Article

Tree Rings of European Beech (*Fagus sylvatica* L.) Indicate the Relationship with Solar Cycles during Climate Change in Central and Southern Europe

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Abstract: The impact of solar cycles on forest stands, while important in the development of the forest environment during climate change, has not yet been sufficiently researched. This work evaluates the radial growth of European beech (*Fagus sylvatica* L.) in the mountain areas of southern Italy and central Europe (Czech Republic, Poland) in correlation to solar cycles (sunspot number), extreme climatic events, air temperatures and precipitation totals. This research is focused on the evaluation of the radial growth of beech (140 dendrochronological samples with 90–247 years of age) from 1900 to 2019. The time span was divided into the following three periods: (1) a period of regular harvesting (1900–1969), (2) a period of air pollution crisis (1970–1985) and (3) a period of forest protection (1986–2019). The results indicate that the solar cycle was significantly involved in radial growth on all research plots. With regard to the evaluated precipitation totals, seasonal temperatures and the sunspot number, the latter was the most significant. Temperatures had a positive effect and precipitation had a negative effect on the radial increment of beech in central Europe, while in southern Italy, the effect of temperature and precipitation on the increment is reversed. In general, the limiting factor for beech growth is the lack of precipitation during the vegetation season. The number of negative pointer years (NPY) with an extremely low increment rose in relation to the decreasing southward latitude and the increasing influence of climate change over time, while a higher number of NPY was found in nutrient-rich habitats compared to nutrient-poorer ones. Precipitation and temperature were also reflected in the cyclical radial growth of European beech. The relationship between solar cycles and the tree ring increment was reversed in southern Italy and central Europe in the second and third (1970–2019) time periods. In the first time period (1900–1969), there was a positive relationship of the increment to solar cycles on all research plots. In the tree rings of European beech from southern Italy and central Europe, a relationship to the 11-year solar cycle has been documented. This study will attempt to describe the differences in beech growth within Europe, and also to educate forest managers about the relevant influence of solar cycles. Solar activity can play an important role in the growth of European beech in central and southern Europe, especially during the recent years of global climate change.

Keywords: tree-ring data; cyclical dynamics; growth adaptation; temperature; precipitation; sunspot number

1. Introduction

European beech (*Fagus sylvatica* L.) is distributed over a large number of environmental zones throughout Europe [1]. A lack of precipitation, associated with drought, limits European beech in its distribution in southern Europe [2–4], while low temperatures and

spring frosts curb the beech in the north [5,6]. European beech thrives in the optimal conditions of central Europe, and at the same time, we are witnessing its retreat from the southern parts of Europe [7]. Lately, due to climate change, this tree species has also been expanding into more northern areas within its distribution range [8–10]. The occurrence of beech forests is limited by late frosts and droughts [11]. In the past few decades, European beech has been showing better results in locations towards the north, such as southern Sweden [12], as well as in mountainous locations, e.g., in the Czech Republic [13–15]. In recent years, however, beech forests have been showing a greater sensitivity to drought [16], yet this tree species can adapt accommodatingly to drought in central Europe under the conditions of global climate change [6,13,17].

Concerning radial growth, European beech adapts better to climatic fluctuations at lower altitudes and in nutrient-rich habitats [18,19]. By contrast, at higher altitudes, there have been greater fluctuations in beech growth since 1975 [20]. Climatic fluctuations in the mountainous areas of central Europe are most frequently caused by lower temperatures, with annual temperatures affecting the radial growth of European beech more than precipitation totals [13,21,22]. Fluctuations in the radial growth of European beech, caused by various biotic and abiotic influences, can lead to cyclic periods [21]. For example, in the 1970s and 1980s, there was a significant negative effect of air pollution on the radial growth of European beech in the mountains of the Czech Republic, which also led to a weakening or even dying of forest stands [23,24]. Notable incremental fluctuations of European beech are also induced by frost, which can affect the increment of the entire vegetation period [21,25].

European beech stands in the Czech Republic and Italy differ in their life cycles as well as their life span. In the Krkonoše Mountains (both in the Czech Republic and Poland), generations of European beech stands are replaced after 230 to 250 years on average [26]. In contrast, old stands of European beech in Italy may live to be around 300 years or more [27,28]. The age of beech stands in Italy will shorten in response to global climate change, especially increasing average temperatures and droughts [28]. However, the radial growth of beech stands in Italy is more affected by the negative effects of drought, which limits the distribution of this tree species in the Apennines [29]. Beech stands in Italy are profoundly more vulnerable and frequently stressed by drought, and this can reduce beech increment over time [27]. In the Mediterranean forests of higher altitudes, there are also spring droughts, which negatively affect the tree rings of European beech [30].

Solar cycles affect the climate of our planet, as was cited by the theory of “solar forcing”, to name one. The theory documents that solar irradiance and geomagnetic activities are important drivers of the Earth’s atmosphere [31]. Some works also describe that solar activity, in the long run, affects the temperature of the Earth’s atmosphere, which can be accompanied by the occurrence of colder winter periods [32]. Solar activity is sometimes a stronger inducer of climate change than anthropogenic influences, also affecting other factors such as precipitation or temperature [33]. Sunspot cycles are also associated with the cycle of the Amazon River flow [34] and are directly related to flood or drought seasons in the Songhua river basin in China [35]. On the other hand, the solar cycles may be associated with drought periods and extreme weather fluctuations, for example in Kuwait [36]. The effects of 11-year solar cycles on climate patterns in Europe have been observed over the last 250 years, while the impact of sunspot activity on the climate increased during the 19th century [37].

Global climate is affected by solar cycles [38,39]; however, the imprint of this cycle might not be the same everywhere. The imprint of solar activity is different in the Indian, Pacific and Atlantic Oceans [40]. There is a large number of factors that react to solar variability differently within terrestrial climate parameters [41]. One important parameter is that solar activity affects the properties and formation of clouds in our atmosphere, which is caused by the ionization of cosmic rays that mirrors 11-year cycles of solar activity [42–44]. Some studies even found a link between tree ring radiocarbon production and sunspots [45,46]. The production rate of radiocarbon isotope is an indicator of cosmic

radiation in the upper atmosphere, which is also connected to the solar cycle [39]. Solar cycles also affect the average monthly temperatures in Europe [47], as well as, indirectly, the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) [48]. Solar cycles throughout the NAO are also partly associated with precipitation occurrence in Europe [49]. Solar activity may also be reflected in many other climatic cycles [50]. Tree rings of beech in the Apennines are associated with the NAO [51], and even the NAO is influenced by the solar cycle [37,49]. It is also important to mention that there is a link between fluctuations in the radial growth of European beech in the mountains of the northeast Czech Republic and solar activity [52,53]. Some research in the field of dendrochronology proves the influence of solar cycles on the radial growth of trees, which is well described by research from northwestern Russia [54,55], Chile [56] and the Tibetan Plateau [57]. The impact of solar cycles can also be negatively reflected in tree rings, which has also been investigated in cork oak (*Quercus suber* L.) [58].

This study focuses on the radial growth of European beech at higher altitudes of the Krkonoše Mountains in Poland and the Czech Republic and in the southern Apennines in Italy. The main objective of this study was to evaluate the initial effect of the temperature, precipitation and sunspot number on the radial growth of European beech during three time periods that cover 119 years of growth history. The time periods were chosen deliberately due to various and important differences in the development of beech stands over time. The first time period (1st period) indicates the phase of man-managed stands of European beech. The second time period (2nd period) indicates the air pollution calamity on research plots in the Czech Republic [23,52], and the same time period was also marked out for Italian research plots in order to maintain comparability of time periods. The third time period (3rd period) denotes the phase without human harvesting interventions, when the beech stands developed naturally and spontaneously. The sunspot number was chosen intentionally to find a possible relationship between the radial growth of European beech and the 11-year solar cycle, which has properties and intensities other than precipitation or temperature. Another aim of this research was to assess the cycles of radial growth of European beech using the Fourier analysis and cross-correlation in relation to the factors examined. This is a very underexplored topical issue regarding the growth process of one of the most important and promising central European tree species during global climate change.

2. Methodology

2.1. Study Area

The studied area is located in the national parks of the Krkonoše Mountains, both in the Czech Republic and in Poland, i.e., in the Krkonoše/Karkonosze Transboundary Biosphere Reserve. Italian research plots are located in the southern Apennines within the Appennino Lucano National Park, near a place called Sellata. A total of 4 permanent research plots were evaluated, of which the first is in the Polish portion of the Krkonoše Mountains in a place called Chojnik, not far from the town of Sobieszów. The second research plot is in Eastern Krkonoše, in Rýchory, near the town of Žacléř. The third and fourth research plots are in the southern Apennines near Sellata. The plots in Krkonoše were established and selected in 1980 for long-term research. All research plots were selected in accordance with the major representation of beech, altitude and homogeneous stand structure of European beech. Samples were taken from forest stands with a 100% share of European beech. All research plots are located in non-intervention areas, where no harvesting operations had been carried out since 1985.

The basic site and stand characteristics are given in Table 1. The worldwide Köppen classification was used for climate categorization in Table 1 [59]. Precipitation and temperature conditions differ for the Czech Republic/Poland and for Italy, as described in Figure 1. The Bedřichov meteorological station for Krkonoše (Chojnik 1 and Rýchory 2) was selected for its data availability, as it has the longest time series for precipitation and temperatures available to the Krkonoše montane region at the altitude of 780 m a.s.l. The

mean annual temperature for Chojnik 1 and Rýchory 2 is 3.7 °C, and the annual total precipitation is 1300 mm. The mean number of vegetation days for Czech and Polish plots is around 120 days and the number of days with snow cover reaches 117 [21]. The mean annual temperature for the Italian plots is 13.7 °C and the mean annual precipitation is 1032 mm according to the Abriola meteorological station (1050 m a.s.l.). The mean number of vegetation days for Italian plots is 135 days (same period for snow cover) [60]. In Figure 1, a descriptive map of research plots is also displayed.

2.2. Data Collection

For dendrochronological analysis of samples from the Czech Republic, Poland and Italy, increment cores were taken from European beech using a Pressler auger, perpendicular to the trunk axis at a height of 1.3 m above the ground. Structurally homogeneous beech stands with stocking of 0.8–1 were selected for sampling. Samples were taken from randomly selected (RNG function) healthy co-dominant and dominant trees, whose average tree diameter at breast height had to be dbh > 30 cm. The height of all sampled trees was measured with a Laser Vertex hypsometer (Haglöf, Långsele, Västernorrland, Sweden). The Vertex hypsometer shows the measurement accuracy (instrumental resolution) to 0.1 m according to the manufacturer. The diameter at breast height was also measured for all trees using a Mantax Blue metal caliper (Haglöf, Långsele, Västernorrland, Sweden). This caliper provides an accuracy (instrumental resolution) of 1 mm according to the manufacturer. These research plots were monitored annually, and their detailed structural analysis was performed every 5 years. A total of 140 samples were taken for dendrochronological analysis; Table 2 offers more detailed information. Increment cores were measured using a LINTAB measuring table [61] with an Olympus microscope. The measuring table provides an accuracy (instrumental resolution) of 0.01 mm, and the TSAP-Win software [61] was used to record the cores. Measurements were made from the bark towards the heartwood, perpendicular to the center of the trunk, so that each tree ring was measured perpendicular to the trunk axis. The subsequent cross-dating of the increment cores was performed with the Cdendro program so that the cross-correlation index was $CC > 25$ for each sample [62].

Monthly temperature and precipitation data for Krkonoše were provided by the Czech Hydrometeorological Institute, Prague [63]. The mean monthly climatic data for the research plots in the Czech Republic and Poland were supplied by the meteorological station of Bedřichov (50°47′30.7″ N 15°08′31.7″ E) at an altitude of 780 m a.s.l.; the station is 35.5/54.3 km away from the research plots in the Czech Republic and Poland, respectively. Monthly temperature and precipitation data for the research plots in Italy were provided by the Italian Civil Protection Authority, Basilicata Region [64]. Characteristics of the Italian research plots were provided by the meteorological station in Abriola (40°30′28.0″ N 15°48′46.6″ E), at an altitude of 1050 m a.s.l. The distance from the Sellata 3 and La Lama 4 research plots to the meteorological station is 3.2/5.1 km, respectively. Annual sunspot number data were taken from the Royal Observatory of Belgium, Brussels [65].

Table 1. Overview of basic site and stand characteristics of research plots in 2019.

Name of Plot	GPS	Altitude (m)	Exposure *	Slope (°)	Height (m)	Diameter (cm)	Volume (m ³ ha ^{−1})	Soil Type	Köppen Classification
Chojnik 1	50°50′12.1″ N 15°38′27.8″ E	510	NW	16	23	39	380	Modal Cambisol	Dfb
Rýchory 2	50°39′57.7″ N 15°53′05.2″ E	760	NE	27	29	44	540	Eutrophic Cambisols	Dfb
Sellata 3	40°32′21.5″ N 15°47′39.9″ E	1275	E	26	33	60	720	Epileptic Phaeozems	Csa
La Lama 4	40°28′22.5″ N 15°45′35.2″ E	1340	SE	7	29	52	560	Haplic Phaeozems	Csa

Notes: * NW—northwest; NE—northeast; E—east; SE—southeast; Dfb—warm summer humid continental climate with large seasonal temperature differences, with warm to hot summers and cold winters; Csa—hot summer Mediterranean climate with dry summers and mild, wet winters.

Figure 1. Location of permanent research plots (black dots) with monthly climatic characteristics of the mean precipitation and mean temperature in the meteorological stations (black stars) in Bedřichov, the Czech Republic, and Abriola, Italy, over the whole time period of 1900–2019.

Table 2. Characteristics of tree-ring chronologies for European beech in research plots for 1900–2019.

Plot Name	No. Trees (Samples)	Age (Min/Max)	Mean RW (mm)	Std. (mm)	R-bar	ESP	SNR	NPY
Chojnik 1	29	90/123	1.99	0.78	0.41	0.94	17	—
Rýchory 2	33	103/182	1.05	0.53	0.26	0.92	11	1913, 1953, 2011, 2016
Sellata 3	40	94/152	2.33	0.69	0.25	0.95	19	1962, 1970, 1988, 1994, 2012, 2013, 2016, 2017
La Lama 4	38	125/247	1.73	0.58	0.34	0.92	12	1933, 1970, 1971, 1981, 2013, 2017

Notes: No. trees—number of trees; Age—age of youngest and oldest sample tree; Mean RW—mean ring width in mm; Std.—standard deviation in mm; R-bar—inter-series correlation; EPS—expressed population signal; SNR—signal-to-noise ratio; NPY—negative pointer years with significantly extreme low radial growth.

2.3. Data Analysis

Dendrochronological data were processed in R software [66] using the “dplr” package [67]. Detrending of each tree was performed by negative exponential detrending with an inserted spline of 1/3 of the age of each tree using “dplr” instructions [68]. Such detrending removes the age trend while maintaining low-frequency climate signals [55,69]. The expressed population signal (EPS) was calculated for the detrended data. The EPS represents the reliability of a chronology as a fraction of the joint variance of the theoretical infinite tree population. The limit for using the data for comparison in relation to the climatic data was a significant EPS threshold so that $EPS > 0.85$ [68]. We also calculated the signal-to-noise ratio (SNR) that represents the signal strength of the chronology and R-bar (inter-series correlations) [70]. The analysis of negative pointer years was carried out [71]. For each tree, the pointer year was tested as an extremely narrow tree ring that did not reach 40% of the increment average from the four preceding years [71]. The occurrence of the negative year was proved if a strong reduction in increment occurred in at least 20% of the trees in the plot.

Spectral analyses for indexed (detrended) radial increments were created with Statistica 13 software [72]. The calculation was performed with the “Single Fourier (Spectral)

Analysis" function, using the output "Periodogram" plot by "Period". Furthermore, this software was used to calculate correlation coefficients and cross-correlations for lag –15 years (in relation to the sunspot number, vegetation season temperature and annual precipitation). With Statistica 13 software (Statsoft, Tulsa), we created cross-periodograms (real), used to study a multivariate spatial process [73]. We also used the "signal" and "dplr" wavelet plot for Krkonoše and Italy for the period 1900–2019 to make the dendrochronological signal more apparent for up to 32 periods/cycles [74,75]. For the next statistical analysis, the time span was divided into the following 3 periods: (1) a period of active forest management and regular harvesting (1900–1969), (2) a period of air pollution crisis characterized by extremely high SO₂ concentrations and acid rains (1970–1985), and (3) a period of forest protection without human harvesting interventions (1986–2019).

3. Results

3.1. Tree-Ring Characteristics and Extreme Climatic Events

Dendrochronological characteristics are described in Table 2 and include the mean tree ring increment at a plot (Mean), age of the youngest and the oldest sample trees (Age), standard deviation (Std.), inter-series correlations (R-bar), expressed population signal (EPS) and signal-to-noise ratio (SNR). The research plots in Italy (Sellata 3 and La Lama 4) show a larger mean increment, on average 25% larger than the research plots in central Europe (Chojnik 1 and Rýchory 2). The age of the research plots indicates that Sellata 3 and La Lama 4 were generally older than Chojnik 1 and Rýchory 2. Even the research plot of La Lama 4 reached up to 247 years. The range between maximum and minimum age was due to age variability in the forest stands; however, all research areas showed a visually homogeneous forest structure. A greater variability of radial growth was found in both locations with lower altitude compared to a higher one, while a higher number of negative pointer years (NPY) characterized by an extremely low increment was found on richer soils compared to poorer ones.

The number of NPY ranged from 0–4 for central Europe and from 6–8 in southern Italy. A climatically significant year common for Rýchory 2 and Sellata 3 was 2016, when the share of precipitation, lower by 26% (compared to the average), was documented in the vegetation season. Another common NPY was recorded in 2013 for the Italian research plots Sellata 3 and La Lama 4, where a higher annual precipitation of 1204 mm (compared to 1024 mm per year on average) and lower seasonal temperatures of 28.3 °C (29.6 °C) were recorded in both plots. One more common NPY for the research areas in Italy was 1970, with the seasonal precipitation totals lower by 15% (240 mm, 280 mm). The year 2017 was also significant for the Italian research plots Sellata 3 and La Lama 4, with the total precipitation during the vegetation season lower by 41% (204 mm, compared to an average of 289 mm), the lowest in 20 years. Similarly, the NPY of 2011 in Krkonoše was negatively affected by an unbalanced frequency of precipitation during the year (monthly variability was higher by 46%). Overall, the NPY show that the Apennines plots (Sellata 3, La Lama 4) have a higher frequency of NPY than central Europe, while the Chojnik 1 research plot, for example, has not recorded a single NPY. Additionally, 15 of the 18 NPY were found in the second half of the solar cycle.

3.2. European Beech Tree-Ring Growth, Sunspot Number and Climate Variations

Figure 2 shows a clear difference between radial growth (a) in the Krkonoše Mountains in central Europe (Poland, Czech Republic) and (b) in the southern Apennines in Italy. The radial growth of beech differentiates itself in each time period. A positive relationship of radial growth in all research plots with the sunspot number is characteristic for the first time period. This fact is also confirmed in Table 3. A change in the trend of radial growth of European beech and the nature of its connection with sunspots occurred in the second time period on the Italian research plots. Another interesting feature of the second time period is a unique low or negative correlation with sunspots on almost all research plots, which is also confirmed in Figure 2 and Table 3. In the second period, there was also a

significant decrease in radial growth on all research plots. In the last, or third, time period, the concurrence of sunspots and radial growth of beech in Italy was the opposite of that on research plots in the Czech Republic and Poland. A typical interconnection with the solar cycle (sunspot number) and the radial growth of European beech is shown in Figure 2. These are, for example, parallel cycles of radial growth with the solar cycle in the first time period, but the solar cycle is also reflected in the third time period (positively and negatively). In Figure 2, a significant reduction in radial growth can also be seen, often during the solar minimum, which can be reported for almost all time periods, except for the Italian research plots, where in the second and third periods, this process was reversed.

Figure 2. Standardized ring width chronologies of European beech on research plots in the Czech Republic/Poland (a) and in Italy (b). RWI: ring width index; spl8: eight-year spline. The periods described in the time window are as follows: 1st period: 1900–1969 (regular harvesting period); 2nd period: 1970–1985 (air pollution crisis period); 3rd period: 1986–2019 (forest protection period).

Table 3 describes the relationship between the radial growth of European beech in the research plots and the sunspot number, annual temperature, vegetation season temperature, annual precipitation and vegetation season precipitation in different time periods. Radial growth of beech reacts to sunspots, temperatures or precipitation differently in every time period. The most significant values were correlated with the sunspot number, then with annual precipitation, and subsequently with seasonal temperatures. Mean annual temperatures and seasonal precipitation totals did not show high correlation values to radial growth, but they also did not show significant results. According to Table 3, solar cycles correlated most significantly with the whole period, and subsequently, with the third time period. The tree ring width index (RWI) showed the most significant positive correlation with solar cycles in Poland and the Czech Republic (RWI Chojnik 1 and Rýchory 2) both for the whole period and the third period. For the Italian plots Sellata 3 and La Lama 4, the correlation results were different, with both plots having negative correlations with the sunspot number. The Sellata 3 plot showed a significant negative correlation over the whole period ($r = -0.25$) and in the third period ($r = -0.37$). La Lama 4 had a significant correlation in the second time period ($r = -0.51$), so all plots

significantly correlated with the sunspot number, depending on the time period. All plots were positively correlated with solar cycles in the first time period, but only the RWI Chojnik 1 plot was significantly positive ($r = 0.31$) in the first period.

Table 3. Correlation coefficients for the tree-ring width index (RWI) of research plots in different time periods to the sunspot number, annual temperature, vegetation season temperature, annual precipitation and vegetation season precipitation. Significant correlation values are in bold; the correlations are significant at $p < 0.05$.

Years	1900–2019	1986–2019	1970–1985	1900–1969
Time Period	Whole Period	3rd Period	2nd Period	1st Period
Sunspot number				
RWI Chojnik 1	0.26	0.37	0.07	0.31
RWI Rýchory 2	0.23	0.54	−0.12	0.19
RWI Sellata 3	− 0.25	− 0.37	−0.43	0.11
RWI La Lama 4	−0.07	−0.02	− 0.51	0.11
Annual temperature				
RWI Chojnik 1	0.14	0.18	0.37	0.10
RWI Rýchory 2	0.05	0.28	0.37	0.07
RWI Sellata 3	−0.04	0.02	−0.07	−0.02
RWI La Lama 4	0.08	−0.23	0.12	−0.08
Vegetation season temperature				
RWI Chojnik 1	0.09	0.09	0.39	0.11
RWI Rýchory 2	0.08	0.28	0.32	0.15
RWI Sellata 3	−0.06	0.04	−0.21	−0.02
RWI La Lama 4	−0.12	− 0.39	0.12	−0.14
Annual precipitation				
RWI Chojnik 1	−0.10	0.00	−0.28	−0.06
RWI Rýchory 2	− 0.18	−0.10	−0.48	−0.19
RWI Sellata 3	0.10	0.05	0.32	0.06
RWI La Lama 4	0.15	0.02	0.11	0.24
Vegetation season precipitation				
RWI Chojnik 1	−0.08	0.04	−0.21	−0.07
RWI Rýchory 2	−0.15	−0.16	−0.45	−0.17
RWI Sellata 3	0.11	−0.01	0.45	0.13
RWI La Lama 4	0.12	0.06	0.20	0.14

Seasonal temperatures had only one significant correlation with radial growth for the La Lama 4 plot in the third time period ($r = -0.39$). In the case of seasonal temperatures, positive correlations were found for the Czech and Polish research plots, while for the Italian ones, the values were mostly negative.

The annual precipitation totals had two significant values: for the Rýchory 2 plot for the whole time period ($r = -0.18$) and for the La Lama 4 plot in the first time period. Annual precipitation totals correlated differently to radial increment than seasonal temperatures or sunspot number. Thus, annual precipitation totals correlated negatively with radial growth in the Czech Republic and Poland in practically all the time periods. The Italian research plots Sellata 3 and La Lama 4 correlated positively with the annual total precipitation in all the time periods.

3.3. Cross-Correlation up to Fifteen Years Back in Relation to Tree Ring Growth

Cross-correlations in Figure 3 show the relationship of the sunspot number, annual precipitation and seasonal temperatures to the radial growth from up to 15 preceding seasons in different time periods. The cross-correlations of this research describe the relationship of radial growth to the studied factors up to 15 years into the past. Cross-

correlations show that the most significant values are found in the sunspot number, while the number of significant values in precipitation and temperature are almost identical. In relation to the radial growth of European beech, the sunspot number correlates in waves. The most concurrent correlations with sunspots on all research plots are found in the first time period. By contrast, in the second and third time periods, the correlations turn completely against each other when the Chojnik 1 and Rýchory 2 plots are positively correlated to the sunspot number, while the Sellata 3 and La Lama 4 plots are negatively correlated to the solar cycle. The most common and highest significant correlation to sunspots in terms of relative lag years is in lag 0 to -1 years for Rýchory 2 and Chojnik 1 in both the whole and first time periods. Nevertheless, the La Lama 4 plot is significant to sunspots in lag -7 to -8 relative years in the third time period. In the second time period, the plots of Sellata 3 and La Lama 4 correlated significantly to the sunspots in lag 0 to -1 relative years. The cross-correlations of radial growth to sunspots show that all time periods contained significant values for almost all research plots.

Figure 3. Cross-correlation of ring width index with sunspot number, precipitation and temperature in the three time periods and the whole time period. Values are significant at $p < 0.05$ and marked with a circle. Lag: year (Lag -1 is the correlation of the 1 preceding year).

Annual precipitation totals and seasonal temperatures cross-correlate less than the sunspot number, which is apparent in Figure 3. In the case of precipitation and temperature, it is also true that the research plots correlate conversely between the plots in Krkonoše and in Italy. For precipitation, the whole time period and the first time period correlate best, which are also the longest monitored time periods. Significant values for precipitation are found in the whole time period for the relative years 0 and -10 . Another important period for precipitation is the first time period, where the values significantly correlate back from lag -6 to -10 relative years. The cross-correlation of radial beech growth and seasonal temperatures only shows significant values in the first time period. The results for precipitation in the first period show a significant value for the research plot Rýchory 2 (lag

−2 relative years), La Lama 4 (lag −2 relative years) and Sellata 3 (lag −4 to −5 relative years and also −12 years).

3.4. Spectral Analysis

Cross-periodograms show common cycles between the radial growth data series in relation to the sunspot number, annual precipitation and seasonal temperatures. Cross-periodograms describe both a negative and positive cyclical relationship between our examined data. Figure 4 describes the whole time period, with an assessment of the influence of “SUNSPOT” (sunspot number), “Total prec.” (annual precipitation) and “Season temp.” (season temperature) on radial growth from all research plots in the period 1900–2019.

Figure 4. Cross-periodogram of ring width index (RWI) with sunspot number (SUNSPOT), annual precipitation (Total prec.) and seasonal temperature (Season temp.) in the whole time period, 1900–2019.

Solar cycles (sunspot number) are reflected in the observed positive radial growth of European beech by 11-year cycles on all research plots. The La Lama 4 research plot, where the 11-year cycle correlated both positively and negatively with the indexed radial growth and the sunspot number, shows 20- and 40-year cycles. On the Chojnik 1 research plot, there was a negative cross-period of radial growth and sunspots in 20- and 40-year cycles. The Rýchory 2 research plot formed negative cross-periods of radial growth and sunspots in 6- and 30-year cycles.

Important cycles of the cross-periodogram for all research plots in relation to precipitation and increment show that on the Italian plots (Sellata 3 and La Lama 4), there were negative values for 30- and 40-year cycles. On the research plots in Krkonoše (Chojnik 1, Rýchory 2), there were various periodic responses of radial growth of European beech to the total precipitation, but it is possible to say that the 30- to 40-year periods were not as significant as in Italy. The cross-periodogram shows that precipitation cycles were negatively correlated with radial beech growth on the Chojnik 1 and Rýchory 2 research

plots. On the Sellata 3 and La Lama 4 plots, positive 60-year precipitation cycles in radial growth have occurred.

The seasonal temperature cross-periodogram shows minor differences. The Chojnik 1 and Rýchory 2 plots had the most legible 25-year positive cycles of seasonal temperatures with radial growth in the periodogram. The cross-periodogram also shows that the research plots in Italy (Sellata 3 and La Lama 4) have had 40-year positive cycles in relation to seasonal temperatures and radial growth. Furthermore, the La Lama 4 plot has had negative 60-year cycles of increment as related to temperature, on the cross-periodogram.

The Fourier analysis in Figure 5 shows the difference between the 1st and third periods. As in the graph in Figure 5, the Chojnik 1 research plot showed 4-, 7-, 11- and 18-year cycles in the first time period. In the third time period, there were 7- to 12-year cycles on the Chojnik 1 research plot. In the first period, the Rýchory 2 research plots showed 4-, 18- and 35-year cycles in radial growth. In the third period, there were 3-, 33- and 7- to 11-year cycles in radial growth on the research plot of Rýchory 2. The Sellata 3 research plot showed 8-, 12- and 24-year cycles in the first period. In the third time period on the Sellata 3 research plot, there were 4- and 12-year cycles in radial increment. The La Lama 4 research plot in the first time period showed 5-, 10-, and 18- to 35-year cycles in relation to the radial growth of beech. In the third period on the La Lama 4 research plot, there were 4-, 5- and 7-year cycles in the radial growth of European beech.

Figure 5. Single spectral analysis of the indexed ring-width chronology for European beech in the first and third periods.

It is evident from Figure 5 that 7- to 12-year cycles most commonly occur in radial growth, but these results are time-period-dependent. Furthermore, each research plot apparently has 9- to 12-year cycles in at least one time period.

The wavelet plot in Figure 6 describes the occurrence of cycles (periods in the graph) in time between the Apennines and the Krkonoše Mountains. It documents that 24- to 32-year cycles during the period 1900–1990 were the most important in Krkonoše. There were also less significant cycles in the period (dark gray color) from 1910 to 1960 in Krkonoše, with approximately 6- and 20-year cycles reported. However, the darkest gray color on the Krkonoše research plots shows that from 1985 to 2018, cycles of around 4 and 12 years were also important. Research plots in Italy revealed significant 16- to 22-year cycles for the period 1900–1940, and also 4-year cycles for the period 2010–2015. Periods from 1920 to 1940 with cycles of about 12 years were less significant on the Italian plots. In addition, there were less significant 3- to 8-year cycles in the period of 1960–2015. The wavelet plot in Figure 6 shows 9- to 13-year cycles, which are the most common for Krkonoše and Italy in the 1990–2019 period, but the results from Figure 6 are below the statistical significance limit.

Figure 6. Wavelet plot calculated from mean RWI (ring width index) of European beech stands in the Krkonosze mountains in Poland and the Czech Republic (**left**) and plots in Italy in the Apennines mountains (**right**). Black color represents the 90% significance level against the dark gray noise level.

4. Discussion

4.1. Different Growth Conditions of European Beech in Central Europe and the Southern Apennines

Beech stands in central Europe have fewer vegetation days than in the Mediterranean, which is reflected in the size of the mean radial growth. Increment on the research plots in Krkonosze is smaller by an order of magnitude (approximately by 25%) than on the research plots in the southern Apennines (Table 2). Beech stands in Krkonosze belong to a European beech provenance more sensitive to drought, which may be related to its earlier fall of the assimilation apparatus. In contrast, beech stands in the Mediterranean are more drought-resistant and defoliate later [28,76]. In the Krkonosze Mountains, temperatures were proven to have a greater effect on the radial growth of European beech than precipitation totals [21,77]. On the Chojnik 1 research plot, our results in Table 3 confirm that temperatures had a higher correlation with radial growth than with the total precipitation, while on the Rychory 2 research plot, this fact is validated in the third time period. The total precipitation had a negative effect on the radial increment in central Europe. Similar negative responses to precipitation were also confirmed by reference sources [22,78]. For beech in Krkonosze, it is also true that with a higher altitude, the temperatures play a greater role in radial increment [79], which is verified by our results. It is evident from Table 3 that in the 1st and third time periods, the temperatures correlated more at Rychory (760 m a.s.l.), which is located higher than the research plot of Chojnik 1 (510 m a.s.l.). Altitude also influenced growth consistency at both locations, while higher incremental variability was found in lower-situated areas compared to those with higher altitude. In general, beech stands have faced increasing drought stress in recent years [11], but in the montane areas of Krkonosze, spring frosts have more significant negative effects [21].

Beech forests in the Mediterranean are also affected by drought and spring frosts, as evidenced, for example, in the Pyrenees [80] and the Apennines [81]. Drought is a limiting factor in the European beech growth in the Apennines [29], as is confirmed by the negatively significant years (NPY) in Italy, where the impact of drought on radial growth was recorded on our plots Sellata 3 and La Lama 4 several times, e.g., in 1970 and 2017. In general, more NPY were detected in central and southern Europe in nutrient-rich habitats compared to the poor ones. On productive sites, climate change can hamper tree growth and forest productivity [82]. Also, other studies have shown that trees were more sensitive to climate on the more productive sites compared to poor ones due to differing proportions of latewood to earlywood [83,84]. Assessing tree responses to climate change without simultaneously considering soil properties and climate may be misleading, since soil nutrients can influence the growth response of trees to drought [85]. Our results also

showed that 15 of the 18 NPY were observed in the second half of the second part of the studied period. An increasing number of NPY during the time may be caused by an increasing number of extreme climatic events in ongoing climate change [80,86,87].

Beech stands in the southern Apennines (Sellata 3 and La Lama 4) were negatively correlated with temperatures and positively correlated with precipitation (Table 3 and Figure 3), which is exactly the opposite from the research plots in Krkonoše. Scientific literature also confirms that these correlations of precipitation and temperature to radial beech growth in the Apennines may be due to winter accumulation of precipitation in the soil [51]. The negative correlation of the beech radial growth to the temperatures on the Sellata 3 and La Lama 4 plots could be explained by the effect of higher temperatures during dry periods [88].

4.2. Solar Cycles, Climate Change and the Possible Link to European Beech

Solar activity affects the climate on our planet [50], which is also reflected in the NAO [37,49]. Many other studies have also shown that the effect of solar activity has an impact on precipitation and temperature [33,34]. Temperatures on the European continent correlate with the NAO mainly during the winter and spring periods [47]. Precipitation totals are also linked to solar activity, but it is important to mention that precipitation is also affected by solar activity during July in Italy and during May, June and July in the Czech Republic [49]. As in Figure 1, there is also a noticeable difference between monthly precipitation totals and temperatures during the year, when precipitation totals differ significantly—in Krkonoše, the main precipitation occurs over the vegetation season, while in Italy, it occurs during the vegetation off-season.

Wind currents high in the atmosphere, or “jet streaming”, are associated with solar cycles, where these wind currents are blocked during the solar minimum [89,90], leading to a colder winter season [91]. In contrast, the solar maximum leads to an acceleration of wind currents [92], which, through “Ferrel cells” [93], increases the pressure of winds affecting the European continent. This may be confirmed by research in Spain, where the solar cycle has been found to be associated with precipitation and wind anomalies [94]. The solar cycle is associated with the occurrence of large forest fires and dry weather seasons during the solar minimum, which has been proven in Turkey [95]. Our research plots in the mountainous areas of the Mediterranean, Sellata 3 and La Lama 4 (Figure 2), have recorded higher increments in recent years (third period) during solar minimums. This fact can be supported by better conditions for growth at higher altitudes, which is confirmed by correlations presented in Table 3, showing the relationship between temperatures and radial growth as being predominantly negative.

Solar cycles are linked to climate change and temperature differences on the planet’s surface. There is a study that describes a possible association of low sunspot activity with climatically cold periods on the Earth [32]. Solar cycles do not affect temperatures and precipitation directly, and it has been shown that solar activity is not imprinted on these factors entirely [86,96]. The total contribution of solar activity to variations in the Earth’s global temperature and climate is insignificant but not negligible [97]. Other studies describe the link between cosmic rays and solar cycles [98]. It is the cosmic rays that are associated with cloud formation, and this also affects the amount of light falling on the planet’s surface, where low solar activity (low sunspots) leads to a higher amount of cosmic rays, creating a thicker cloud cover and cooling the planet [38,39]. Our results may be related to the decreasing activity of sunspots [99] due to the fact that there has been a lower radial growth in Krkonoše since around 1990 (Figure 2a), and a decrease in the radial growth of beech in the southern Apennines since 2010 (Figure 2b). In the central Apennines, there has also been a long-term reduction in the radial growth of European beech due to drought since 1970 [27], while concurrently, sunspot number has been lower since 1980 (Figure 2). Our results show the response of radial growth to solar cycles in Figures 2 and 3 and Table 2, when the research areas in Krkonoše correlated positively and the areas in southern Italy correlated negatively in the third time period. The opposite reactions of the

radial growth to the solar cycle were observed in our results after 1960. Simultaneously, global temperature was affected due to increasing CO₂ since 1960, which disturbed the natural process of solar cycles [100]. This fact of opposite correlations could be attributed to solar activity or climate change, where both factors are accompanied by changes in the NAO [47]. This is because changes in air temperatures on the surface of the Earth can also be related to the changes in low and high pressures above Europe [91,101].

4.3. Feedback and the Relationship of Radial Growth to the Sunspot Number Across the Time Frame

Solar cycles play a role in the radial growth of European beech in Krkonoše, which has been proven in the vicinity of research plots in Rýchory [52]. Our results confirm that not only Rýchory 2, but also the northern part of Krkonoše (Chojník 1), are associated by positive correlations (Table 3) with the solar cycle during the first and third time periods (Figures 2–5). A positive relationship of Scots pine growth has also been found in northwestern Russia [55]. It was also confirmed in Krkonoše in the 1980s, when an air pollution calamity (high SO₂ concentrations) occurred, reducing the radial growth of European beech [21,24,102]. Our results from the research plots in Chojník 1 and Rýchory 2 in the second time period also describe this event. In the second period, there was also a decrease in radial growth on the Italian research plots of Sellata 3 and La Lama 4, while Figure 3 shows a significant result of the negative cross-correlation with solar activity for both Italian plots. In the third time period, the negative relationship between the plots in the Apennines (Sellata 3 and La Lama 4) also continued, while the first and second periods could be compared to the research of solar cycles and their relation to cork oaks in the Mediterranean in Portugal, where a negative relation between tree bark increment and the solar cycle was confirmed [58]. Other studies have also confirmed a negative correlation of solar cycles with the radial growth of *Pinus pinaster* in northern Portugal. The same study found a minor negative correlation of radial growth and solar cycles in southern Slovakia [103].

Cross-correlations in Figure 3 show the feedback of the radial growth of European beech and solar cycles on the Italian research plots in the third time period, where Sellata 3 showed significant correlations in the 7 to 8 preceding years. This could indicate a possible shift in the effect of solar activity in the Apennines. We can even find regression correlations of increment and solar cycles in the first and second time periods for the Italian plots, which are 1- to 2-year shifts in the significant correlation coefficients. The effect of cross-correlations with solar cycles could be attributed to the effect of the NAO, while for European beech, the influence of the NAO on the radial growth in central Italy was confirmed [51]. Changes in the radial growth of European beech in Italy in the second and third time periods may have been due to the influences of the NAO over Europe, which may have caused different responses of cross-correlations between Krkonoše and the Apennines [104,105].

4.4. Recorded Cycles in Beech Tree Rings

In terms of radial growth, our results in Figures 5 and 6 show 9- to 12-year cycles most frequently recorded for each research plot in at least one of the time periods. These periods are associated with solar activity, which has 8- to 12-year cycles. These cycles have been recorded in the radial growth of various tree species, e.g., in Europe [103], Russia [55], South America [106] and Asia [57]. Furthermore, 4- to 7-year cycles have been reported for radial growth, which can be classified as the “Schwabe cycle”, the second harmonic cycle of the sun associated with the aforementioned cosmic rays [107]. The high-frequency oscillations for about three years might be associated with the frequent changing in global temperatures [108,109]. In addition, Figure 4 shows a minor share of 4- to 7-year cycles in a cross-periodogram with temperatures and precipitation, where, e.g., 8-year cycles have been recorded in Germany as being most synchronous with the vegetation phenology of beech [110]. Short (3- to 4-year) cycles can also be found in the cross-periodogram of radial growth and precipitation, and again, they may be linked

to the NAO [49]. Longer (17- to 35-year) cycles could be assigned to the 22-year Hale cycle, which repeats through meteorological indicators such as temperature and ozone concentration [40] or precipitation [49]. This 22-year cycle has even been found in tree rings in Tibet [57] and northwestern Russia [55]. Our results also partly include the occurrence of 33- to 36-year cycles, which might indicate the dynamics of droughts [108]. Multi-year cycles in the cross-periodogram are among the influences of the Gleissberg cycle, which takes 80–90 years [40]; this cycle is linked to global temperature changes [97].

5. Conclusions

Solar cycles were recorded in the tree rings of European beech both in Krkonoše and in the southern Apennines. A higher number of negative significant years, characterized by extremely low radial increments, were recorded in southern compared to central Europe, while a lower number of NPY was found at nutrient-poorer sites. The frequency of NPY also increased over time with increasing frequency of extreme climatic events in response to climate change, especially droughts in vegetation periods. Radial growth on individual research plots correlated differently within each time period. The most significant values were recorded for the sunspot number (compared to temperature and precipitation), which correlated profoundly with the radial growth of beech. Each research plot correlated at least once with the sunspot number. Research plots in Krkonoše responded positively to the sunspot number, seasonal temperatures and annual precipitation totals, while the research plots in the southern Apennines correlated in exactly the opposite way than those research areas in central Europe. In the first time period (1900–1969), there were positive correlations with the sunspot number on all research plots. In the second time period (1970–1985), there was a decrease in radial growth both in the Apennines and Krkonoše. In the last, third period, time period (1986–2019), there were the most significant correlations between the radial growth of beech and the sunspot number, while precipitation and temperature correlated less significantly. In total, 4- to 7-year, 9- to 12-year and 17- to 35-year cycles were found in the radial growth of beech. Cross-periodograms of beech radial growth confirmed mainly 11-year cycles of solar activity and 30-year cycles for annual precipitation totals. This research demonstrates that solar cycles manifest differently in central and southern Europe. Research of the intensity and repetition of solar cycles can be helpful in uncovering new and unexplored processes that affect radial growth across Europe. Our findings could help in understanding the adaptation of forest management to climate change. Moreover, the solar cycles might be observed in radial growth even without radiocarbon analysis. This study should improve the forestry and climatological research understanding of natural cycles and their effect on the radial growth of European beech during global climate change.

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