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Dendroclimatological Analysis of Fir (*A. borisii-regis*) in Greece in the frame of Climate Change Investigation

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Abstract: The potential correlation between fir tree-ring width (*Abies borisii regis* Mattf.) variability and the respective variability of the main climatic parameters in the region of University Forest of Pertouli (central Greece) are being analyzed in the current study, taking into consideration a 60-year period (1961–2020). Correlation and response function analyses were applied to examine the climate–tree-growth relationship. Precipitation was found to be the most crucial and driving factor that most intensively influences the tree growth of *A. borisii-regis* trees under Mediterranean climate conditions. It was evident that this species is characterized by drought sensitivity and even a short and mild drought event could significantly influence adversely its growth and productivity. June, May and July precipitation present the higher and statistically significant correlation of monthly precipitation with tree-ring width, affecting the ring-width variability by 31.2%. Temperature (mean, max or min) does not seem to highly influence the tree growth, despite the obvious and statistically significant trend increase that has been recorded in the last decades within the frame of climate change. June maximum temperature presents a strong negative correlation with tree-ring width, while April maximum temperature is positively correlated with tree-ring width. The combined impact of precipitation and max temperatures on tree-ring growth is 38.5%. Snow did not reveal any statistically significant correlation to tree-ring width, independent of the height of monthly snow accumulation. *A. borisii-regis* grown in high altitudes in the Mediterranean region demonstrate high adaptability to the recorded temperature increase and could potentially be able to adapt in future to even warmer climate conditions. The constructed tree-ring chronology could be utilized towards the implementation of further dendroclimatological analyses and climate reconstruction.

Keywords: dendrochronology; drought stress; climate change; ring; SPEI; tree growth

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1. Introduction

The biomass generation and productivity rate of a forest ecosystem depends on several factors such as the plant species, site slope, climatic and soil conditions, biotic factors, etc. The width of a tree ring is largely determined quantitatively by the rate and duration of cell division by the vascular cambium [1]. Therefore, the tree-ring width is the outcome of the interaction of complicated internal and environmental factors, among which the climate plays a notable role [2,3]. Tree rings provide long-term information concerning forest productivity and depict forest responses to environmental stimuli. Specifically, the global climate change intensifies the frequency, severity and duration of extreme climatic phenomena [4], causing devastating flash floods and droughts [5], under which, trees annual growth is usually adversely affected [6]. In such cases trees may become susceptible to microorganisms devastating action [7–9] and encounter high mortality rates [10]. Apart from the abrupt changes in temperature and rainfall, factors such as the biotic stresses, air pollution, natural or anthropogenic disturbances may influence the wood structure

among the different growth rings [11]. Such structural changes of the tree rings contribute to the deeper comprehension and quantification of the impact of these factors on tree growth [1,12,13].

Under favorable growing conditions, the cambium may be active almost throughout the entire year [14]. Nevertheless, under the adverse conditions prevailing in warm Mediterranean sites, the cambium usually stops dividing during the summer, as a result of drought [14], as well as during prolonged dry winters or sites of extremely low temperatures [15]. Generally, low growth rates are caused by drought stress during very warm periods, with the most frequent reason to be the water deficit recorded during spring [16]. The activity of the cambium zone is restored when water availability is re-established [10]. The start of the growing season in Mediterranean regions is approximately the first 2 weeks of May and usually lasts until approximately September [17–21]. The "hydrological" year is defined as a period of 12 months, from October of the previous year until September, and is widely utilized for research purposes, especially in the Mediterranean region [3,22]. In general, Mediterranean hydroclimatic conditions are characterized by mild and rainy winters, hot and dry summers, and extreme hydrological events [23–25]. Winter rainfalls that precede the formation of the tree rings during spring, as well as the spring total precipitations that coincide with the beginning of the tree-ring development play a key role in the biosynthesis of growth-ring wood mass. Concerning each one of the species, the wide tree rings are observed in hydrological years that present high rainfall sum values during winter and spring, while the beneficial outcome of the winter precipitation could be accredited to the water storage into the ground for utilization during the growing season [3]. Moreover, the spring precipitation is also crucial due to the increased water demands for the various physiological processes, such as the severe cambial re-activation and growth discharge after winter inactivity.

Regarding the temperature during spring, the converse relation to the growth-ring width is being recorded. This could be explained by the aforementioned positive relation between precipitation and growth, as well as the negative relationship between growth and evapotranspiration processes. More specifically, higher temperatures result in a higher rate of evapotranspiration, when water flow could be restricted by high water storage in the ground. Therefore, the growth rings of low width are recorded in years that are characterized by severe precipitation reduction and extremely high temperatures during the growing season (March–September), or a reduction of precipitation level during the winter months, just before the growing season [3]. In general, the larger the water excess, the higher the rise in growth-ring width and the other way round.

Fir (*Abies borisii Regis* Mattf.) is an endemic hybrid species of *A.alba* and A.cephalonica spread in the southern Balkan Peninsula, and disperses mainly in the northern and central part of Greece [26,27], with a common distribution from 38° N to 40° N latitude. It appears in the humid bioclimatic layer and out of the Mediterranean climate (European type) and into less compact rocks, particularly of flysch [28]. Fir is characterized by a strong adaptability in variant Mediterranean climatic and soil conditions and, therefore, it has been utilized in the past in dendroclimatological studies carried out in Mediterranean area [29], including Greece [30,31]. The intense growth of fir all over many basins, as well as the occurrence of older trees, renders it an optimal species to be analyzed for the evaluation of fir growth response to potential changes in climatic conditions. The hybrid fir of *A. borisii-regis* presents a higher mean ring width than *A. cephalonica* for comparable conditions and age [28]. Papadopoulos et al. [3] detected that climate plays a crucial role in the growth-ring width variability of this species in some Mediterranean sites. A positive correlation of growth-ring width with winter and spring temperatures and a negative correlation with summer (August) temperatures have been observed. Manetti and Cutini [32] reported for *A. alba* grown in central Italy, that April temperatures are crucial for defining the duration of the growing period and, therefore, growth-ring width. Other studies reported that the main climatic parameter influencing the growth-ring width of fir appears to be the late spring and early summer rainfalls, recorded as well in studies dealing with other Mediterranean

plant species [33,34]. Nevertheless, a positive relation of growth-ring width to July–August precipitations has also been identified [3,35]. In parallel, growth ring to climate relation in central Greece seems to be dependent also on the species' adaptability to climatic-edaphic conditions [28]. As it is evident, only limited information has been detected in the literature concerning the response of *A.borissi-regis* to climate variability, its wood biosynthesis rate, and its sensitivity or adaptability to such potential climate changes.

Parallel to the globally reported climate change that occurs gradually, it has been also observed that the climatic parameters highly diversify regionally from site to site, depending on plant species and geomorphology among other factors, and it is evident that ring growth patterns geographically differ (for example from a south to north direction) among the different fir populations. Further research efforts that would provide knowledge on current and future fir forest reactions worldwide to climate variability are considered highly necessary and would undoubtedly contribute to the supportive tools of preparation for rational forest management and decision making.

Therefore, the objective of this study is the analysis of the variability of fir tree-ring width and its correlation with main climatic parameters. *A.borisii regis* was chosen to be examined, since there is a great lack of information concerning its growth response to climatic factor variability, especially in regions of southern Europe and Greece. The inter-annual variability of tree-ring width is being quantified and the potential adaptability/sensitivity of fir trees to extreme climatic events is being investigated. To the best of our knowledge, this is the first investigation exploring the potential impact of climate change on *A. borisii-regis* tree-ring width, through a trend analysis of the monthly temperatures (average, highest and lowest ones) and precipitation data.

2. Materials and Methods

2.1. Study Area

The tree sampling site was located in central continental Greece (Figure 1), in the eastern part of the Pindos Mountain range (rain shadow), within an altitudinal zone from 1200 to 1500 m a.s.l. In the current work, a fir (*A. borisii-regis*) population of "Pertouli" area was chosen to be examined, and where it was feasible, older fir stands were selected, being characterized by similar canopy, exposure and site quality. The University Forest of Pertouli in the Pindos region (Trikala, Central Greece) was chosen to be the study area, since it constitutes a significant timber productive forest at an altitude of about 1100–1700 m, where the highest fir availability in the whole country stands out (Table 1). The site quality was determined using the University Forest Management Plan of the decade 2009–2018 (pp. 65–74, [36]).

Table 1. Sampling area and site characteristics.

Study Area	Latitude	Longitude	Altitude (m)	Exposition	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Mean DBH (cm)
Pertouli University Forest	39.542484°	21.464476°	1200–1500	SE-E	9.1	1471.4	67.5

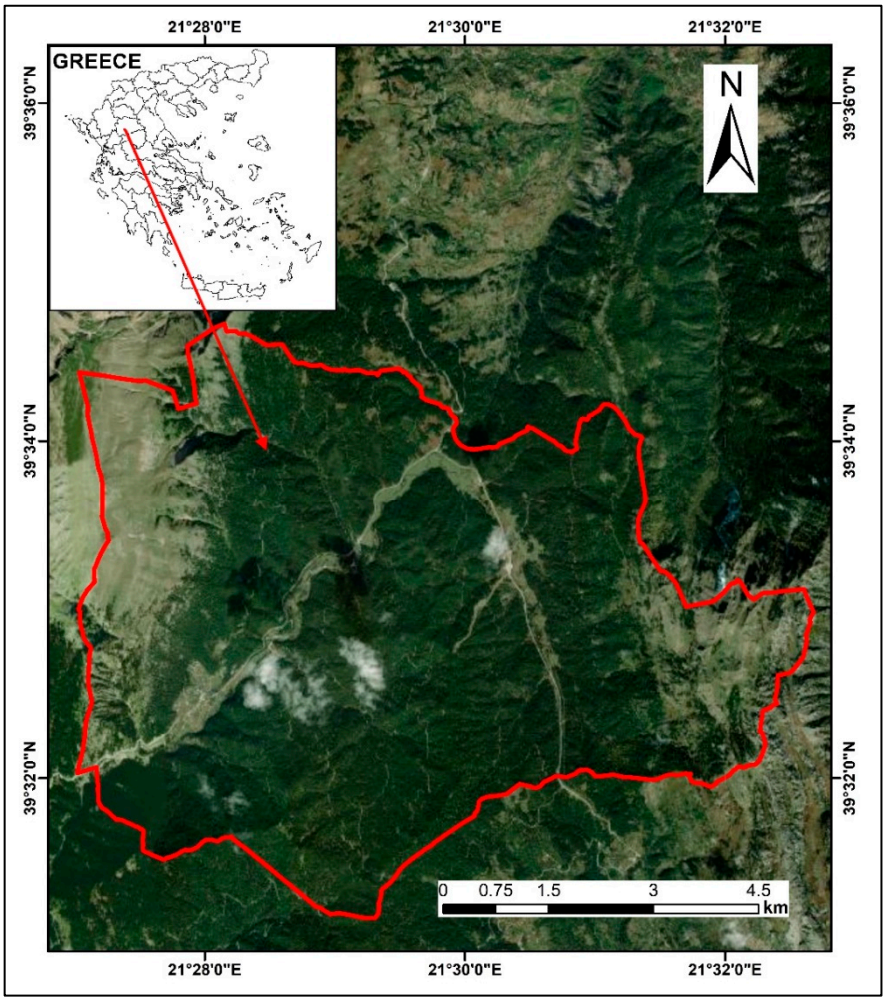


Figure 1. Study area. The red line presents the borders of Pertouli University Forest.

2.2. Sampling and Tree-Ring Analysis

From a wide and quite uniform area of the University Forest, 25 dominant and healthy trees of high age were selected. Sites with obvious natural or anthropogenic disturbances were avoided. Where it was possible, two sample cores were obtained from each of these trees, around the breast height (1.3 m). In total, 39 cores were obtained for the purpose of this work. A 3-threaded Pressler's increment borer (Haglöf, Sweden) of 50 cm length was used.

The radial increments were conditioned in a climate chamber under constant conditions (20 °C temperature and 65% relative humidity) until constant weight, then mounted on a special wooden support and sanded gently using a sanding sheet of 100 grit until the growth rings were clearly visible, in order for the cross-dating to be accurately implemented. Afterwards, the cores were scanned applying a 1600 dpi resolution, and were measured to the closest 0.001 mm and cross-dated visually using a pointer year. The qualitative result of the cross-dating process was assessed with the help of COFECHA software [37]. To evaluate the relations of climate with growth rings, index chronology was created using ARSTAN package [38]. A double detrending process was applied: firstly a negative exponential or linear regression was applied and subsequently, a cubic smoothing spline function, retaining 50% of variance at a wavelength of 30 years [39]. This standard procedure gave the transformation of raw tree-ring widths into indices as a result. In these indices, autoregressive modeling [40] was applied to eliminate the remaining first-order temporal autocorrelation. The well-known dendrochronological statistical parameters [2,41] were calculated. Concerning the raw chronologies, the average growth-ring width, standard

deviation, mean sensitivity and first-order auto-correlation coefficient were calculated. Respectively, concerning the residual data, the average correlation between all series (RBAR), Expressed Population Signal (EPS) and Signal to Noise Ratio (SNR) were calculated. RBAR ranges from 0 to 1, where 1 indicates perfect common variance. Independently from the sample size, RBAR is an unbiased measure of common signal strength [38,40,42].

The representation of a theoretical population chronology of an infinite number of trees by using a finite-sample chronology was measured by the EPS [39,40,43]. EPS ranges from 0 to 1, where 1 indicates perfect agreement with the population chronology. The signal strength of a tree-ring series chronology usually changes over time in relation with the fluctuation of the RBAR value and the alternation of sample depth, which in turn influences the EPS. Consequently, it is significant to explore the temporal characteristics of RBAR and EPS to achieve a higher comprehension of the dates that the chronology could become untrustworthy during the series interpretation. The running RBAR and EPS values were estimated by applying a 50-year moving window with 25-year overlaps.

2.3. Climate Data and Trend Analysis

The necessary climatic data of the study area, referring to precipitation and temperature, were obtained from the regional meteorological station, established and managed by the Department of Forestry & Natural Environment of Aristotle University of Thessaloniki (AUTh). The time series was complete without missing values, the length was 60 years (1961–2020) and provided daily measurements for the precipitation (rain and snow) and temperature (mean, maximum (max) and minimum (min) values). Max and min monthly temperature values were used to detect any significant relation with the tree-ring width, to determine if extreme climatic conditions influence the growth of firs in the study area. A trend analysis of the monthly temperatures (average, highest and lowest ones) and rainfall data was implemented, performing the Mann–Kendall test [44,45] and Sen's slope [46], to investigate if there is any significant trend (increase or decrease) in climate conditions for the last 60 years and the potential effects on tree-ring growth. The trend analysis was applied in a hydrological year base, following the growing and dormant seasons of Mediterranean climate. Due to paper length restriction, the aforementioned findings are presented only for the annual precipitation and the mean annual temperature.

The 12-month Standardized Precipitation Evapotranspiration Index (SPEI) [47] was calculated to detect the drought years and the potential effect on tree-ring width. SPEI contributes to the quantification of dry period strength/severity in accordance with its intensity and time, and can identify the beginning and ending of drought phenomena. SPEI constitutes a multi-scalar drought index that takes into account both precipitation and temperature, with the capability to calculate drought at different time scales. Due to its capability to combine both factors of temperature and precipitation, SPEI seems to be an advantageous index of drought, taking into consideration that evapotranspiration is one of the most significant forms of water loss in drought episodes under high temperatures [48].

2.4. Climatic Conditions and Tree-Ring Width Correlation Analysis

Climate-growth relations were assessed by applying multiple regression analysis [49–51]. As the dependent variable of this regression was considered to be the indices of the tree-ring chronology, while independent variables were considered the monthly climatic parameters (precipitation in various combinations with average, maximum and minimum temperatures) from October of the previous year (n-1 year) up to September of the following year. The specific duration is widely applied in dendroclimatological approaches in the Mediterranean basin [52]. SPSS 25 software was used to analyze statistically the results, at a significance level of 0.05.

3. Results and Discussion

3.1. Tree-Ring Analysis

From the initial sample of the obtained cores coming from 28 trees, three cores were excluded during the processing of the results and the statistical analysis. The main reason for this exclusion of these three cores was that they displayed ambiguous tree-ring formation, and, therefore, could not be correlated to the other cores. In parallel, the analysis in COFECHA software confirmed that these three cores should be excluded from the analysis. Therefore, the final tree sample that was inserted in the statistical analysis was composed of 25 trees.

The time span of master dating series used in the analysis was from 1833 to 2020 (188 years) and the portion with two or more series was 151 years (1870–2020). The mean tree-ring width of the raw data was measured to be 3.099 mm, the respective standard deviation value 1.186, the value of mean sensitivity 0.191 and the mean value of the first-order autocorrelation coefficient (AC1) was found to be 0.757. The low values of mean sensitivity and the relative high values of AC1 suggest that the low-frequency variance (long term trends) is dominant in the study area [2,28,53]. The average good site quality of the Pertouli forest, the summer drought-thermal period, the high mean annual precipitation and the relatively low mean annual temperatures are variables that do not vary intensively during the year or among the years. Stress derived from drought phenomena seems to be maintained at a low level, and as a consequence, growth-ring formation and wood biosynthesis were balanced during consecutive years. This balance was found to be in agreement with the higher values of the first-order autocorrelation.

Figure 2 demonstrates the non-standardized (A) and standardized (B) growth-ring chronologies of fir (*A. borisii-regis*) in Pertouli University Forest. The (A) was mentioned to comprehend approximately the potential low frequency trend that might have been removed during the detrending process of the raw tree-ring width data. The trends of the non-standardized series (Figure 2A) are a combination of biotic and long-term climatic trends. The peak of ring-width values concerning the late period of the 19th and early period of the 20th century is related to the lower sample depth referring to those years, and maybe to the high tree-ring width values of young healthy trees [54]. The low sample depth until 1885 does not allow us to draw safe conclusions in regards to this period.

Figure 3 presents the running series of RBAR and EPS, calculated using the 50-year moving window with overlaps of 25 years. The average RBAR has been assessed to be 0.307 and the SNR 11.08. The running RBAR and EPS plots exhibited that the chronology could not be considered permanently reliable over time. RBAR slightly decreases during a period (1965), though in general, the variations in this measure of signal strength seem to be stable. EPS also was recorded to be stable and over 0.85, though in the period of 1915 it was just below the threshold [41], which could be accredited to the decrease in the sample depth. The high values of RBAR, SNR and EPS indicate a clear response to environmental and stand factors. Similar results were presented by a previous study of Pasho et al. [55] that concerns the same hybrid fir species (*A. borisii-regis*) grown in Albania, as well as in Greece by Papadopoulos [28]. Based on the aforementioned analysis, it could be declared that the constructed tree-ring chronology can be considered as reliable and could be utilized towards the implementation of further dendroclimatological analyses.

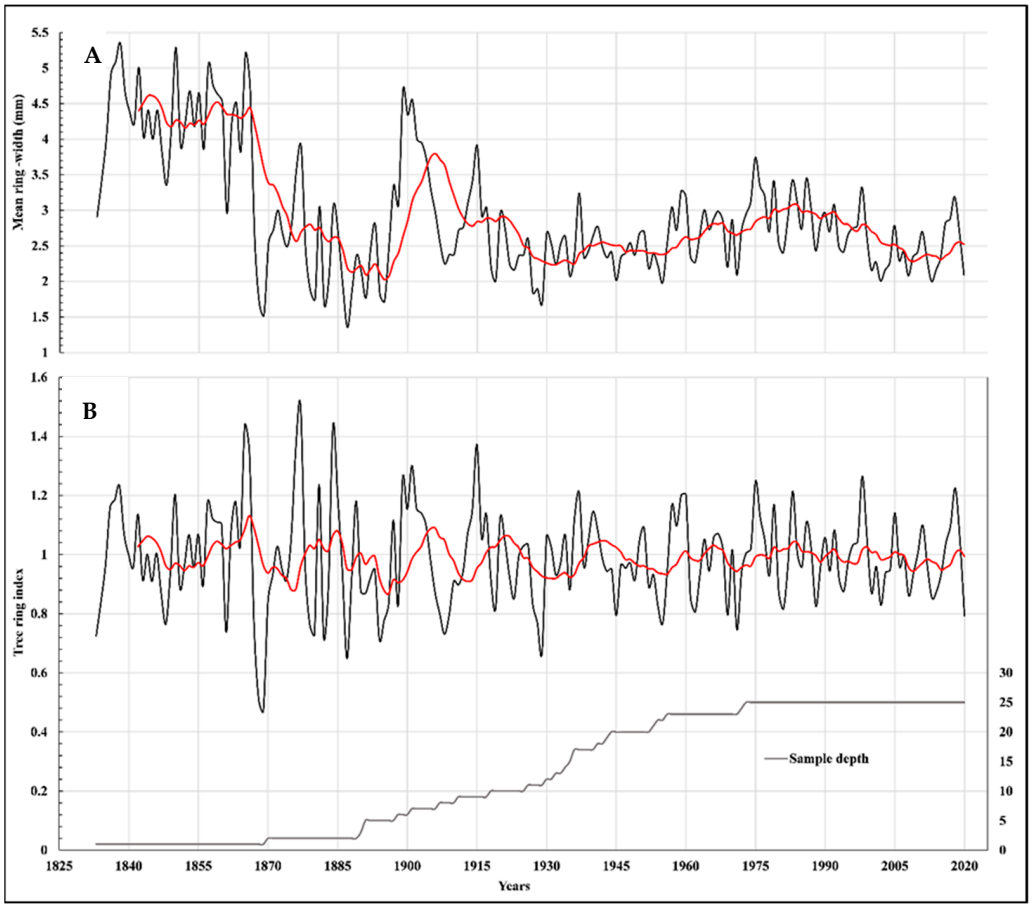


Figure 2. *A. borisii-regis* tree-ring chronology in Pertouli University Forest. Plot (**A**) shows non-standardized annual tree-ring width. Plot (**B**) shows the standardized annual tree-ring index. The red line superimposed on both tree-ring plots indicates the mean moving average of 10 years.

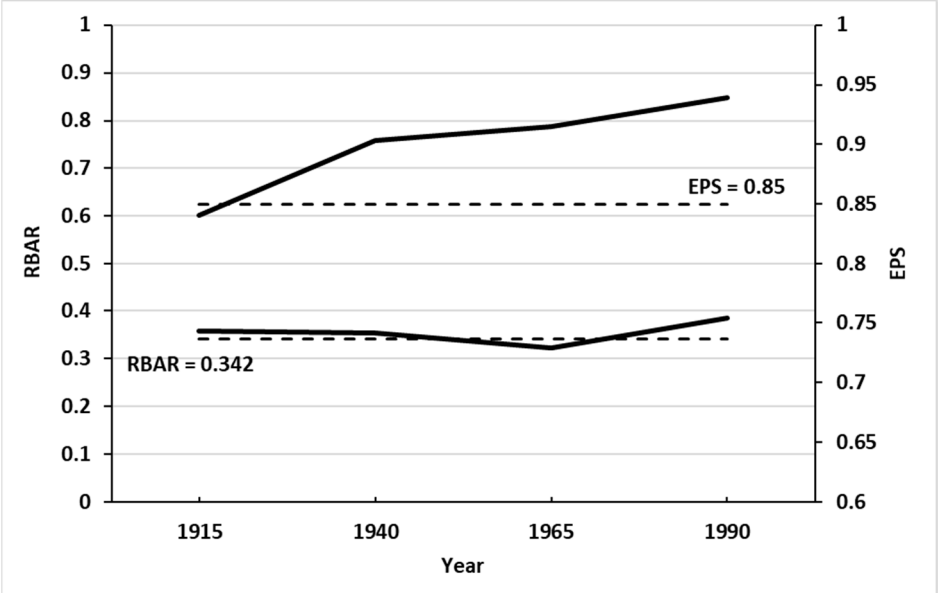


Figure 3. Running RBAR and EPS plots of the *Abies borisii-regis* chronology based on a 50-year window with 25-year overlaps.

3.2. Climate Trend Analysis

The Mann–Kendall test and Sen's slope were calculated to detect the potential trends in the annual and monthly values of precipitation and temperature. Figure 4A reveals that the precipitation in the study area fluctuated during the last 60 years but remained relatively stable over time. The intersection of the forward and backward curves within the confidence lines defines the beginning point for a sudden change in the time series. Additionally, the intersection point in time series is statistically significantly only in the case that at least one point in the curve u(d) (solid line) falls out of the confidence interval. The tests showed that there is no significant trend in precipitation (0.05 sig. level) in the study area. The same test was separately applied for each month, and the results revealed that there are no significant trends (decrease or increase) in monthly values of precipitation.

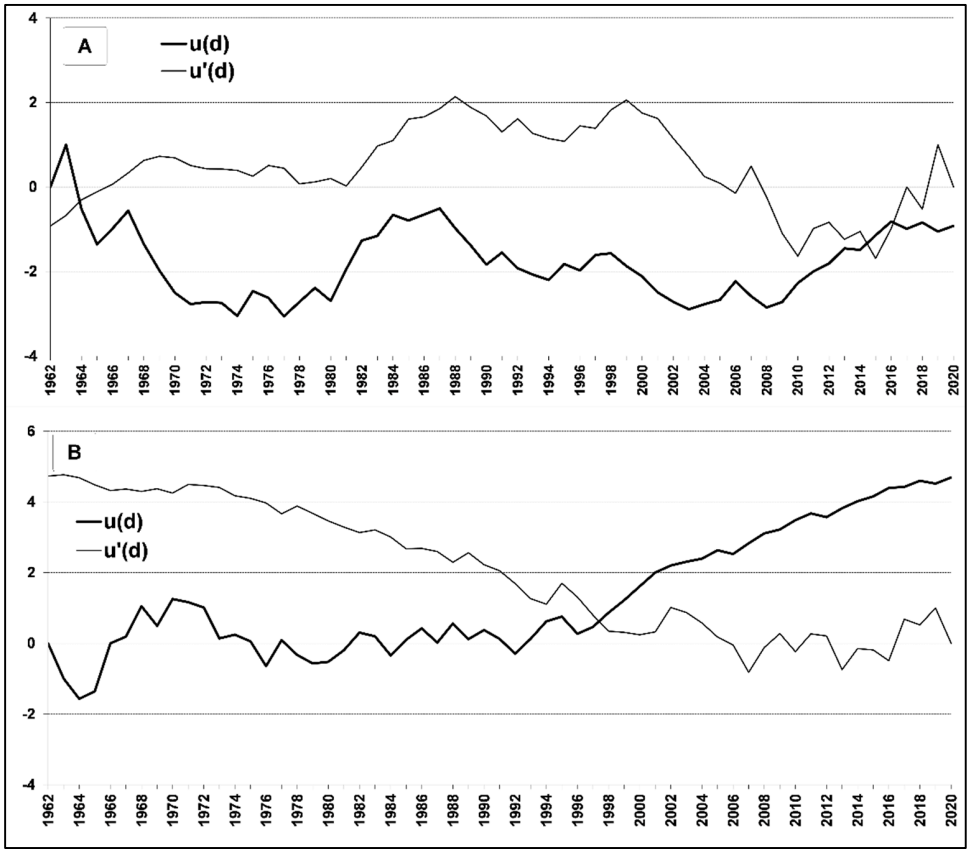


Figure 4. Graphical representation of sequential Mann-Kendall test for annual precipitation (**A**) and for the mean annual temperatures (**B**) in Pertouli, with forward trend u(d) (solid line) and backward trend u′(d) (dashed line) at the 0.05 confidence level.

Concerning the trend of the mean annual temperature values in the study area, Figure 4B presents a statistically significant increase in temperature over time. More specifically, the mean annual temperature remained stable until the year 1998, when an abrupt increase in temperature occurred and the temperature continued to increase until the year 2020. The trend analysis of the mean monthly values revealed that the increase in annual temperature is attributed mainly to the months of January, February, March, June, July, August and October, which showed a statistically significant increase in temperature. Additionally, the trend analysis on max and min monthly temperature values demonstrated a statistically significant increase in almost all months (except for November, and min temperatures of December, January and February).

Figure 5 presents the graph of the Mann–Kendall trend test that was applied on the assessed tree-ring indices. The graph reveals that there is no statistically significant trend within the tree-ring chronology, despite the fluctuation that is evident during the

first decades (1883–1900), which could be partially attributed to the low sample depth of that period. The trend analysis of the values of precipitation, temperature and tree-ring indices revealed that precipitation might be the driving factor that most intensively influences the growth of *A. borisii-regis* trees, where Mediterranean climate conditions prevail. Temperature (mean, max or min) does not seem to influence at the same extent the tree growth, despite the obvious and significant increase that has been recorded the last decades. In the following sections, the implications and interactions among tree growth, precipitation and temperature were discussed and thoroughly analyzed.

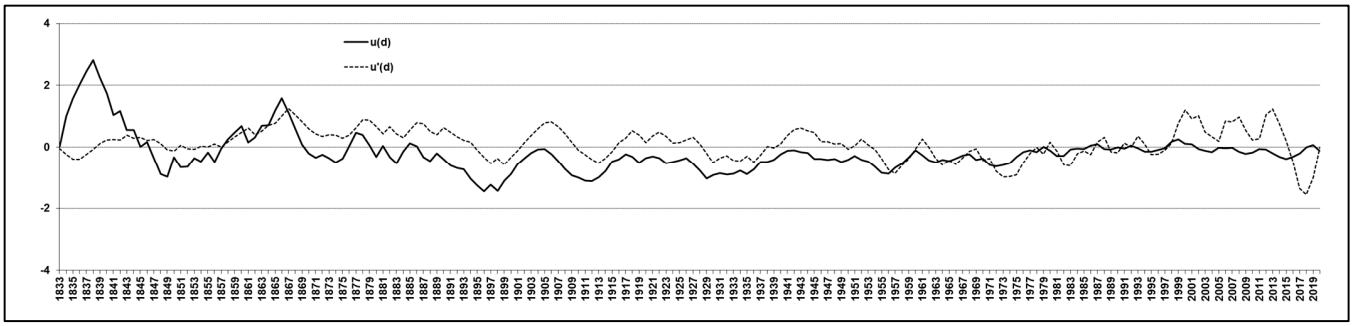


Figure 5. Graphical representation of sequential Mann-Kendall test for the annual standardized tree-ring time series in Pertouli, with forward trend u(d) (solid line) and backward trend u′(d) (dashed line) at the 0.05 confidence level.

3.3. Relations between Tree-Ring Growth and Climatic Conditions

Figure 6 presents the calculated 12-month SPEI index for the study area superimposed by the annual ring-width deviation index. It is evident that even the droughts of the shortest period and lowest intensity could significantly adversely influence the tree growth and productivity. Forests growing in the temperate climates such as that of Mediterranean climate seem to be susceptible to droughts and appear to respond even to short and intermediate duration drought episodes (<1 year) [56].

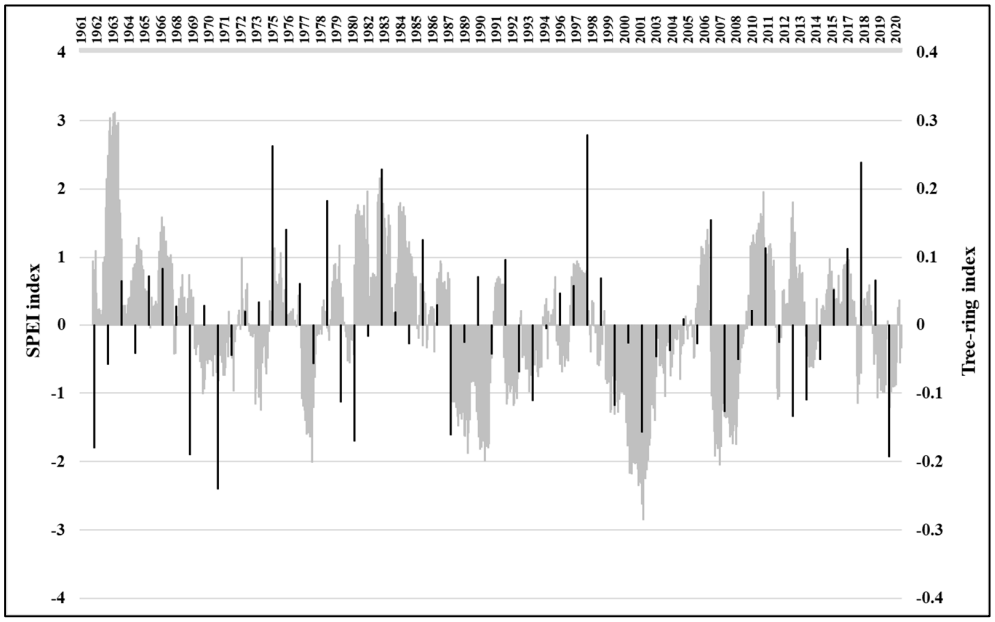


Figure 6. SPEI index for a 12-month period (gray columns), from 1961 to 2020 in Pertouli University Forest and the annual ring-width deviation index (black columns). Categorization of dryness by SPEI: Near normal (−1 to 1); Moderate dryness (−1.49 to −1); Severe dryness (−1.99 to −1.5); Extreme dryness (less than −2). The same ranges for positive values indicate wetness conditions.

Multiple regression analysis (mean monthly rainfall, snow and temperature) revealed that monthly precipitation is the most critical factor that highly affects fir growth in Mediterranean climate at high altitudes. Specifically, May, June and July are the months that presented the higher statistically significant correlation with tree-ring width (Figure 7). The precipitation of these three months seems to be critical for tree growth, since it affects 31.2% of the ring-width variability within the hydrological year (Table 2). Similar findings were reported in Greece by Papadopoulos [28] and Koutavas [57], as well as some other Mediterranean species [34,58]. Specifically, positive relations with precipitation of late spring and summer months were recorded by Pasho et al. [54] in regards to *A. borisii-regis* species of south Albania. Furthermore, Papadopoulos et al. [3] reported that the role of climate in the growth-ring width variability of fir is very significant in some Mediterranean sites, highlighting that the tree-ring width is positively correlated to the precipitation of June. As they explain, this tendency is attributed to the fact that in June a great tree growth activity takes place, parallel to the starting point of the drought period in Mediterranean climate. Nevertheless, the factor of snow did not reveal any statistically significant correlation to tree-ring width, independently of the height of monthly snow accumulation in the winter. This could be explained by the fact that the snow cover is being both created and melted (after a short period) during the winter period. Therefore, it is being rapidly transformed into surface and groundwater runoff, lost as it flows into streams, and it cannot be utilized by the trees at the beginning of or during the growing season when the water requirements are very high.

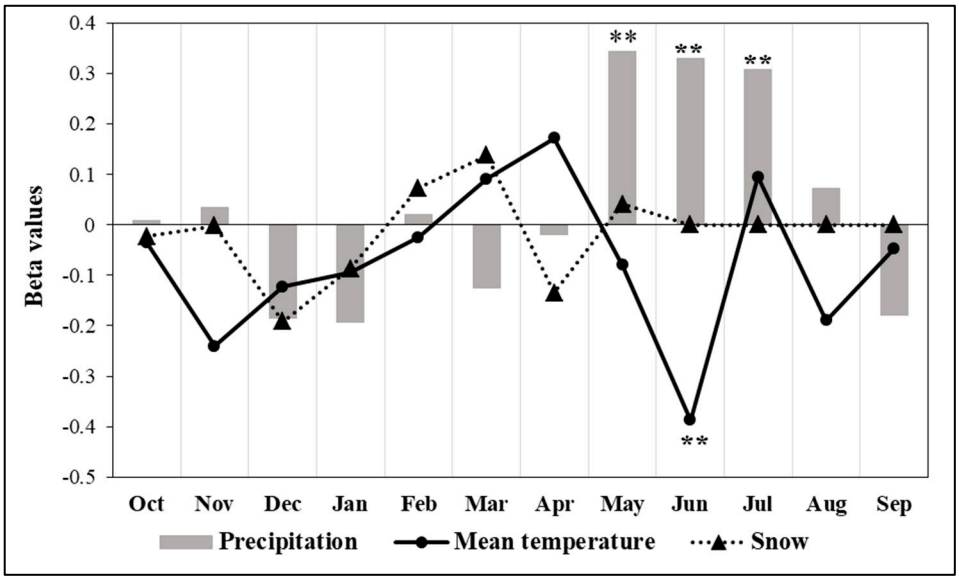


Figure 7. Response of tree-ring width to mean monthly rainfall, snow and temperature of the hydrological year in Pertouli University Forest (significance of correlation: ** $p \leq 0.01$).

Table 2. Results of multiple regression analysis for explaining tree-ring width variability by mean monthly precipitation and temperatures (mean, max and min) calculated for the hydrological year.

Predictors	R^2	*f* Value	df	*p* Value
Precipitation (May, June, July)	0.312	8.3	58	0.00012
Mean temperature (June)	0.15	8.9	52	0.004
Max temperature (April, June)	0.22	7.1	52	0.002
Precipitation (May, June, July) with mean temperature (June)	0.364	6.8	52	0.00018
Precipitation (May, June, July) with Max temperature (April, June)	0.385	5.6	52	0.00038

Generally, several researchers [19,59,60] have reported that species' sensitivity to climate variations may result in distinct spatial responses, reflecting the complexity of the Mediterranean climate, with large differences between various areas and basins. The current analysis confirms that the growing period in the high altitudes (1200 m a.s.l) of Pindos Mountain range starts mainly from April–May and lasts until August. However, previous studies that were conducted in similar conditions with *Abies* species showed that the growing period could be prolonged until September–October, depending on the species' water and temperature sensitivity, climate and geomorphological conditions [18–21,28,55]. For that reason, the monthly precipitation of these months constitutes an extremely crucial factor for the tree growth, wood biosynthesis and forest productivity in general. Concerning the correlation with the mean monthly temperatures, the multiple regression showed that June temperature negatively correlated with tree-ring width. June by itself affects 15% of tree-ring width variability in the Pertouli fir forest. The combined impact of precipitation and temperature factors on tree-ring growth was calculated to be 36.4%.

Figure 8 presents the multiple regression results concerning the correlation among tree-ring width, mean monthly precipitation and extreme (maximum and minimum) monthly values of temperature. It is evident that the precipitation of the months of May, June and July are the most significant factors that influence the tree-ring width. The monthly minimum temperature values do not seem to affect in any way the tree growth, except for June min temperature that revealed a positive correlation to tree growth, though statistically insignificant. The results of multiple regression models (Table 2) revealed that the monthly maximum temperatures have a higher impact on tree-ring width compared to the monthly mean values. The maximum temperatures could influence the variability of the tree-ring width by 22%. Specifically, max temperatures of April and June influence most intensively the tree growth. April max temperature has a positive effect on the increase of tree-ring width, a fact which could be attributed to the early activation of cambium, causing a prolonged growing season, which benefits the formation of large tree rings. June max temperature presented a strong negative effect on tree-ring growth. Based on the analysis results, June can be considered as the most significant month for the formation of tree rings, since the climate conditions and daylight duration during this month are very crucial to the ring width values [61]. The high maximum temperatures of June tend to increase the evapotranspiration process and quickly exhaust the available water excess of the soil, increasing the stress that fir stands experience.

It is evident that precipitation is the most significant factor that highly influences tree growth of *A. borisii-regis* in the study area. Temperature (and especially high values) could also affect tree-ring formation, though at a lower extent. The results of tree-ring width climate analysis of the current study are in accordance with previous studies carried out so far. These studies [18,62] revealed that precipitation had stronger and more significant impact on fir (silver fir) radial growth, particularly at the beginning of the growing season (April and May), and in the crucial July−September period. Similar findings have been reported also in Balkans [28,50]. Regression and trend analysis exhibited that *A. borisii-regis* grown in high altitude in Mediterranean region could sustain the recorded significant increasing trend of temperatures and potentially could be able to adapt in even warmer climate conditions in future. However, a potential decrease of annual precipitation in the future frame of climate change, accompanied by more severe drought episodes, would undoubtedly have a significant adverse effect on the forests of *A. borisii-regis*, the tree-growth and productivity rate. Walder et al. [21] have concluded that as long as annual precipitation is not too low and summer drought conditions not too extreme (i.e., less than three months), silver fir has the potential to thrive under warm Mediterranean conditions.

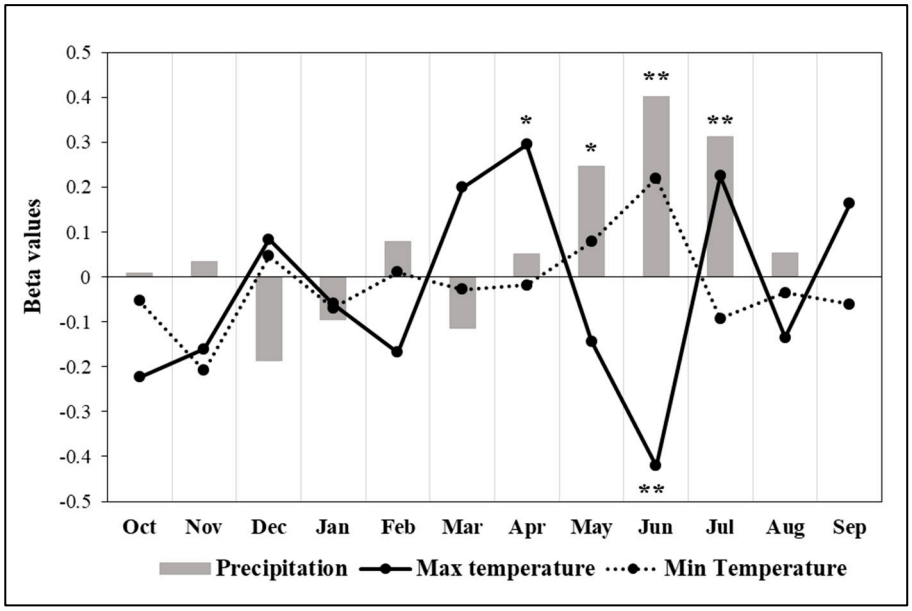


Figure 8. Response of tree-ring width to mean monthly precipitation, maximum and minimum temperatures of the hydrological year in Pertouli University Forest (significance of correlation: * $p \leq 0.05$; ** $p \leq 0.01$).

The findings of this work could be useful towards the examination of this species growth, wood formation as well as its response to climatic factors. They could serve as a forest management guide in providing solutions to the previously reported [28] diminution of fir populations in the Mediterranean region attributed to general climate change and to increase the productivity rate of fir forests and production of high-quality timber. Moreover, the findings of correlations between tree-ring width to climatic factors over time could be utilized to investigate the hybrid fir species' potential sensitivity or adaptability to stress generated by factors whose action rise in the frame of climate change, as well as their potential utilization in future afforestation or plantations establishment. The current dendroclimatological research findings contribute to the development, preservation and protection of fir population in the Mediterranean region, Greece and specifically in the University Forest of Pertouli, a forest of great importance due to, among other reasons, its high social contribution and high timber production of high quality, given the quality of wood production in Greece.

4. Conclusions

The results revealed that the average good site quality of the Pertouli forest, the summer drought-thermal period, the high mean annual precipitation and the relatively low mean annual temperature are variables that do not vary intensively during the year or among the years. In the last decades, temperature (mean, max and min values) has been found to present a significant upward trend over time, in the context of global climate change; however, this was not expressed as a statistically significant decrease in tree-ring width or wood biosynthesis. June temperature was negatively correlated with tree-ring width, since its high maximum temperatures tend to increase the evapotranspiration and loss of water available in soil. The monthly maximum temperatures appear to have a higher impact (22%) on tree-ring width compared to the mean monthly values, a fact which is crucial to future dendroclimatological analysis. *A. borisii-regis* grown in high altitude in Mediterranean region could sustain the recorded increasing trend of temperature and potentially could be able to adapt in even warmer climate conditions in future.

Precipitation constitutes the most significant and driving factor that most intensively influences the tree growth of *A. borisii-regis* trees under Mediterranean climate conditions. Short periods of drought, detected in the time-series analysis in this study, seem to signifi-

cantly affect the growth of fir trees only for a short period, by slowing down the growth of the tree only for a few months or years, while fir trees as a whole seem to be able to cope with drought stress and be able to return to the normal rhythms of growth. Stress derived from drought phenomena is maintained at a low level, and, as a consequence, growth rings formation and wood biosynthesis seem to be balanced. However, a potential decrease of annual precipitation in the future frame of climate change accompanied by more severe drought episodes undoubtedly have a significant adverse effect on the forests of *A. borisii-regis*, the tree-growth and productivity rate. May, June and July are the months that presented the higher and statistically significant correlation of monthly precipitation to tree-ring width, since they affect 31.2% of the ring-width variability with June to be the most significant and crucial month within the hydrological year for the formation of tree rings (impact of 15%). The combined impact of precipitation and temperature factors on tree-ring growth was measured to be 36.4%.

The constructed tree-ring chronology can be utilized in the implementation of future dendroclimatological analyses. Generally, the current dendroclimatological research findings contribute to supportive tool preparation towards the rational forest management, policy making, and more specifically, to the development, preservation and protection of fir population in Greece and Mediterranean region.

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