Radial growth and climatic influences on Greek fir: Tree ring analysis from Kirphi mountain, Central Greece

Panagiotis P. Koulelis[1]*, Alexandra Solomou[2], Vassilia Fassouli[3], Panos V. Petrakis[2], Ioannis Spanos[1]

[1]Forest Research Institute - ELGO DIMITRA, Vasilika, 57006, Thessaloniki, Greece
[2]Institute of Mediterranean Forest Ecosystems - ELGO DIMITRA, Ilisia, 11543, Athens, Greece
[3]Ministry of Rural Development and Food, 6 Kapnokoptiriou str, 10433 Athens, Greece

Abstract

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In the era of global climate fluctuations, understanding the intricate relationship between trees and climatic factors is crucial for assessing ecosystem resilience and adapting to environmental changes. This study explores the radial growth of Greek fir (*Abies cephalonica*) in response to climatic factors in Kirphis mountain, Central Greece. The plants diversity of the area makes Kirphi one of the most crucial reserves for endemic flora, necessitating focused conservation efforts for its preservation. Using detailed tree ring analysis, gridded climate data, and data from nearby meteorological stations, we investigated how climatic variables influence fir growth dynamics. Despite the moderate climate signal observed, our findings highlight the sensitivity of fir growth to climatic variability, with significant correlations identified between tree-ring width and drought indices. Drought conditions, measured by SPI-12 and PDSI-12, significantly affect fir ring growth. The strongest correlation was observed with SPI-12, indicating that long-term precipitation patterns play a key role. A lower correlation with evapotranspiration suggests adaptation to droughts, while the positive link with annual precipitation shows water availability is important but not the only factor. Ultimately, this research may provide valuable insights into the adaptive strategies of Greek fir forests in response to climatic fluctuations, potentially informing conservation and management practices in Mediterranean mountain ecosystems.

Keywords

Central Greece, climate, drought, fir decline, Greek fir, radial growth

Introduction

Understanding how trees respond to climatic factors is increasingly crucial for evaluating ecosystem resilience and managing environmental changes, especially as global climate patterns shift. The unique ecological context of Kirphis mountain serves as an ideal setting for this exploration, promising to enrich our understanding of the intricate dynamics shaping the growth of Greek fir in the face of contemporary climatic challenges. The sensitivity of tree growth behavior to warmer or drier climates can vary depending on the species. The anticipated rise in the severity and frequency of drought occurrences globally, as predicted by studies such as Field et al. (2012) and Giorgi et al. (2011), could significantly impact tree growth, as noted by Dobbertin (2005). Simultaneously, over recent decades, severe drought events, marked by elevated temperatures and reduced precipitation, have led to pronounced episodes of forest dieback across Europe, as documented by Penuelas et al. (2001) and Dobbertin (2005).

Particularly, the forests in Southern Europe have been impacted by direct abiotic disturbances, such as droughts

*Corresponding author:
e-mail: pkoulelis@elgo.gr

and other climatic variables (McDowell et al., 2008; Allen et al., 2010; Adams et al., 2017; Choat et al., 2018) leading to reduced forest productivity (Ciais et al., 2005) and increased tree mortality (Colangelo et al., 2018; Navarro-Cerrillo et al., 2018 and Navarro-Cerrillo et al., 2020). In Greece, water scarcity appears to be the main climatic factor constraining forest growth. Various studies have demonstrated a significant correlation between water availability and both tree ring width and overall tree growth across different forests and tree species (Dobbertin, 2005; Gentilesca et al., 2008; Koulelis et al., 2019, 2022, 2023; Koutavas et al., 2008; Mazza et al., 2014; Papadopoulos, 2016; Sarris et al., 2007; Sass-Klaassen et al., 2007; Zheng et al., 2022).

Three fir species are found in Greece: *Abies alba* Miller, restricted to the northern border, *Abies cephalonica* Loudon, native to the Mediterranean region, and *Abies borisii-regis* Mattf (Strid and Tan, 1997). *A. cephalonica* is endemic to Greece, primarily in the southern and central regions, while *A. borisii-regis*, endemic to the southern Balkan Peninsula, is mainly located in northern and central Greece (Athanasiadis, 1986). In the northern parts of the country, *A. alba* is dominant, but it is replaced by *A. borisii-regis* in the south. *A. borisii-regis* is morphologically intermediate between *A. alba* and *A. cephalonica*, likely the result of hybridization and introgression between the two species (Mitsopoulos and Panetsos, 1987). It is sometimes divided into two varieties—borisii-regis and pseudocilicica—which have limited taxonomic significance. In central and southern Greece, *A. cephalonica* replaces the other two species at latitudes corresponding to Mt. Vardoussia, Mt. Giona, and Mt. Parnassos. *Abies cephalonica* (Greek fir) found mainly in the mountainous regions of mainland Greece, including the Pindus range, Peloponnese, Mount Parnassus, Mount Giona, and Euboea.

Central Greece and the Peloponnese represent a crucial ecological boundary for Greek fir (*Abies cephalonica*), marking some of the species' southernmost distribution limits. Fir populations in these regions are typically fragmented and isolated, forming "island-type" distributions due to the lack of physical connectivity among stands (Papageorgiou et al., 2015). The natural range of Greek fir extends from 300 to 2,300 m asl (Aussenac, 2002; Gouvas and Theodoropoulos, 2022), with populations most commonly found between 600 and 2,100 m and an optimal altitudinal range of 800–1,200 m (Panetsos, 1975). These forests are predominantly located in the meso- and montane-Mediterranean zones (600–1,900 m asl), where conditions are most favorable (Samaras et al., 2015).

Greek fir thrives in Mediterranean montane climates characterized by cold, wet winters and warm, dry summers, with mean annual precipitation ranging from 500 mm in southeastern Greece to over 1,800 mm in the western parts of south-central Greece (Gouvas and Sakellariou, 2011). The majority of precipitation falls during autumn and winter, while prolonged droughts may occur in summer (Aussenac, 2002). The species is adapted to both calcareous and siliceous soils, frequently found on steep, rocky slopes, and tolerates shallow, well-drained substrates. Greek fir also shows greater drought resistance compared to other Mediterranean firs (Aussenac, 2002; Bergmeier, 2002). However, despite this adaptability, several decline symptoms—including crown dieback, needle loss, discoloration, and mortality of twigs, branches, or entire trees—have been reported, primarily linked to drought stress (Papageorgiou et al., 2015).

The decline or dieback of Mediterranean fir forests in Greece, particularly in southern and central regions, has been primarily linked to extreme drought periods and fluctuations in Spring and Winter temperatures (Brofas et al., 1994; Markalas et al., 1992; Papadopoulos et al., 2007; Tsopelas et al., 2004). Researchers have investigated the relationship between tree-ring width and precipitation as well as temperature on a localized level for Greek fir (Koulelis et al., 2022, 2023; Koutavas, 2013; Papadopoulos et al., 2007, 2009). Tree rings serve as a valuable source of information for investigating these subjects, as they contain a wealth of information about environmental changes. They can be measured and dated with high precision, capturing variations on a sub-annual scale (Baillie, 1982; Pearl et al., 2020; Schweingruber, 2012; Speer, 2010; Stokes, 1996). Fritts (1976) found that tree ring width variance is generally controlled by factors influencing growth. Tree-ring evidence from many different biophysical settings supports the idea that tree growth is limited by water in a wide variety of ecosystems and by energy (growing season length, degree days, or mean temperature) in other ecosystems (Waring and Running, 1998). In addition, both, short and long-term tree responses to drought should be considered in order to retrospectively assess forest vulnerability (Camarero et al., 2018), so it is suggested that understanding how trees respond to drought over different time frames is essential for assessing the overall resilience and susceptibility of a forest ecosystem to drought stress. Forest ecosystems are typically resilient, with many species and ecosystems have historically adapted to changing conditions. However, future changes might be too extreme or rapid for some species and ecosystems to adapt, potentially leading to local extinctions and the loss of vital functions and services. This could include a reduction in forest carbon stocks and a diminished capacity to sequester carbon (Seppälä et al., 2009).

Our previous studies observed a decline in the Mean Relative Annual Periodic Increment (MRAPI) for both basal area and volume from 1996 to 2009 at the fir ICP Level II monitoring plot on Timfristos mountain, central Greece. However, this reduction was relatively minor, indicating that overall, basal area growth remained stable. Despite numerous tests, we did not identify significant correlations between the MRAPI of fir volume and total summer season precipitation (May–August) (Koulelis et al., 2019).

Similar findings were observed for fir plots on Mt. Giona (Koulelis et al., 2022, 2023). We noted a decline in the growth index for stands at two different altitudes after 1999, signaling unfavorable growth conditions for nearly the past two decades. The diminished Average Ring Width Index (ARWI) aligned with the Standardized Precipitation Index (SPI), reflecting two decades of mild to moderate precipitation conditions, whether wet or dry. Over a span of 55 years, we investigated one extreme drought event and one extreme wet event, both of which resulted in negative or positive changes in growth. However, less severe events had a less discernible impact on measurable tree ring growth. A decrease in growth was observed after 1998 for both elevations, not directly linked to the SPI but seemingly associated with observed defoliations caused by the European Fir Budworm (EFB). Our five-year study confirmed that the EFB sporadically inflicts severe defoliation on Greek fir trees at mountains Giona and Parnassus, disrupting the relationship between climate and tree ring width, particularly due to EFB attacks at mountain Giona.

This study investigates the relationship between climatic variability and the radial growth of Greek fir, aiming to determine how climate influences tree growth patterns. Through detailed tree ring analysis and the use of both local meteorological and spatially resolved climate data, we focus on Mount Kirphis in Central Greece, where Greek fir is examined as a potential bioindicator of regional climate conditions.

Materials and methods

Area description

Kirphis mountain located in Greece to the north of the bay of Antikyra in the Gulf of Corinth within the territory of Phocis. It is situated adjacent to Mount Parnassus, with the valley of the Pleistos river separating the two (Fig. 1). It is located a few kilometers away from the cities of Arachova and Delphi. While the mountain is substantial in size, it often resides in the shadow of mountain Parnassus and is commonly regarded as its "foothill". Nonetheless, it stands as a separate mountain range with a character uniquely distinct from that of Parnassus. The highest peak of Kirphis, known as Xirovouni (1,560 meters), is situated directly south of Zemeno (where the two examined stands are located) and is often used to denote the entirety of Kirphis or at least its eastern section. Despite the rugged and steep terrain on the northern side of Xirovouni, it features expansive and densely wooded areas of Greek fir, while the remainder of the range is covered with scrubland and shrubs, interspersed with patches of oak and cedar trees.

The vegetation of Mount Kirphi (Xerovouni) is highly diverse due to its limestone geology and varied climate, with over 600 plant species recorded (Kokmotos, 2008). Greek fir forests dominate the northern slopes, while lower zones host shrublands, including *Quercus coccifera*. Several rare and endemic species—such as *Achillea umbellata* and *Arenaria phitosii*—highlight the mountain's botanical importance (Dimopoulos, 1993; Dimopoulos et al, 2013). Kirphi serves as a key refuge for Central Greece's endemic flora, emphasizing the need for targeted conservation efforts.

Data collection and methodology

The forests in this region mostly consisted of natural Greek fir stands (Fig. 2). The selected trees of the stands were relatively healthy and showed no severe damage/defoliation or logging impacts. The two study sites, Stand 1 and Stand 2, are both situated facing north near the village of Arachova, with altitudes of 777 m and 800 m, respectively. These stands are located close to each other, and we decided to follow this approach to maintain consistent microclimatic conditions, experience similar disturbances or environmental events, and expand our sampling across a broader range of trees within the mountain landscape. In the first round of measurements (Spring of 2024), the average age of trees in Stand 1 and Stand 2 is 66 and 63 years, respectively, indicating relatively young stands. The average height of trees in Stand 1 is 15.32 meters, while in Stand 2, it is 11.47 meters. In the initial measurement, we took core samples from 5 trees per plot. We conducted additional core sampling in July 2024, taking samples from 10 more trees (5 per plot). These new measurements were incorporated into our initial results. We primarily selected similar trees to maintain consistency with the standards set in the first round of measurements. The characteristics of the stands and the descriptive statistics are presented in Tables 1, 2.

This data is meant to be compared with published studies on fir trees in the mountains of central Greece. This comparison will enhance our research on fir tree responses and provide deeper insights into the relationship between growth and climate within this specific fir ecotope (Fig. 2).

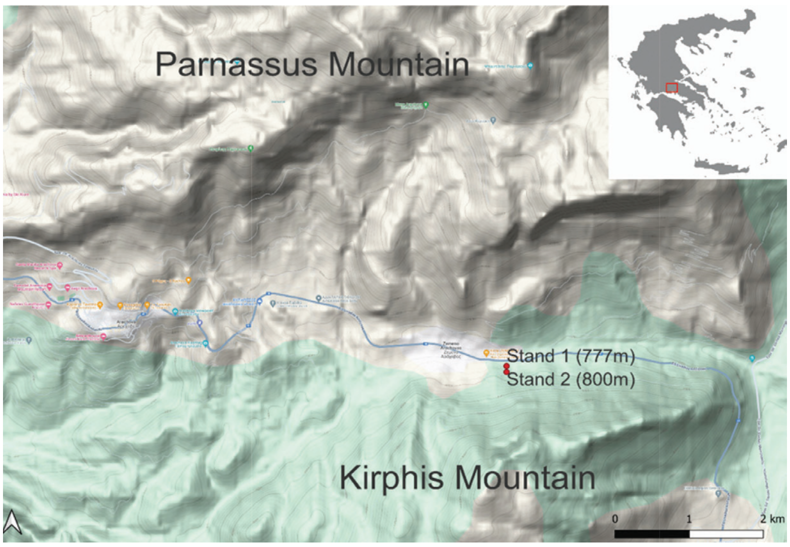

Fig. 1. Location of study area (Stands 1 and 2). Map created with QGIS 3.22.3 (QGIS Development Team, 2021).

Fig. 2. The northern side of mountain Kirphi, south of Parnassus. Photo by Panagiotis Koulelis.

Table 1. Characteristics of the examined fir stands

Stand No	Latitude	Longitude	Aspect	Altitude (m)	Number of trees	Trees cored	Average age
1	38°28'29"N	22°38’44”E	N	777	10	10	65
2	38°28' 26.3"N	22°38’35.5”E	N	800	10	10	64

Table 2. Summary statistics for DBH and Height (Mean, Range, SD)

		Mean	SD	Min	Max
S1	DBH	36.80	10.291	25	57.5
	H	15.32	1.91	11	17.6
S2	DBH	34.10	11.551	23	55.0
	H	11.47	1.755	8.4	14.3

In terms of sampling, we followed the same methodology as in our previous studies (Koulelis et al., 2022, 2023) obtaining two wood cores per tree at breast height above ground from a total of 20 dominant or co-dominant trees for two stands and 10 trees per stand. As Fritts (1976) proposed two cores from each of 20 or more trees may be a typical sample, although even smaller can be used where there is good cross dating and a large amount of ring-width variability. These trees were spaced at least 5 meters apart and sampled using a 400 mm long and 5.15 mm wide increment borer, specifically the Mora three-threaded auger manufactured by Haglof (Haglof Inc., Sweden). Following preparation, which involved air drying and hand sanding, we conducted tree ring measurements using LignoVision software (version 1.40). The ages of the trees ranged from 51 to 79 years in Stand 1 (S1) and from 56 to 71 years in Stand 2 (S2) (Table A1 appendix).

Cross-dating of the tree-ring samples was performed through manual inspection, where growth patterns across all samples were visually identified and matched. The growth patterns across samples were carefully synchronized using characteristic noted years such as unusually wide or narrow rings. This process involved identifying locally absent or false rings and iteratively comparing samples to ensure consistency across the chronology. This approach was supported by statistical validation to ensure the accuracy and consistency of the tree-ring chronologies. Bernabei et al. (2018) stated that cross-dating can be assessed both statistically and visually and Papadopoulos (2013) discussed the application of standard dendrochronological techniques, including visual comparisons, to cross-date samples from Aleppo pine forests, suggesting that visual examination is a key component of the process. This is consistent with Trouet et al. (2006), who underlined that cross-dating often involves visual comparisons of growth curves to align ring-width series.

For the average growth index calculation, Fritts (1976) proposed various biological growth functions for curve fitting processes, including parabolas, hyperbolas, logarithmic, and polynomial functions. It is well-documented in the literature that such patterns are commonly observed when analyzing ring width data from numerous coniferous species growing in drought-exposed environments. As a result, we applied standard nonlinear functions to determine appropriate tree growth models over time, specifically focusing on the exponential decay function, which was found to be more suitable. To address age-detrending and eliminate potential inconsistencies, we applied Fritts’ (1976) Average Ring Width Index (ARWI) standardization method, which inherently includes both standardization and detrending. This method ensures that age-related growth trends are effectively accounted for in our analysis. Evaluation of the ring width models involved assessing the adjusted coefficient of determination ($A_{dj}\ R_{sqrj}$), significance ($p < 0.05$), F statistic, Root Mean Square Error (RMSE), and the Durbin-Watson Statistic to examine autocorrelation among residuals (errors) in the ring width model’s predictions over time. Model fitting was conducted using the trial version of SigmaPlot 14.5 (Systat Software, Inc.). Finaly, following Wigley et al. (1984) and Briffa and Jones (1990) the Expressed Population Signal (EPS) was calculated as:

$$EPS = \frac{N\bar{r}}{1+(N-1)\bar{r}},$$

where N is the number of trees that are included and $\bar{r}$ the average inter-series correlation coefficient. In this case, the Expressed Population Signal (EPS) for both stands was calculated at 0.779, with an average inter-series correlation coefficient ($\bar{r}$) of 0.15, indicating a moderate signal strength in the data given the sample size (N = 20).

Moreover, we visually identified specific years where growth declines and/or notably different growth patterns appeared in the master chronology. These years in the ARWI highlight significant events that may serve as indicators of particular climatic or ecological conditions. These years exhibit extreme values (either particularly wide or narrow rings) that stand out from the rest of the data.

Climate data were obtained from nearby ground meteorological station, which were available only for the period from 1976 to 2010 (Hellenic National Meteorological Service, 2024). More specifically, we requested and obtained temperature and precipitation data from the Hellenic National Meteorological Service for the Arachova meteorological station (Station code: 16666, elevation: 950 m, geographic coordinates: 38.48°N, 22.58°E). This station is located 5.7 km from the selected stands. To extend our investigation and cover a longer climatic period, we acquired climate time series data on temperature, precipitation, the Palmer Drought Severity Index (PDSI), and actual evapotranspiration using the online application ClimateEngine.com. These data were sourced from the TERRACLIMATE 4000 m (1/24-degree) monthly dataset (1965–2022) and the CHIRPS 4800 m (1/20-degree) pentad dataset (UCSB/CHG), (Huntington et al., 2017).

Results

Tree growth

For both stands and each tree, the three-parameter exponential decay function yielded satisfactory results.

$$Y = Y_0 + a\ exp\ (-b^x)$$

The parameter estimates for the 20 models are detailed in Table 3. The adjusted coefficient of determination (adjusted R_{sqr}) ranged from 0.435 to 0.653 for Stand 1 and from 0.479 to 0.872 for Stand 2, with a significance level of $p < 0.0001$ across all 20 models. The Durbin Watson statistic was utilized to test for autocorrelation, and the results ranged from 1.56 to 2.55 for Stand 1 and from 1.55 to 2.29 for Stand 2, indicating the absence of autocorrelation. Additionally, the RMSE values varied from 45.56 to 76.87 for Stand 1 and from 21.89 to 80.31 for Stand 2. Furthermore, the F-statistic exhibited consistently low, acceptable values across all 20 models. Subsequently, the equation was solved for the expected yearly growth (Y_t). The measured ring widths (W_t) were then converted to average ring-width indices (ARWI) by dividing each width for year t by the expected growth (Y_t).

$$RWI = \frac{W_t}{Y_t}$$

This conversion serves to eliminate the growth trend and standardize the variance, making it approximately consistent across the entire time series. After formulating and resolving all the aforementioned equations and concluding all ring measurements from every tree, the Average Ring Width Indices (ARWI) values were computed. Subsequently, two new master averaged indices, one for each stand, were plotted (see Fig. 3). As per Fritts (1976), this standardization process ensures that all ring width curves converge toward a uniform mean value. Consequently, a tree record exhibiting substantial average growth will not overshadow other records. The ensuing figures illustrate

Table 3. Parameter estimates for the exponential decay model and the single and three-parameter average ring width functions for both stands (10 trees $stand^{-1}$)

$Y_t = y_0 + a \times exp(-b \times t)$	P	F	$A_{dj}\ R_{sqrj}$	RMSE	Durbin-Watson Statistic
S1					
1	<0.0001	143.44	0.551	45.56	1.66
2	<0.0001	151.45	0.653	65.17	1.63
3	<0.0001	136.98	0.598	55.77	2.55
4	<0.0001	108.56	0.471	49.17	1.56
5	<0.0001	400.91	0.435	76.87	1.61
6	<0.0001	120.76	0.563	60.32	1.72
7	<0.0001	135.18	0.59.2	52.34	1.65
8	<0.0001	148.29	0.575	58.15	1.71
9	<0.0001	110.67	0.510	50.67	1.62
10	<0.0001	155.54	0.605	57.45	1.68
S2					
1	<0.0001	110.53	0.644	72.71	2.29
2	<0.0001	431.82	0.844	21.89	1.55
3	<0.0001	228.09	0.576	38.53	1.63
4	<0.0001	352.99	0.861	30.82	1.78
5	<0.0001	132.02	0.479	80.31	1.83
6	<0.0001	420.16	0.839	23.47	1.60
7	<0.0001	395.72	0.854	25.38	1.70
8	<0.0001	370.25	0.840	27.91	1.68
9	<0.0001	450.91	0.872	22.53	1.79
10	<0.0001	410.39	0.848	24.63	1.65

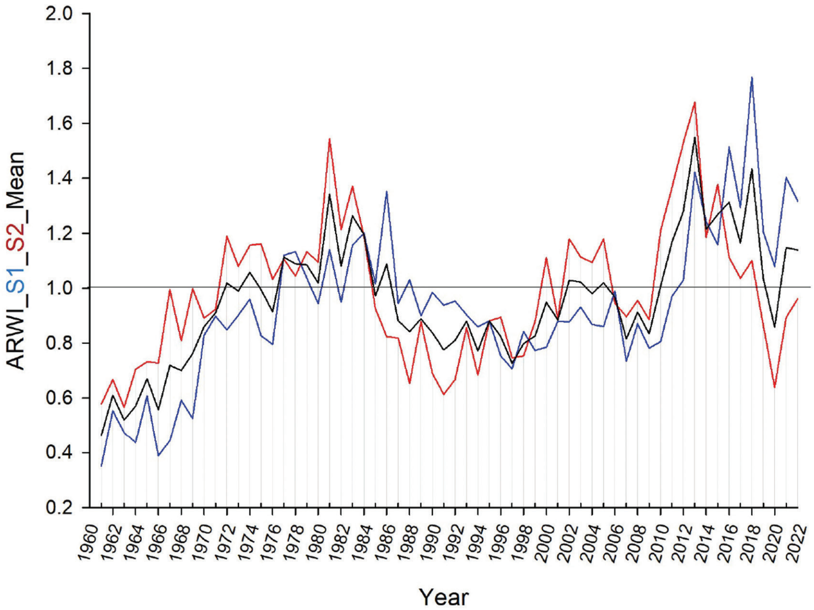

Fig. 3. Ring width index for Stand 1 (blue line), Stand 2 (red line) and area mean (black line).

the anticipated year-to-year variation and reveal consistent annual fluctuations in the mean growth of each stand.

In general, both growth indices follow similar trends, as expected. There is an increasing trend from 1960 to the early 1980s, followed by an almost stable period for the next 20 years until 2010. After 2010, a significant increasing trend is observed, which is followed by sharp declines after 2013 and 2018 respectively. There are also some critical years where the increasing trend in growth of the first stand is not matched by a corresponding decreasing trend in the second stand (e.g., 1988, 1991), or years where the trends are not as steep or pronounced. This variability may be explained by the number of trees cored or the accuracy of the selected exponential decay model for each case. The area ARWI, represented by the black line, provides an overarching average of the ring width indices, smoothing out individual stand variations to present a general growth trend for the entire area. This composite measure helps in identifying broader ecological or climatic influences affecting the region's forest growth dynamics over time.

Drought conditions

The SPI (Fig. 4) is based on the probability of precipitation over various time scales, according to the user's interest (McKee et al., 1993).

The Standardized Precipitation Index (SPI) is a widely used measure for drought classification. The SPI classes range from extremely dry (SPI ≤ –2), indicating extreme drought conditions, to extremely wet (SPI ≥ 2), indicating significant excess precipitation. Intermediate classes include severely dry (–2 < SPI ≤ –1.5), moderately dry (–1.5

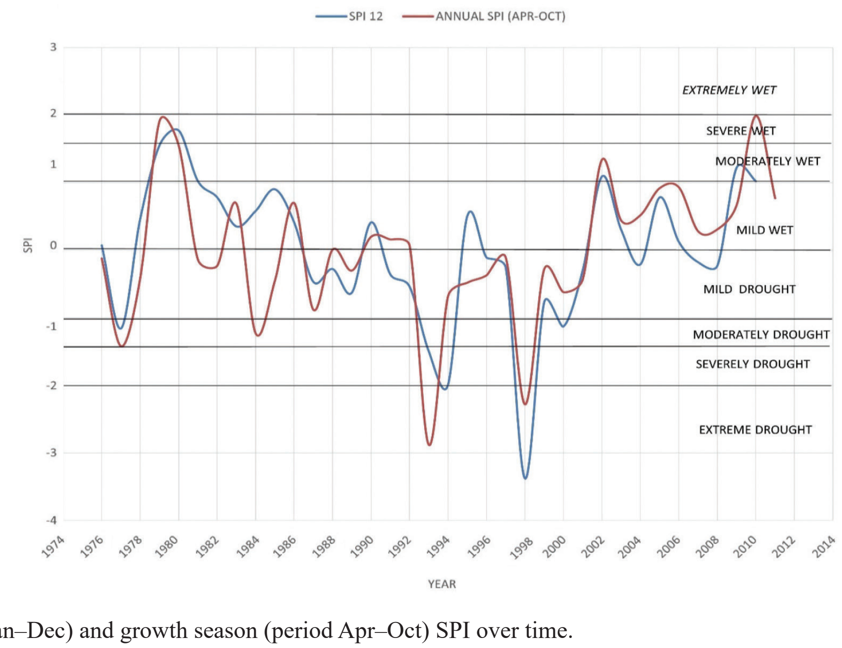

Fig. 4. Annual (Jan–Dec) and growth season (period Apr–Oct) SPI over time.

Table 4. Drought categorization according to SPI values (McKee et al., 1993)

SPI values	
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
0 to 0.99	Mildly wet
0 to –0.99	Mild drought
–1 to –1.49	Moderate drought
–1.50 to –1.99	Severe drought
–2.00 or less	Extreme drought

< SPI ≤ –1), near normal (–1 < SPI < 1), moderately wet (1 ≤ SPI < 1.5), and severely wet (1.5 ≤ SPI < 2). These classifications help in assessing drought severity and managing water resources effectively (Table 4).

Figure 4 illustrates the annual (January–December) SPI and the growth season (April-October) SPI values for the available time series. Specifically, the annual SPI is the SPI-12 for December, and the growth season SPI is the SPI-6 for October. The diagram clearly shows that the period from 1976 to 1992 was normal to wet, with a particularly wet period in 1979–1980. The years 1993–1994 and 1998–1999 were dry. Both indices (annual SPI-12 and growth season SPI-6) reflect similar climatic conditions with minor variations. Notably, Greece experienced one of its most severe droughts in 1993 and again in 1998 (Karavitis, 1998).

Correlations

Tree ring growth is influenced by species, age, heredity, and the climatic conditions of the study site (Vieira et al., 2008). Additionally, the complexity of tree growth can be affected by competition with neighboring trees and lianas, the ingrowth of the stand, and genotypic variation in a specific area (Cook, 1987; Koulelis et al., 2022; Zweifel et al., 2007). According to Papadopoulos (2016), who quantified and analyzed the inter-annual variability of fir site chronologies, climate is the primary factor affecting tree growth on a latitudinal scale.

In the examined area, our analysis of SPI data and tree growth over the period from 1976 to 2010 (SPI data were obtained from nearby ground meteorological stations), (ARWI mean) revealed a significant correlation (Pearson) with SPI-12 ($r = 0.5$, $p < 0.05$), while no correlation was found for SPI-6. Additionally, we tested the climate engine data for more correlations over the period from 1976 to 2022. We found significant correlations with actual evapotranspiration, PDSI-12, and total annual precipitation (Fig. 5).

Discussion

Long-term dry conditions are not observed, and the growth of the Greek fir under current conditions can be considered quite normal. Looking back, after the implementation of the dendrochronological analysis, if we exclude the years up to 1976, where an increasing growth trend is evident due to the young age of trees, we can identify specific years with notable growth declines, as shown in Figure 3.

These declines could be attributed to various factors, including climate. These decline years include 1976, 1988, 1991, 1994, 1997, 2008, 2010 and 2020, where both stands experienced marked declines in growth. Some of these declines may be explained by severe drought events, as depicted in Figure 4, such as those in 1993, 1998, and less severe events like 2007, though not all declines correlate with such events. While the extreme drought in 1993 clearly impacted on fir growth in 1994, the drought of 1998 did not have the same effect. Compensatory effects may have occurred in subsequent years, where growth in certain years could have partially offset the declines, suggesting some resilience in the stands. However, these compensatory effects and this statement overall need further investigation to determine their significance and frequency.

Additionally, previous studies have identified instances of reduced tree growth unrelated to climate or weather events (Koulelis et al., 2022). Therefore, in this specific area, it is challenging to definitively attribute significant growth declines solely to extreme drought events. To receive more climatic insights from the tree ring analysis, we performed the correlations outlined in section 3.3, identifying broader relationships between the AWRI and actual evapotranspiration, SPI-12, PDSI-12, and total annual precipitation. The observed correlation between the Standardized Precipitation Index (SPI) and tree growth highlights the critical role of water availability in determining annual tree growth. Drought conditions, as measured by the SPI-12 and PDSI-12, clearly have a profound effect on tree ring

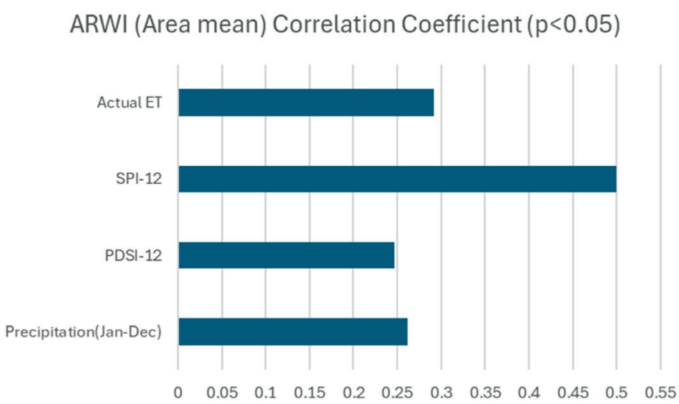

Fig. 5. ARWI area Pearson correlation with climatic variables (SPI-12 data received from a nearby ground meteorological station).

growth. Our findings are consistent with previous research on fir (Koulelis et al., 2022, 2023), which also identified SPI as a reliable indicator of tree growth variability. This agreement reinforces the validity of the SPI as a crucial metric for studying the impact of drought on tree growth, consistent with findings from other studies on both conifers and non-conifers (e.g. Dow et al., 2024, Kempes et al., 2018, Pasho et al., 2011, Peña-Gallardo et al., 2018).

Our comprehensive tree ring analysis has unveiled significant correlations between average tree ring width and various climatic variables, offering profound insights into the impacts of climate on fir's tree growth. The strongest correlation observed was between average tree ring width and the SPI-12 (Standardized Precipitation Index over 12 months), with a coefficient of 0.5. This robust relationship suggests that prolonged precipitation patterns over a year substantially influence tree growth, as periods of higher precipitation likely provide the necessary water resources for optimal tree growth. Additionally, a positive but relatively low correlation (0.29) was found between average tree ring width and actual evapotranspiration and can be explained by vegetation's adaptation to periodical drought conditions, leading to stomatal closure and a negative correlation between growth and vapor pressure deficit (VPD) (Kharuk et al., 2017; Koulelis et al., 2023; Trotsiuk et al., 2021). Furthermore, our analysis highlighted important correlations with PDSI-12 (Palmer Drought Severity Index over 12 months) and total annual precipitation. The PDSI-12 is a measure of long-term drought conditions, and its correlation with tree ring width underlines the sensitivity of trees to prolonged dry periods. Trees tend to exhibit reduced growth during extended droughts, reflected in narrower rings. The modest yet positive correlation (0.26) with total annual precipitation (from January to December) suggests that while water availability throughout the year is an important factor influencing tree growth, it is not the sole determinant as initially thought (e.g Oogathoo et al., 2024). Higher annual precipitation typically translates to better soil moisture and water supply for trees, promoting wider growth rings.

The positive correlations with SPI-12, PDSI-12, and precipitation confirm that the principal factor affecting tree growth at a latitudinal scale is climate (e.g. Papadopoulo, 2016; Koulelis et al., 2022). Our field analysis revealed, for the first time in this particular area, a strong relationship between precipitation and fir growth.

Understanding the relationship between climate variability and tree growth is essential for predicting future impacts on forest ecosystems and developing effective management strategies. The strong influence of climate conditions—particularly drought—on tree growth highlights the need for adaptive measures in forest planning. In the Mediterranean, and especially in the case of Greek fir, forest management must go beyond the stand level and adopt a broader, landscape-based approach. The region faces increased uncertainty due to climate change, with heightened risks of wildfires, drought, and pest outbreaks (Palahi et al., 2008), as well as potential declines in productivity (Harkonen et al., 2019). Sustainable forest management, therefore, must prioritize long-term resilience and ecosystem stability, integrating climate adaptation into planning for fir forests in Greece.

Conclusions

Understanding relationships between tree growth and climate helps in predicting how future climate variability might impact fir's ecosystems and informs forest management and conservation strategies.

Current conditions for Greek fir growth, even on northern aspects, can generally be characterized as normal. Excluding data prior to 1976, as early years often yield less reliable climate information, the dendrochronological analysis revealed significant growth declines in certain years. These declines may be caused by severe drought events, but not all of them are linked, suggesting that other factors are also involved. Prior studies have also noted growth reductions unrelated to climate. Even though drought conditions, measured by SPI-12 and PDSI-12, significantly affect Greek fir's ring growth. The strongest correlation was between tree ring width and SPI-12, suggesting that prolonged precipitation patterns influence growth.

A lower correlation with actual evapotranspiration reflects vegetation's adaptation to periodic droughts. The PDSI-12 correlation highlights tree sensitivity to long-term dry periods. The modest yet positive correlation with annual precipitation suggests that while water availability is important, it is not the only factor influencing tree growth. However, these findings are region-specific and may not necessarily apply on a wider scale. The relatively low EPS value of 0.779 suggesting moderate signal strength. Future studies involving multiple species and broader geographic areas, may aim to increase the sample size or refine data collection methods to enhance the reliability of the signal and expand upon our results. However, this study is part of an extensive, multi-year research project focused on Greek fir in central Greece, which corroborates and builds upon our previous findings regarding its response to climate.

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Appendix

Table A1. Tree measurements in both stands

S1 Tree No	DBH (cm)	H (m)	S2 Tree	DBH (cm) No	H (m)
1	31	16.60	1	31	12.2
2	33	15.40	2	29	9.80
3	29	17.60	3	23	11
4	36	15.9	4	43	12.70
5	57.5	16.50	5	26	12.20
6	39.5	16.30	6	27	8.40
7	32	14.40	7	33	12.70
8	33	11	8	23	9.70
9	25	13.50	9	51	11.70
10	52	16	10	55	14.30