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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Potential altitude change of oriental spruce in Türkiye due to global climate change

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Abstract

Global climate change stands as the most consequential challenge capable of directly or indirectly impacting Earth's diverse living organisms and ecosystems. This study aims to clarify the shifts in potential distribution areas of the Oriental spruce, a key tree species widely distributed across Türkiye, which has been observed to shift its distribution toward higher altitudes in recent decades, deviating from its historical natural range. The investigation delves into the species' viable distribution zones across altitude increments, spanning intervals up to the year 2100, scrutinizing two distinct climate scenarios: SSPs 245 and SSPs 585, referring to the Shared Socioeconomic Pathways used in CMIP6 to project greenhouse gas emissions under moderate (SSPs 245) and high (SSPs 585) trajectories. The findings manifest a discernible trend: under the SSPs 245 scenario, there emerges a contraction in suitable zones below 1300 m, accompanied by an upswing above 1300 m. In stark contrast, the SSPs 585 scenario foresees an expansion predominantly within the 1800–2600 m range, juxtaposed with declines across below 1800 m and above 2600 m. In terms of aggregate suitable distribution area, an estimated 13.58% diminution emerges under the SSPs 245 scenario, while a substantial 32.08% reduction surfaces under the SSPs 585 scenario, both by the year 2100. These revelations underscore the imperative for prompt action, not only to safeguard the Oriental spruce but also to inform broader conservation and adaptation efforts in the face of escalating global climate change.

Keywords Oriental spruce · SSPs 245 · SSPs 585

Introduction

Global climate change is an urgent issue with far-reaching impacts on ecosystems and biodiversity. Today, "global climate change" has become an urgent and irreversible global issue that requires consistent, focused attention worldwide. This phenomenon, currently exerting its impact, is poised to reverberate across ecosystems, ultimately embracing all life forms in the future (Cetin et al. 2023). The pervasive influence of climatic parameters on the phenotypic traits of organisms underscores their centrality, given that these parameters stand as the pivotal environmental factors

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directly shaping the existence of organisms (Zeren Cetin 2024).

While acknowledging the intricate and uncertain nature of the process's effects, a consensus prevails regarding certain outcomes, notably an inexorable rise in temperatures, erratic precipitation patterns, and heightened drought occurrences (Koc (Koc, and Koç, 2021)). Forest ecosystems, distinguished by their long-living tree populations, are among the most vulnerable to the impacts of global climate change. The prolonged lifespan of trees heightens their exposure to these environmental shifts. Forests play a critical role in global carbon storage, sequestering approximately 7.6 gigatons of CO_2 annually (Pan et al. (Pan, et al., 2011)), which highlights their influence on the trajectory of global climate change. Notably, forests act as effective and cost-efficient solutions for mitigating global greenhouse gas emissions, with afforestation and reforestation strategies estimated to contribute up to 23% of the total climate mitigation potential by 2030 (Griscom et al. 2017). Consequently, safeguarding forest ecosystems against the perils of global climate change and curtailing species and population losses assumes paramount significance. In this context, a crucial imperative lies in the anticipation of potential shifts in the optimal distribution zones of trees, constituting the foundation of wooded expanses, and the subsequent implementation of requisite measures.

This study aims to identify suitable altitudinal distribution areas for Oriental spruce (*Picea orientalis* L.), a significant tree species for Türkiye, with most of its natural range located within the country's borders.

Material and method

This study draws upon the comprehensive database of Picea orientalis, a widely distributed tree species across Türkiye, as documented by Euforgen (2023). Picea orientalis predominantly spans through Türkiye and the Caucasus region, where it notably thrives in the Eastern Black Sea mountain range. Within this context, it emerges as a dominant constituent of forested landscapes, boasting evergreen foliage and impressive dimensions, often attaining a towering height of 70 m coupled with a diameter ranging from 1.5 to 2 m. This resilient species predominantly populates the wooded expanses on the northern-facing, moisture-laden slopes, situated within an altitudinal range spanning from 50 to 2400 m. It frequently forms pure or blended stands, often mingling with companions like Pinus sylvestris, Abies nordmanniana, and Fagus orientalis, further enhancing the ecological diversity of the region (Güner et al. 2022).

In this study, the MaxEnt 3.4.1 program (Phillips and Dudik 2008)) was used to model both the current and potential distribution areas of *Picea orientalis*. Meanwhile, the visualization of the outcomes was achieved utilizing ArcGIS 10.5 software. (ESRI 2020). MaxEnt's operational approach is based on the principle of maximum entropy, involving the estimation of functions that link environmental variables with habitat suitability. This integration enables assessment of the ecological and potential geographic range of a species (Phillips et al. (Phillips et al. 2017)). Despite its initial design for using solely extant data for species-habitat matching, MaxEnt is acknowledged for its adeptness in dealing with both actual and simulated datasets, showcasing robust performance (Elith et al. 2011, 2020).

Before embarking on the process of modeling species distributions, a meticulous scrutiny of bioclimatic variables and distributions pertinent to Picea orientalis was undertaken. Bioclimatic variables, as utilized by Graham (2003), Garcia et al. (2013), were carefully chosen to thoroughly represent the species' current and potential habitat. The climate model employed in this study features a spatial resolution of 2.5 min and is based on the atmospheric component of the Centre National de Recherches Météorologiques model version 6 (CNRM-CM6-1). Model performance was evaluated using established methods, including Receiver Operating Characteristic (ROC), Area Under Curve (AUC) values, and the Jackknife test, ensuring a thorough validation process (Phillips et al. (Phillips, et al., 2017)). Recent studies continue to validate the CNRM-CM6-1 model and other CMIP6 models, employing robust evaluation techniques like ROC, AUC, and Jackknife tests. For example, studies by Ayugi et al. (2021) and Feyissa et al. (2023) demonstrate the efficacy of these models in simulating regional climate patterns and addressing climate variability, particularly in rainfall prediction across Africa. Additionally, the study on Vietnam used CNRM-CM6-1 to simulate temperature and precipitation changes up to 2100, reinforcing its reliability for climate impact assessments (Voldoire et al. 2019; Duy et al. 2023; Eyring et al. 2016). These studies underscore that CMIP6 models, including CNRM-CM6-1, show notable improvements in spatial resolution and physical representation compared to CMIP5, making them highly valuable for contemporary climate modeling efforts across different ecosystems (Voldoire et al. 2019; Duy et al., 2023; Eyring et al. 2016).

In this study, the initial phase involved the determination of the present suitable distribution areas of the species along with the altitude-related modifications within these areas. Subsequently, the proportional distribution of the species across various altitude ranges was calculated. To achieve this, altitude ranges were divided into 100-m intervals up to 2000 m, and 200-m intervals beyond 2000 m. This stratified approach was chosen for both ecological and statistical reasons. First, over 85% of the current known distribution of Picea orientalis is concentrated below 2000 m (Güner et al. 2022), necessitating finer resolution in this range to

capture potential microclimatic variations and subtle shifts in suitability. Second, at higher elevations, the spatial extent of available habitat decreases significantly and data density becomes sparser, making 200-m intervals more appropriate to avoid overfitting and ensure model stability. This two-tiered strategy ensures a balance between ecological sensitivity and computational robustness in assessing future distributional shifts. The subsequent stage encompassed the modeling of the species' suitable distribution areas based on altitude, spanning 20-year intervals up to the year 2100, incorporating the SSPs 585 SSPs 245 scenarios. With the existing suitable distribution area set as the baseline at 100%, the proportion of the suitable distribution areas in forthcoming years was calculated concerning the present distribution areas while taking altitude into account. Consequently, distinct proportional alterations grounded in altitude were computed and subsequently presented in tabular form to facilitate interpretation.

It is important to note that MaxEnt provides deterministic projections and does not inherently produce confidence intervals for spatial suitability outputs. Although this limits statistical uncertainty quantification, the model's internal validation metrics—such as AUC scores and Jackknife tests—offer robust indications of predictive reliability. Additionally, while this study employed a single-model approach using MaxEnt due to its proven effectiveness for presence-only ecological data, future studies may benefit from ensemble modeling frameworks (e.g., BIOMOD or ensemble SDMs) to compare outputs across multiple algorithms. Moreover, sensitivity analysis of key input parameters—such as regularization multiplier settings or variable selection thresholds—was not conducted in the present study but is highly recommended in follow-up research to evaluate the model's stability and generalizability.

To reduce spatial autocorrelation and sampling bias in the occurrence dataset, a spatial thinning procedure was implemented using a minimum distance threshold of 1 km between points. This ensured spatial independence among training data, improving model reliability and minimizing overfitting risks. While MaxEnt handles presence-only data well, model extrapolation beyond the environmental conditions of the training data can pose challenges. Therefore, we evaluated areas where the model projected outside the training range using MaxEnt's clamping and extrapolation settings. Areas with high extrapolation risk were interpreted cautiously, particularly in future scenario maps beyond the species' current ecological niche.

The climate projections were based solely on the CNRM-CM6-1 GCM from the CMIP6 ensemble, which has demonstrated good regional performance. However, we recognize that using a single GCM may not fully capture the range of potential future climates. To address this limitation, future studies should incorporate ensemble modeling with multiple GCMs to quantify uncertainty propagation in climate simulations.

Occurrence data for Picea orientalis were obtained from the EUFORGEN database and verified for consistency. Despite efforts to use only high-quality data, potential biases may persist due to uneven sampling across elevation gradients or underrepresentation in remote areas. These limitations are acknowledged as potential sources of uncertainty in model projections.

Performance, contribution of environmental variables for model

The modeling conducted as part of this study was subjected to rigorous validation, yielding a high degree of predictive accuracy. The training dataset yielded an impressive ROC curve validation value of 0.980 (AUC > 0.5), while the test dataset exhibited a commendable value of 0.939 (AUC > 0.5), affirming the model's robust predictive capability (Fig. 1).

Furthermore, the Jackknife analysis of environmental variables revealed that "Precipitation Seasonality" (Bio 15) exerted the strongest influence on the distribution of Picea orientalis, contributing over 50% to the model's training performance. This was followed by "Precipitation of the Warmest Quarter" (Bio 18), "Precipitation of the Driest Quarter" (Bio 17), and "Maximum Temperature of the Warmest Month" (Bio 5). These variables are ecologically relevant as they directly impact the soil moisture regime, evapotranspiration rates, and seasonal stress tolerance—all critical for the survival and regeneration of spruce in montane forest ecosystems. In particular, Picea orientalis is highly sensitive to drought and heat extremes during the growing season, making these variables highly informative for modeling habitat suitability.

To address potential multicollinearity, we conducted a preliminary correlation analysis among the bioclimatic variables and excluded variables with high pairwise correlations ($r > 0.8$) to avoid redundancy and inflation of variable importance. This step ensured a robust model by preserving variables that are both ecologically meaningful and statistically independent, thus enhancing the reliability of the contribution scores presented in Fig. 1.

Distribution for potential future of oriental spruce (*Picea orientalis* L.)

The outcomes of the model encompassing future projections (2040, 2060, 2080, and 2100) for oriental spruce under the scenarios SSPs245 and SSPs 585 are visually presented in Fig. 2.

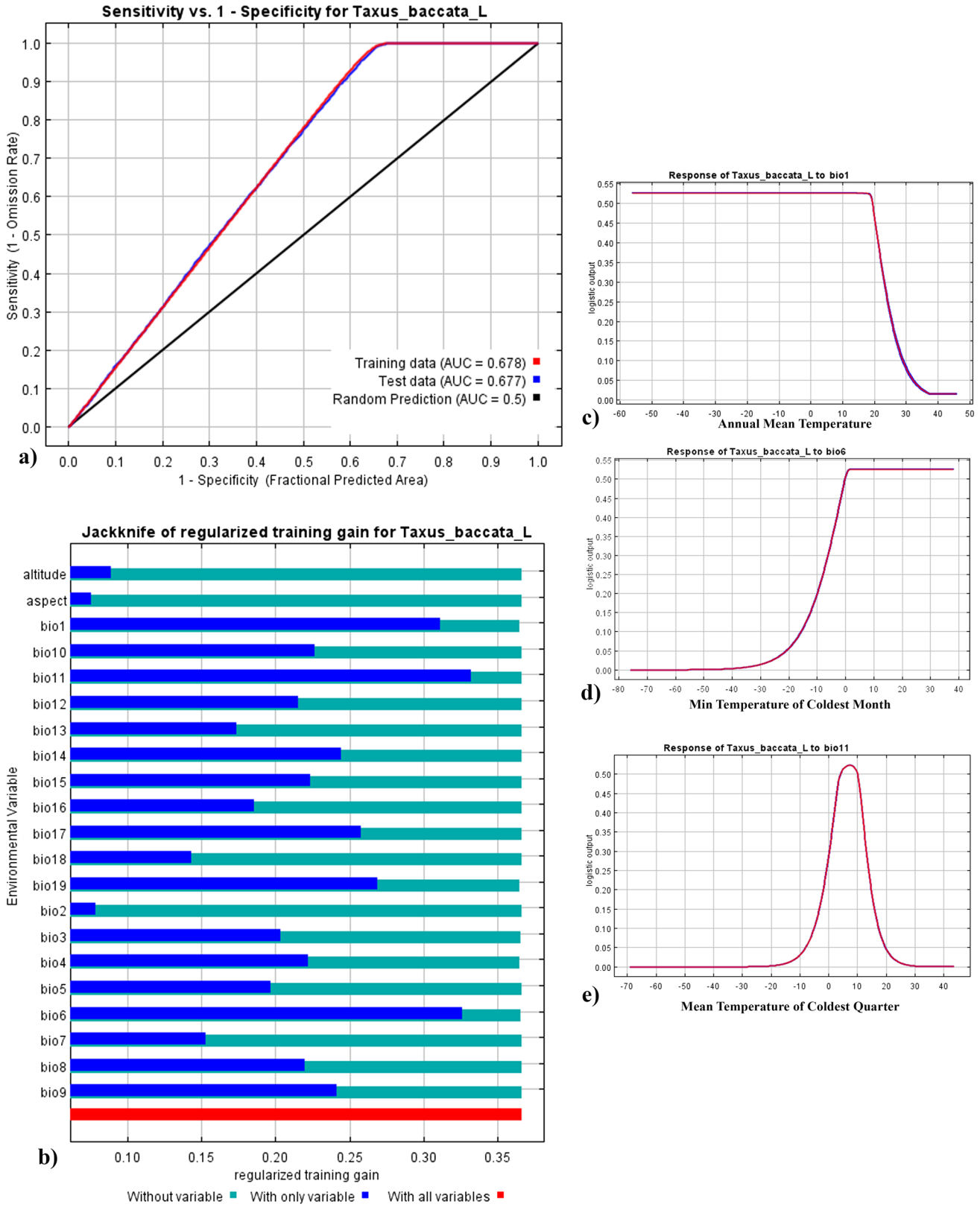

Fig. 1 ROC curve and AUC value of the model (**a**), influence of environmental variables (**b**), response curves (**c**, **d**, **e**)

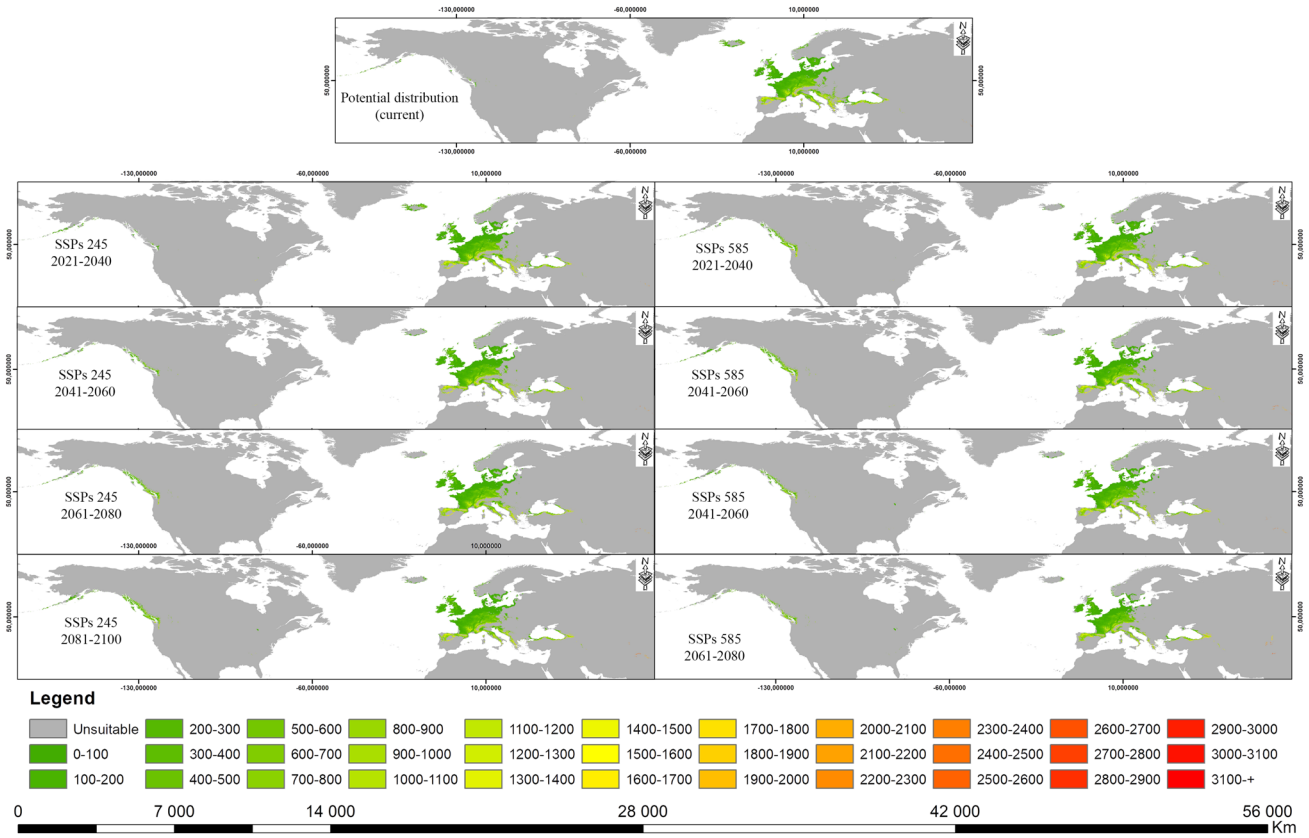

Fig. 2 Distribution potential of oriental spruce, Türkiye

An examination of the maps illustrating the potential future distribution of *Picea orientalis* L. under the SSPs 245 scenario reveals that there will be slight expansions in the species' distribution areas, particularly in Northwestern Anatolia, by the year 2060 However, these gains are projected to swiftly diminish in the subsequent period, leading to declines in the distribution areas, particularly in Northeastern Anatolia. Conversely, under the SSPs 585 scenario, substantial contractions are anticipated in the suitable distribution areas for Picea orientalis across both Northwestern and Northeastern Anatolia, commencing after the year 2040.

Numerical data on the spatial distribution of the potential distribution area of *Picea orientalis* L. by the altitude changes in the course of time are presented in Table 1.

An examination of Table 1 indicates that the species exhibits its highest distribution density at altitudes below 100 m, closely followed by the range of 1000-1100 m. Conversely, distribution areas above 3000 m are notably constrained, accounting for just 0.4% of the total. Analyzing the projected alterations in suitable distribution areas, significant declines are foreseen, especially at lower altitudes. Below the 100 m mark, the anticipated suitable distribution area by 2100 is forecasted to contract to 65.5% of the present extent under the SSPs 585 scenario, and even more drastically to 4.68% under the SSPs 245 scenario. These estimates signify losses surpassing 95% in both scenarios.

Likewise, under the SSPs 245 scenario, substantial declines are projected at altitudes lower than 1300 m by the year 2100. Only a marginal increase is expected within the altitude range of 400-600 m. In all other altitude bands, the reduction in suitable distribution areas could escalate to 56.63%, most notably at the 1000-1100 m elevation. Within the SSPs 585 scenario, the diminishment rates could be even more pronounced. Notably, at the 1000-1100 m elevation, where the most significant losses are predicted, the suitable distribution areas by 2100 would constitute just 21.01% of the present extent, indicating a loss of approximately 79%. Since this elevation range currently harbors the species' highest distribution, it can be inferred that population losses could reach substantial magnitudes.

The comparison of SSPs 245 and SSPs 585 scenarios reveals distinct patterns. Under SSPs 245, habitat contraction is projected mainly below 1300 m, with modest gains at mid- to high elevations, indicating a manageable shift in distribution. In contrast, SSPs 585 predicts much more drastic reductions in suitable habitat, particularly below 1800 m, and limited expansion confined to the 1800–2600 m range. These results suggest that SSPs 585 would pose a far more

Table 1 Projected Proportional Changes (%) in the Suitable Distribution Area of Picea orientalis across Altitude Bands (m) under SSPs 245 and SSPs 585 Scenarios (2040–2100). The values represent the percentage of suitable area relative to the baseline current distribution (100%)

Altitude (m)	Baseline Area (%)	SSPs 245				SSPs 585			
		2040	2060	2080	2100	2040	2060	2080	2100
0–100	8.47	80.12	116.37	70.76	4.68	89.47	74.85	70.18	65.50
100–200	6.40	84.50	118.60	67.44	96.90	97.67	75.97	70.54	54.26
200–300	6.40	92.25	127.91	79.07	69.77	99.22	88.37	85.27	71.32
300–400	5.75	100.00	131.90	81.90	90.52	106.03	90.52	97.41	81.03
400–500	4.51	106.59	162.64	89.01	117.58	98.90	98.90	101.1	82.42
500–600	3.47	120.00	211.43	105.71	121.43	118.57	110.00	110.00	94.29
600–700	3.87	105.13	165.38	82.05	97.44	98.72	88.46	97.44	67.95
700–800	5.06	98.04	115.69	72.55	68.63	89.22	71.57	84.31	63.73
800–900	4.41	97.75	150.56	84.27	87.64	83.15	73.03	77.53	57.30
900–1000	6.00	96.69	86.78	69.42	50.41	76.03	67.77	56.20	45.45
1000–1100	7.04	89.44	90.14	78.17	44.37	83.80	65.49	57.75	35.21
1100–1200	6.84	96.38	96.38	80.43	57.97	84.06	71.74	49.28	21.01
1200–1300	5.65	104.39	95.61	99.12	75.44	92.11	87.72	64.91	41.23
1300–1400	3.62	105.48	112.33	101.37	123.29	87.67	93.15	68.49	64.38
1400–1500	1.98	110.00	197.50	122.50	152.50	95.00	117.50	100.00	85.00
1500–1600	2.13	113.95	137.21	116.28	106.98	106.98	104.65	100.00	76.74
1600–1700	1.54	116.13	196.77	125.81	141.94	109.68	106.45	106.45	77.42
1700–1800	1.39	117.86	178.57	132.14	110.71	110.71	110.71	132.14	96.43
1800–1900	1.19	112.50	158.33	141.67	145.83	108.33	112.5	133.33	129.17
1900–2000	1.34	122.22	144.44	144.44	122.22	111.11	111.11	107.41	122.22
2000–2200	3.52	98.59	91.55	136.62	49.30	101.41	112.68	118.31	116.90
2200–2400	2.88	98.28	153.45	117.24	167.24	103.45	89.66	112.07	131.03
2400–2600	3.17	107.81	107.81	95.31	125.00	110.94	101.56	110.94	103.13
2600–2800	1.88	110.53	131.58	81.58	221.05	113.16	81.58	110.53	97.37
2800–3000	1.09	109.09	168.18	77.27	209.09	113.64	86.36	86.36	77.27
3000–3200	0.30	116.67	150.00	50.00	400.00	133.33	33.33	50.00	50.00
3200–3400	0.05	100.00	600.00	100.00	300.00	100.00	100.00	100.00	0
3400–3600	0.05	100.00	0	0	0	100	0	0	0
Total	100.00	99.01	126.67	88.84	86.42	95.54	85.47	83.04	67.92

serious threat to Picea orientalis, both in terms of total habitat loss and the isolation of remaining suitable zones.

When examining scenario SSPs 245, it becomes evident, suitable distribution areas will exhibit spatial expansion at altitudes surpassing 1300 m (with the exception of the 2000-2200 m range) until the year 2100, in comparison with current levels. Particularly notable are the substantial increases anticipated at altitudes exceeding 3000 m. Nevertheless, considering the inherently confined distribution at these elevations, the magnitude of this augmentation is deemed insignificant. Conversely, within the SSPs 585, an expansion in distribution of the suitable area is foreseen solely within the altitude range of 1800-2600 m.

Considering these outcomes, it is projected that by the year 2100, there will be an approximate loss of 13.58% in the SSPs 245 scenario and a more severe loss of 32.08% under the SSPs 585 scenario. These findings carry substantial conservation implications. A reduction of over one-third of the currently suitable habitat under high-emission trajectories signals a heightened risk of population fragmentation, genetic bottlenecks, and localized extirpations, particularly in low-elevation and isolated populations. In response, conservation strategies should prioritize the identification and preservation of potential climatic refugia at higher elevations and latitudes. Moreover, ex-situ conservation efforts such as seed banking, and in-situ strategies including assisted migration and habitat restoration, should be integrated into regional forest management policies. These measures are crucial to maintaining the ecological resilience and evolutionary potential of Picea orientalis in the face of accelerating climate change.

Results and discussion

The findings from this study underscore substantial shifts in the distribution of potential of areas of oriental spruce with respect to altitude, driven by the effects of climate change.

These alterations predominantly manifest as a reduction in suitable habitats below 1300 m altitude and an expansion above this threshold under the SSPs 245 scenarios, projected until the year 2100. Conversely, the SSPs 585 scenario anticipates a modest increase, reaching up to 31%, within the altitude range of 1800-2600 m by the year 2100. However, this scenario also predicts a considerable decline, up to 79%, in suitable distribution at other altitude ranges.

In light of the study's findings, a notable reduction in distribution of the suitable regions for oriental spruce until the year 2100 is evident. This trend aligns with prior research indicating that global climate change tends to trigger substantial alterations in species' natural distribution areas, often leading to a contraction in these areas. This pattern is consistent with investigations conducted on various species within Türkiye. Similar observations were made in the case of Fraxinus excelsior, where the projected potential distribution area in the year 2100 under the SSPs 245 scenario was 153,329 ha and 155,819 ha under the SSPs 585 scenario, compared to the current 165,910.3 ha. Moreover, studies have also indicated potential population decreases of up to 56% in Fagus sylvatica and Picea abies within Europe (Eurostat 2018).

Numerous global studies have consistently underscored substantial declines in regions of distribution of diverse speci. For instance, Gómez-Pineda et al. 2020) highlighted the potential for loss habitat in mountainous regions of Mexico to escalate significantly, projecting reductions ranging from 46 to 77% by the year 2060. Similarly, Li et al. (2020) cautioned about the vulnerability and potential threat to trees, estimating that approximately 23% to 57% of tree species in China could face such risks by 2070. Even the most optimistic projection revealed an 18% vulnerability or threat, with some species hovering on the brink of extinction (Li et al. 2020). The effection of global change climate on trees has been noted to extend beyond spatial alterations, significantly influencing their quality, health, and developmental patterns (Daniel et al. 2017).

The findings of this study reveal a significant change in distribution of the regions of suitable of *Picea orientalis*, especially with regard to altitude. The research notably points out that the primary environmental variable affecting the species' distribution is "Precipitation Seasonality" [Bio 15], closely followed by "Precipitation of the Driest Quarter" [Bio 17], "Precipitation of the Warmest Quarter" [Bio 18], and "Maximum Temperature of the Warmest Month" [Bio 5]. Importantly, these parameters exhibit a strong correlation with altitude. Upon scrutinizing the outcomes of the present study, a notable trend emerges whereby the suitable distribution areas of oriental spruce exhibit a discernible shift toward higher altitudes. This pattern aligns with analogous findings from other investigations. For instance, Gómez-Pineda et al. (2020) postulated a comparable upward shift in suitable distribution areas for coniferous trees in Mexico. This phenomenon can be attributed to the overarching impact of global warming, which precipitates a general temperature rise across climates (Koc 2022). It is well-established that altitude corresponds to a decrease in temperature, with a decrement of 1 °C in dry air and 0.6 °C in humid air occurring per 100 m of elevation gain (Cüce et al. 2020). Consequently, in light of the projected temperature surge linked to global warming, an upward migration of suitable distribution areas becomes an outcome.

Climate change is expected to cause shifts in precipitation, increased temperatures, longer growing seasons, and more frequent summer droughts. The ramifications of change of global climate are anticipated to manifest in a multitude of ways. Among these potential effects, noticeable shifts in precipitation patterns and elevated temperatures, along with prolonged growing seasons and heightened summer droughts, stand out as particularly evident (Huang et al. 2020). As climatic conditions evolve, trees are expected to respond through of the mechanism such as climatic for adaptation, to local acclimatization, migration, in some cases, diminished vitality (Benito Garzón, et al., 2019; Gárate-Escamilla et al. 2019; Shen et al. 2008). Furthermore, climate change could potentially yield adverse outcomes such as the infiltration of alien species, while simultaneously yielding favorable results such as heightened timber production owing to increased concentration CO2 (Brundu et al. 2020).

Prior research has underscored that change for climate is poised to exert direct effects on forest tree species, while concurrently acting as a secondary menace by catalyzing the proliferation of detrimental fungi and insects. This dual effect has the potential to eventually jeopardize the existence of pristine forests within specific regions (Iverson et al. 2016; Shen et al. 2008). Furthermore, alterations in the availability of water and nutrients, compounded by factors such as soil degradation triggered by changes in precipitation patterns, the emergence of geographical barriers, human-induced impacts like modifications in agricultural and pasture areas, and the proliferation of competitive species, could significantly reshape the distribution ranges of various species (Peñuelas et al., 2018).

Furthermore, the magnitude and implications of trees' susceptibility to change of climate ll exhibit notable heterogeneity. The alterations in climatic parameters will engender stressors; nevertheless, the stressors induced by climate change upon tree species can diverge contingent on the specific species. The reactions and capacities of species to these stressors can manifest discrepancies not only among various species but also within distinct origins and individual specimens (Seidl et al. 2012; Staver and Levin 2012; Wootton and Emmerson 2005). This variability can be attributed to the intricate interplay between environmental factors and

genetic constitution that shapes phenotypic traits (Kurz et al. 2023).

Another pivotal determinant that will intricately shape the potential reactions of tree to change of the climate global encompasses microclimatic and micro of the edaphic factors. Research has elucidated that these micro-environmental conditions might wield a more pronounced influence than overarching climatic classifications. Consequently, it becomes evident that repercussions of change of the climate global will be subject to substantial fluctuations at both region, localized scales (Seidl et al. 2012; Staver and Levin 2012; Wootton and Emmerson 2005).

While precipitation seasonality (Bio15) emerged as the most influential variable in the Jackknife analysis, other climatic factors—including precipitation of the driest and warmest quarters (Bio17, Bio18) and maximum temperature of the warmest month (Bio5)—also demonstrated considerable explanatory power. These parameters reflect seasonal climatic extremes that are ecologically critical for the growth and survival of Picea orientalis, particularly in montane environments. Their inclusion highlights the species' sensitivity to both water availability and heat stress during critical phenological phases. The interplay between these variables suggests that changes in climate variability, not just annual means, will play a pivotal role in the future viability of spruce populations. Future studies incorporating ensemble models and uncertainty quantification could refine the spatial projections and help prioritize conservation responses under different risk scenarios.

Conclusions

The outcomes of the current study underscore the impending substantial contractions in the distribution regions suitable of oriental spruce (*Picea orientalis* L.) for during future, potentially leading to losses of up to 32%. Moreover, it is represented that these suitable distribution areas will shift to higher altitudes. This predicament necessitates the implementation of human-intervened migration mechanisms to ensure the species' survival. The absence of such interventions could potentially escalate population losses beyond the projected thresholds. Hence, grounded in these findings, it is advisable to recalibrate existing forest management plans accordingly. Furthermore, it is prudent to embark on meticulous and localized investigations, extend similar inquiries to other species to construct fresh models based on evolving climate and environmental dynamics, formulate the most precise prognostic scenarios, and proactively facilitate the migration of species to forthcoming suitable habitats through artificial means.

Based on the projections, conservation priorities should be scenario-specific. Under the SSPs 245 pathway, efforts should focus on enhancing habitat connectivity across mid-elevation ranges (1300–2000 m), allowing for gradual migration and reducing fragmentation risks. For SSPs 585, more aggressive interventions are required, including assisted migration to high-altitude refugia (above 2000 m), ex-situ conservation of genetic material, and climate-adaptive forest management to buffer populations against rapid climatic shifts. Monitoring programs should be implemented to track real-time distributional changes and guide adaptive responses.

The methodological integration of high-resolution climate modeling (CNRM-CM6-1) with a robust species distribution algorithm (MaxEnt), coupled with dual-scenario (SSPs 245 and 585) analyses, provides a scientifically sound and comprehensive projection of altitudinal shifts in Picea orientalis. High AUC values affirm the reliability of the results, while the identification of precipitation seasonality and temperature extremes as key drivers underscores the importance of seasonal climatic variability in future habitat suitability. These insights contribute not only to regional forest conservation strategies in Türkiye but also to the broader global discourse on species response to climate change in mountainous biomes.

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Code availability Not applicable.

Declarations

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