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The impact of selected climatic factors on the growth of Greek fir on Mount Giona in mainland Greece based on tree ring analysis

Der Einfluss ausgewählter klimatischer Faktoren auf das Wachstum der griechischen Tannen auf dem Berg Giona am griechischen Festland mittels Jahrringanalyse

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Keywords: *Abies cephalonica*, climate, dendrochronology, tree growth, drought index

Schlüsselbegriffe: *Abies cephalonica*, Klima, Dendrochronologie, Baumwachstum, Dürreindex

Abstract

Tree ring chronologies are considered critical when investigating important relations between tree growth and climate. In the present study, we studied the impact of precipitation and air temperature on *Abies cephalonica*, an endemic Greek species, by evaluating radial growth data from tree ring analysis. The two sampled stands had elevations of 988 m and 1.274 m above sea level, respectively, and were located on Mountain Giona in central Greece. The hyperbola two-parameter function was used for fitting a tree growth model and detrending, separetly for the two sites. After detrending, the Average Tree Ring Width Index (ARWI) values were calculated and the averaged values per site were standardized and plotted. Due to the lack of temperature data, during the last 30 years, we used the Standardized Precipitation Index (SPI) based only on precipitation, to investigate the impact of extreme drought on *Abies cephalonica* growth at the two sites. We tested both a 6-month time step (SPI6) calculated for March to August and a 12-month step (SPI12) calculated for October-Sep-

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tember and representing the hydrological year and correlated the results with ARWI. Furthermore, separate correlations between selected average temperatures, precipitation (for period 2009–2019) and radial growth were tested. We found that SPI is useful to reveal negative or positive growth due to extreme climate conditions. The extreme drought event of 1985 (SPI < –2) was followed by an important growth decrease for both stands. In contrast, the extremely wet year of 1971 (SPI > 2) was followed by increased growth in the following year (1972), again for both stands. Less pronounced events, as indicated by the SPI, caused less clear impacts on the measured radial growth. A general decline in growth was observed after 1998 for both elevations and was not connected with SPI. We suggest that this decrease was associated to observed defoliations by *Choristoneura murinana*, a moth feeding on shoots.

Zusammenfassung

Jahrringchronologien sind essenziell für die Untersuchung der Zusammenhänge zwischen Baumwachstum und Klima. In dieser Studie haben wir die Auswirkungen von Niederschlag und Lufttemperatur auf die in Griechenland endemische *Abies cephalonica* untersucht, unter Verwendung von Durchmesserzuwachsdaten aus Jahrringanalysen. Die zwei untersuchten Bestände befinden sich auf 988 m bzw. 1.274 m über dem Meeresspiegel am Berg Giona in Zentralgriechenland. Mit einer Zwei-Parameter-Hyperbel-Funktion haben wir für beide Bestände ein Baumwachstumsmodell entwickelt, um den Alterstrend zu entfernen. Danach wurden der durchschnittliche Jahrringbreitenindex (ARWI) berechnet und die gemittelten Werte pro Standort analysiert. Weil Temperaturdaten für die letzten 30 Jahren fehlen, haben wir den Standardized Precipitation Index (SPI) verwendet, der nur Niederschlagsdaten benötigt, um die Auswirkungen extremer Dürre auf das Wachstum von *Abies cephalonica* in den beiden Beständen zu untersuchen. Wir haben den Dürreindex für ein 6-monatiges Zeitfenster (SPI6) und den Zeitraum März–August und für 12 Monate (SPI12) von Oktober–September für das hydrologische Jahr berechnet und mit ARWI korreliert. Darüber hinaus wurden Korrelationen zwischen Durchschnittstemperaturen, Niederschlag (Zeitraum 2009–2019) und Wachstum getestet. Unser Ergebnisse zeigen den Wert von SPI, um negatives oder positives Wachstum aufgrund von extremen Klimaereignissen zu quantifizieren. Das extreme Dürreereignis von 1985 (SPI < –2) bewirkte für beide Bestände einen deutlichen Wachstumsrückgang. Andererseits folgte auf das extrem nasse Jahr 1971 (SPI > 2) ein verstärktes Wachstum im folgenden Jahr (1972) wiederum für beide Bestände. Schwächere Ereignisse auf Basis des SPI hatten weniger deutlichen Einfluss auf das gemessene Durchmesserwachstum. Nach 1998 konnten wir für beide Standorte einen generellen Rückgang des Durchmesserwachstums beobachten, dies Stand nicht mit Änderungen im SPI in Verbindung. Vermutlich ist der beobachtete Nadelverlust durch *Choristoneura murinana*, eine triebfressende Mottenart, der Grund dafür.

1 Introduction

1.1 Climatic changes and extreme weather events affecting tree growth

Forests are facing great challenges, as they have to cope with unceasing pressure due to climate variation and climate change. Many widespread temperate European tree species are more vulnerable to extreme summer drought and heat waves, than previously thought (Schuldt *et al.*, 2020). Very recently, many central European forests faced severe stress due to the extreme drought event, that occurred in 2018 and which was expressed through various processes (*e.g.* needle discoloration in coniferous tree species) leading even to increased tree mortality.

Extreme weather conditions, including frost episodes and their relationships with growth, were analyzed by several Central-European studies. Kunes *et al.* (2014) compared the survival rate, growth performance and nutrition of large and common-sized planting stock of *Sorbus aucuparia* L. on a frost-exposed site and answered whether fertilizing had any effect on the plantations. Gallo *et al.* (2014) examined the proper silvicultural and reforestation methods under the significant occurrence of severe late frost episodes in the layer of air immediately above ground in frost-hollow sites and proposed the use of advanced large-sized planting stock. Finally, Galo *et al.* (2017) measured the growth performance and resistance to ground late frosts of *Fagus sylvatica* L. plantation in the Czech Republic.

Focussing on Souther Europe, during the last century forests in this region have been subject to direct abiotic disturbances, *e.g.*, droughts and other climatic factors (McDowell *et al.*, 2008; Allen *et al.*, 2010; Adams *et al.*, 2017; Choat *et al.*, 2018). This has resulted in reduced forest productivity (Ciais *et al.*, 2005) and increased tree mortality (Colangelo *et al.*, 2018; Navarro-Cerrillo *et al.*, 2018). Another study compared the growth, survival and health of those types of planting stock under a weeded and non-weeded regime in a dry and warm climate (Galo *et al.*, 2020). In this regard, several research efforts have been focused on a better understanding of the relationship between climatic conditions (*e.g.* precipitation and temperature) and tree growth (Fritts, 1976; Spiecker, 1999; Lindner *et al.*, 2014; Rohner *et al.*, 2016; Seiler *et al.*, 2017), considering time-series of climatic parameters and repeated measurements of tree height and diameter.

Tree growth is highly dependent on site, species, climatic conditions, provenances, and management schemes (Spiecker, 2002). Bräuning *et al.* (2017) summarized some studies that addressed the impacts of extreme climate events on forests and trees, with emphasis on drought. The authors mostly included papers using a tree-centered approach and explicitly addressing the adaptive capacity of trees at any level of composition. Dobbertin (2005), in a review, focussed on tree growth as indicator of tree vitality, that is responsive to environmental stress and concluded that ring width can be used for this purpose. Useful information regarding survival probabilities of trees and growth assessments on monitoring plots can be derived from ring width.

1.2 Fir forests, growth and management in Greece

In Greece, water scarcity is probably the main climatic constraints limiting forest growth. Studies have presented a robust correlation between available water and tree ring width and tree growth in different Mediterranean forests and for different tree species (*e.g.*, Sarris *et al.*, 2007; Papadopoulos, 2016; Fyllas *et al.*, 2017; Koulelis *et al.*, 2019). There are three fir species in Greece, *Abies alba* Miller, restricted to the northern border of the country, the Mediterranean *Abies cephalonica* Loudon and *Abies borisii-regis* Mattf (Strid and Tan, 1997). *A. cephalonica* is an endemic Greek species expanding mainly in southern and central Greece while *A. borisii-regis*, an endemic of the southern Balkan Peninsula, disperses mainly in the northern and central part of the country (Athanasiadis, 1986). Namely, in the northern parts of Greece, the species *Abies alba* dominates and is replaced by *A. borissi-regis*. *A. borisii-regis* is morphologically intermediate between *A. Alba* and *A. cephalonica* and apparently evolved as a result of hybridization and introgression between these species (Mitsopoulos & Panetsos, 1987). It is often divided into two varieties (*e.g.* Christensen in Strid, 1986) *borisii-regis* and *pseudocilicica*, which have little taxonomic significance. In the central and southern Greece, the Greek fir replaces the other two at a geographical latitude corresponding to Mt. Vardoussia, Mt. Giona, and Mt. Parnassos. Papadopoulos (2016) has investigated tree ring patterns and climate responses of three fir populations along a latitudinal gradient in Central Greece, showing that the main climatic factors affecting tree ring width of fir trees are late spring and summer precipitations, with a positive correlation. Tree ring widths were also positively influenced by the temperatures of October and April (before the growing season). In addition, other research revealed a significant CO_2 fertilization effect on Greek fir operating through restricted stomatal conductance and improved water-use efficiency, implying that atmospheric CO_2 is overcompensating for growth declines anticipated from drier climate (Koutavas, 2013).

Greek fir trees, together with oak, beech, pine and spruce, are of major economic importance to Greece. According to Strid and Tan (1997), fir is distributed across the country. Some simple connections with forest inventory data indicate the importance of this tree species, which is one of the most economically important forest tree species in Greece. Greek fir forests represent 43.133.020 m^3 tradeable industrial roundwood, accounting for 30.23% of the total production (Hellenic Ministry of Agriculture, 1992). Assuring sustainable timber production at a national level is one of the main goals of the last Greek Forest Strategy (Ministry of Environment & Energy, 2018). Important in this context, is knowledge of growth rates of commercial species, to balance harvesting and regrowth. In the examined literature, it is suggested that forest growth does not only describe the volume production potential of forests and the dimension and quality of the produced wood but is also a valuable base for understanding interactions between trees and their environment. In this sense, tree ring analysis contributes to cost-efficient forest management.

Updated information on tree and stand growth is relevant for ecological, economic, and social aspects of forest management. Fürst *et al.* (2007) reported that process-oriented forest management should be able to combine ecological and economic view with the optimization of forest management planning and decision making as well. Moreover, forest management goals and methods must be based on a sound knowledge of natural processes and their potential external drivers and pressures, which allow forest dynamics to be predictable under different management regimes (Bergeron and Harvey, 1997).

Simultaneously, in Mediterranean forestry, many management objectives cannot be evaluated at forest stand-level. The increasing risk and uncertainty, involved in Mediterranean forestry decision making, is one of the greatest challenges in forest planning. Apparently, climate vagaries will continue to be a source of uncertainty in relation to forest dynamics thus increasing the risk of forest fires and droughts as well as spreading new diseases or plagues (Palahi *et al.*, 2008). At the same time, potential changes in temperature or precipitation in the Mediterranean countries, might lead to clear reductions in productivity (Harkonen *et al.*, 2019). However, the concept of sustainable forest management, strongly contrasts this widely used information, aims to encourage the long-term use of natural resources and to facilitate the protection of forest ecosystems.

1.3 Tree ring as a powerful tool to assess forest production

Tree rings may also be used as a significant data source since they store the radial and height increment over time, revealing environmental conditions and related tree responses (Spiecker, 2002). Tree rings are sensitive to water deficiency; thus, tree growth may be affected by droughts or extremely wet periods (Eilmann and Rigling, 2012). Several studies have investigated the correlation of tree rings with climatic variations (Leal *et al.*, 2008; Panayotov *et al.*, 2011; Martínez del Castillo *et al.*, 2018) to indicate impacts and growth patterns, as the tree's adaptive capacity to small or large-scale climatic changes can be observed during long-term monitoring (Koulelis *et al.*, 2018). Mikulenka *et al.* (2020) evaluated the effect of climate and air pollution on radial growth of silver fir and Norway spruce in mixed age-varied (56–146 years) forests in a protected landscape area in the Czech Republic. In the Western Bohemia, the Czech Republic, Gallo *et al.*, (2020) used among others core analysis on four research plots in order to compare the structure and production of *Pinus sylvestris* L. stands managed under different silvicultural systems with different climatic conditions. On the other hand, the response of forest ecosystems to extreme climate events varies. For example, mature forest ecosystems may persist for many decades or centuries without considerable variations in tree species composition, mainly due to cyclic regeneration processes (Zukrigl *et al.*, 1963; Fischer, 1997; Körner, 2013).

1.4 Abiotic factors (drought indices)

The available water of an area is highly dependent on precipitation and evapotranspiration. Precipitation is a random and measurable variable, constituting the main parameter, which affects water availability, without an intense seasonality in many locales. Evapotranspiration is one of the most important parameters affecting the water balance of an area; it presents seasonal behavior and can be estimated by several methods. Drought (that is, shortage of water supply) is considered a significant factor in increased tree mortality (Allen *et al.*, 2010). Increased drought frequency has been identified as important to trigger insect or pathogen outbreaks, either directly by affecting insect population dynamics and indirectly by altering host plant growth and defense mechanisms (Weed *et al.*, 2013; Marini *et al.*, 2017). To detect drought impacts on tree growth through tree ring width, several drought indices can be used. These indices are combinations of indicators encompassing mostly meteorological and hydrological data (Cancelliere *et al.*, 2007; Tigkas, 2008). They are applied to identify, categorize, and classify drought events according to their magnitude, duration, and spatial extent (Wilhite and Glantz, 1985). Although the results of all indices are not efficient for all areas and in all cases, some do perform better than others in specific situations (Keyantash and Dracup, 2002).

In the 20th century, several indices, dependent on precipitation, evapotranspiration and soil water holding capacity, have been developed for drought quantification, monitoring, and analysis (Du PIsani *et al.*, 1998; Heim 2002; Keyantash and Dracup, 2002; Vicente-Serrano *et al.*, 2010). In forestry, Sánchez-Salguero *et al.* (2017) used the standardized precipitation-evapotranspiration index (SPEI) to detect changes in drought severity after correlation with defoliation variables in pines and oaks. It was found that drought conditions were linked to enhanced defoliation. In addition, the SPEI has also been used by Bose *et al.* (2020) to identify growth and resilience responses of Scots pine to extreme droughts across Europe. This study showed that there are significant effects between the frequency of droughts and the resistance to extreme droughts. For instance, more frequent drought events lead to less resistant Scots pines to extreme drought. Correlation analysis has been employed by Pasho *et al.* (2014) to investigate the impacts of climatic drivers (temperature, precipitation) and drought, using the SPEI calculated at cumulative time scales (1–12 months), on tree ring width in *Abies borisii-regis* (Mattf.) trees from South-Eastern Albania. The study concluded that "under a future reduction of summer precipitation and temperature increase, *Abies borisii-regis* (Mattf.) may show a decrease in earlywood formation, causing a decline of radial growth."

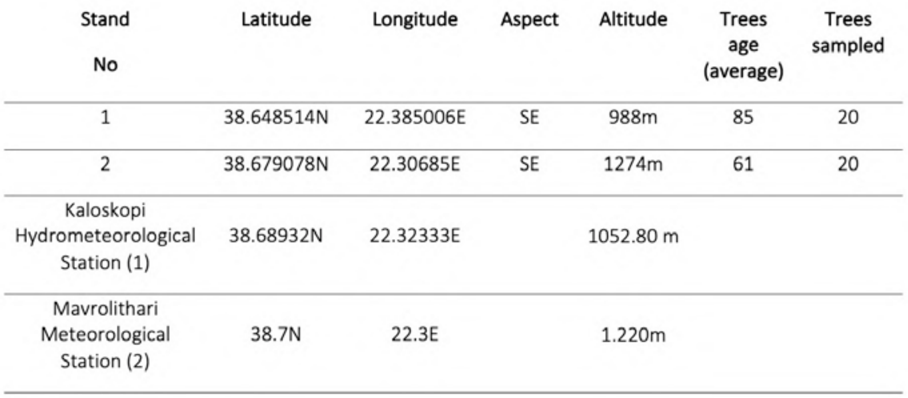
Therefore, the main hypothesis of the study is that SPI is able to identify drought impacts on the growth of Greek fir at Mt. Giona in central Greece using information from radial growth and tree ring analysis.

2 Material and methods

2.1 Study area

Table 1: Characteristics of the examined fir stands and used meteorological stations at Mt Giona.

Tabelle 1: Merkmale der untersuchten Tannenbestände und verwendeten Wetterstationen am Berg Giona.



Stand No	Latitude	Longitude	Aspect	Altitude	Trees age (average)	Trees sampled
1	38.648514N	22.385006E	SE	988m	85	20
2	38.679078N	22.30685E	SE	1274m	61	20
Kaloskopi Hydrometeorological Station (1)	38.68932N	22.32333E		1052.80 m		
Mavrolithari Meteorological Station (2)	38.7N	22.3E		1.220m		

The study sites were located in Central Greece, on Mt Giona, near the village of Kaloskopi. The elevation of the two sample stands was 988 m (Stand 1) and 1.274m (Stand 2) above sea level, respectively (Fig. 1). Both stands faced southeast (Table 1). The forests in this region mostly consisted of natural Greek fir (*Abies cephalonica*) stands. The fir forest is affected by both natural and anthropogenic disturbances, such as insects, logging, and visitors. More specifically, the most important insect observed is the defoliator *Choristoneura murinana* Hb. (Lep., *Tortricidae, Archipini*), European fir budworm (hereafter as EFB), while there is no reference in the last 60 years of severe attacks of *Scolytidaes*. Most commonly observed wood-boring insects are the *Phaenops knotecki* (Col., *Buprestidae*) and *Acathocinus reticulatus* (Col., *Cerambycidae*) (Kailidis and Georgevits, 1972; Markalas, 1992). However, the two selected stands were relatively healthy and showed no severe damage or logging impacts.

The mean annual precipitation, derived from the available time series (1963–2019), was 890 mm. Maximum annual precipitation was observed in 1963, with 1.866 mm, and the corresponding minimum for 1984, with 382 mm. Dry periods generally last from June to September, with an average cumulative precipitation of 115 mm (median of 89 mm). The mean monthly precipitation for this period (June–September) is 29 mm, with a corresponding median of 18 mm. The temperature in the last 11 years (time series 2009–2019) varied between –19.4 °C in January to 32.8 °C in August. The field study, which included tree ring extraction and ring handling (air drying, ring width measuring, and storing) was carried out between August and September 2020.

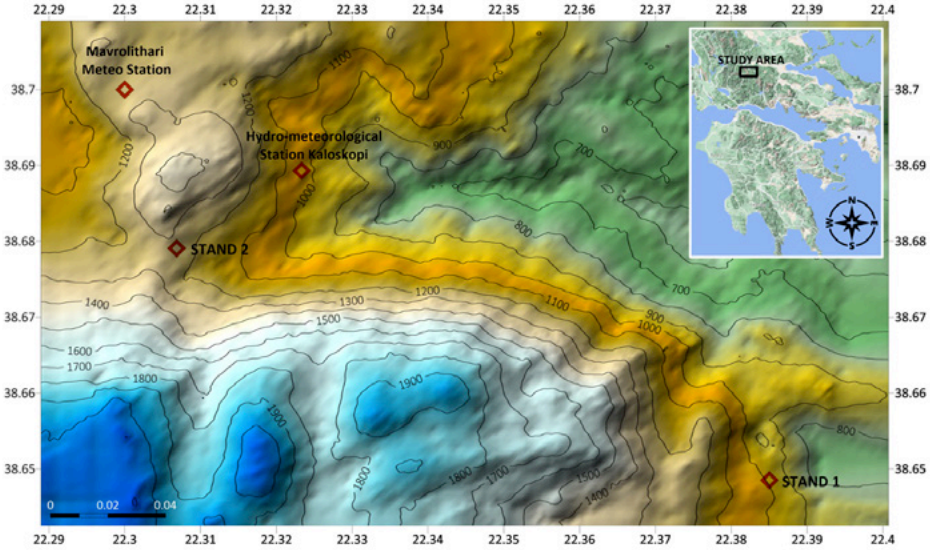


Figure 1: Location of study areas in central Greece.

Abbildung 1: Lage der Untersuchungsregion in Zentralgriechenland.

i) Climate data

The climatic data required for this study were monthly precipitation, monthly average air temperature, monthly maximum air temperature, and monthly minimum air temperature. The precipitation data used (daily values converted to monthly values) were derived from the Kaloskopi hydrometeorological station (coordinates: 38.68932N, 22.32333E, at 1052.80 m above sea level), owned by the Ministry of Environment and Energy (Hellenic Ministry of Environment and Energy, 2020). The particular station is located 64m higher than stand 1 and 222m lower than stand 2. The available precipitation time-series covered a period of 56 years (1963–2019). The station Kaloskopi has not any available temperature data. Thus, the only available and reliable temperature data were collected from the Mavrolithari meteorological station (coordinates: 38.7N, 22.3E, at 1,220 m), (Fig. 1) owned by the National Observatory of Athens, Institute of Environmental Research and Sustainable Development (National Observatory of Athens, 2020), but covering only a period of 11 years (2009–2019). The distance between the two stands was calculated to 13.9km and the horizontal distance using

Google Earth to 7.596 km. In addition, the distance between Stand 1 and Kaloskopi hydrometeorological station is about 11.4 km and the Mavrolithari meteorological station is about 15.8 km as well. The same distances from Stand 2 are 3.8 km and 6.4 km, respectively. The available temperature time-series covered a period of 11 years (2009–2019). Finally, both stations Kaloskopi and Mavrolithari, presented data with minimum gaps in the pertinent time-series.

ii) Drought indices

Several drought indices are available to define and monitor a drought event (see Paulo *et al.*, 2012; Spinoni *et al.*, 2015; Haied *et al.*, 2017). While some are based on precipitation, others take into consideration both precipitation and evapotranspiration.

Precipitation-based indices cannot reflect any temperature changes which may boost a drought event, thus, such indices should be used with caution, in areas with high precipitation amounts (*e.g.* mountainous areas), as in these areas, changes in temperature may cause water shortages due to high evapotranspiration values (Gocic and Trajkovic, 2014; Fassouli *et al.*, 2021 Khan *et al.*, 2018). On the other hand, evapotranspiration-based indices, require, by definition, a "well-watered" crop (Pruitt, 1966; Doorenbos and Pruitt, 1977; Allen *et al.*, 1998; Alexandris *et al.*, 2006). This prerequisite may present difficulties for the accurate application of evapotranspiration-based indices over an area, since even during a "normal period" (and without irrigation), potential evapotranspiration pre-conditions may not apply in a semiarid area, as the soil water content is naturally low over an extended period of time (Roo *et al.*, 2012). Thus, a drought may be inaccurately estimated (Karavitis *et al.*, 2012a; 2014; Tsesmelis *et al.*, 2019).

In this study, the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993) was used, which is based on the probability of precipitation for various time scales, depending on the user's interest (Ibid). This cumulative probability of observed monthly precipitation is then transformed into a standard normal variable through fitting a gamma distribution (Thom, 1966) and using the shape and scale parameters, α and β. The cumulative probability of precipitation is then calculated through the gamma distribution:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} = \int_0^x x^{\hat{\alpha}-1}\, e^{-\frac{x}{\hat{\beta}}} dx \qquad (1)$$

Where x = precipitation, Γ is the gamma equation, defined as

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1}\, e^{-y} dy \qquad (2)$$

Given that the gamma distribution cannot be determined for x = 0 and a rainfall distribution may contain zero values, the cumulative probability, H(x), becomes

$$H(x) = q + (1 - q)G(x) \tag{3}$$

Where q is the probability of zero precipitation.

Subsequently, the cumulative probability, H(x), is transformed into the standard normal random variable Z with mean = 0 and variance = 1, representing the value of the SPI. The random variable Z may be easily calculated using the approach of Abramowitz and Stegun (1964), which converts the cumulative probability to a normalized variable Z.

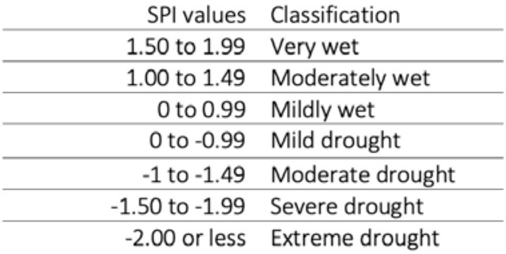
As described by McKee *et al.* (1993), SPI may be calculated for any number of months, but it is mostly based on 3, 6, 9, 12, 24 and 48 month periods of (cumulative) precipitation (Narasimhan and Srinivasan, 2005; Logan *et al.*, 2010; Khan *et al.*, 2018). In this regard, SPI 6 is the index value, derived from cumulative precipitation of six months' period, etc.

A drought episode (the specific analysis of drought is based on the definitions that the SPI provides and under conditions the term drought could be characterized otherwise as an abnormality of the precipitation values) is defined by consistently negative values of the index, less than or equal to –1, and the episode continues until the index reaches positive values. The duration of the episode is determined by the time between the beginning and the end of this period. The magnitude of the drought episode is measured by the sum of the index values for the drought months.

The values of the index range from 2.00 and above (extremely wet period) to less than –2.00 (extreme drought), while the range from 0.99 to –0.99 indicates normal conditions (McKee *et al.*, 1993, Table 2).

Table 2: Drought categorization according to SPI values (Mc Kee et al. 1993).

Tabelle 2: Kategorisierung von Dürreereignissen nach SPI-Werten (Mc Kee et al. 1993).



SPI values	Classification
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

The SPI is the index employed in this study to identify and categorize drought periods, based on the precipitation data availability in the case study and because of its satisfactory performance. It would be interesting to test also another index, based on evapotranspiration, but unfortunately, reliable temperature data are not available for the area of Kaloskopi, which is a mountainous and forested area. The SPI can be used to compare drought events over different timescales and among areas with different climatic conditions (Bonaccorso *et al.*, 2003; Khan *et al.*, 2018); it can also be applied in drought warning systems and drought severity assessment. To provide reliable results, it requires data from a time period of at least 30 years (McKee *et al.*, 1993), which was guaranteed in our study (1963–2019). As described by Karavitis *et al.*, (2011), SPI includes the overall goals of indicators, which are credibility and relevance in technical aspects, and relevance with policy. Furthermore, Hayes, M.J. *et al.*, (1999), concluded that SPI identified better the onset and severity of a drought event in 1996, one month in advance, compared to Palmer Drought Severity Index (PDSI), when both indices were applied in the Southern Great Plains and the southwestern United States. In another study (Lloyd-Hughes, B. and Saunders, M.A., 2002) it is found that SPI is the most appropriate drought index, as it is calculated using the 2-parameters gamma distribution, which describes best the monthly precipitation. In addition, in the same study, they compared SPI to PDSI and they found that SPI provided a spatial standardization, which was more suitable than the one provided by the PDSI. Finally, SPI is highly applied in Greece, providing reliable results (Tsakiris, G. *et al.*, 2004; Livada, I. *et al.,* 2007; Loukas, A. *et al.*, 2007; Vasiliades, L. *et al.*, 2009).

iii) Wood cores sampling

In each stand, 20 dominant or co-dominant trees, separated by at least 5m from each other, were selected for wood core sampling. From every selected tree, two wood cores were extracted at breast height above ground, orthogonally with respect to each other, using a 400 mm long and 5.15 mm wide increment borer Mora three-threaded auger by Haglof (Haglof Inc. Sweden). The wood cores were stored in straw and transported carefully to the laboratory. After their preparation (air drying and hand sanding), measurements were performed using the LignoVision software (version 1.40).

iv) Tree rings analysis

Using the obtained wood cores, times-series of ring widths from the 20 trees per plot were calculated. Tree age ranged from 61 to 136 years in Stand 1 (988 m) and from 50 to 83 years in Stand 2 (1.274 m) (Table 3).

Table 3: Age of the sampled trees per stand.

Tabelle 3: Alter der beprobten Bäume pro Bestand.

Tree number	Stand 1 (988 m)	Stand 2 (1274 m)
1	61	50
2	136	55
3	62	66
4	80	55
5	81	56
6	85	52
7	66	71
8	63	69
9	110	62
10	68	61
11	93	62
12	85	83
13	85	68
14	120	66
15	118	67
16	75	51
17	81	56
18	84	65
19	65	59
20	85	50
Mean	85.2	61.2

The time-series were plotted as a function of the dated year along with the curve that was fitted to each data set and the equation that described them. Such curves are generally satisfactorily estimated by fitting a curve to the data with the following hyperbola, two-parameter function:

$$Y_t = \frac{at}{b+t} \tag{4}$$

where the values of a, b vary from series to series depending upon the slope of the curve required to fit the data and y_t is the expected growth in a given year t. Evaluation of the ring width models was based on the adjusted coefficient of determination (R_{adj}), the root mean square error (RMSE), and the significance ($p < 0.05$). Moreover, the Durbin Watson statistic was employed to test for autocorrelation. According to

Fritts (1976), various biological growth functions have been used for the curve fitting process, such as parabolas, hyperbolas, logarithmic, and polynomial functions. The literature referred that this kind of plots are typical if ring width data derived from many coniferous species growing on drought-subjected sites (ibid).

Since the sampling date of all trees was known, the tree rings were visually cross-dated against each other, aiming to eliminate possible inconsistencies and missing rings. After the construction of the appropriate curve for each tree, the equation was solved for the expected yearly growth (Y_t). The measured ring widths (W_t) were converted to average ring–width indices (ARWI) by dividing each width for year t by the expected growth (Y_t), using the following equation:

$$\mathrm{ARWI} = \frac{W_t}{Y_t} \qquad (5)$$

This conversion both removes the trend in growth and scales the variance so that is approximately the same throughout the entire length of the time series. It is important to underline here these specific stands have not been managed during the study period, so there were no tree removals to impact trees growth. Finally, the standardized ring-width indices were averaged to obtain a mean chronology per stand and the Average Tree Ring Width Index (hereafter referred as ARWI) was plotted, one at 988 m and another one at 1.274m.

Fritts (1976) suggested that the scaling of all series to mean values is an important feature of standardization, as slow-growing trees, which are possibly under climate stress, often provide more information on climatic variation than fast-growing ones.

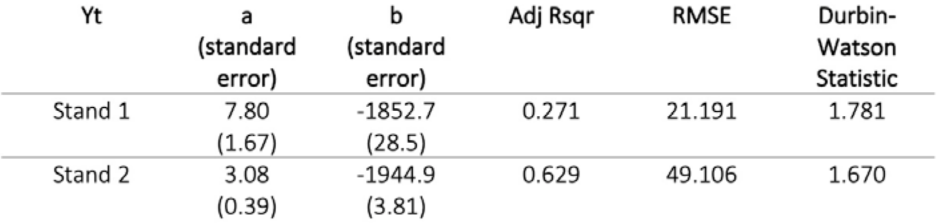
In the second part of the analysis, the correlation coefficient was used to measure the correlation between two-time series, ARWI and one climatic sequence such as the SPI index and average maximum and minimum monthly temperatures after standardization during the period from March to August, regarding the current and the previous year (available data 2009–2019). It's important to underline here, that we didn’t construct a regression model which requires multicollinearity test between predictors, but we performed individual correlations between one dependent and one independent variable. The SPI index was implemented in the case study for a period of 55 years (1964–2019). In particular, the SPI with a 6-month time step was calculated and the period of March to August was selected (SPI6 August) for the relative correlations, as this period presents the tree growth period. In addition, SPI12 September (period October–September) was also calculated and tested, representing the hydrological year. This analysis validates the impact of extreme drought on growth of the particular species, regarding two different elevations for comparisons.

3 Results

We used a common nonlinear function for determinating an appropriate tree growth model against time usingthe hyperbola two-parameter function. The results were satisfactorily for both stands based by plotting ARWI against time for the observed stands. We discarded the early rings from oldest trees, mostly from stand 1, as we did not have reliable climate data for this time, and thus the curve fitting process was based on data from 1965 onward. Table 4 shows the results of the evaluation of the fitted model for both sites. RMSE and the Durbin Watson statistic were accepted for both models. The R_{adj} test revealed that the model fits better at the higher elevation, which was expected because the higher stand (stand 2) was younger than stand 1 and seems like an even-aged stand as well. The better fitting results are shown in Figure 2, where the hyperbola function worked better at the higher elevation (b), with less outliners than in stand at lower elevation (a). Other nonlinear or even linear growth functions, such as parabolas, logarithmic functions and polynomials, were also tested, but based on the above criteria, the selected function performed better.

Table 4: Parameter estimations for the hyperbola function Yt = at/(b + t) predicting average ring width for the two stands. All coefficients were highly statistically significant (p<0.001).

Tabelle 4: Parameterschätzungen des Hyperbelfunktion Yt = at/(b + t), die Jahrringbreite für beide Bestände schätzt. Alle Koeffizienten waren statistisch sehr significant (p<0.001).



Yt	a (standard error)	b (standard error)	Adj Rsqr	RMSE	Durbin-Watson Statistic
Stand 1	7.80 (1.67)	-1852.7 (28.5)	0.271	21.191	1.781
Stand 2	3.08 (0.39)	-1944.9 (3.81)	0.629	49.106	1.670

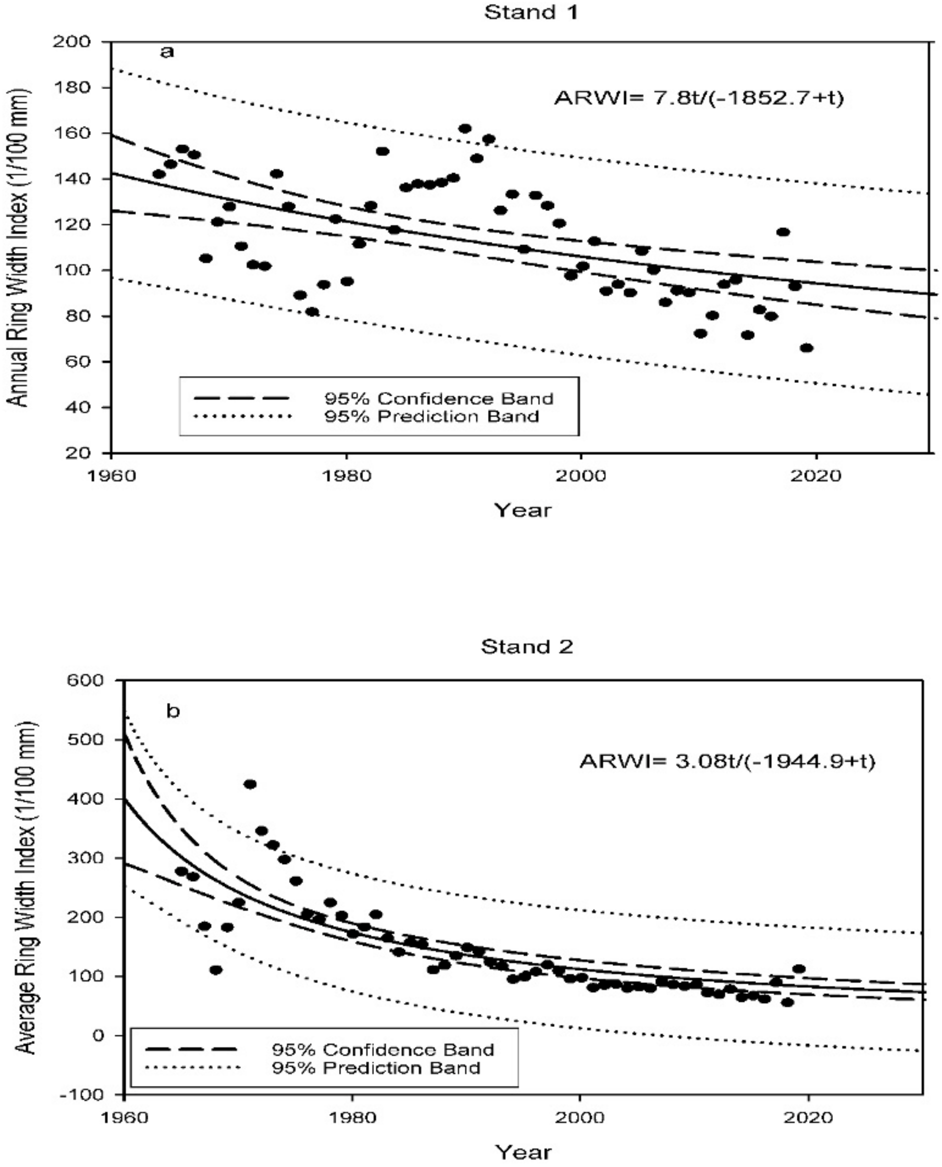


Figure 2: Tree ring width versus time in Stand 1 (a) and Stand 2 (b). The plots were produced by the hyperbola 2-parameter function (see Table 3).

Abbildung 2: Jahrringbreite versus Zeit in Bestand 1 (a) und Bestand 2 (b). Die Plots wurden durch die Hyperbel-2-Parameter-Funktion erstellt (siehe Tabelle 3).

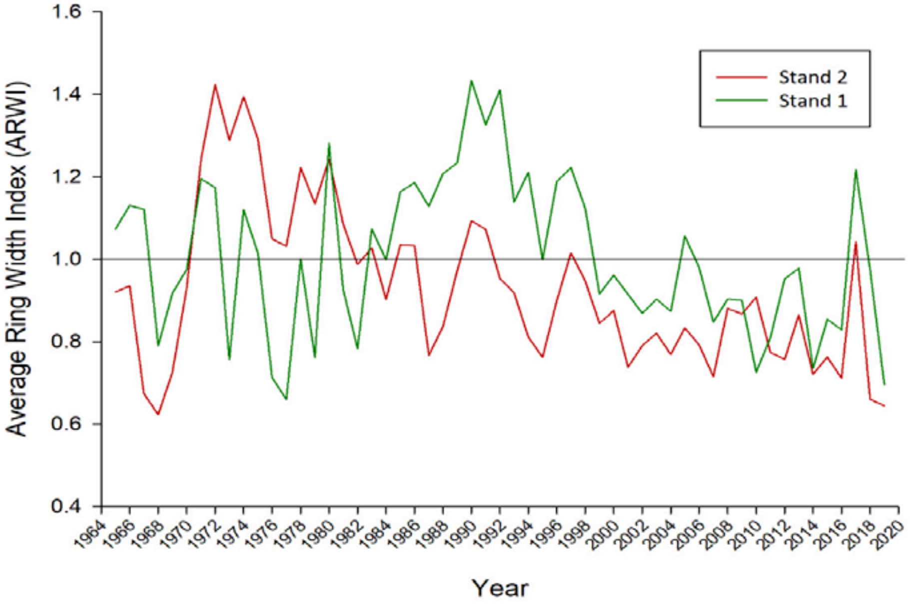


Figure 3: Average ring width index for both stands.

Abbildung 3: Durchschnittlicher Jahrringbreitenindex für beide Bestände.

After constructing and solving the equation, the ARWI values were calculated and the averaged values per site were plotted (Fig. 3). This standardization equalizes or brings all ring width curves to a uniform mean value, so that a tree record with a large average growth will not dominate other records (Fritts, 1976). In other words, this process represents, more or less, the mean chronology trends of ring width per stand, which can be easily analyzed in comparison with local climate data. The ARWI shows the expected variation from year to year, with several annual similarities in fluctuations of the average growth per stand (Fig. 3).

Correlation analysis between the ARWI (Fig. 3) and the SPI index (Fig. 4) revealed a positive relationship only with the SPI 6 of the previous year (6-month growing season index) for both stands (stand 1, $r = 0.239$, $p<0.05$), (stand 2, $r = 0.254$, $p<0.05$). Tree ring width could be affected at first by climate variables of the year before the growing season and secondly by the current year conditions (Vieira *et al.*, 2009).

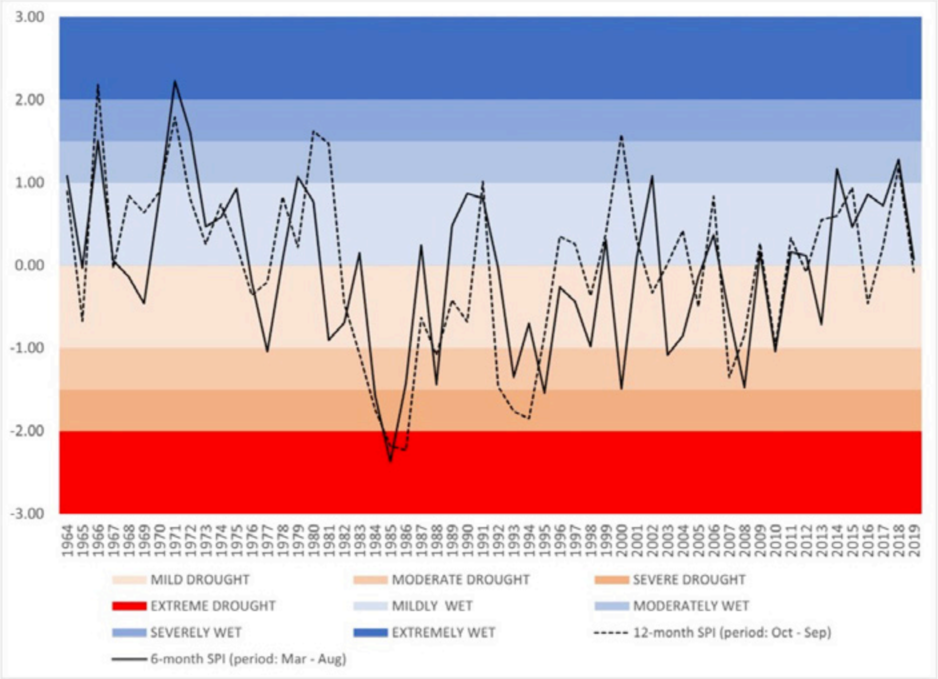


Figure 4: Annual SPI 6 (period Mar–Aug) and SPI 12 (period Oct–Sep) over the study period.

Abbildung 4. Jährlicher SPI 6 (Zeitraum Mär–Aug) und SPI 12 (Zeitraum Okt–Sep) im Untersuchungszeitraum.

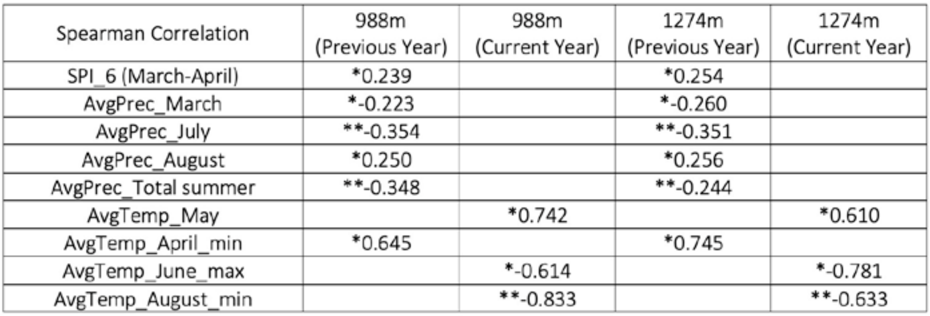
Figure 4 presents the SPI values for the examined period. We observed 1 year which was extremely dry (1985; SPI < −2), 3 years (1995, 2000, and 2008; SPI ≈ −1.5) on the edge between moderate and extreme drought, 7 years (1977, 1988, 1993, 1998, 2003, and 2011; SPI between −1.5 and −1) with moderate drought, and 6 years (1969, 1981, 1994, 1996, 2004, and 2013; 0 < SPI < −1) with mild drought. The extreme drought of 1985 and 1986 was followed by an important decrease below an ARWI of 0.8 for both stands. In most of the times, there were also decreases in growth, mostly after an extremely severe drought. This impact was more pronounced for stand 2. The different stands differed in water availability, as at higher elevations, evapotranspiration is lower, and therefore, severe drought events do not have severe impacts on tree growth. However, the severe droughts of 1994 and 2000 reduced the growth in both stands in the following years.

We observed 1 year which was extremely wet (1971; SPI > 2) and 5 years which were moderately wet (1966, 1979, 2002, 2014, and 2018; 1 < SPI < 1.5). No severely wet years were found, but many years showed a mild water availability (0 < SPI < 1). The extremely wet year of 1971 was followed by increased growth in the following year (1972) in both stands, which was expected. Mostly, moderately wet years (*e.g.*, 1979, 2002, and 2014) resulted in an increased growth index. Although this finding is useful in the prediction of growth rates, not all cases of drought or wet events, as indicated by the SPI, result in decreased or increased growth respectively. The latter observation was expected, mainly because tree growth depends on various factors, apart from precipitation.

Vicente-Serrano *et al.* (2010) report that mathematically, the SPEI is similar to the SPI (standardized precipitation index), although the first includes the role of temperature. However, due to the lack of temperature or evapotranspiration data, we could not calculate other indices, such as the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano *et al.*, 2010) or the Reconnaissance Drought Index (RDI, Tsakiris and Vangelis, 2005). Determining these indices based on a short period most likely leads to overestimation. Therefore, we used correlation analysis to examine the relationship between the available and reliable temperature data for this period (2009–2019) with the ARWI to explain the reduction in growth, at least partially. Minimum, maximum, and average temperatures were examined for this scope, and the significant results are presented in Table 5.

*Table 5: Correlation between ring width and climate parameters. Only the statistical important results are presented (*p<0.05, **p<0.001).*

Tabelle 5: Korrelation zwischen Jahrringbreite und Klimaparameter. Es werden nur die statistisch wichtigen Ergebnisse dargestellt (*p<0.05, **p<0.001).



Spearman Correlation	988m (Previous Year)	988m (Current Year)	1274m (Previous Year)	1274m (Current Year)
SPI_6 (March-April)	*0.239		*0.254	
AvgPrec_March	*-0.223		*-0.260	
AvgPrec_July	**-0.354		**-0.351	
AvgPrec_August	*0.250		*0.256	
AvgPrec_Total summer	**-0.348		**-0.244	
AvgTemp_May		*0.742		*0.610
AvgTemp_April_min	*0.645		*0.745	
AvgTemp_June_max		*-0.614		*-0.781
AvgTemp_August_min		**-0.833		**-0.633

4 Discussion

Tree ring growth depends on species, age, heredity, and climatic conditions of the study site (Vieira *et al.*, 2009), and the complex phenomenon of tree growth could therefore also be a factor of competition with neighboring trees, stand ingrowth, or genotypic variation in a particular area. Papadopoulos (2016), using quantification and analysis of the inter-annual variability of fir site chronologies, has shown that the principal factor affecting tree growth at a latitudinal scale is climate. According to the tree ring-to-climate relationships examined by this author, late spring and summer precipitation are the main climatic factors affecting the growth of Greek fir populations.

In our case, the SPI considers only the total precipitation of the month and no other weather conditions in general or over a long period. Nevertheless, several studies have shown that precipitation is the main variable determining the onset, duration, intensity, and end of droughts (Chang and Cleopa, 1991; Heim, 2002). For this reason, other parameters important for trees, such as average monthly precipitation of the growing season (March to August) and total summer precipitation (June to August), were correlated with the ARWI for both elevations.

The average precipitation of July and the total summer precipitation of the previous year were negatively correlated with AWRI in the stand with the lower elevation. The negative or low positive correlations between summer month precipitation and ring width confirm that moisture availability limits tree growth (Seiler *et al.*, 2017). Similar results have been reported for *Pinus halepensis* (Aloui, 1982) and *Pinus sylvestris* (Tessier, 1984). Moreover, we did not observe negative or positive correlations between monthly precipitation and tree growth regarding the current year. In contrast, a low positive correlation between August precipitation in the previous year and ARWI was found. The only positive correlation of August precipitation with ring growth is in accordance with Papadopoulos' assumption (2016) that the main climatic factor affecting fir tree ring growth is late spring and summer precipitation. This low correlation could be explained by the fact that the late summer precipitation is not available for growth in the following year as it is used for secondary growth needs in the same year, explaining the negative correlation between previous average summer temperatures and tree ring growth.

Comparing both early spring precipitation and temperatures, we found a negative low correlation between the average temperature of March and ARWI and a high positive correlation between the minimum temperature of April and tree ARWI for both sites. The negative effect of late winter and early spring precipitation in both stands can be attributed to restricted soil water availability due to low air and soil temperatures, which happens when water in the rhizosphere is frozen. In these seasons, early or late frosts are common, causing cambium necrosis and negatively affecting tree ring width during the following growth period (Papadopoulos, 2016). Koutavas (2013) reported that the combination of water surplus and low temperatures affect negatively tree ring growth due to evaporative cooling. Over time, the higher air temperatures in April and May provide water for various physiological processes, such as intense cambium reactivation and growth.

Spring temperatures considerably define growing season length and tree ring width (Manetti and Cutini, 2006). Seiler *et al.* (2017) found similar positive correlations between spring temperatures and ring width, suggesting that high spring temperatures promote an early start of the growing season. Touchan *et al.* (2014) also reported positive relationships with spring temperatures, in agreement with Koutavas (2013) for *A. cephalonica* and Carrer *et al.* (2010) for *A. alba*. Our results are compatible with the above reports by the high positive correlation, for both sites, between average May temperature of the current year and ARWI. Positive correlations of spring air temperatures confirm the beneficial effect of high spring temperatures, which seemed to be more important for stand 1 at the lower elevation (r = 0.742). High spring temperatures had a less intense impact at the higher elevation.

In summer months, the rising temperatures lead to growth reduction due to climate-induced drought. This effect though was not obvious in our study because *A. cephalonica* is a drought-tolerant species (Athanasiadis, 1986). However, negative correlations between ring width and summer temperature have previously been described in north-eastern Greece and the Spanish Pyrenees (Tardif *et al.*, 2003) as well as in Turkey (Hughes, 2001; Griggs *et al.*, 2007). According to Seiler *et al.* (2017), these correlations may be related to heat waves and the negative effect of drought stress on tree growth. Our results indicate that in the study area, June and August are crucial for tree growth. The average maximum temperature of June and the average minimum temperature of August, regarding the examined period, were strongly negative correlated with the ARWI, irrespective their elevation. Interestingly, the following correlation was stronger for stand 1 (r = –0.833) than for stand 2 (r = –0.643), mainly because of the higher elevation of stand 2 and its corresponding higher resistance to high temperatures.

On the other hand, Koutavas (2013) found that in the late 20th–early 21st century, there was no statistically significant relationship between moisture and Greek fir's growth. He implied a remarkable enhanced resistance to drought, also partly found in this study (Fig. 4; Table 5). Our results also testified that precipitation is critical for growth in late spring early summer in the form of significant correlations between ARWI and SPI6. However, we found a reduced fir growth in the late 20th–early 21st century in disagreement with an earlier study by Koutavas (2008) on Greek fir and Mt. Ainos.

However, it is difficult to state suggestions for growth response to stand environmental factors due to the absence of clear favorable climatic conditions and so, tree-ring and climate relationships can be mainly affected by non-climatic factors (Seiler *et al.*, 2017). As a result, the observed correlations don't indicate cause-reaction relation. For instance, Simunek *et al.* (2021) trying to better understand cyclical regu¬larities of forest tree species growth, founded highest positive significant correlation coefficient between radial growth of European beech and the number of sunspots, followed by the correlation with air temperature in the growing season.

Although, climate differentiation and tree adaptability to climate-soil conditions may follow a stand or regional pattern, it is strongly influenced by the genetic component of the species. Moreover, precipitation is the main parameter affecting water availability. Further analysis of Figure 4 reveals a reduced growth index for both stands after 1999. With only two years of increase (2005 and 2018), the ARWI shows values below 1, indicating unfavorable growth conditions for almost 2 decades. The reduced ARWI over the last 20 years, according to the SPI, is collateral to those 2 decades of mild or moderate precipitation conditions, wet or dry. Even at an elevation of 1.274 m, where hypothetically, the conditions could be more ideal for fir growth, with cooler winters, later snow melt, more rain, more soil organic matter, decreased evapotranspiration, less temperature extremes, and generally decreased stress, the AWRI values were alike those at the lower elevation. The recovery of SPI in the years after 1998 is not generally followed by AWRI recovery or a slight recovery occurred after 2 or 3 years. The recovered ARWI takes quite low values, usually below 0.8, in many years after 1998. Especially after 2008, there is a divergence between SPI and ARWI which coincides well with a known defoliation, observed by local people (beekeepers, foresters, herb collectors) which is presumably incurred by EFB. Additionally, in 2019 defoliation caused extremely low values of ARWI and coincided with an observed outbreak of EFB. In other words, it is difficult to explain this decline with extreme or long events of drought but more due to the EFB impact. Nevertheless, these observations require further investigation.

5 Conclusions

A thorough understanding of tree growth for different sites, species, provenances, climatic conditions, and management schemes is crucial for foresters, forest owners, forest managers, and stakeholders in general. In this study, one extreme drought event and one extreme wet event, were investigated during a period of 55 years using a common drought index. Those extreme events were translated to negative or positive changes in growth. Other milder events, as indicated by the SPI, were less easily imprinted on the measurable tree ring growth. It seems that the growing season (March to August) SPI of the previous year played an important role in extreme drought event analysis and indicated the potential of the current year to cause important fluctuations in tree ring growth. A decline in growth was observed after 1998 for both elevations, not connected with SPI but seems to be associated with observed defoliations of the insect European fir budworm (EFB). However, this observation requires more data collection and further analysis.

Forest management practices targeted at one or more of these ecosystem services should address droughts, particularly in areas expected to receive more frequent and long-term drought events. Future research involves thorough knowledge of drought impacts on trees and ecosystems. This will be focussed on economically important species such as Greek fir aiming to enable projections of forest dynamics across the 21st century providing information support for sustainable forest management at a national level.

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