

Climate change impacts on maximum temperature trends in *Pinus brutia* Ten. breeding zones

Pinus brutia Ten. ıslah zonlarında iklim değişikliğinin maksimum sıcaklık eğilimlerine etkisi

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Abstract

Tree breeding is essential for improving forest resilience to climate change. *Pinus brutia* Ten., a key conifer species in Türkiye, is managed through breeding programs across six climatic zones. Rising maximum temperature (Tmax) and vapor pressure deficit (VPD) may threaten the adaptive capacity of these programs. This study analyzed historical (1960–2014) and projected (2014–2100) Tmax trends across five breeding zones using TerraClimate data and the NEX-GDDP-CMIP6 ensemble under the SSP5-8.5 scenario. Linear regression revealed strong spatial variability, with the Aegean, Marmara, and Western Anatolian Inland zones showing the highest historical warming (up to 0.56 °C per two decades). Future projections indicate consistent warming across all zones, ranging from 0.59 to 2.24 °C per two decades.

Keywords: Climate change, trends in maximum temperature, breeding zones, ecophysiology, google earth engine

Öz

Ağaç ıslahı, orman ekosistemlerinin iklim değişikliğine karşı dayanıklılığını artırmada kritik bir rol oynamaktadır. *Pinus brutia* Ten. (kızılçam), Türkiye’de önemli bir iğne yapraklı tür olup altı iklim zonunda yürütülen ıslah programlarının odağındadır. Artan maksimum sıcaklık (Tmax) ve buhar basıncı açığı (VPD), bu programların uyum kapasitesini tehdit etmektedir. Bu çalışmada TerraClimate verileri ve SSP5-8.5 senaryosu altındaki NEX-GDDP-CMIP6 projeksiyonları kullanılarak beş ıslah zonu için tarihsel (1960–2014) ve gelecek (2014–2100) Tmax eğilimleri analiz edilmiştir. Sonuçlar mekânsal farklılıklar göstermiş; Ege, Marmara ve Batı Anadolu İç zonlarında en yüksek tarihsel ısınma (20 yılda 0,56 °C) belirlenmiştir. Gelecek projeksiyonları tüm zonlarda her 20 yılda 0,59–2,24 °C arasında artış öngörmektedir.

Anahtar Kelimeler: İklim değişikliği, maksimum sıcaklık trendleri, ıslah zonları, ekofizyoloji, google earth engine



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1. Introduction

Tree breeding plays a pivotal role in enhancing the adaptive capacity of forest ecosystems under rapidly changing climatic conditions. As extreme events such as heatwaves, droughts, and prolonged dry periods become more frequent and severe, forest trees must withstand increased environmental stress while maintaining productivity. Breeding programs that prioritize genetic traits related to drought tolerance, thermal resilience, and growth performance are thus central to sustaining forest health and productivity. The genetic diversity within and among tree populations forms the foundation of these adaptive responses, serving as a buffer against climatic variability and contributing significantly to long-term ecosystem resistance and resilience (Ennos, 2014; Fady et al., 2015). Integrating genetic improvement with adaptive forest management strategies offers a robust approach to enhance the resilience and sustainability of forest landscapes (Vinceti et al., 2020; Gray et al., 2016).

Among the key environmental stressors, maximum temperature (T_{max}) and vapor pressure deficit (VPD) are critical determinants of drought intensity in conifer species. T_{max} directly regulates vital physiological processes such as photosynthesis, respiration, and transpiration. However, VPD is an indicator of atmospheric moisture demand that escalates under warming conditions. Thus intensifying transpirational water loss (Eamus et al., 2013; Dannenberg et al., 2022; Will et al., 2013). This combination amplifies drought stress, particularly in arid and semi-arid regions where species such as *P. brutia* are widely distributed.

P. brutia is a priority species in tree breeding program, covering approximately 5.3 million hectares and contributing about 6.2 million m³ of the national roundwood production (OGM, 2023). *P. brutia* breeding program in Türkiye was structured into six major breeding zones (BZ): Mediterranean, Aegean, Marmara, Amanos Mountains Inland, Western Anatolian Inland, and Black Sea. Each zone was divided by elevation classes and breeding activities have predominantly focused on the 0-800 m elevation range, targeting traits such as survival rate, growth performance, and stem quality (Atalay et al., 1998). It is important to note that breeding efforts have primarily concentrated on specific elevation sub-zones within each major BZ. Such as, in the Mediterranean and Aegean BZs, breeding efforts have primarily targeted the 0-400m and 401-800m elevation range. In the Marmara BZ, breeding activities have focused on the 201-600 m elevation range, while in the Amanos Mountains

Inland BZ, efforts have centered on the 401-800 m. In the Western Anatolian Inland BZ, breeding studies have predominantly been conducted within the 301-800 m elevation range, primarily for conservation purposes (Boydak and Çalikoğlu, 2000).

Despite these efforts, climate change continues to pose significant challenges. Rising temperatures and declining precipitation are expected to further reduce growth rates and seedling survival (Lu et al., 2014). Particularly in the Mediterranean region, where baseline conditions are already hot and dry, climate models project over 30% reduction in precipitation and temperature increases exceeding 4-5 °C by the end of this century (Giorgi and Lionello, 2008). These projections highlight the urgent need for robust and climate-informed breeding strategies.

Given the increasing exposure of BZs to warming and atmospheric moisture stress, it is essential to understand T_{max} trends in both historical and future contexts. Therefore, this study aims to assess spatio-temporal patterns in T_{max} trends across the BZs of *P. brutia* in Türkiye. The specific objective is to quantify these trends under both historical observations and future climate scenarios, thereby informing adaptive breeding strategies and contributing to enhancement of the climate resilience of forest ecosystem strategies.

2. Materials and Methods

2.1. Study area

The study area was delineated based on the BZs of *P. brutia* to define elevation-based sub-zones within these major BZs, digital elevation data from the Shuttle Radar Topography Mission (SRTM, earthdata.nasa.gov/data/instruments/srtm) with a 30-meter spatial resolution were employed (Farr et al., 2007). The continuous elevation raster was classified into discrete elevation bands corresponding to the predefined breeding sub-zones. This classification was conducted using the Google Earth Engine (GEE, earthengine.google.com) platform. Accordingly, each major BZ was subdivided into elevation-based sub-zones. Specifically, the Mediterranean and Aegean zones were stratified into four elevation classes: 0-400 m, 401-800 m, 801-1200 m, and >1200 m. The Marmara zone was categorized into 0-200 m, 201-600 m, 601-1000 m, and >1000 m. Similarly, the Amanos Mountains Inland and Western Anatolian Inland zones were divided into 0-400 m, 401-800 m, 801-1200 m, and >1200 m sub-zones (Figure 1).

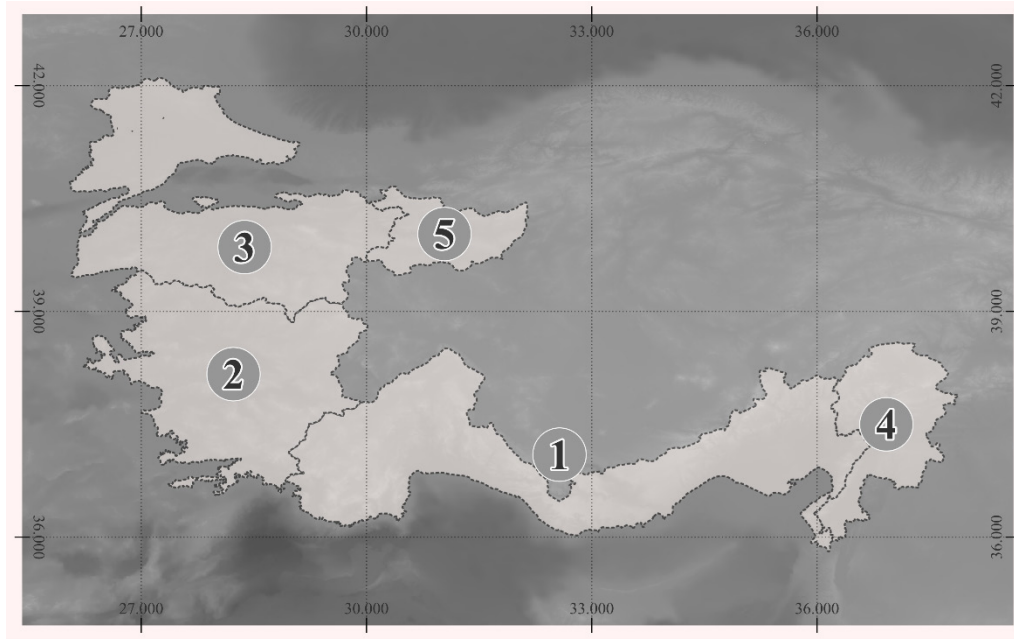


Figure 1. *P. brutia* BZs (except for BZs in Black Sea region)

Şekil 1. Kızılçam ıslah zonları (Karadeniz Bölgesi'ndeki ıslah zonları (IZ) hariç)

In Figure 1, 1) represents Mediterranean BZ, 2) represents Aegean BZ, 3) represents Marmara BZ, 4) represents Amanos Mountains Inland BZ, 5) represents Western Anatolian Inland BZ./ Şekil 1'de, 1) Akdeniz IZ'nu, 2) Ege IZ'nu, 3) Marmara IZ'nu, 4) Amanos Dağları IZ'nu, 5) Batı Anadolu İç IZ'nu ifade etmektedir.

2.2. Dataset collections

To assess historical trends in monthly average Tmax from 1960 to 2014 across the main BZs and their sub-zones, the TerraClimate (climatologylab.org/terraclimate.html) dataset (Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces developed by the University of Idaho) was employed (Abatzoglou et al., 2018). This analysis was performed within the GEE environment, enabling pixel-level evaluations across the entire study area.

For future climate projections spanning 2014 to 2100, the NASA Earth Exchange Global Daily Downscaled Climate Projections (NEX-GD-DP-CMIP6) dataset was utilized (Thrasher et al., 2012). Daily Tmax values were aggregated to compute monthly averages, and units were converted from Kelvin to degrees Celsius to ensure consistency with historical records. Trends in projected monthly average Tmax were quantified for each pixel within the study area under the high-emission SSP5-8.5 scenario. Seven global climate models from the NEX-GDDP-CMIP6 ensemble were selected for analysis: UKESM1-0-LL, EC-Earth3, CanESM5, ACCESS-CM2, GFDL-ESM4, KI-Ost-ESM, and FGOALS. In order to understand variation in Tmax trends, average of the Tmax values was quantified within each sub-zone. All geo-

spatial visualizations and map-based analyses were performed in QGIS (qgis.org) using raster outputs downloaded from GEE.

2.3. Trends in historical and projected future climate

To quantify interannual trends in monthly average Tmax, Sen's slope approach was employed (Sen, 1968; Yin et al., 2021). The slope of the regression line (θ_{Slope}) was calculated for both historical and future monthly average Tmax datasets using the following equation:

$$\theta_{Slope} = \left(\frac{n \sum_{i=1}^n (i \cdot X_i) - (\sum_{i=1}^n i) \cdot (\sum_{i=1}^n X_i)}{n \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \right)$$

Where,

θ_{Slope} : is the linear slope of the time series variable, which represents the rate of increase or decrease over the study period,

n : is the number of years in the study (in this case, $n=20$),

X_i : is the value of the climate parameter (e.g., monthly average maximum temperature) in year i ,

i : is the time index for each year, ranging from 1 to n .

3. Results

3.1. Historical trends in monthly maximum temperature (1960-2014)

Between 1960 and 2014, historical trends in monthly Tmax across the BZs exhibited considerable spatial variation, with increases ranging from 0.19 °C to 0.56 °C per two decades (Figure 2). Notably, a pronounced disparity was observed between the northern and southern BZs. The Marmara and Western Anatolian Inland BZs demonstrated the highest warming rates, with Tmax trends approximately twice as high as those observed in the Med-

iterranean BZ.

The most substantial increase in Tmax was recorded in the eastern part of the Marmara BZ, reaching approximately 0.56 °C per two decades. A clear distinction was evident between the northern and southern subregions of the Marmara BZ, with the southern part experiencing significantly higher warming. A similar pattern was observed in the Aegean BZ, where the Tmax trend in the northern region was nearly double that of the southern region. The southern Aegean region exhibited trends closely resembling those of the Mediterranean BZ.

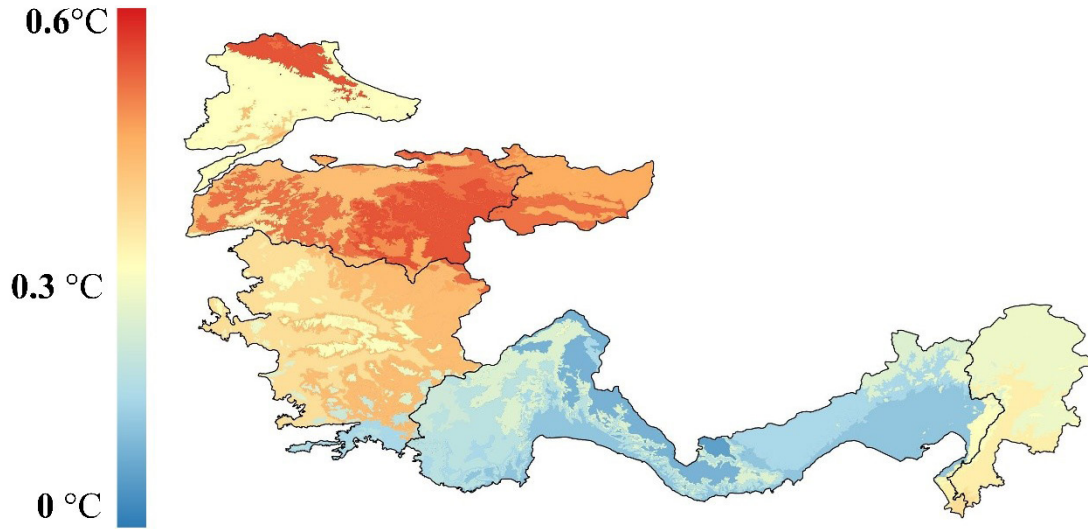


Figure 2. Historical trends in maximum temperature from 1960 to 2014 within the *P. brutia* BZs
Şekil 2. Kızılcām IZ'larında 1960-2014 dönemi maksimum sıcaklık değerlerindeki tarihsel eğilimler

Within the Mediterranean zone, the eastern and western regions showed relatively similar warming trends, ranging from 0.19 °C to 0.39 °C per two decades. Additionally, the Amanos Mountains Inland BZ exhibited a modest north-south gradient in Tmax trends, with values ranging from 0.34 °C in the southern part to 0.5 °C in the northern part.

3.2. Historical trends in monthly average vapor pressure deficit (1960-2014)

Between 1960 and 2014, historical trends in monthly average vapor pressure deficit (VPD) across the BZs varied between 0.01 MPa and 0.06 MPa per two decades. A clear spatial disparity was evident, particularly between low and high elevations. The highest VPD trends, ranging from 0.05 to 0.06 MPa, were predominantly observed at lower elevations within the Aegean and Marmara BZs.

In the northern Marmara BZ, VPD trends were nearly twice as high as those in the southern Marmara zone. A similar contrast was found in the Ae-

gean BZ, where the eastern region exhibited VPD trends approximately double those of the western region. In the Mediterranean and Amanos Mountains Inland BZ, a consistent elevation-related pattern was observed: Lower elevations experienced significantly higher increases in VPD compared to higher elevations (Figure 3).

3.3. Projected future trends in maximum temperature (2014-2100)

Projected trends in Tmax under the SSP5-8.5 scenario, simulated using the global climate models FGOALS, EC-Earth3, GFDL-ESM4, ACCESS-CM2, KIOST, UKESM1-0-LL, and CanESM5 for the period 2014-2100, are presented in Figures 4 for the *P. brutia* BZs. The projections consistently indicate an overall increase in Tmax across all zones; however, the magnitude of this increase exhibits notable spatial variability.

In the FGOALS climate model (Figure 4), the projected trends in Tmax across the BZs varied from a

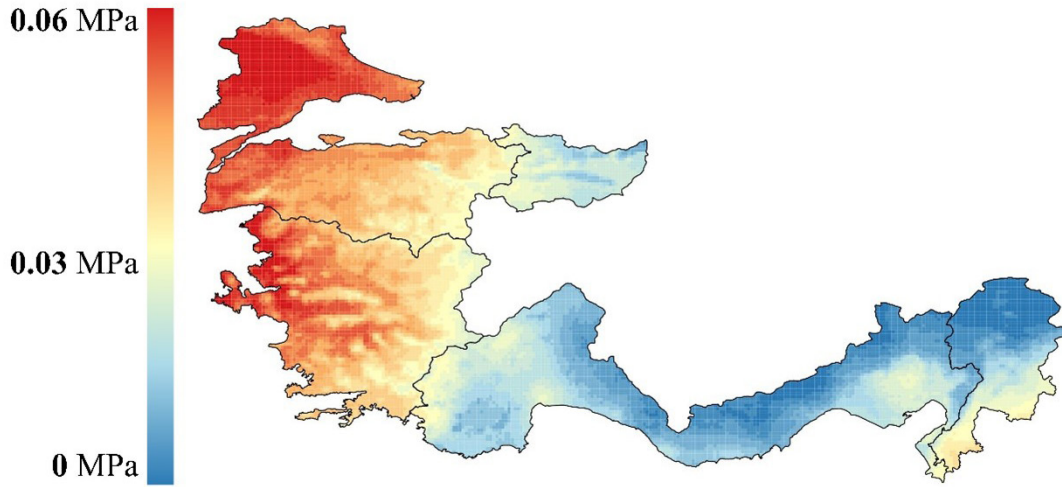


Figure 3. Historical trends in VPD from 1960 to 2014 within the *P. brutia* BZs
Şekil 3. Kızıldağ IZ'larında 1960-2014 arası VPD değerlerindeki tarihsel eğilimler

minimum of 0.59 °C to a maximum of 0.96 °C per two decades. Notably, a distinct spatial disparity was observed within the Mediterranean BZ, with the eastern region exhibiting consistently higher Tmax trends compared to the western region, which displayed more heterogeneous and generally lower trend values. The Aegean BZ also showed relatively lower Tmax trends, with a minimum of 0.59 °C and a maximum of 0.78 °C, indicating a narrower range of warming. In contrast, the Marmara BZ revealed a pronounced north-south gradient. In the northern part, Tmax trends ranged mostly between 0.59 °C and 0.67 °C, whereas in the southern part, values were predominantly between 0.78 °C and 0.82 °C. A similar warming pattern was observed between the Western Anatolian Inland BZ and the southern Marmara BZ, both indicating elevated Tmax trends.

Among all regions, the Amanos Mountains Inland BZ exhibited the highest increase in average Tmax, reaching up to 0.96 °C per two decades. The upper elevations of this zone showed the most pronounced warming across all BZs. Interestingly, the Tmax trends in the Amanos Mountains Inland BZ closely resembled those observed in the eastern Mediterranean BZ, suggesting a shared regional warming dynamic.

In the EC-Earth3 climate model (Figure 4), the projected trends in Tmax across the BZs ranged from 1.18 °C to 2.24 °C per two decades. A clear spatial contrast was observed between the eastern and western parts of the Mediterranean BZ, with the eastern region exhibiting markedly higher Tmax trends, particularly in the upper range, where values mostly ranged between 1.56 °C and 2.06 °C. The Amanos Mountains Inland BZ displayed a

patchy spatial pattern in the upper range of Tmax trends, indicating localized variations in warming intensity. In the Aegean BZ, the lower elevations exhibited lower Tmax trends compared to the upper elevations, suggesting an elevation-related gradient in temperature increases.

Additionally, the northern part of the Marmara BZ showed lower Tmax trends relative to the southern part, highlighting a consistent north-south warming disparity. A similar contrast was evident between the Western Anatolian Inland BZ and the northern Marmara BZ, with the former experiencing generally higher Tmax trends.

In the GFDL-ESM4 climate model, the projected trends in Tmax across the BZs ranged from 0.90 °C to 1.29 °C per two decades. In the Mediterranean BZ, higher Tmax trends were observed at upper elevations (1.08 °C to 1.25 °C), compared to lower elevations (0.90 °C to 1.02 °C). A similar elevation-based pattern was evident in the Aegean BZ, where Tmax trends ranged from 1.02 °C to 1.13 °C at lower elevations and increased up to 1.29 °C at higher elevations. A distinct spatial contrast was also observed between the northern and southern parts of the Marmara BZ, with Tmax trends in the south being up to 25% higher than in the north. Similarly, in the Amanos Mountains Inland BZ, lower elevations exhibited Tmax trends approximately 10%-15% lower than those at higher elevations, indicating a consistent elevation-related gradient in warming across multiple BZs (Figure 4).

In the ACCESS-CM2 climate model, the projected trends in Tmax across the BZs ranged from 1.23 °C to 1.81 °C per two decades. The highest Tmax trends were observed at lower elevations

in the Marmara BZ. However, there was no notable difference between the northern and southern subregions of Marmara. In the Mediterranean BZ, Tmax trends were higher at lower elevations, ranging from 1.36 °C to 1.43 °C. In contrast, Tmax in the western part of the Mediterranean BZ predom-

inantly ranged between 1.23 °C and 1.36 °C, while the eastern part exhibited values reaching up to 1.61 °C. Notably, the Tmax trend in the higher elevations of the Amanos Mountains Inland BZ was approximately 15% to 18% greater than in the lower elevations (Figure 4).

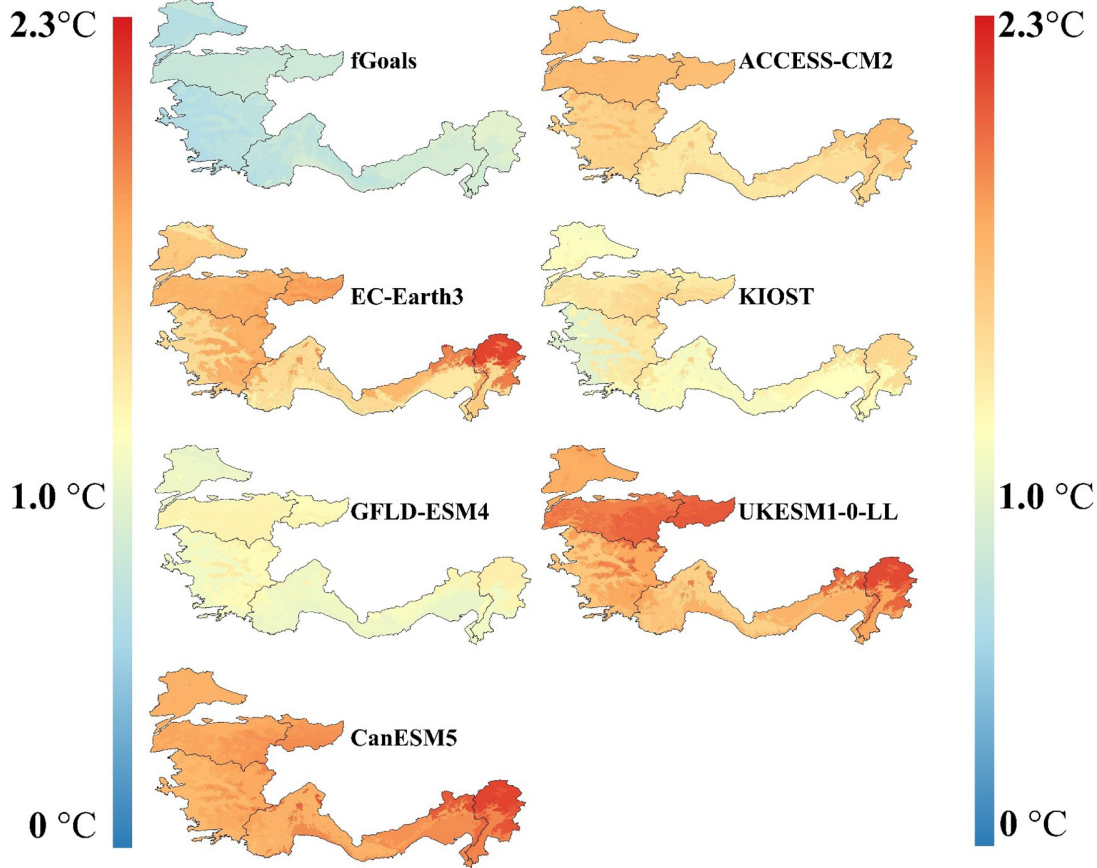


Figure 4. The projected trends in maximum temperature from 2015 to 2100 within the *P. brutia* BZs, based on the FGOALS, EC-Earth3, GFDL-ESM4, ACCESS-CM2, KIOST, UKESM1-0-LL, CanESM5 climate models under the SSP5-8.5 scenario

Şekil 4. SSP5-8.5 senaryosu altında FGOALS, EC-Earth3, GFDL-ESM4, ACCESS-CM2, KIOST, UKESM1-0-LL, CanESM5 iklim modelleri temel alınarak, kızılçam IZ'larında 2015-2100 arası maksimum sıcaklık eğilimleri

According to the KIOST model, Tmax trends ranged from 0.77 °C to 1.52 °C per two decades. The highest trends were found in the southern Marmara, southern Western Anatolia, and the upper elevations of the Amanos Mountains Inland BZs. In these areas, Tmax trends were nearly double those observed in the lower elevations of the Aegean BZ. A significant spatial contrast was evident within the Marmara BZ, where the southern region experienced Tmax trends approximately 40% higher than the northern region. Furthermore, in both the western and eastern parts of the Mediterranean BZ, lower elevations generally showed higher Tmax trends than higher elevations (Figure 4).

In the UKESM1-0-LL model, Tmax trends across

BZs varied between 1.43 °C and 2.19 °C per two decades. In the western Mediterranean BZ, lower elevations tended to exhibit higher Tmax trends than upper elevations. In the eastern Mediterranean region, upper elevations showed increases in Tmax trends reaching up to 2.19 °C. A clear contrast was observed between the southern and northern parts of the Marmara BZ, with the southern region exhibiting substantially higher warming trends. Similarly, in the Aegean BZ, upper elevations generally experienced higher Tmax trends compared to lower elevations (Figure 4).

The CanESM5 model projected Tmax trends ranging from 1.57 °C to 2.12 °C per two decades across the BZs. In the western part of the Mediterranean

BZ, lower elevations generally exhibited higher Tmax trends, whereas in the eastern region, Tmax values in the upper elevations reached as high as 2.12 °C. In the Amanos Mountains Inland BZ, Tmax trends at upper elevations were approximately 10% higher than those at lower elevations. Likewise, the upper elevations in the Aegean BZ showed higher Tmax trends compared to the lower elevations. Interestingly, the difference between the northern and southern parts of the Marmara BZ was relatively small in this model (Figure 4).

4. Discussion and Conclusion

Historical and projected climate trends reveal heterogeneity across *P. brutia* BZs in Türkiye. In lower elevation zones of the Marmara and Aegean regions, historical data indicate significant increases in Tmax and VPD, suggesting rising evapotranspiration demand and longer growing seasons. These conditions necessitate breeding strategies that target heat and drought-tolerant genotypes. Conversely, the Mediterranean and Amanos Mountains Inland zones exhibit more moderate historical changes, though projections still indicate warming trends of 0.6-2.1 °C over the coming decades. These asynchronous climatic trends indicate that BZs are experiencing varied trajectories of climate change. Some zones face concurrent increases in Tmax and VPD, while others exhibit more stable moisture regimes. These spatial patterns are vital for identifying climate-resilient areas and for targeting breeding efforts based on zone-specific vulnerability profiles.

The analysis of projected Tmax trends under the high-emission SSP5-8.5 scenario reveals a consistent warming pattern across *P. brutia* BZs throughout the 21st century. While the magnitude and spatial distribution of the warming differ among global climate models (GCMs), several robust patterns emerge that may have important implications for climate adaptation strategies in forest tree breeding programs. Across all seven GCMs evaluated, including FGOALS, EC-Earth3, GFDL-ESM4, ACCESS-CM2, KIOST, UKESM1-0-LL, and CanESM5, Tmax is projected to increase substantially with decadal trends ranging from as low as 0.59 °C (FGOALS) to as high as 2.24 °C (EC-Earth3). This broad range underscores the model-dependent uncertainty inherent in climate projections, especially when applied to regional scales. Nonetheless, certain spatial consistencies are observed across models. Most notably, the Amanos Mountains Inland BZ and eastern Mediterranean BZ consistently emerge as larger of warming trends, particularly at higher elevations.

This may reflect a broader elevation-related amplification of warming.

A prevalent finding among multiple models, including EC-Earth3, GFDL-ESM4, KIOST, and CanESM5, is the presence of elevation gradients in Tmax trends, with upper elevations frequently experiencing stronger warming trends than lower elevations. This result is particularly salient in the Amanos and Aegean BZs. Such elevation-dependent warming could exacerbate physiological stress in high-altitude *P. brutia* populations, especially where water availability is already marginal. However, this pattern is not uniformly observed across all models; for example, in ACCESS-CM2 and KIOST, lower elevations in some regions also show elevated Tmax trends, suggesting that topographic modulation of warming may vary with model structure and regional climate dynamics.

Another notable spatial feature is the north-south disparity in Tmax trends, particularly in the Marmara BZ. Most models, including FGOALS, EC-Earth3, GFDL-ESM4, KIOST, and UKESM1-0-LL, indicate higher warming in the southern Marmara subregion relative to the north. This consistent pattern may reflect differences in continentality and proximity to marine influences and should be taken into account when assessing vulnerability and designing assisted migration or seed transfer strategies.

The Mediterranean BZ, encompassing both western and eastern sectors, displays significant intra-regional heterogeneity in Tmax trends. Generally, the eastern Mediterranean BZ exhibits higher Tmax trends than the western part, particularly under EC-Earth3, UKESM1-0-LL, and CanESM5. This spatial divergence may be linked to prevailing atmospheric circulation regimes and land-atmosphere feedbacks specific to the eastern Mediterranean basin, which is known to be a climate change hotspot. Also, the Aegean and Western Anatolian Inland BZs exhibit warming trends, although their magnitude and pattern vary across models. Several models (e.g., GFDL-ESM4, UKESM1-0-LL, CanESM5) suggest enhanced warming at higher elevations, which could impact growth dynamics and drought tolerance of *P. brutia* genotypes currently adapted to these sites, particularly where water supply is limited.

VPD induces stomatal closure to reduce transpirational water loss; however, this protective response concurrently limits carbon uptake and disrupts internal water transport (Eamus et al., 2013; Dannenberg et al., 2022). When environmental stress exceeds physiological tolerance thresholds, hy-

draulic failure driven by cavitation and xylem embolism may occur, substantially increasing the risk of mortality (Williams et al., 2014; Gamelin et al., 2022). Yin et al. (2021) showed that a 1 °C increase in temperature can extend drought duration and severity by 20.7% and 32.6%, respectively. Nevertheless, several studies suggest that VPD may be a more influential driver of drought intensity than temperature alone, particularly during prolonged dry periods (Will et al., 2013; Eamus et al., 2013). Accordingly, both the Aegean and Marmara BZ are expected to experience increasing drought duration and severity (Figures 2 and 3). At higher elevations, historical and many projected Tmax trends exceed those observed at lower elevations, whereas historical VPD trends show the opposite pattern. This contrast suggests that growing season length may increase at higher elevations, while lower elevations are likely to face a greater frequency of extreme drought events throughout the century (Figure 4). Intra- and inter-population variability in traits such as stomatal regulation, water-use efficiency, and hydraulic conductivity may offer potential pathways for adaptation. However, even genetically resilient genotypes possess physiological limits beyond which survival is no longer possible under extreme climatic conditions (Anderegg et al., 2016). Identifying these thresholds is therefore essential for improving tree mortality models and for developing effective seed transfer or assisted migration strategies that explicitly incorporate climatic extremes into the selection of climate-resilient seed sources (Muñoz and Trujillo, 2020; Yuan et al., 2019).

In conclusion, despite inter-model variability, the results consistently indicate a widespread and regionally differentiated increase in Tmax trends across *P. brutia* BZs under SSP5-8.5. The projected future trends suggest potential shifts in thermal regimes that may exceed current adaptive limits of some *P. brutia* populations. Particularly at risk are Aegean and Marmara BZs that are already subject to high evaporative demand. These findings highlight the urgent need to integrate future climate projections into long-term forest genetic resource management, including the selection of heat and drought-resilient genotypes and the refinement of breeding and conservation strategies tailored to regional warming trajectories. Most importantly, the prevailing climatic conditions underscore the necessity of integrating ecophysiological insights such as water use efficiency and hydraulic conductivity studies with tree breeding approaches. This study strongly advocates for the support of research projects that integrate ecophysiology and tree breeding, particularly those that address the impacts of

climate change on temperature and drought.

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Authors' contributions

Main idea/Planning: Sefa Karabaş, Data collection and analysis: Sefa Karabaş, Literature review: Sefa Karabaş, Erkan Babat, Review and correction: Sefa Karabaş, Erkan Babat

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