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Article

Growth Response of European Beech (*Fagus sylvatica* L.) and Silver Fir (*Abies alba* Mill.) to Climate Factors along the Carpathian Massive

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Abstract: European forests are becoming increasingly threatened by climate change and more frequent droughts. The likely responses of species to climate change will vary, affecting their competitiveness, their existence, and consequently, forest management decisions and measures. We determined the influence of climate on the radial growth of European beech and silver fir along the Carpathians to find similarities between the two species and the main differences. Along the Carpathian Mountains, seven sites with mature fir–beech stands above 800 m above sea level were selected and analyzed. Our study confirmed different responses depending on species and location. A more pronounced response of tree growth to climate was observed on the eastern side of the Carpathians, while it was less expressed or even absent on the southern sites. Both beech and fir show better radial growth with higher precipitation in July and slower growth with higher average and maximum temperatures in June of the current year. Fir demonstrates a positive correlation between radial growth and temperature in winter, while beech demonstrates a negative correlation between radial growth and temperature in summer. In the 1951–1960 decade, the average tree ring widths in fir and beech were largest at the southern sites compared to the other sites, but since 2011, the southern sites have had the lowest increase while northern sites have had the largest. Both species respond differently to climate and are likely to follow different competitive paths in the future.

Keywords: climate change; dendrochronology; radial growth response; meteorological parameters

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1. Introduction

Due to climate change and more frequent droughts, European forests are becoming increasingly threatened [1,2]. The dependency of tree growth on precipitation has increased during the last century, and drought has experienced an upward trend since the 1950s. The latitudinal progression of radial growth decline and the proportion of positive trends strongly support the rapid northward advance of the Mediterranean climate caused by global changes and its effect on tree ecology [3].

In our research, we focused on European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.), which are likely to be the two most important tree species for a large part of Europe's mid- and high-altitude forests in the future [4].

Beech is a dominant forest tree species in Europe [5], with a wide distribution range between Scandinavia and the Mediterranean [6]. Despite its functional adaptability and great ecological plasticity, it is affected by drought, as confirmed by studies of its response in southern Europe [7]. It thrives in pure and mixed stands with conifers, especially firs, whose distribution is mainly limited to the area of the Alps and the Carpathians [8]. A long-term decline in radial growth at lower elevations in Central Europe since around the 1980s [9–11] suggests that it is sensitive to a warmer and drier climate [12].

Silver fir, as one of the most important conifers of European mountain forests, predominates in cold temperate areas [13]. Its regression over Europe, e.g., [14,15], affected its use and economic value [16]. Fir forms heterogeneous stand structures; its ecotypes show great variation in their resistance to frost, drought, and shade. Natural regeneration of fir is questionable when stands are managed with clearcutting and a short regeneration period [4]. Climate change is believed to have had an adverse impact on the growth performance of autochthonous fir populations in Europe in recent decades [17,18]. While causes of fir decline such as climate change, air pollution, and overbrowsing are difficult to control, silvicultural measures (e.g., creation of suitable stand climate, promotion with tending and preservation of seed trees) are becoming even more significant for its conservation.

In a study at the Balkan Peninsula along the Dinaric high karst, where different and well-expressed ecological factors intertwine at relatively short geographical distance (approx. 1000 km) [19], response of beech and fir from the southern, warmer, and dryer sites already served successfully as a most probable future prediction for the same species' response in currently less-extreme sites northward [20]. Carpathians at more complex sites comprise sufficient latitudinal and longitudinal gradients, connected with significant differences in temperature/precipitation as well as differences in their seasonal pattern [21].

The quality and future of fir–beech forests is in tight connection with our understanding of tree-responses to environmental parameters. Dendrochronological analyses of stand growth provides a historical retrospective of the response to climatic factors in different time series of mature trees [22]. In predicting the consequences of climate change on tree species, studying the response of species on a geographic gradient may highlight the crucial parameters important for tree growth on a larger scale, help to predict future responses, and optimize the future forest management.

In the presented study, we were interested in discerning if there are similar responses between tree species along the Carpathian arc. The aim was to determine the influence of climate on the growth of beech and fir along the geographical gradient (a), to find similarities or differences between the two species (b), and to compare responses in time with respect to eventual changes in the growth response (c).

2. Materials and Methods

Along the Carpathian Mountains, seven sites with mature fir–beech stands located between 820 and 1038 m above sea level were selected and analyzed (Figure 1 and Table 1). At the study sites, the average temperature is 7.3 °C and the average temperature in the growing season (from May to August) is 15.8 °C. The average precipitation is 60.7 mm per month and 91.5 mm per month from May to August. The meteorological data were calculated for the years 1950 to 2020 (Table 2).

At each site, 15 mature dominant fir and beech trees were double cored, which gave, in total, 105 sampled trees for fir and 105 sampled trees for beech. All sampled trees were healthy trees with no visible signs of stem damage or any kind of declining tree vitality. Tree cores were packed into plastic straws, marked, and transported to the dendrochronology laboratory.

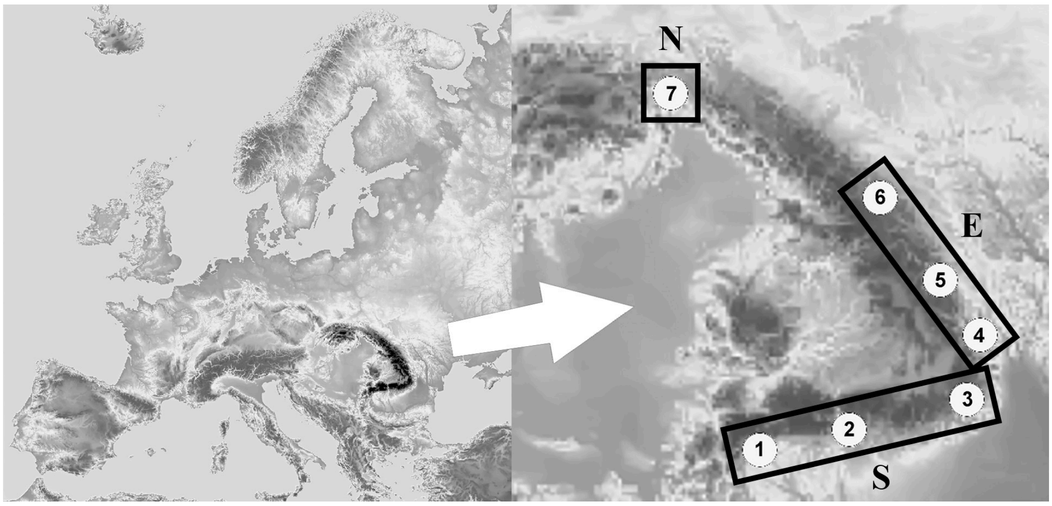

Figure 1. Location of research sites. The white arrow shows the enlarged area of the Carpathians; the numbers in the circles indicate the numbers of the plots, and the black squares show the plots grouped according to their exposure.

Table 1. Locations, forest label, altitude, and coordinates of research site locations.

No.	County	Plot	Managed/Old Growth Forest	Altitude (m)	E (DMS)	N (DMS)
1	Gorj	Tismana	managed	985	22°55′1.00″	45°10′10.00″
2	Arges	Arefu	managed	995	24°39′4.00″	45°27′37.00″
3	Buzau	Zagon	old growth	1038	26°13′44.00″	45°36′51.00″
4	Vrancea	Soveja	managed	830	26°36′14.00″	46°0′5.00″
5	Neamt	Tarcau	managed	950	26°10′6.00″	46°51′15.00″
6	Suceava	Frumosu	managed	850	25°40′60.00″	47°28′6.00″
7	Bardejov	Livovska huta	managed	880	21°0′59.62″	49°15′17.06″

Table 2. Meteorological data for southern (S), eastern (E), and northern (N) sites.

Group of Research Sites	Average Temperature (°C)	Temperature May to AUGUST (°C)	Average Precipitation (mm/Month)	Precipitation May to August (mm/Month)
S: site 1, 2, 3	7.7	15.9	65.1	96.4
E: site 4, 5, 6	7.1	16.0	53.9	84.1
N: site 7	7.2	15.5	63.1	94.0

The cores were dried under load for fourteen days to prevent decay. Each core was mounted and glued on a wooden support and sanded with progressively finer sandpaper with grid from 180 to 600. After sanding, the cores were cleaned of all particles with an air blaster. The cores were then scanned with an ATRICS [23] image capturing system, and annual radial increments were measured to within 0.01 mm using CooRecorder and CDendro software v. 9.8.1 (Cybis, Stockholm, Sweden), which also served as quality control for the measured tree-ring width (TRW) sequences. TRW sequences were visually and statistically synchronized with PAST-5 v. 5.0.610 (SCIEM, Vienna, Austria). Quality control was also performed by checking and correction. We calculated correlations between trees in CDendro and created a plot chronology that we compared to individual trees. Any tree ring width sequence that did not fit well into the plot chronology were corrected in CooRecorder and returned into data pool. In very rare cases with obvious tree ring width anomalies, cores were excluded from further processing. We paid attention to missing and false tree rings, as well as rotated sections of the cores. Individual TRW were standardized to remove long-term trends using a cubic smoothing spline of 67% with a frequency cutoff of 50% in R program's dplR library [24].

The expressed population signal (EPS) was used to assess the representativeness of a small sample relative to the signal of the total population. EPS values range from 0 to 1, with values greater than or equal to 0.85 considered high enough to indicate a common signal in the entire population [25]. This common signal may be associated with environmental or climatic factors; however, in many cases it is a climatic signal contained in the tree rings. In this study, EPS was used as a measure of common signal in site chronology.

TRW chronologies with detrended index, residual (RES), and standard (STD), were created for each site and tree species. Indexed TRW chronologies were compared to monthly mean temperatures, maximum temperatures, monthly sum of precipitation, and two drought indices using the bootstrapped resampling method and calculating the correlation coefficient in the treeclim library [26] of the R program. Temporal correlation between tree-ring proxies and combinations of monthly and seasonal variables was examined using monthly gridded temperature, precipitation, and drought data ($0.5 \times 0.5°$ grids) from the CRU TS and CSIC database, available online in KNMI Climate Explorer (http://climexp.knmi.nl, accessed on 5 April 2023). Each tree-ring proxy was tested against monthly meteorological data or different combinations of seasonal variables to find the best possible combination of influencing climate variables. We analyzed the period from 1950 to 2016.

To show whether trees along the Carpathians respond similarly to meteorological data, correlation coefficients above 0.2 and below −0.2 were considered. If such a value was confirmed in at least three studied sites, we marked a particular month with a climate parameter as important for certain species.

The sites on different sides of the Carpathians were grouped into three clusters: southern group—sites 1, 2, 3; eastern group—sites 4, 5, 6 and northern site number 7. We calculated the average TRW for fir and beech by decades from 1950 on.

3. Results

3.1. General Climate Response

The expressed population signal [25] is high for both species (above 0.85; except for the fir chronology of site 1). This indicates that the calculation of the climate–growth relationship can be performed and that the results should have a reasonable statistical interpretation. Because of the high EPS value, we were able to perform a climate–growth analysis (Table 3).

Table 3. Expressed population signal (EPS) in site chronologies of beech and fir.

Site	*F. sylvatica*	*A. alba*
1	0.864	0.818
2	0.869	0.869
3	0.862	0.878
4	0.874	0.893
5	0.855	0.898
6	0.952	0.864
7	0.919	0.877

Above-average precipitation in July positively affected TRW of both species (Figure 2). Precipitation in June also had a positive effect on radial growth of beech. In contrast to fir, above-average September precipitation had a negative effect on beech radial growth. September growth is difficult to interpret because the growing season is over by this time.

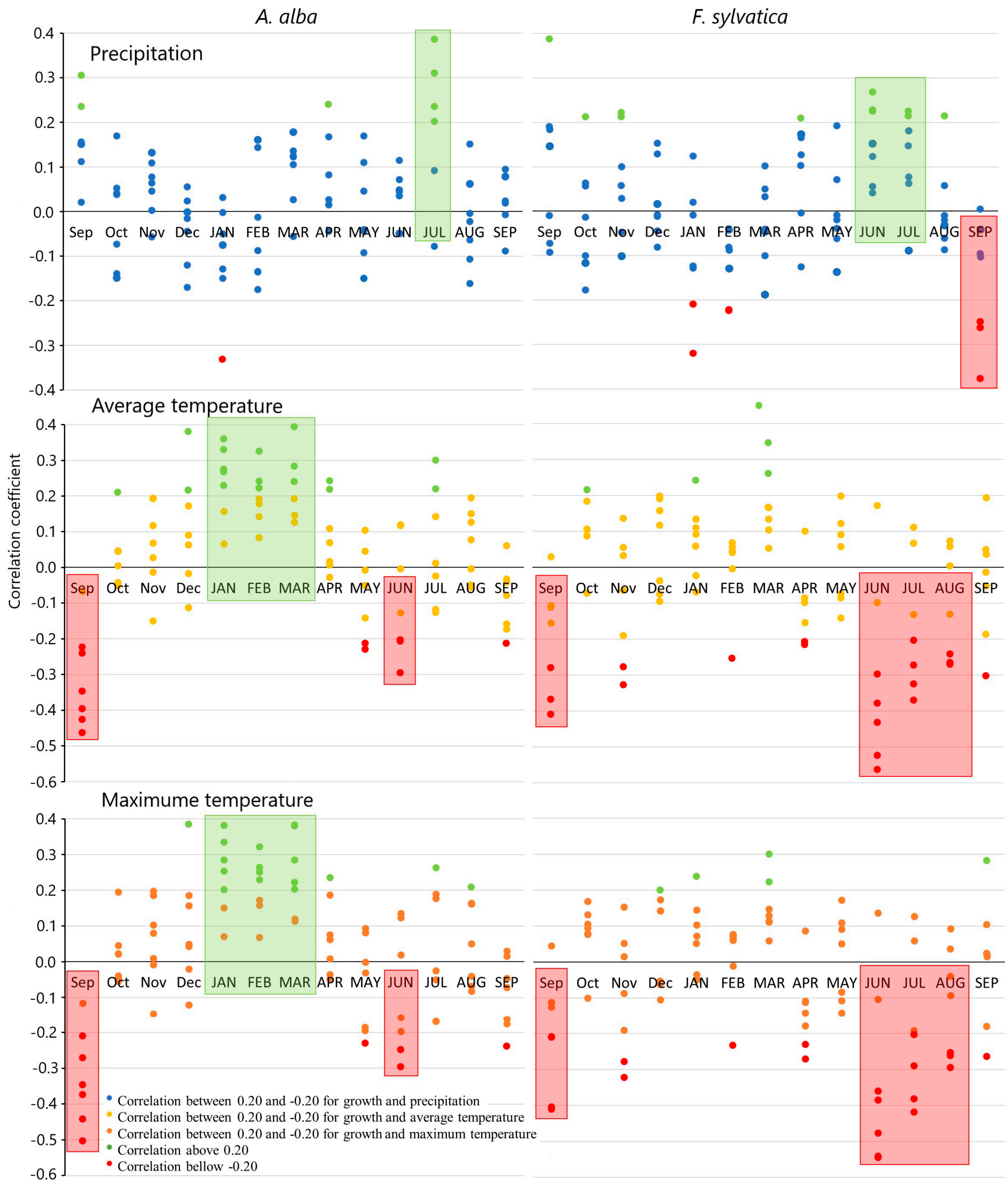

Figure 2. Correlation between fir and beech TRW and climate parameters (all sites). Transparent red and green rectangles mark months or group of months important for tree ring formation.

In both species, above-average temperatures in June and September of the preceding tree ring formation negatively affect TRW. Winter temperatures from January to March have a positive effect on fir growth. The correlation between the temperature during the September of the preceding tree ring formation and TRW is significant. Beech growth responds differently to climate than fir, although the trees were sampled at the same sites and in the same forest stands. Above-average temperatures in June have a more pronounced negative effect on beech growth, which continues during the summer in July and August. Unlike fir, no significant positive correlation on at least three sites between average or maximum temperature and TRW in beech was confirmed.

The influence of the average and maximum temperature for both species on radial growth of trees is similar. Winter temperatures from January to March have an even more significant positive influence on fir growth, and all other correlations with maximum temperature are similar to correlations with average temperature.

3.2. Comparison of Beech and Fir Climate Response between Southern, Eastern and Northern Carpathians

Our study showed different responses depending on species and location (Figure 3). Results are consistent with the response in Dinaric montane forests of fir and beech [20]. A more significant correlation between tree growth of both species and seasonal variables was observed on the eastern Carpathian sites, and a less or not significant correlation was observed on the southern sites. Fir on the northern site have even fewer significant correlations than on the southern sites, while beech on the northern site have more significant correlations than on the southern sites but fewer than on the eastern sites. Both species have the same number of significant correlations at the eastern sites, but fir has slightly more significant correlations at the southern sites.

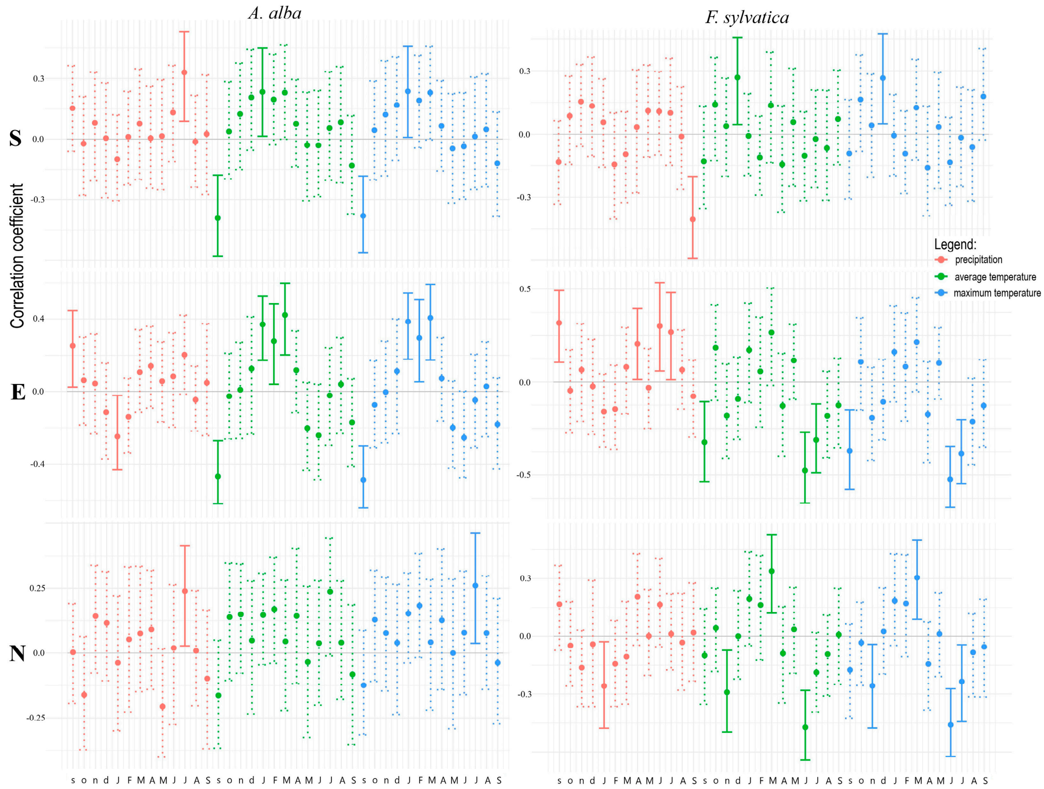

Figure 3. Correlation between fir and beech TRW and climate parameters for southern (S), eastern (E), and northern (N) sites. Solid vertical line shows significant and dotted vertical line unsignificant correlations.

3.3. Growth Response of Beech and Fir in Time

Figure 4 shows average non standardized (age trend not removed) TRW of fir and beech for south, east, and north Carpathians by decades since 1951. We took a basic approach and are aware of the shortcomings of non-standardized data, but we wanted to show a growth trend (since the trees had similar ages) that standardization would otherwise cancel out. Beech on the southern sites shows consistent growth in time, while fir's growth is decreasing. Both tree species show an increasing average TRW on the eastern sites, which started decreasing in the last decade. Fir on the northern side shows the largest increase, while beech shows a relatively constant tree ring width for the last three decades. Compared to beech at southern sites, beech at eastern sites grew more slowly in the first decade (1951–1960) and at northern sites in the first two decades (1951–1970) (Figure 4, right panel). After 1961, beech began to grow better at eastern sites, followed by northern sites a decade later. After 1971, beech grew better on both the northern and eastern sites and continues to outgrow beech on the southern sites in the present.

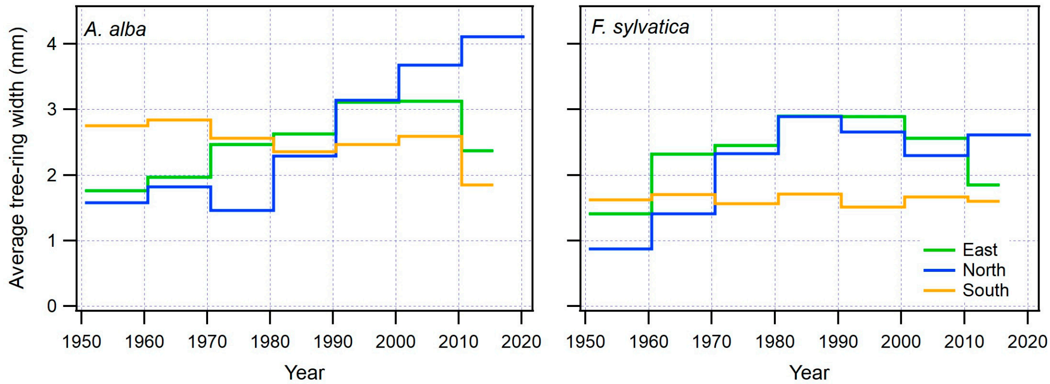

Figure 4. Average TRW of fir (**left**) and beech (**right**) by decades since 1950.

The decadal growth pattern of fir is similar to that of beech, but the average TRW of fir was higher on the southern sites compared to the northern and eastern sites until the decade 1981–1990, when the eastern sites began to grow better, and until the decade 1991–2000, when the northern sites also began to grow better (Figure 4, left). In the most recent decade (2011–2020), the southern and eastern sites have shown a decline in TRW, while TRW at the northern sites continues to increase.

3.4. Climate Response between South, East, and North Carpathians

Fir and beech responded differently on the studied sites over time (Figure 5). Fir on the eastern sites respond most consistently compared to the southern and northern parts, where the response became more pronounced after 1961, especially if we consider the above-average winter temperatures. On the southern sites, July precipitation significantly correlated with fir's radial growth since 1961, while on the eastern and northern sites, correlation became significant only after 1976. On the southern sites, only September precipitation had a negative effect on beech growth, while on the eastern and northern sites, above-average summer temperatures in both June and July negatively affected growth, which is becoming more pronounced over the years. Above-average March temperatures as well as June precipitation have positive effects on beech growth on the eastern sites.

When radial growth was compared with drought indices SPEI for 3 (SPEI-3) and 6 (SPEI-6) months, no patterns were apparent between sites and species (see Figure A1). At the southern sites, the drought index correlated significantly with the radial growth of fir only during the September of the preceding tree ring formation, while there was no correlation for beech. At the eastern sites, the drought index correlated positively with the radial growth of fir during September, October, and November, while it correlated negatively during February and March. The drought index in the September of the year preceding tree ring formation and the months October, November, June, July, and August correlated significantly with radial growth of beech. At the northern sites, fir radial growth had no correlation with either SPEI-3 or SPEI-6, while beech radial growth had a positive correlation with SPEI-3 in June and a negative in February and March and a negative correlation in March with SPEI-6.

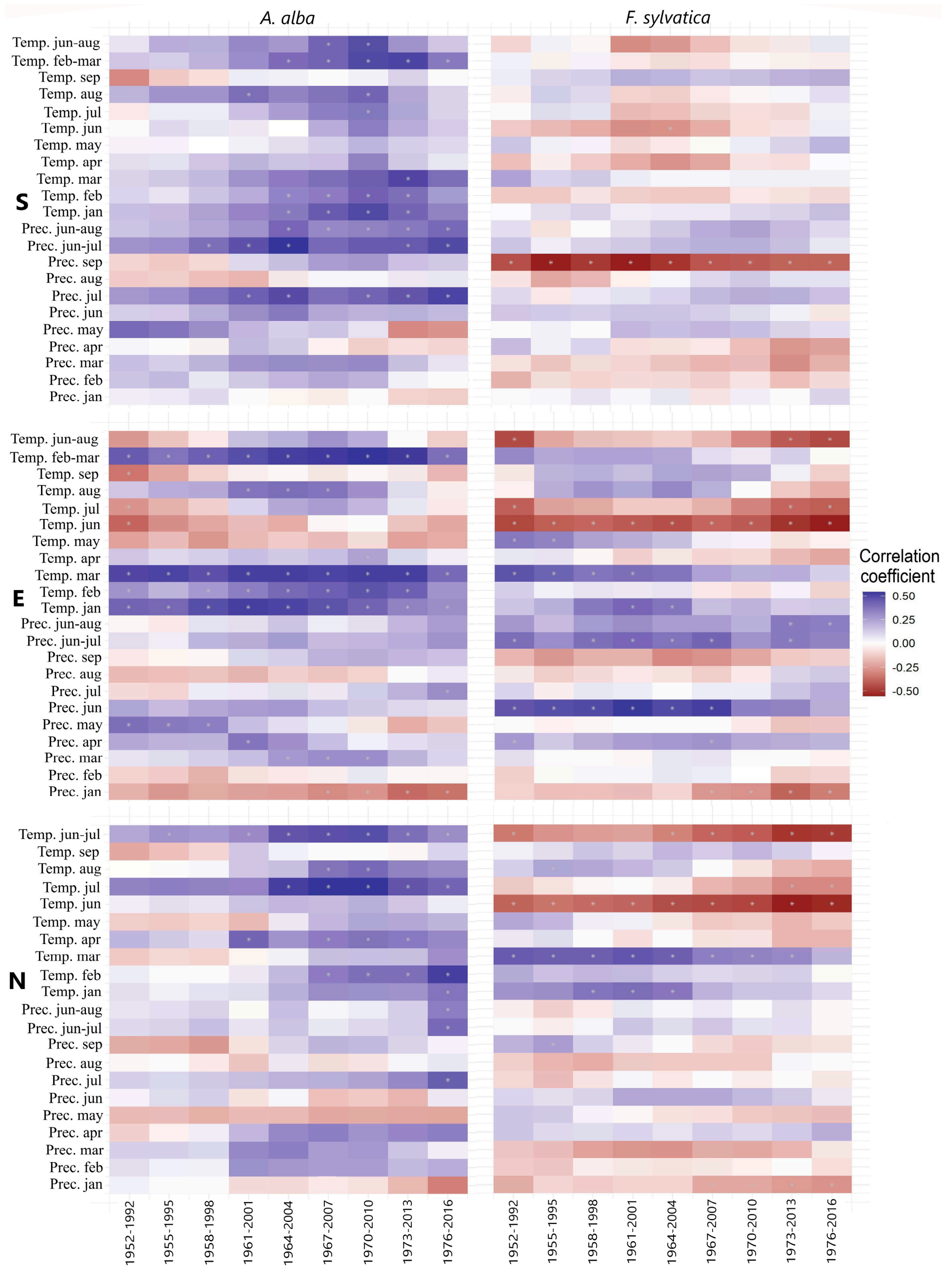

Figure 5. Temporal comparison between fir and beech TRW on different sites (southern (S), eastern (E), and northern (N) sites).

3.5. Comparison of Climate Response between Managed and Old Growth Forest

TRW in the old growth forest (site 3) was compared to TRW in the closest managed forest (site 4). The compared sites have different elevations of more than 200 m. Fir responded positively to precipitation in July at both sites and to precipitation in the September of the preceding tree ring formation in the managed forest. Precipitation in November of the preceding tree ring formation had a positive effect on beech growth at both sites, but only in the managed forest in June and July. Precipitation in September also has a negative effect on beech TRW in the old growth forest. Above-average temperatures in the September of the preceding tree ring formation had a negative effect on fir growth. In the old growth forest, above-average temperatures in June negatively affected fir growth, while in the managed forest, this is valid for May. In the managed forests, above-average winter temperatures in January, February, and March also had a positive effect on fir growth. Maximum temperatures had the same effect for fir and beech. In both the old growth and the managed forests, above-average temperatures in September, June, July, and August had a negative effect on beech growth. The same response is seen in the old growth forest in April, and in the managed forest in September.

4. Discussion

We have achieved the stated objectives of the study, which were to determine the effect of climate on the growth of beech and fir along the geographic gradient, to determine similarities or differences between the two species, and to compare their responses over time to determine any changes in the growth response.

This study showed that a more significant correlation between tree growth and seasonal variables was observed on the eastern side of the Carpathian arc, while it was less evident or absent at sites on the southern side (sites 1, 2, 3). In comparable studies, the response to different climatic variables was decreasing or was absent on the south side of the studied transect due to genetic adaptability, phenotypic plasticity, or both [20]. The reason for the different response could also be that the eastern side of the Carpathians is affected by a climate with continental nuances and Baltic influences [27]. Fir and beech on northern sites react differently to meteorological parameters.

Above-average precipitation in July had a positive effect on radial growth in both species, and in beech also in June. In the course of climate change, we do not expect above-average precipitation in summer; on the contrary, we expect more summer drought.

Silver fir is an extremely demanding species regarding site conditions [28] and less tolerant to environmental change than the European larch or white pine [29,30]. In this study, we showed that fir responds negatively to above-average temperatures in the June and in September of the preceding tree ring formation, with above-average summer temperatures likely to become more frequent under climate change, while warmer winters increase fir radial growth. Above-average maximum winter temperatures from January to March have an even more significant positive influence on fir growth than above-average temperatures. Fir, as an evergreen tree species, enjoys warm winters, while beech, as a deciduous tree species, is not as affected by warm winter temperatures. Mihai et al. [31] showed high genetic variability within the silver fir studied in the Carpathians. They confirm that climate change could increase fir productivity at higher elevations, while climatically marginal environments and low elevations, such as edges of the Eastern Carpathians and the Banat region, may be exposed to higher risk [31] due to higher temperatures and lack of moisture.

Current fir populations have well-preserved genetic resources and relatively high genetic variability [32] but are threatened by pressure from herbivores, large-scale reforestation of old fir stands, inappropriate management practices [4], reductions in population density that can lead to fragmentation, self-pollination, genetic drift [7], and predicted climate change, and particularly increases in temperature and lack of precipitation [33].

Beech does not thrive in too-hot summers during the active growth phase, while this is not so pronounced in fir. Above-average temperature in the summer months had a negative effect on radial growth, so the higher summer temperatures may cause disturbances in beech growth. In the Eastern Carpathian region, changes in beech forests have been noted in recent decades [34], while old-growth beech forests in the Northwestern Carpathians were considered stable [35]. Martinez del Castillo et al. [36] predicted a substantial decline in beech growth across Europe, ranging from −20% to more than −50% by 2090, depending on the region and climate change scenario (CMIP6 SSP1-2.6 and SSP5-8.5).

A comparison of average TRW over decades shows the better growth of fir at the northern and eastern sites and a slight decrease at the southern sites. Beech demonstrates more consistent radial growth in the south, but its growth increases less than that of fir on the eastern and northern studied sites.

The effect of global warming becomes evident in comparison of fir and beech response in time. Since we wanted to know the recent growth trend due to climate change, we calculated the average TRW for fir and beech by decades from 1950 on. Fir on the southern side shows a decreasing trend in TRW over time, signaling that these sites are gradually becoming unfavorable for fir. At the same time, the eastern and especially the northern sites are becoming more favorable for the growth of both species.

Of particular concern is the negative effect of above-average summer temperatures on beech growth, which is becoming more significant over the years, while July precipitation indicates an increasingly positive effect radial growth of fir. We may expect more frequent above-average summer temperatures and the absence of summer (July) precipitation, reflecting along both latitude and longitude; thus, future differences in the seasonal responsiveness of beech and fir may be expected. Extreme weather events and increasing average temperatures will also influence the future demographics of fir, i.e., to higher elevations and northward, as mentioned by Tinner et al. [37] and Klopčič et al. [38]. At the same time, a similar response of beech at the expense of fir and its general spread in Central Europe was observed by Šamonil [39], Vrška [40], and Janík [41]. Our results confirm the increasing dependence of trees on precipitation over the past century and coincide with the increasing drought events after 1951. The likely response of species to climate change will vary, affecting their competitiveness, their existence, and consequently, forest management decisions and measures [42].

In southwestern Europe, fir is more resilient to climatic extremes compared to other tree species [8]. At the same time, two fir populations have been distinguished in the Carpathian region: the eastern one, which is similar to the Balkan population; and the western one, which is less sensitive to summer droughts [8]. In the south-exposed areas of Eastern Carpathians, fir was the least sensitive of studied tree species [43]; its growth rate increased continuously and remained at a high level even in old individuals compared to Scots pine or Norway spruce. Fir growth was significantly and positively correlated with December temperatures and spring precipitation in April and May [43]. Although growing under the same conditions, European beech and silver fir have shown remarkably different growth patterns over the past half century. While fir has responded positively to recent warming, beech growth has declined at all examined sites, suggesting that fir is less susceptible to warmer and drier conditions than beech [8]. Long-term growth patterns and the growth–climate sensitivity of fir and beech did not differ significantly between managed and unmanaged forests.

5. Conclusions

Predicted forest productivity loss is mostly pronounced at the southern limit of beech's natural distribution, where drought intensity is expected to increase [36]. Our study confirmed different responses depending on species and location. A more pronounced response of tree growth to climate was observed on the eastern side of the Carpathians, while it was less pronounced or absent at the southern sites. Both beech and fir show better radial growth with higher precipitation in July and slower growth with higher average and maximum temperatures in June of the current year. Fir shows a positive correlation between radial growth and temperature in winter, while beech shows a negative correlation between radial growth and temperature in summer. In the 1951–1960 decade, average tree ring widths for fir and beech were largest at southern sites compared to other sites, but since 2011, the increase has been smallest at the southern sites and greatest at the northern sites. Despite the adaptive diversity of beech populations, the survival of beech and other temperate tree species in the future is uncertain as the rate, uniformity, and intensity of climate change vary among different sites. We may expect strong climate variability in the future in the southern forest ecoregion, while northern sites still exhibit stability and structural resistance. Temporal changes in species composition led to minor fluctuations in stand parameters that do not threaten the long-term coexistence of beech and fir [44]. Beech populations at the edge of the species' range have great adaptive potential, and their persistence appears to contribute to forest stability throughout Europe, which requires the adaptation of forest management and conservation policies [45–47].

Author Contributions: Conceptualization, P.C.A., T.L. and M.Č.; methodology, P.C.A., T.L. and M.Č.; validation, P.C.A., T.L. and M.Č.; formal analysis, P.C.A. and T.L.; investigation, P.C.A., T.L., M.H. and M.Č.; resources, T.L. and M.Č.; data curation, P.C.A., T.L. and M.Č.; writing—original draft preparation, P.C.A., T.L. and M.Č.; writing—review and editing, P.C.A., T.L. and M.Č.; visualization, P.C.A. and T.L.; supervision, M.Č.; project administration, M.Č.; funding acquisition, T.L. and M.Č. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The non-meteorological datasets presented in this study are available on request from the corresponding author. Publicly available meteorological datasets were analyzed in this study.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

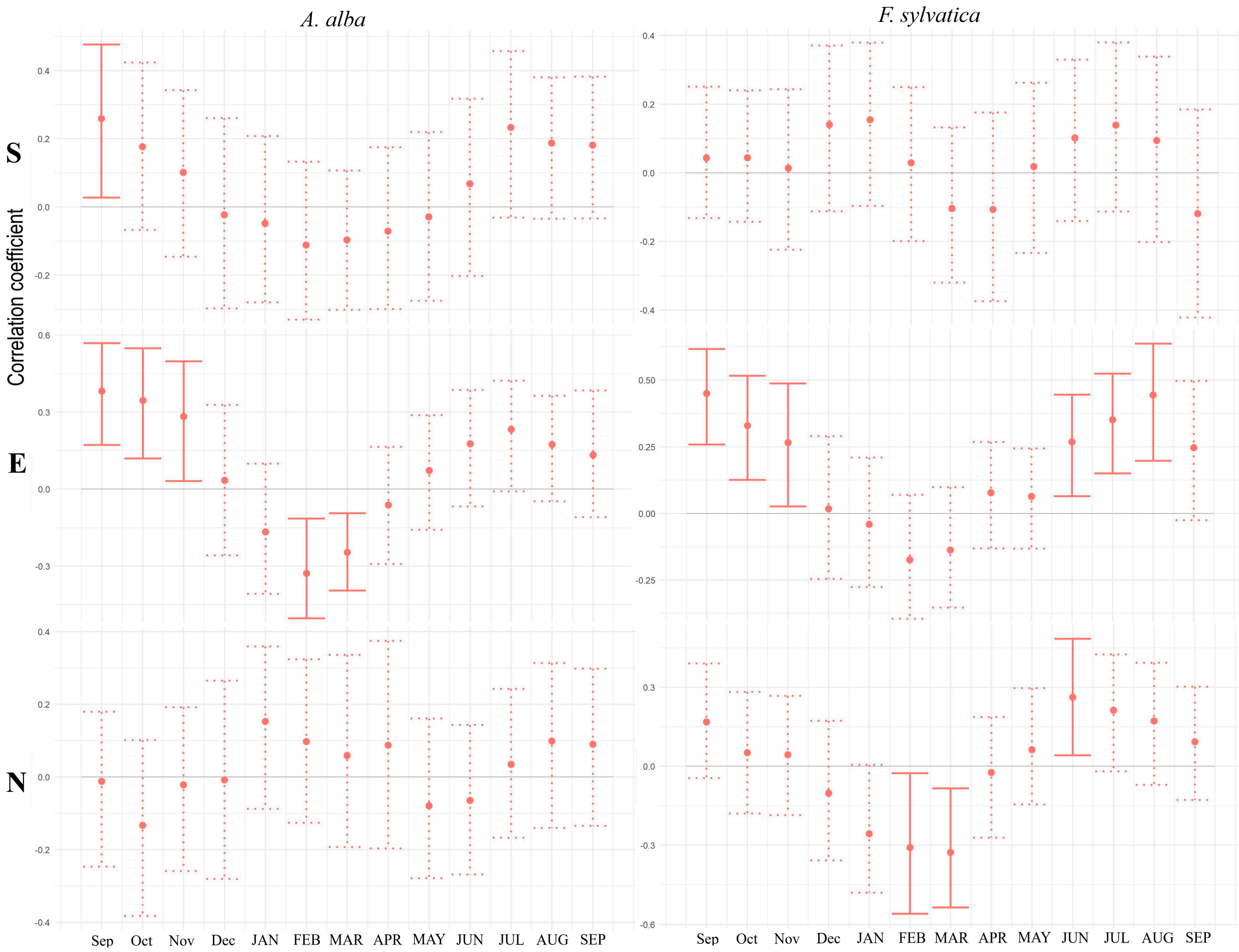

Figure A1. Correlation between fir and beech TRW and SPEI 3 indices for southern (S), eastern (E), and northern (N) sites. Solid vertical line shows significant and dotted vertical line unsignificant correlations.

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