temperature is between 8.0 and 16.0 °C and where the mean temperatures during the driest and warmest quarters do not exceed 26 °C.

As global warming values increase from 4.5 W to 8.5 W m^{-2}, Bio15 and Bio10's contribution to the model by 2100 is not statistically significant in terms of contribution percentage and permutation importance values, whereas Bio1 shows a statistically significant increase in its contribution (from 0.913 to 13.864) (Table 2). This suggests that the distribution of the species is significantly influenced by temperature patterns. Additionally, Bio15, which contributes optimal conditions for species distribution between 15 and 25 mm, remains significant in both short-term (2040) and long-term

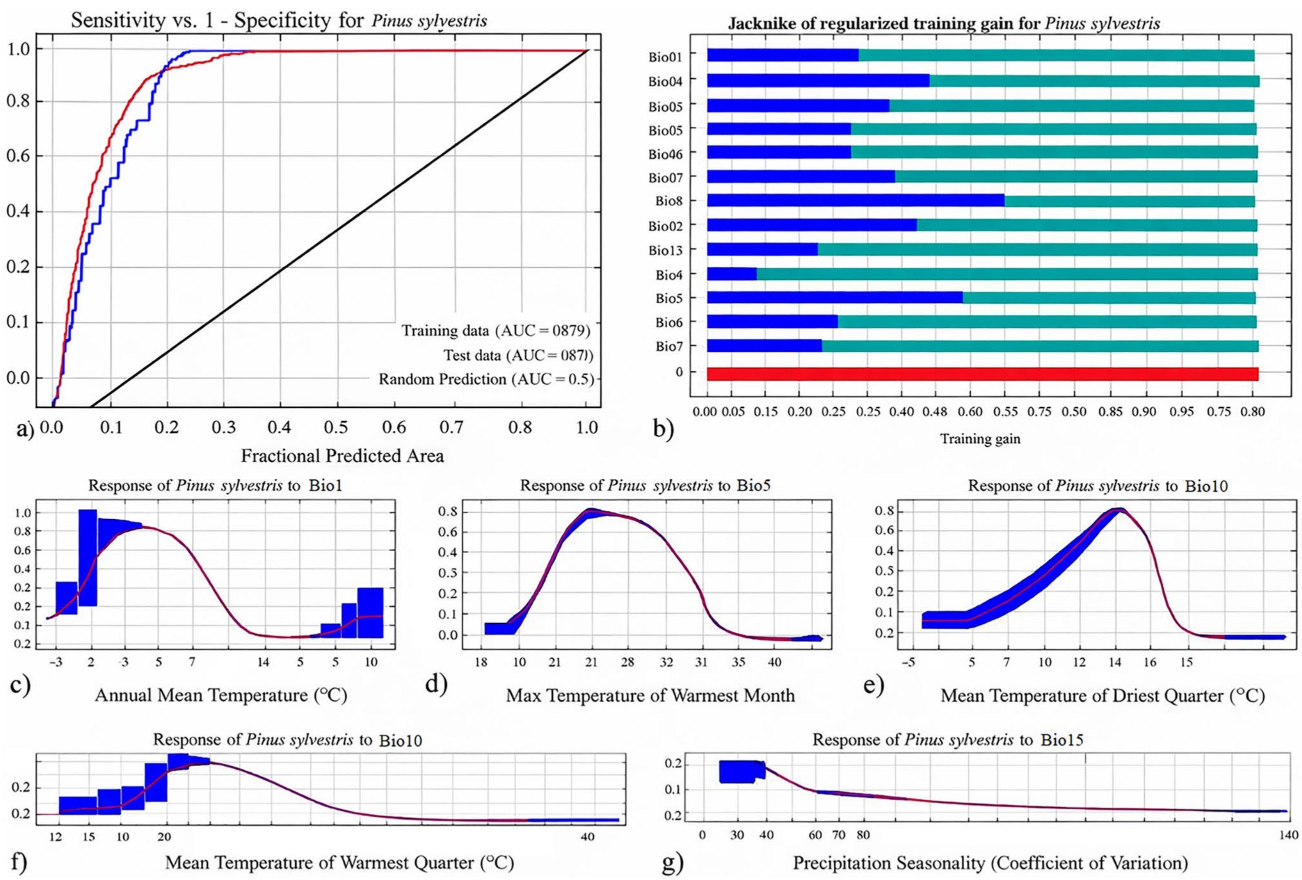

Fig. 2 Influence of environmental variables on *Pinus sylvestris* distribution

Table 2 Mean contribution and permutation importance of predictors under SSP2-4.5 and SSP5-8.5 scenarios

Variables	Percentage contribution				Permutation importance			
	SSPs 245		SSPs 585		SSPs 245		SSPs 585	
	2040	2100	2040	2100	2040	2100	2040	2100
Bio9	3.465	0.015	0.067	8.374	0.615	0.308	0.636	0.522
Bio10	17.221	19.478	14.959	13.795	3.453	0.239	3.104	2.546
Bio1	0.586	0.913	7.726	13.964	1.753	2.030	3.766	3.842
Bio15	37.267	25.061	29.459	30.139	31.948	34.985	34.086	38.593
Bio5	4.976	3.280	0.276	1.893	1.914	2.388	0.064	4.238

(2100) projections in terms of contribution percentage and permutation importance.

The potential distribution areas of *P. sylvestris* under SSPs 245 and SSPs 585 climate scenarios are shown in Fig. 3.

In the SSPs 245 scenario, the distribution area of *P. sylvestris* is expected to decrease after 2060, particularly in southern regions, and potentially disappear in southwestern Türkiye by 2100. In SSPs 585, this reduction could occur even earlier, with the species disappearing from both southwestern and southeastern regions by 2040. Limited distribution areas in the northern Marmara region are projected to decline by 2100 under SSPs 245, while under SSPs 585, they may start shrinking by 2060 and vanish by 2100 (Table 3).

Table 3 outlines the projected changes in suitable distribution areas of *P. sylvestris* for the years 2040, 2060, 2080, and 2100 compared to current levels. According to SSPs 245, the suitable distribution area is predicted to decrease to 99.27% of its current level by 2040, then to 83.63% by 2060. Following this, a slight recovery is expected, with

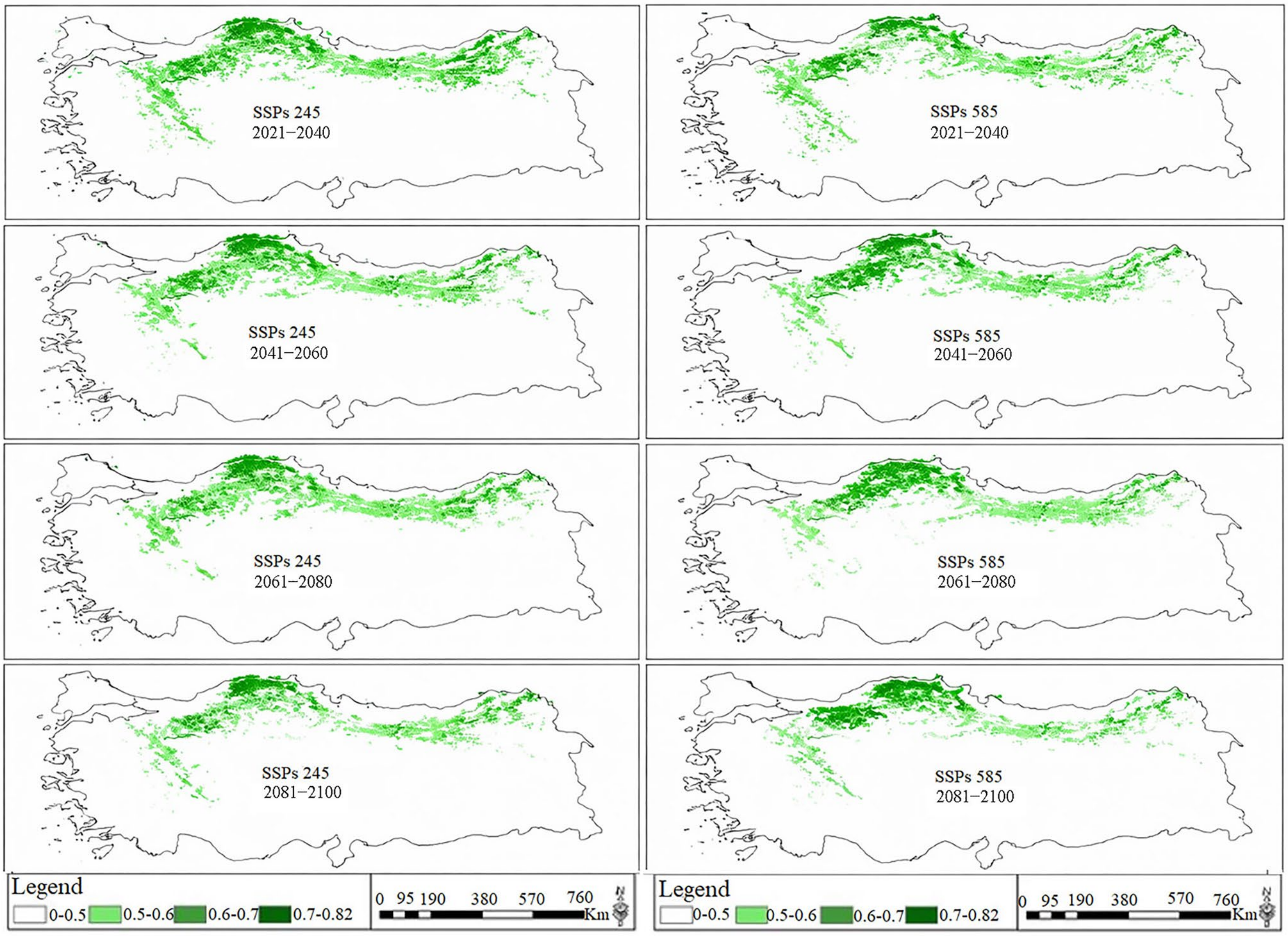

Fig. 3 Projected distribution of *Pinus sylvestris* under SSP2-4.5 and SSP5-8.5 scenarios

Table 3 Projected changes in the suitable range of *Pinus sylvestris*

Models	Potential distribution (current)	Years			
		2040	2060	2080	2100
SSPs245	100	99,27	83,63	97,6	106,02
SSPs585		92,94	81,89	93,57	96,13

areas reaching 97.6% by 2080 and expanding to 106.02% by 2100. Under SSPs 585, suitable areas are expected to decrease to 92.94% of their current level by 2040 and to 81.89% by 2060. However, with a slight recovery, the proportion of suitable habitat in these areas is projected to reach 93.57% by 2080 and 96.13% by 2100.

Discussion

General trend of habitat changes under climate change

The results of this study indicate that, influenced by climate change, the suitable habitat for Scots pine (*P. sylvestris* L.) in Türkiye may experience shifts in distribution, with an overall decline projected up until 2060, followed by a minor expansion thereafter. These findings align with previous studies that anticipate substantial alterations in species biota due to climate impacts (García-Valdés et al. 2015). In other research focusing on forest trees in Türkiye, similar changes in natural distribution ranges have been forecast, typically showing habitat contraction in response to global climate trends. For instance, it has been estimated that suitable habitats for *Tilia platyphyllos* could reduce by around 15% and for *Fraxinus excelsior* by 9% (Neirynck et al. 2000), with similar or even larger impacts projected for other species in various regions worldwide. In China, up to 23–57% of tree species may face habitat risks by 2070 (Przybylo et al. 2000), and mountainous areas in Mexico may experience habitat losses between 46 and 77% for several species by 2060 (Gómez-Mendoza and Arriaga 2007; Hanberry 2026).

Regional and species-specific impacts on Scots pine

These trends suggest that Scots pine may lose suitable habitat until 2060, with slight recovery expected afterward. This fluctuation points to a high risk of population losses, particularly as the species would require human-assisted migration to adapt to newly suitable habitats. This pattern, seen in other studies, suggests a common challenge for plant species in the face of rapid climate shifts (Cantürk et al. 2024; Zeren Cetin et al. 2025a, b). Regionally, significant population declines are anticipated in Türkiye's Marmara and southern areas, similar to findings in other studies that highlight potential habitat loss in these regions for species such as *Tilia cordata* and *Tilia tomentosa* (Canturk and Kulaç 2021). These shifts are largely attributed to temperature increases, which projections show may rise by as much as 6 °C in Türkiye's Aegean region.

Distributional and altitudinal shifts in tree species

Temperature increases have been noted to potentially expand certain forest areas (Schweiger and Svenning 2024), yet distribution shifts are likely for numerous species. Projections in Europe indicate that species like *F. excelsior* and *Quercus robur* may expand in range, while species such as *Picea abies* and *P. sylvestris* may see reductions (Varol et al. 2021). Altitudinal shifts are also anticipated; for instance, populations of *Carpinus betulus* below 1600 m could decline by over 25% (Varol et al. 2022). Meanwhile, an expansion in suitable habitats for *Abies cilicica* at higher altitudes is predicted, with increases surpassing 30% at elevations above 3000 m by 2040 (Tekin et al. 2022).

Advances in modeling and key variables

Recent studies have further emphasized the importance of integrating high-resolution climatic and edaphic variables into species distribution modeling to better capture the dynamics of tree species under future climate scenarios. Building upon the findings of Abolmaali et al. (2018), who demonstrated the sensitivity of forest species to temperature and precipitation variability, more recent works (Varol et al. 2021, 2022; Tekin et al. 2022; Cantürk et al. 2024; Zeren Cetin et al. 2025a, b) have shown that incorporating topographic and soil moisture indices enhances predictive accuracy and ecological interpretability in Maxent-based projections. Similarly, Zeren Cetin et al. (2025a, b) highlighted the need to account for extreme temperature indices and drought frequency when modeling coniferous species distributions in Eurasia. These studies collectively support the present findings, reinforcing the ecological significance of variables such as Bio9, Bio10, and Bio15, and underscore the novelty of applying updated SSP-based modeling frameworks for regional forest management planning.

Cascading impacts on species physiology and forest ecosystems

Temperature shifts will likely impact species health, quality, and growth rates (Manrique-Ascencio et al. 2024). For example, in Southeast Asia, species like *Chukrasia tabularis* are projected to show a 9–20% decrease in growth, potentially affecting carbon dynamics in tropical forests (Tipu et al. 2021). Increased temperatures and shifts in precipitation, along with stress factors like UV-B radiation, pose additional challenges for plant development and resilience (Ozel et al. 2021). These stressors are likely to compound the pressures of climate change, affecting overall ecosystem health (Gómez-Guerrero and Doane 2018).

Complex interactions and future ecosystem pressures

The broad impacts of climate change on ecosystems are expected to manifest through complex interactions among numerous factors. Rising temperatures may increase the frequency of wildfires and pest infestations (van Lierop et al. 2015), thereby impacting tree vitality, local adaptation, and resilience (Loehman et al. 2017). While some species may suffer from invasive species or habitat loss, others may benefit from higher CO_2 levels, potentially increasing wood production in certain regions (Franks et al. 2014). These effects will result from the interdependent influences of environmental factors on forest ecosystems, including the spread of pests (Volney and Fleming 2000), fungi (Bullington et al. 2026), and changes in water and nutrient cycles (Jones et al. 2009), alongside more frequent and intense forest fires (Pausas and Keeley 2014).

Policy implications and recommendations for forest management

In light of the projected habitat shifts of *P. sylvestris* under changing climatic conditions, the following strategies are recommended to support forest sustainability and adaptive management in Türkiye:

Assisted migration: Actively relocate *P. sylvestris* populations to higher altitudes or northern regions where future climatic conditions are projected to be favorable.

Mixed forest establishment: Promote the development of mixed-species stands to enhance ecosystem resilience, biodiversity, and adaptive capacity against climate-induced stress.

Adaptive silvicultural practices: Incorporate flexible management approaches, such as selective thinning and regeneration with climate-tolerant provenances, to sustain forest productivity.

Monitoring and early-warning systems: Strengthen remote sensing and GIS-based monitoring for early detection of habitat degradation, pest outbreaks, and drought stress.

Conservation of genetic diversity: Preserve local genotypes and seed sources through ex-situ and in-situ conservation to maintain adaptive potential under future climates.

These adaptive measures will contribute to sustaining forest ecosystem services, carbon sequestration capacity, and biodiversity conservation under future climate scenarios.

Conclusion

Global climate change, an irreversible process, will directly and indirectly impact all organisms and ecosystems worldwide. Türkiye, as one of the "countries at risk," is particularly vulnerable to these changes, with projections suggesting more severe impacts here compared to other regions. Since climate change is likely to progress at a pace that plants may struggle to adapt to, it is essential to anticipate changes early to mitigate species and population losses, particularly for those with restricted distribution areas. The varied impacts of climate change on forests necessitate differentiated silvicultural approaches for different species, which depend on the ecological context and adaptive capacities of each species. Therefore, current forest management strategies and silvicultural practices must be revised and redesigned with climate change considerations.

The findings indicate that Scots pine populations in Türkiye will likely experience significant shifts in distribution, with notable losses expected in the southern and Marmara regions. Based on these results, facilitating species migration where Scots pine populations are predicted to decline, introducing suitable species in these areas to prevent deforestation, and establishing mixed forests, which are more resilient to biotic and abiotic stresses compared to monocultures, are recommended.

This study provides a model that can inform similar research efforts. It underscores the importance of conducting similar studies on other species in different regions, developing new models that consider evolving climate and environmental conditions, identifying the most realistic scenarios, and facilitating the artificial migration of species to suitable habitats to reduce species and population losses. Additionally, establishing mixed forests emerges as a vital strategy to address the uncertainties posed by climate change.

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Author contributions Mohammed Miftah Mohammed Bouzqayyah: data curation, methodology, software, writing—review and editing. Dilek Birgul Zeren: data curation, methodology, software, writing—review and editing. Tugrul Varol: conceptualization, methodology, software, validation, visualization, writing—original draft. Hakan Sevik: data curation, methodology, software, writing—review and editing. Ugur Canturk: data curation, methodology, software, writing—review and editing. Halil Baris Ozel: methodology, validation, writing—original draft, writing—review and editing. Mehmet Cetin: methodology, validation, writing—original draft, writing—review and editing.

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

Declarations

Conflict of interests All 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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