ISPARTA UYGULAMALI BİLİMLER ÜNİVERSİTESİ

Turkish Journal of Forestry | Türkiye Ormancılık Dergisi
2025, 26(2): 137-147 | Research article (Araştırma makalesi)

Climate-growth relationships and growth trends of *Cedrus libani*, *Pinus brutia*, and *Pinus nigra* subsp. *pallasiana* in the Boz Mountains (Western Türkiye)

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Abstract: The ongoing climate change is increasingly affecting the growth conditions of forest trees. In the Mediterranean region, a reduction in precipitation and an increase in temperature are anticipated, which will have an adverse impact on tree growth. We used dendrochronology methods to analyze the impact of climate variables (air temperature, precipitation, relative humidity, and vapor pressure deficit) on stem growth of planted Taurus cedar (*Cedrus libani* A. Rich) and natural occurring Turkish pine (*Pinus brutia* Ten.) and Anatolian black pine (*Pinus nigra* subsp. *pallasiana* (Lamb.) Holmboe) growing in the Boz Mountains, Western Türkiye. We further investigated their growth trends based on basal area increment to detect growth differences between these three ecologically and economically important forest tree species. Taurus cedar showed a positive growth trend indicating good tree vitality. Turkish pine and black pine showed neither a positive nor a negative growth trend over the past 25 years. Turkish pine exhibited the greatest year-to-year variability in tree ring width and basal area increment and was the most sensitive to climate, resulting in significant response function and correlation analysis results. Turkish pine growth was most limited by winter precipitation and current year's July precipitation. Radial growth in black pine was negatively correlated to high temperatures and dry conditions in current year May. Our results further showed, that Taurus cedar was the least sensitive to year-to-year climate variability.
Keywords: Anatolian black pine, Dendrochronology, Taurus cedar, Tree-ring, Turkish pine

Boz Dağlar'ında (Batı Türkiye) *Cedrus libani*, *Pinus brutia* ve *Pinus nigra* subsp. *pallasiana*'nın iklim-büyüme ilişkileri ve büyüme eğilimleri

Öz: İklim değişikliği orman ağaçlarının büyüme koşullarını giderek daha fazla etkilemektedir. Akdeniz bölgesinde, yağışlarda bir azalma ve sıcaklıkta bir artış beklenmekte ve bu durum ağaç büyümesini olumsuz şekilde etkileyecektir. Bu çalışmanın amacı, Batı Türkiye'nin Boz Dağlarında bulunan ağaçlandırma sahasındaki Toros sediri (*Cedrus libani* A. Rich) ile doğal yetişen kızılçam (*Pinus brutia* Ten.) ve Anadolu karaçamında (*Pinus nigra* subsp. *pallasiana* (Lamb.) Holmboe) dendrokronolojik yöntemler kullanarak bazı iklim parametrelerinin (sıcaklık, yağış, bağıl nem ve buhar basıncı açığı) gövde büyümesi üzerindeki etkisini analiz etmektir. Ekolojik ve ekonomik açıdan önemli olan bu üç orman ağacı türü arasındaki büyüme farklılıklarını tespit edebilmek için göğüs yüzey alanı artışına dayalı büyüme eğilimlerine bakılmıştır. Toros sediri, iyi bir ağaç canlılığına işaret eden pozitif bir büyüme eğilimi göstermiştir. Kızılçam ve Anadolu karaçamında son 25 yılda ne pozitif ne de negatif bir büyüme eğilimine rastlanmamıştır. Kızılçam, yıllık halka genişliği ve göğüs yüzeyi alanı artışında yıldan yıla en büyük değişkenliği sergilemiş ve iklim koşullarına en yüksek duyarlılığı göstermiştir. Bundan dolayı bu çalışmada en anlamlı tepki fonksiyonu ve korelasyon analizi sonuçlarına kızılçamda rastlanmıştır. Kızılçamın büyümesini en çok kış yağışları ve halka oluşum yılının temmuz yağışları olumsuz yönde etkilemiştir. Anadolu karaçamında ise, halka oluşum yılının mayıs ayındaki yüksek sıcaklıklar ve kurak koşullar yıllık halka gelişimini olumsuz yönde etkilemiştir. Ek olarak, sonuçlarımız çalışma sahasındaki sedirlerin yıldan yıla değişen iklim özelliklerine karşı çok duyarlı olmadığını ortaya koymuştur.
Anahtar kelimeler: Anadolu karaçamı, Dendrokronoloji, Toros sediri, Yıllık halka, Kızılçam

1. Introduction

Ongoing global climate change affects tree growth in many regions, including Mediterranean forest ecosystems (Allen et al., 2010). Increasing temperatures and changes in precipitation patterns have a detrimental impact on tree vitality and growth (Vacek et al., 2023). However, species growing in the same region may have different growth responses to climatic conditions (Michelot et al., 2012). Information on tree growth responses to environmental factors can help to predict how ongoing climate change might affect tree growth (Anderegg et al., 2015; Salomon et al., 2022).

One method for examining the influence of environmental factors on tree growth is the application of dendrochronological techniques, which deal with the dating and study of annual growth increments (i.e., tree rings) in woody shrubs and trees (Fritts, 1976; Coulthard and Smith, 2013). Tree-rings serve as key ecological indicators of environment and climate change, given that year-to-year fluctuations in environmental factors result in variations in tree-ring widths (Zhang, 2015). Several studies have been

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Received (Geliş tarihi): 22.07.2024, **Accepted** (Kabul tarihi): 13.03.2025

Citation (Atıf): Güney, A., Erkan, T., Oğlakcı, R., Özer, E., 2025. Climate-growth relationships and growth trends of *Cedrus libani*, *Pinus brutia*, and *Pinus nigra* subsp. *pallasiana* in the Boz Mountains (Western Türkiye). Turkish Journal of Forestry, 26(2): 137-147.
DOI: 10.18182/tjf.1508195

conducted in Türkiye to investigate the influence of climate on tree growth (diameter growth) of different tree species (Akkemik, 2000; Kara, 2011; Touchan et al., 2014; Alkan and Irdem, 2023). In these dendroclimatological studies, precipitation and temperature conditions, which generally influence tree ring width, were analyzed. For Anatolian black pine (*Pinus nigra* subsp. *pallasiana* (Lamb.) Holmboe) it was reported that drought was one of the main factors limiting annual ring development (Touchan et al., 2005; Akkemik et al., 2008; Köse et al., 2012). Doğan and Köse (2019) found that, in the mountainous regions of southwestern Türkiye, warmer temperatures and higher precipitation early in the growing season promote radial growth of Anatolian black pine. However, during the summer, increasing temperatures and drought limited growth with the drought effect being more pronounced in trees growing at lower elevation. Low precipitation was also found to be a major limiting factor for the growth of Taurus cedar (*Cedrus libani* A. Rich) at the northern border of its natural distribution (Akkemik, 2003). In the case of Turkish pine (*Pinus brutia* Ten.), it was shown that annual diameter increment was generally positively influenced by months with high precipitation and negatively affected by high temperatures and low precipitation (Reis et al., 2018; Yurtseven, 2021). In addition to investigating tree growth responses to climatic variables, the analysis of growth trends provides a more comprehensive understanding of long-term changes in tree vitality and productivity (Dobbertin, 2005). Growth trends are based on basal area increment data calculated from tree-ring width series. For vital trees, growth trends are typically positive, provided that the trees have not entered senescence, and thus, these trends offer valuable insights into how tree species are adapting to changing environmental conditions over time (LeBlanc, 1990; Kašpar et al., 2024).

Anatolian black pine, Taurus cedar (hereafter referred to as black pine and cedar, respectively), and Turkish pine are all ecologically and economically important forest species in Türkiye. Turkish pine is fast-growing and the primary tree species with the largest distribution area after oak, covering 5.2 million ha and about 23% of Türkiye's forests (General Directorate of Forestry, 2020). It is distributed between 0-1500 m altitude in the Mediterranean, Marmara and Black Sea regions of Türkiye where the Mediterranean climate is dominant (Yaltırık and Boydak, 2000). Third comes black pine with 4.2 million ha and 18% forest cover (General Directorate of Forestry, 2020). In Türkiye, black pine is found at altitudes ranging from 400 to 2100 m in all mountainous regions to the west of the Anatolian Diagonal (Akkemik, 2014). Cedar only covers approximately 1.8% of Türkiye's forests with 0.4 million ha (General Directorate of Forestry, 2020). It is typically found between 800 and 2100 m in the Taurus Mountains (Boydak and Çalıkoğlu, 2008). However, in Finike, it is observed at altitudes as low as 500 m, while in the Bolkar Mountains, it can reach elevations of up to 2400 m. Cedar is utilized in a multitude of forestation and afforestation initiatives within and beyond Türkiye (Boydak, 2007; Ducci et al., 2007). Furthermore, it is considered as a potential alternative conifer species for the establishment of climate-resistant viable forests in Central Europe (Messinger et al., 2015; Zsolnay et al., 2023).

All three conifer species are relatively drought-tolerant, yet little is known about the extent to which they might respond to increasing drought severity and frequency. Climate change scenarios predict that drought conditions in the Aegean region of Türkiye will intensify in the coming years (General Directorate of Meteorology, 2014). Therefore, more studies are needed to better understand the relationship between climate and tree growth, as well as to assess growth trends under ongoing climate change, particularly in the Aegean region.

The Boz Mountains, situated in Western Türkiye, represent one of the Aegean Region's most notable locations for the presence of Turkish pine and black pine forests (Dönmez and Aydınözü, 2012). The local climate is characterized by a transition from Mediterranean to continental, with seasonal droughts that contributed to the formation of various vegetation types (Günal, 2013). In addition to seasonally dry coniferous forests, this area is home to a variety of other natural habitats, including maquis, deciduous forests, and mountain pastures (Günal, 1992; Hepcan et al., 2009). The area includes a natural park (Ovacık Natural Park), a wildlife development area, and a former research forest. Additionally, it includes a small stand of cedar trees that were planted around the mid-1970s. This region is outside of the natural distribution range of cedar, which allows for an investigation of the growth of cedar in comparison to natural occurring Turkish pine and black pine in the same area. A number of studies have analyzed the growth performance and climate-growth relationships of cedar, Turkish pine, and black pine (Akkemik, 2003; Ladjal et al., 2007; Messinger et al., 2015; Öner et al., 2015; Janssen et al., 2018). However, to the best of our knowledge, this study is the first to include a comparison of the growth responses of these three species growing in the same area and in the mid-elevation belt.

The main objective of this study was to determine the impact of inter-annual climate fluctuations on the annual growth increments of Taurus cedar, which is non-native to the Boz Mountains, and natural occurring Turkish pine and Anatolian black pine. The specific objectives were (1) to detect growth differences among the three species, (2) to investigate whether growth trends show a decline in response to ongoing climate change, and (3) to identify which climate variables (precipitation, temperature, relative humidity, vapor pressure deficit) most significantly affect radial growth.

2. Materials and methods

2.1. Site description

The sampling sites were situated in the northwestern parts of the Boz Mountains in Izmir, Western Türkiye (Figure 1). In this region, Turkish pine is the dominant forest species at the lower ranges of the mountains (derived from forest maps of the General Directorate of Forestry). At altitudes around 700 m black pine starts to become the dominant species and can be found at up to 1300 m (Günal, 2013). This area is characterized by a Mediterranean climate (Figure 2) with rainy winters and hot and dry summers (Malkoç and Nurlu, 2023). The first sampling site was situated at an altitude of 800 meters (38°20'57.96"N, 27°41'0.82"E) within a pure black pine stand. In very close proximity to the first sampling site, a cedar nursery was established around the mid-1970s (Figure 3). The terrain was relatively flat with an average slope of 9% and a north-west aspect. The second sampling site was located in a pure Turkish pine stand at an altitude of 500 m (38°24'10.18"N, 27°39'47.29"E) with a north-west aspect and an average slope of 27%. At both sampling sites the understory was minimal with a sparse herb layer at most (Figure 3). The distance between the two sampling sites was approximately 6 km. Site codes were created for each species based on the research area and species name. The codes consisted of an abbreviation for the research area (BM for Boz Mountains) followed by the species abbreviation: *Cedrus libani* (CL), *Pinus brutia* (PB), and *Pinus nigra* subsp. *pallasiana* (PN).

2.2. Sample collection and tree-ring width analysis

Tree coring was performed on 13 cedar, 16 Turkish pine, and 14 black pine trees of similar age (Table 1) using a HAGLÖF increment borer that is 5.15 mm in diameter. All trees appeared healthy and had no visible signs of any damage. Diameter at breast height (DBH) and tree height was measured using a caliper (HAGLÖF). Tree height was similar for the measured individuals and ranged between 19 and 21 meters. For each tree, two increment cores were collected at breast height (1.3 m above the ground) from opposite sides of the stem. Cores were stored in paper straws which allows the cores to air dry (Hood et al., 2020). After the cores were left to dry for a week, they were mounted on wooden holders with the transverse plane facing up. They were then sanded using progressively finer grits (120, 220, 320, and 400) until a smooth and flat surface was created and tree rings became clearly distinguishable. A flatbed scanner with an optical resolution of 1200 DPI was utilized to produce high-quality images of the cores. A precision ruler was scanned alongside the tree cores as a scale reference. The images were calibrated to ensure accurate scale and tree ring widths (TRW) were measured using the image processing software ImageJ (National Institutes of Health, Bethesda, MD, USA). This method allows for precise measurements with an accuracy of at least 0.01 mm, which is the standard in dendrochronological studies (Touchan et al., 2005; Galván et al., 2012). Tree ring widths were measured from bark to pith. Since we sampled living trees, crossdating was performed using the method proposed by Yamaguchi (1991) by comparing the narrowest rings in the ring series. The quality of crossdating and measurement accuracy of tree-ring series was assessed using the COFECHA software (Holmes, 1983; Grissino-Mayer, 2001). We used a 20-year segment length with a 10-year lag for all three species (Foster et al., 2015). Some tree-ring series that could not be crossdated and showed weak correlation with the other series of the species were removed from the analysis. The remaining series correspond to the number of tree cores shown in Table 1.

Each crossdated tree-ring series was detrended using the Dendrochronology Program Library in R (*dplR*) version 1.7.7 developed by Bunn (2008) for the R freeware program (R Core Team, 2024; http://cran.r- project.org/). We used the interactive detrending function, which enables the user to select the detrending curve that best fits each time series (Bunn and Korpela, 2020). All tree-ring series were detrended with a cubic smoothing spline, which allows for greater flexibility in the removal of non-climatic variance (Cook and Peters, 1981) and which results in dimensionless growth indices fluctuating around 1. The selected length of the smoothing spline was 15 years for all species, with the objective of maximizing climate correlations (Foster et al., 2015). First-order auto-correlation (Ar1) and mean sensitivity (MS) were calculated on individual detrended series and averaged to determine the influence of the previous year's growth on the current year's growth and the year-to-year variability, respectively. A standard chronology was built for each species from the detrended series using Tukey's biweight robust mean (Bunn and Korpela, 2020). For each standard chronology, we calculated the mean inter-series correlation (Rbar, the average pairwise correlation between series), the overall inter-series correlation (the correlation between a series and the master chronology), and the expressed population signal (EPS, a statistic to determine whether a chronology correctly represents the population signal of a data set) (Bunn, 2008). Correlation between the three index-chronologies was evaluated by calculating Pearson's product moment correlation coefficients (r) and evaluating its corresponding t-values (Baillie and Pilcher, 1973).

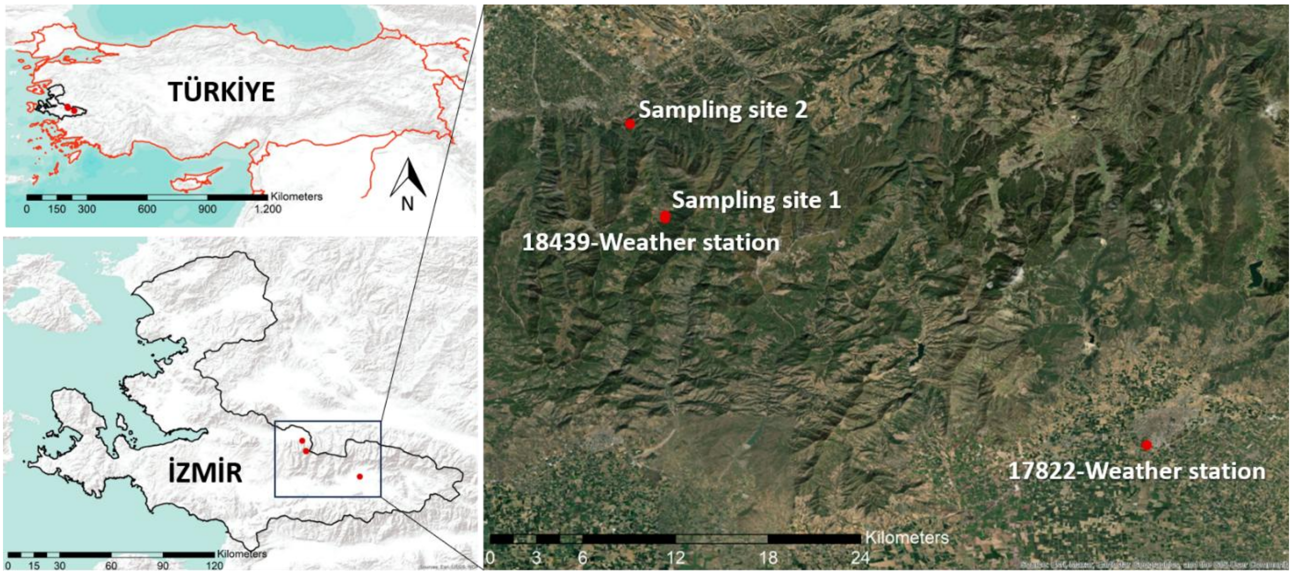

Figure 1. Location of sampling sites and weather stations in Izmir Province, Western Türkiye. Sampling site 1 includes BMCL (*Cedrus libani*) and BMPN (*Pinus nigra* subsp. *pallasiana*); Sampling site 2 corresponds to BMPB (*Pinus brutia*). Climate data were obtained from the Ovacık weather station (ID: 18439) in the Boz Mountains and the weather station in Ödemiş (ID: 17822)

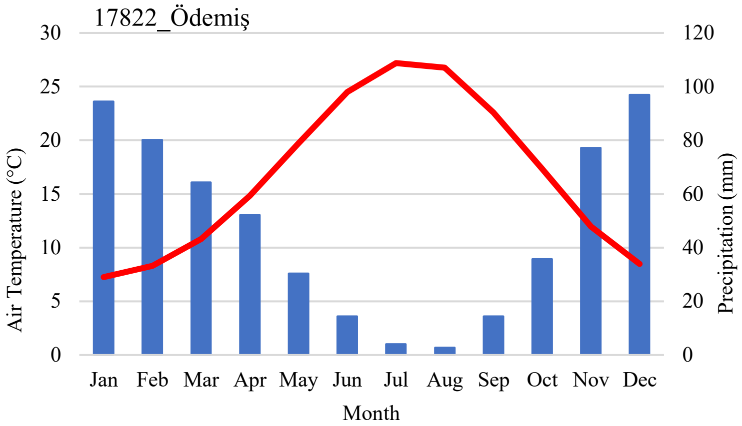

Figure 2. Climate diagram of mean monthly precipitation (blue bars) and temperature (red line) for the Ödemiş weather station (17822) for the period 1970–2023. Climate data were obtained from the Turkish State Meteorological Service

Figure 3. Cedar (a) and Turkish pine (b) sampling sites situated in the northwestern parts of the Boz Mountains in Izmir, Western Türkiye

To study the long-term growth trends of the species, basal area increment (BAI) was calculated from TRW measurements according to the formula:

$$BAI = \pi(R_n^2 - R_{n-1}^2) \quad (1)$$

Where R_n is the radius increment in the year n and R_{n-1} is the radius increment in the previous year. BAI is more closely related to biomass increment than TRW (Schuster and Oberhuber, 2013) and in contrast to TRW series, age-related trends in BAI are typically positive and do not exhibit a decline until trees begin to senesce (LeBlanc, 1990). A one-way ANOVA and Tukey's post-hoc test ($\alpha = 0.05$) were used to test for differences in mean DBH, age at DBH, and radial growth (TRW, BAI) between species.

2.3. Climate-growth analysis

Climate data were obtained from the Turkish State Meteorological Service for the Ödemiş (38°12'56.51"N, 27°57'51.10"E; 111 m, station ID 17822) and Ovacık (38°20'52.08"N, 27°41'0.96"E; 800 m, station ID 18439) weather stations. The Ödemiş station (Figure 1) is the closest to the sampling sites with a longer record that goes back to 1945. The Ovacık weather station, which is situated within the study area very close to sampling site 1, started recording in 2014. This would have been a too short period for our analysis. We therefore calculated mean monthly precipitation and temperature for the 1970-2023 period using data from the Ödemiş station since this was the time span, we used for our analysis (Figure 2). The mean annual precipitation and temperature for Ödemiş were calculated as 564 mm and 16.6°C, respectively. We also calculated annual means for the period 2014-2022 for both weather stations, to see how they differ. With a mean annual precipitation and temperature of 989 mm and 13.0°C, respectively, Ovacık is more humid and cooler than Ödemiş (mean annual precipitation: 535 mm; mean annual temperature: 17.5°C) for the same period.

For the climate-growth analysis, we used monthly mean, maximum and minimum air temperature, precipitation sum, mean relative humidity (RH) and mean vapor pressure deficit (VPD). VPD was calculated using the Tetens method (Alizadeh et al., 2021). High VPD increases water loss from soils and has direct impact on plant physiology thus contributing to drought events and plant water stress (Dai, 2013). To assess the influence of specific climate variables on radial stem growth, climate-growth analysis was performed using the package *treeclim* version 2.0.6 in R (Zang and Biondi, 2015). Bootstrapped Pearson's correlation coefficients were computed between tree-ring index chronologies of each species and monthly values of each of the climate variables (Biondi and Waikul, 2004). We further assessed the relationships between index chronologies and the climate variables mean temperature and precipitation using response function analysis (Dağdeviren et al., 2004; Gauli et al., 2022). Analysis included monthly data from July of the previous year to October of the current year, because the previous year's growing season may have an impact on the current year's growth (Fritts, 1976).

3. Results

Cedar showed a different pattern of radial growth (TRW) and BAI compared to Turkish pine and black pine, especially when considering the last 25 years (Figure 4). In contrast, radial growth and BAI followed a similar pattern for Turkish pine and black pine, although Turkish pine showed a pronounced increase in BAI during the years 1998 and 2002. A positive (increasing) growth trend was observed for cedar, while the annual BAI remained at a similar level (a neither positive nor negative/decreasing growth trend) for both pine species (Figure 4b). Mean TRW and BAI did not show significant differences among the studied species (Table 1). DBH and age at DBH were significantly higher in Turkish pine and lowest in cedar.

Among the species studied, radial growth was most influenced by the previous year's growth in black pine (Ar1= 0.778), followed by cedar and Turkish pine (Table 2). The low mean sensitivity in cedar indicates that this species is not very sensitive to climate variability at the sampling site. In contrast, both pine species showed intermediate sensitivity to climate variability. The standard chronologies for the Boz Mountains cedar, Turkish pine, and black pine are shown in Figure 5. With an Rbar of 0.466 and an overall inter-series correlation of 0.599 Turkish pine showed the best agreement across growth indices, indicating that trees within this species share a common growth signal (Table 2). The lowest Rbar (0.230) and overall inter-series correlation (0.414) was calculated for cedar. For all chronologies, the EPS was above the critical value of 0.85 (Wigley et al., 1984). The correlation between the cedar and Turkish pine index chronologies was low (r= 0.298, *t*-value = 2.03, *p*-value= 0.049) and not significant between the other chronologies ($p > 0.9$).

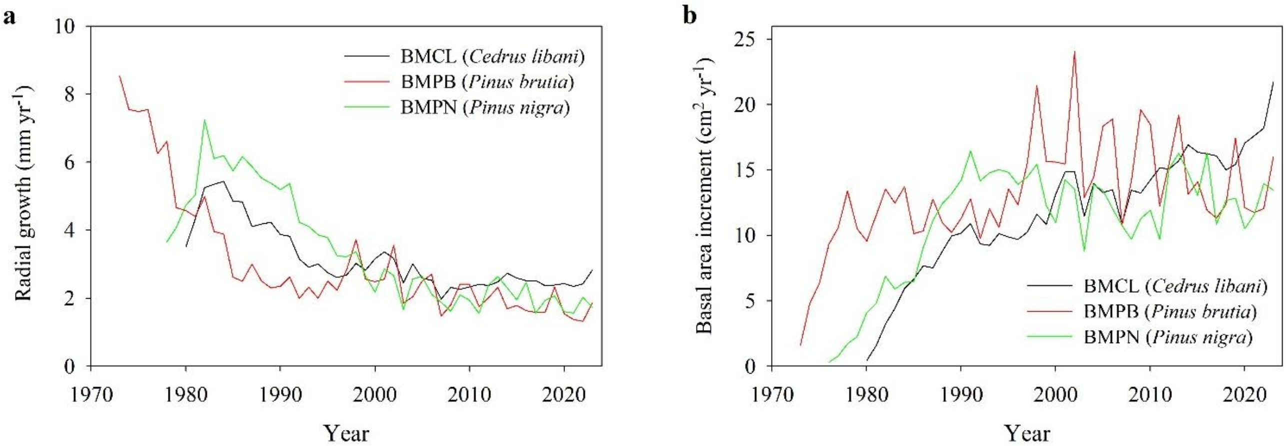

Figure 4. (a) Mean radial growth (tree ring width) and (b) mean basal area increment (BAI) of Taurus cedar (*Cedrus libani*), Turkish pine (*Pinus brutia*), and Anatolian black pine (*Pinus nigra* subsp. *pallasiana*) growing in the Boz Mountains (Western Türkiye)

Table 1. Mean and standard deviation (sd) of diameter at breast height (DBH), estimated age at DBH, tree ring width (TRW), and basal area increment (BAI) of Taurus cedar (*Cedrus libani*), Turkish pine (*Pinus brutia*), and Anatolian black pine (*Pinus nigra* subsp. *pallasiana*)

Site code	Species	Number of trees/cores	DBH (cm)	Age at DBH	TRW (mm yr^{-1})	BAI (cm^2 yr^{-1})*
BMCL	*Cedrus libani*	13/22	30.2 ± 3.8a	43 ± 1a	3.04 ± 0.4a	12.85 ± 2.5a (n=11)
BMPB	*Pinus brutia*	16/29	36.2 ± 6.4b	49 ± 3b	2.81 ± 0.6a	13.42 ± 5.5a (n=9)
BMPN	*Pinus nigra*	14/23	33.5 ± 5.6ab	45 ± 9ab	2.91 ± 0.5a	12.36 ± 2.6a (n=11)

*Average was calculated from cores that included the most inner tree-ring. Different letters after mean and sd values denote significant differences ($p < 0.05$).

Estimations of bootstrapped Pearson's correlation functions between tree-ring index chronologies and specific monthly climate variables revealed that there are species-specific differences in the influence of these variables on tree growth (Table 3). For cedar, meaningful and significant correlations were identified only for maximum and minimum temperature. Specifically, minimum temperature during December and April were positively correlated with growth, whereas maximum temperature in May was negatively correlated with growth. A significant correlation was observed between all climate variables and radial growth in the case of Turkish pine. During certain months of the spring and summer seasons, mean and maximum temperatures, as well as VPD, were negatively correlated with growth of Turkish pine, whereas precipitation and RH showed a positive correlation. The strongest positive correlation was detected between growth and precipitation in December (of the previous year). The strongest negative correlation was detected between growth and maximum temperature in September (of the current year). In black pine, radial growth was negatively correlated with mean temperature and VPD in May and positively correlated with precipitation in January (Table 3). Same as for the other studied species, growth showed a positive correlation with minimum temperature in December.

The response function analysis yielded no statistically significant results for cedar (Figure 6). Similar to the correlation analysis, precipitation in October of the current year was negatively correlated with black pine growth. The response function analysis for Turkish pine yielded in the most significant results, indicating that precipitation variability in December of the previous year and July of the current year exerts a significant controlling influence on Turkish pine growth.

Table 2. Descriptive statistics of the standard chronologies

Site code	Species	Ar1	MS	Rbar	Overall inter-series correlation	EPS
BMCL	*Cedrus libani*	0.701	0.166	0.230	0.414	0.868
BMPB	*Pinus brutia*	0.671	0.280	0.466	0.559	0.962
BMPN	*Pinus nigra*	0.778	0.246	0.368	0.510	0.928

Ar1 = mean first-order autocorrelation; MS= Mean sensitivity; Rbar = mean inter-series correlation, EPS = expressed population signal.

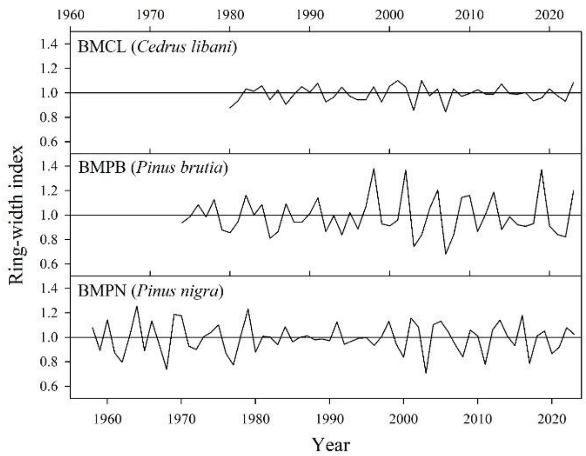

Figure 5. Tree-ring index chronologies of Taurus cedar (*Cedrus libani*), Turkish pine (*Pinus brutia*), and Anatolian black pine (*Pinus nigra* subsp. *pallasiana*) growing in the Boz Mountains (Western Türkiye)

Table 3. Bootstrapped Pearson's correlation coefficients (R) for climate-growth-correlations between monthly climate variables and ring-width index chronologies of Taurus cedar (*Cedrus libani*), Turkish pine (*Pinus brutia*), and Anatolian black pine (*Pinus nigra* subsp. *pallasiana*)

Climate variable	*Cedrus libani* (BMCL)		*Pinus brutia* (BMPB)		*Pinus nigra* (BMPN)	
	Month	R	Month	R	Month	R
Mean temperature (°C)			APR	-0.313	MAY	-0.304
			MAY	-0.338		
			JUL	-0.330		
Maximum temperature (°C)	FEB	0.290	JUL	-0.208	APR	0.329
	MAY	-0.307	SEP	-0.426		
Minimum temperature (°C)	dec	0.330	dec	0.289	dec	0.207
	APR	0.366				
Precipitation (mm)	sep	-0.311	dec	0.521	JAN	0.262
			APR	0.287	OCT	-0.380
			JUL	0.370		
			SEP	0.330		
Relative humidity (%)			APR	0.367	MAY	0.272
			MAY	0.339		
Vapor pressure deficit (kPa)			APR	-0.311	MAY	-0.300
			MAY	-0.346		
			JUL	-0.322		

All correlations are significant at the $p < 0.05$ level. Months of the preceding and current year are written in lower case letters and capital letters, respectively.

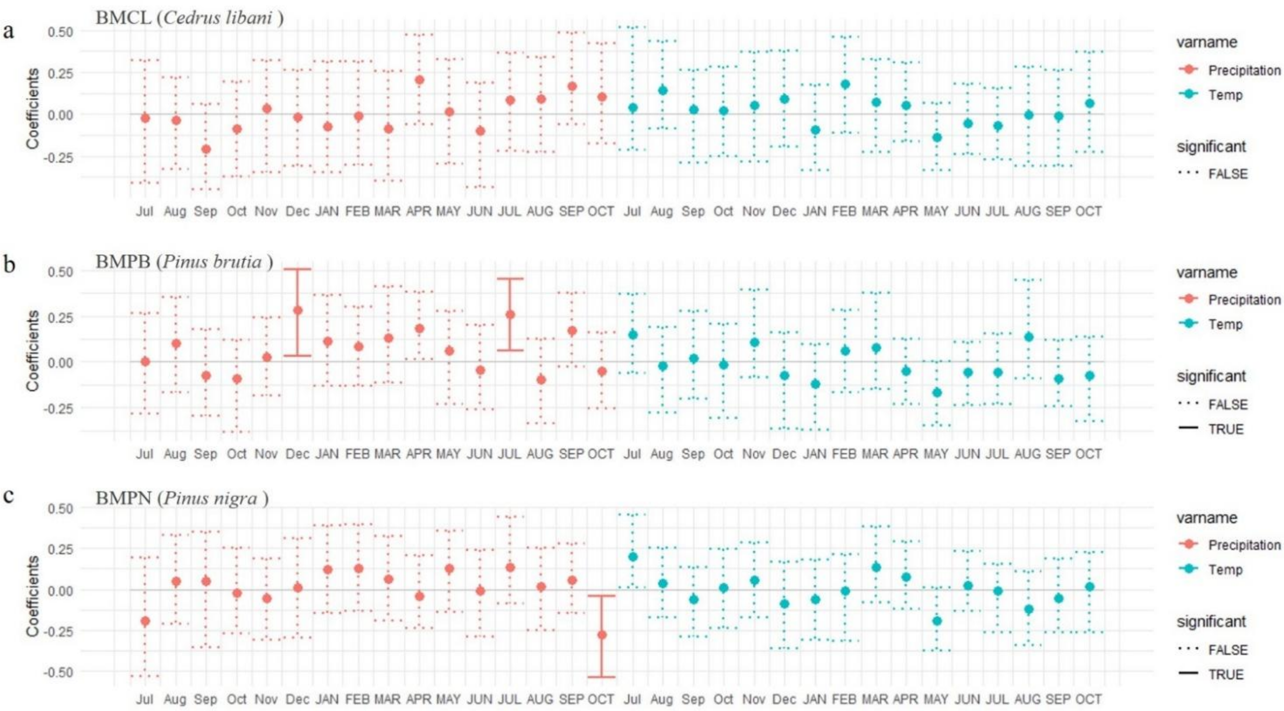

Figure 6. Response coefficients for monthly precipitation (red) and mean monthly temperature (blue) from the previous July to the current October for tree-ring chronologies of (a) Taurus cedar (*Cedrus libani*), (b) Turkish pine (*Pinus brutia*), and (c) Anatolian black pine (*Pinus nigra* subsp. *pallasiana)* growing in the Boz Mountains (Western Türkiye). The preceding year is indicated by lowercase letters, while the current year is indicated by uppercase letters.

4. Discussion

Although growing in the same area, the investigated species exhibited contrasting growth trends. Cedar was the only species that showed a clear positive growth trend over the past 25 years. Both Turkish pine and black pine showed a constant (neither positive nor negative) growth trend. These species-specific differences of trees growing in the same region can be attributed to various factors, often rooted in the species' physiology and growth strategies (e.g., Castagneri et al., 2013; Gribbe et al., 2024; Kašpar et al., 2024). One potential important physiological factor that can lead to a constant or negative growth trend, even under favorable growth conditions, is tree age. Age-related trends in BAI often show a decline when trees enter senescence (LeBlanc, 1990). Cedar and black pine are long-lived species with lifespans exceeding 700 and 1000 years, respectively (Boydak and Çalıkoğlu, 2008; Sevgi et al., 2022). Therefore, we conclude that the black pines in our study can be considered relatively young and the observed constant growth trends are more likely to be influenced by environmental factors rather than age-related decline. In contrast, Turkish pine is considered a relatively short-lived species with an average lifespan between 120 and 150 years (Nahal, 1983). However, other studies have reported lifespans ranging from 150 to 300 years (Griggs et al., 2014), 250 to 305 years (Boydak, 2004) and sometimes exceeding 400 years (Touchan et al., 2005; Ministry of Environment, Urbanization and Climate Change, 2019). Nevertheless, although this species can potentially live for more than 250 years, it has been demonstrated that its annual growth (in m^3/ha) peaks around the age of 40-60 years, after which it begins to decline (de Miguel Magaña, 2014; Kahriman et al., 2023). Therefore, the constant growth trend observed in Turkish pine could at least partially, be attributed to age-related decline in growth capacity. Following this, we argue that the observed constant growth trends in both Turkish pine and black pine may be caused by the increase in temperatures and drought negatively affecting radial growth which is supported by the findings of other studies. Janssen et al. (2018) investigated recent growth trends of black pine growing in the Lake District in Southwest Türkiye which is close to the species’ southern distribution limit. They found that after the 1970s, growth significantly decreased which was strongly correlated with increased temperatures and summer drought. Numerous other studies have indicated that black pine is a drought-sensitive species that is negatively affected by climate change (Martín-Benito et al., 2008; Köse et al., 2012; Sánchez-Salguero et al., 2013; Klisz et al., 2023). Should temperatures and drought further increase in the study region as expected, black pine vitality might decline and growth trends may shift toward negative. Turkish pine, on the other, is a relatively fast-growing conifer that is considered to be among the more drought-tolerant species (Boydak, 2004; Veuillen et al., 2023). It is less sensitive to drought than black pine (Deligöz and Cankara, 2020; Mazza et al., 2021), but less tolerant of cold temperatures (Semerci et al., 2021). Given its greater drought tolerance, a positive growth trend might have been expected which further supports our assumptions that the constant growth trend in Turkish pine was in part attributed to tree age.

Consequently, growth trends can be regarded as indicators of tree vitality and forest productivity (Dobbertin, 2005; Sökücü and Güney, 2021). Negative growth trends are usually indicative of declining tree vitality which can be attributed to a multitude of biotic (e.g., mistletoe infestation;

Noetzli et al. (2003) and abiotic (e.g., drought; Diers et al., 2023) factors. The observed positive growth trend in the investigated cedars indicates that, at this time, these trees are vital, productive, and not negatively affected by the recent increase in temperatures or other potential environmental disturbances or stress factors. As cedar is known to be drought tolerant with the capacity for fast recovery from climatic extremes, this finding was not unexpected (Güney et al., 2020; Zsolnay et al., 2023). Additionally, a number of studies have documented that cedar shows good growth performance and adaptation in various afforestation projects and plantations outside its natural range (Boydak, 2003; Boydak, 2007; Messinger et al., 2015; Zsolnay et al., 2023). However, it is currently unclear whether the positive growth trend of cedar in the Boz Mountains will persist in the future, given the projected increase in the frequency and severity of drought events associated with climate change (IPCC, 2021).

Other reasons for the differences in growth trends in the species investigated might be potential differences between the sampling sites that we were not able to investigate (e.g. differences in soil properties, water availability). Management practices can also significantly affect growth (trends) as can be seen from the pronounced increase in BAI during the years 1998 and 2002 in Turkish pine. This growth release was probably caused by thinning (Schuster and Oberhuber, 2013).

Our analyses revealed that Turkish pine exhibited the highest year-to-year variation in both BAI and TRW, making it the most sensitive species to climate variation in this study. This could again be attributed to differences in slope and soil conditions between sampling sites (Doğan and Köse, 2015) which could alter water availability, as well as to differences in the physiological responses of the investigated species (Griggs et al., 2014; Deligöz and Cankara, 2020). This climate sensitivity of Turkish pine was also reflected in the significant results obtained from the correlation and response function analyses. A positive response was found to winter precipitation and to current year July precipitation. Further, radial growth of Turkish pine was limited by high temperatures and dry conditions during the summer months and September. These findings suggest that winter precipitation plays a pivotal role in maintaining soil water reserves during the growing season (Rozas et al., 2011). Water availability is crucial for the process of tree ring formation. In many species of the Mediterranean, dry conditions and high temperatures during summer can result in the early cessation of cambial activity and the formation of new xylem cells (Camarero et al., 2010; Vieira et al., 2017). Unless favorable conditions return during early autumn (e.g., autumn precipitation) cambial activity does not resume and the early cessation of wood formation can result in the formation of narrow tree rings. The number of studies investigating the climate-growth relationship in Turkish pine is relatively limited. Griggs et al. (2014) also found precipitation to be the most important factor favoring growth, although Turkish pine growing in Cyprus was mainly influenced by previous year September precipitation and current year May precipitation. According to the literature, only two studies have investigated the impact of climate variability on Turkish pine growth in the Izmir region (Doğan, 2020; Yurtseven, 2021). In line with our results, Turkish pine growth showed a significant negative correlation with maximum July temperature and a significant positive correlation with precipitation during several months. Besides Turkish pine, Yurtseven (2021) also analyzed the climate-growth of black pine, both species situated in the upper elevation range of the Yamanlar Mountain. The location and characteristics of the sampling sites and the older age of the trees (>160 years) might be some of the reasons why black pine resulted in more significant results in the study of Yurtseven (2021) than in our study. In his study, black pine growth was favored by warm conditions during February and March and high precipitation during spring, while according to our results, winter precipitation and cool and moist conditions during May favored black pine growth the most. These differences in the growth responses between months could also be attributed to the fact that our study trees were located at lower elevations, where temperatures in May are generally higher than at higher elevations, which may influence the sensitivity of trees to climatic variables during the growing season (Fritts, 1976; Doğan and Köse, 2015).

In our study, cedar was the least sensitive to climate variation, resulting in no significant findings in the response function analysis. Cedar is a preferred species in dendrochronological studies due to its longevity and high sensitivity to climate variability (Akkemik, 2003; Touchan et al., 2005). In purely dendrochronological studies that focus on climate-growth relations, sample trees are usually selected from sites were growth is most limited by environmental parameters to get a good climatic response (Fritts, 1976). These would be for example trees that grow at their distributional limit, or at hillslopes with restricted water supply. Our cedars were located in the mid-elevation belt, the terrain was relatively even, and environmental conditions were not as harsh as for example at the treeline or higher elevations. Also, given its deep taproot, cedar's water supply may not have been significantly restricted even during the dry months (Boydak, 2003; Güney et al., 2020). However, this study was not focused on dendrochronology for climate reconstruction purposes. Rather, our goal was to compare the growth performance of non-native cedar with that of Turkish pine and black pine in that area, and to identify the climatic parameters most influencing their growth. Still, our results from correlation analysis indicate that, in general, warmer winter and early spring temperatures promote growth, but high temperatures in May limit radial growth of cedar. Although temperature is an important driver of tree growth (Huang et al., 2020) many studies clearly show that precipitation is the primary limiting factor in regions such as the Mediterranean (Akkemik, 2006; Sarris et al., 2007; DeSoto et al., 2014). For instance, Touchan et al., (2014) investigated the influence of climate on the growth of several tree species (including those in our study) based on a large dataset covering the Eastern Mediterranean and Near East. They were able to show that the most important factor affecting growth in that region is May and June precipitation. This indicates that if spring and early summer droughts continue to intensify due to ongoing climate change, tree growth in the Aegean Region could be severely impacted with potential long-term consequences for forest health and productivity.

5. Conclusions

Taurus cedar showed the best growth performance and was the least sensitive to climate variability among the studied species. This suggests that these cedars are vital and are currently growing in conditions that are still favorable for their growth. The positive growth trend also indicates resilience to the ongoing increases in temperature, highlighting the potential of Taurus cedar for successful forestation outside its natural range. This has significant implications for forest management, both within and outside Türkiye. Native Anatolian black pine showed lower growth performance with a constant growth trend over the past years probably caused by the increased temperatures at its lower distribution range. Turkish pine showed a similar growth performance as Anatolian black pine which might be partly age-related. On the other hand, Turkish pine was the most sensitive to variation in climate. This allowed to show a more distinct and measurable relationship between climate variables and tree growth. In line with other studies, the combination of high temperatures and low precipitation during July of the current year had the most limiting effect on Turkish pine growth. Our findings suggest that if temperatures and drought continue to increase in the study area, as expected under climate change, black pine growth and vitality may be the first to decline, making it more susceptible to other stressors (e.g. bark beetles) and raising the need for adaptive forest management strategies. Our results may serve as a first step towards a more comprehensive study to investigate the vitality and growth performance of ecologically and economically important forest species under climate change in Türkiye.

Acknowledgements

Eren ÖZER received funding from the 2209-A-Research Project Support Programme for Undergraduate Students (Project number: 1919B012318955) of the Scientific and Technological Research Council of Türkiye (TÜBİTAK). We would like to thank Mustafa BATUR, Niyazi ÖZÇANKAYA and Burak BAHAR for their assistance in the field.

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