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Finding an imprint of solar and climatic cycles in tree rings of European beech (*Fagus sylvatica* L.)

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Abstract: The present study is focused on European beech (*Fagus sylvatica* L.) growth in eastern Bohemia in the Broumovské stěny National Nature Reserve, Czech Republic. The objective of this research was to develop an evaluation of European beech radial growth in relation to solar activity (number of sunspots), air temperature in the growing season, annual precipitation and air pollution (SO_2 depositions). The highest positive significant correlation coefficient was found between radial growth of European beech and number of sunspots, followed by the correlation with air temperature in the growing season. The radial growth showed a negative significant correlation with SO_2 depositions. The correlation of the radial growth indicates that precipitation and sunspots have a lower correlation coefficient with beech growth than seasonal temperature during an air pollution disaster in the 21st solar cycle. Radial growth, precipitation total and air temperature in the growing season were processed by spectral analysis for the evaluation of periodic cycles. The 7.5- to 11-year cycles were observed in air temperature and in sunspot cycles. Precipitation and air temperature in the growing season indicate a higher frequency at 3.7-year cycles. The long-term periodicity of radial growth was influenced by both solar activity and fluctuations of growing-season air temperature.

Keywords: sunspot area; solar activity; cyclicity; radial growth; Central Europe; air pollution load

European beech (*Fagus sylvatica* L.) is the most widespread deciduous tree species in Central Europe (Pretzsch et al. 2013; Sharma et al. 2016; Štefančík et al. 2018b). This tree species is very important, both from an economic point of view and for ecological aspects (Podrázský et al. 2014; Bulušek et al. 2016; Štefančík et al. 2018a). In addition, the importance of European beech is increasing as a replacement for Norway spruce due to the ongoing climate change (Vacek et al. 2019a), as there are large-scale declines and disturbances of sensitive spruce stands (Toth et al. 2020). The growth of European beech forests can be influenced by several factors, such as temperature and precipitation (Remeš et al. 2015; Gallo et al. 2017; Vacek et al. 2019b), air pollution (Breckle, Kahle 1992; Králíček et al. 2017), game damage (Slanař et al. 2017; Vacek 2017), habitat conditions (Dittmar et al. 2003; Vacek et al. 2015b; Hájek et al. 2020) including weed competition in the initial stage of growth (Gallo et al. 2018a, b), silvicultural interventions (Sharma et al. 2019; Vacek et al. 2020a) and previous land use (Rozas 2003; Cukor et al. 2017). One of the important factors affecting radial growth of European beech is also solar activity and its cycles (Komitov, Kaftan 2019).

Eleven-year solar cycles are defined by the sunspot area on the Sun's surface. Many indicators of solar activity (Hathaway 2015) are associated with these solar cycles that are part of natural

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variability of the Earth's climate (Kadonaga et al. 1999). In the past, it was proved that solar cycles influence the water cycle of the planet Earth (Al-Tameemi, Chukin 2016). Solar cycles also influence the atmospheric circulation in higher parts of the atmosphere of the northern hemisphere, which is manifested in so called North Atlantic atmospheric circulation (Brugnara et al. 2013). With increasing altitude above sea level, the influence of solar cycles on the air temperature is increasing (from 1 500 to 8 000 m) (Kumar et al. 2018). There are also studies showing that the solar activity has a long-term impact on the temperature of the Earth's atmosphere, which is accompanied by the occurrence of colder winter seasons (Lockwood et al. 2017). Other research works have proved that the effect of solar activity also influences precipitation and temperature (Mauas et al. 2016; Baker et al. 2018). The solar activity even impacts on the properties and formation of clouds in the atmosphere, which is caused by cosmic-ray ionization that reflects 11-year cycles of solar activity in a reverse way (Jayaraman et al. 1998; Haywood, Boucher 2000; Maghrabi, Kudela 2019). Consequently, fluctuations in the Earth's surface irradiance occur. Researches in the field of dendrochronology document the effect of solar cycles on tree ring radial growth, which was described by studies conducted in northwestern Russia (Shumilov et al. 2011; Kasatkina et al. 2019), Tibetan Plateau (Wang, Zhang 2011) or Chile (Rigozo et al. 2002).

The growth dynamics of European beech is responding to 11-year solar cycles in the Krkonoše Mountains (Šimůnek et al. 2021). The solar cycles were found also in the radial growth of other tree species across Europe (Dorotovič et al. 2014) and Russia (Shumilov et al. 2011). Scientific studies also documented that the main commercial tree species (European beech, Norway spruce, Scots pine, European larch and sycamore maple) in the studied Sudetes mountain range respond very well to seasonal temperature and subsequently to precipitation (Vacek et al. 2017; Putalová et al. 2019; Cukor et al. 2019, 2020). The action of the abovementioned climate factors is cyclical in various intervals, and therefore more detailed research may be very useful for the forestry sector. Another example of beech's growth being influenced by cyclical events is for example the natural regeneration of beech stands regenerating after fire in 5–12 years (Maringer et al. 2020). The productivity cycle of European beech is repeated within 2–20 years (Müller-Haubold et al. 2015). The productivity of European beech stands was found to be associated with precipitation and temperature factors at a given site (Drobyshev et al. 2010; Bogdziewicz et al. 2019). These facts suggest a conclusion that the cyclical growth of European beech stands is related with cycles of mast years (Drobyshev et al. 2010).

The present study demonstrates the theoretical cyclicity of radial growth by means of a spectral analysis of European beech in eastern Bohemia (Broumovské stěny National Nature Reservation) in relation to air temperature, precipitation and solar activity. The main objective was to determine the cyclic nature of European beech radial growth by a dendrochronological analysis. The study evaluates correlations and spectral analysis of radial growth, sunspot number, air pollution (SO_2 depositions), air temperature and precipitation. The outcomes of this study could be used as background material for a more exact definition of the cyclicity of natural influences on European beech growth under the conditions of climate change.

MATERIAL AND METHODS

Study site. The study site is located near the town of Broumov in the Broumovské stěny National Nature Reserve (NNR) within the Broumovsko Protected Landscape Area in the eastern part of the Czech Republic (Figure 1). The NNR was established in 1956 due to a unique pseudokarst relief in Upper Cretaceous block sandstones occurring in the form of extensive rock walls and is made up by acidophilic and herb-rich European beech forests and scree forests. The study area is situated at an altitude of 610–640 m a.s.l. on the slope with eastern aspect and gradient of 28–43° on GPS 50°34'31.7"N 16°15'42.2"E. Modal Cambisol and Cambic Rankers are the prevailing soil types. Average annual air temperature was 7.3 °C and average precipitation total was 744 mm in 1961–2018.

Studied stands have been left to spontaneous development in this area and are in the initial break-up stage according to Korpeľ (1995). The stand structure is mostly composed of two storeys: an old-growth European beech forest (150–210 years of age) is in the overstorey and predominantly European beech undergrowth (5–30 years of age) is in the lower storey. Stand volume on average reaches 550 $m^3 \cdot ha^{-1}$ with mean stocking of 0.7, tree height

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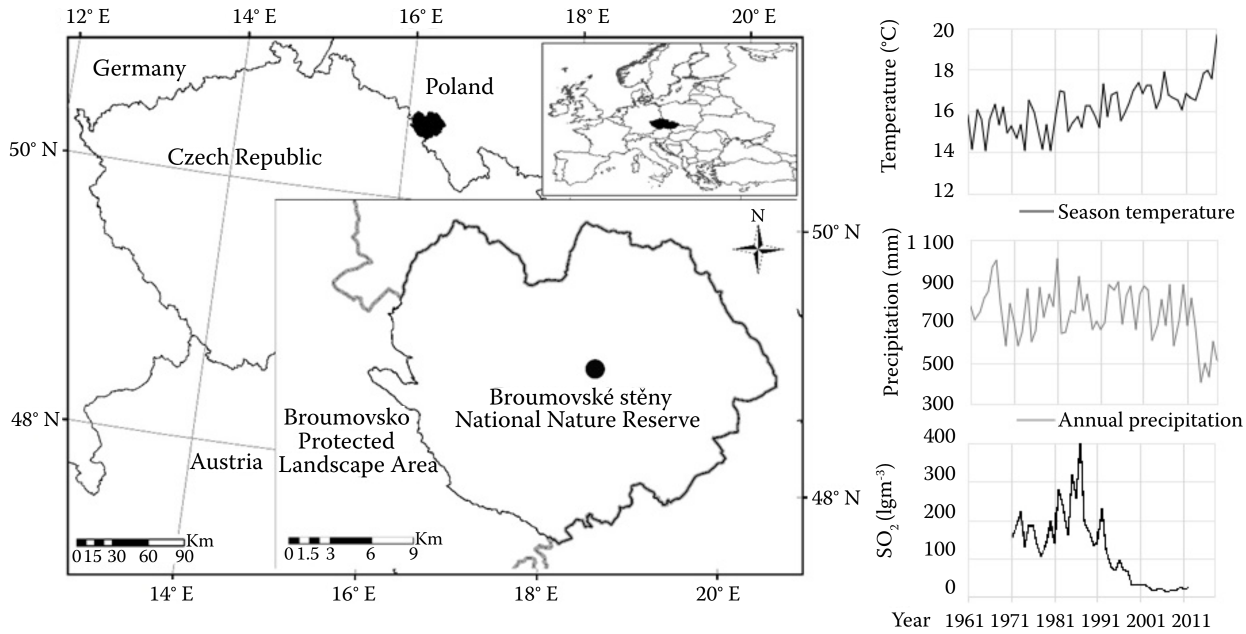

Figure 1. Localization of studied European beech forest stands in the Broumovské stěny National Nature Reserve in the Broumovsko Protected Landscape Area (left) and a demonstration of temperatures, precipitation and SO_2 concentrations (right)

of 36 m and diameter at breast height of 53 cm (Vacek et al. 2015a). European beech (*Fagus sylvatica* L.) is the main overstorey species in the forest stands with the admixture of Norway spruce (*Picea abies* /L./ Karst.), sycamore maple (*Acer pseudoplatanus* L.) and rowan (*Sorbus aucuparia* L.). From the point of view of typology, research plots are classified as 5A, i.e. *Acereto-Fagetum lapidosum* (enriched stony sycamore-beech stands) (Viewegh et al. 2003). Information on the stand structure was computed from the field measurement of dendrometry variables using the Field-Map technology (IFER-Monitoring and Mapping solutions Ltd., Czech Republic). More detailed characteristics of the area of interest and permanent research plots were published by Vacek et al. (2015a). The vegetation season lasts for 150 days, which corresponds to the period from May to September (Šimůnek et al. 2019, 2021). The vegetation season was considered to be the mean from May to September for air temperature (Šimůnek et al. 2020). The precipitation was used as the annual sum of precipitation. We decided to use annual precipitation on the basis of a study from the nearby Krkonoše Mts., where the main significant correlation between monthly precipitation and tree ring growth was revealed by the Dendroclim software (2002) outside the growing season (from January to March) (Šimůnek et al. 2019).

Data collection. Dendrochronological samples were taken with a Pressler borer in a perpendicular direction to the centre of the tree trunk. Thirty samples (one bore per tree) were taken from codominant and dominant trees at breast height of 1.3 m above the ground according to Kraft (1884). The collected dendrochronological cores were measured with an Olympus microscope using a LINTAB measurement table (Rinntech 2010). The crossdating of the increment cores was performed with the Cdendro software (Cybis Elektronik & Data AB, Version 7.7, 2020) so that the cross-correlation index (CC) was > 25 for each sample.

Data on precipitation and temperature were used from the Trutnov meteorological station of the Czech Hydrometeorological Institute. The weather station located in the town of Trutnov was used for this study. This meteorological station is 24 km from the studied area with an altitude of 460 m a.s.l. (50°34'10.9''N, 15°54'42.0''E). The analysed period was intentionally chosen as the years from 1961 to 2018 because of the availability of climate data (precipitation, temperature). Data on maximum SO_2 depositions were represented by the arithmetic mean of data from 5 measuring stations (Hony, Souš, Jizerka, Bedřichov,

https://doi.org/10.17221/94/2020-JFS

Šerlich) situated in the Sudetes Mountains nearby. Data sets of SO_2 maximum of each included station were incomplete due to short periods of recording. The stations were located 1 (the closest station Hony) to 68 km from the research plot and in an altitudinal range of 510–905 m. The station Hony recorded SO_2 measurements during the period 1970–2012. Solar activity data used originated from the World Data Center SILSO (WDC-SILSO 2020), Royal Observatory of Belgium, Brussels.

Data analysis. All data were processed by the R software (Version 3.6.0, 2019) using dplR (Zang et al. 2018), signal (Ligges et al. 2015) and waweslim packages (Whitcher 2020). Two steps in detrending were used. Detrending of samples was calculated by the negative exponential function in the first step. In the second step of detrending a spline evaluated as 2/3 of the age for each tree sample was used. The spline for the second step of detrending was evaluated for each tree individually based on the age of the sample and the values of the spline ranged from 113.3 to 140.0. The mean dendrochronological curve was calculated as the mean from each detrended tree sample. The used detrending maintained low-frequency variability and removed the age trend at the same time (Shumilov et al. 2011). Detrended tree-ring series of individual trees were averaged. The 8-year spline was calculated from the mean detrended data curve to remove yearly short-time fluctuations. Detrended data series were used for the spectral analysis by the "redfit" function or Schulz's REDFIT (version 3.8e, 2002) program when this function estimates the red-noise spectrum of a time series (Schulz, Mudelsee 2002) with an optimum testing spectrum against the red-noise background using the analysis of Monte Carlo simulations. This computation was done following the instructions for R according to Bunn and Korpela (2018b).

Basic dendrochronological indicators were computed according to the procedure for dplR (Bunn, Korpela 2018a). For detrended tree ring growth data the basic dendrochronological indicators were computed like the expressed population signal (EPS). The EPS is a confidence of dendrochronological data in relation to testing reliability against climate data. The inter-series correlations (R-bar) were computed. The R-bar is a correlation between dendrochronological series/samples (Fritts 1976). These indicators were computed for the used period 1961–2018. The EPS in our study is larger than 0.85, which is a significant level for the climate calculations (Wigley et al. 1984).

Correlations between radial growth, air temperature, precipitation, sunspots and maximum SO_2 depositions were computed in Statistica 13 software (Version 13.5.0.17, 2018). A situation map was made in ArcGIS 10 software (Version 10.8, 2020).

Since 1961 there have been five sunspot cycles on the Sun's surface that are chronologically numbered as solar cycles 20 to 24. All used data series were divided according to the time span of solar cycles into five sections. Each solar cycle was divided according to the years determined from the World Data Center SILSO (WDC-SILSO 2020). The sunspot cycles in this study are defined by the sunspot number and year window which are as follows: cycle 20 in 1964–1976; 21 in 1976–1986; 22 in 1986–1996; 23 in 1996–2008; 24 in 2008–2018.

RESULTS

The basic dendrochronological description of European beech chronology indicates that the EPS indicator (0.91) is sufficiently significant for a climate analysis (Table 1). The mean tree-ring width of European beech in Broumovské stěny NNR reached 1.87 mm with growth variability (standard deviation) 0.7 mm. The inter-correlation (R-bar) value, describing the similarity of tree samples to each other, was 0.26.

Figure 2 documents that the solar cycles impact on radial growth of European beech. The influence of solar cycles on European beech growth is evident almost in every solar cycle. Radial growth of European beech in Figure 2 copies rises and falls of solar activity but there are also exceptions when this phenomenon was dispelled. This phenomenon was dispelled by the impact of air-pollution load (high

Table 1. Overview of the basic research plot characteristics and dendrochronological description

Plot name	Exposure	Altitude (m)	Tree height (m)	Diameter (cm)	Forest type	Stand stocking	Age range	No. of samples	Mean tree-ring (mm)	St. dev.	R-bar	EPS
Broumov	East	620	36	53	5A2	0.8	150–210	30	1.87	0.7	0.26	0.91

St. dev – standard deviation; R-bar – inter-correlation; EPS – expression population signal

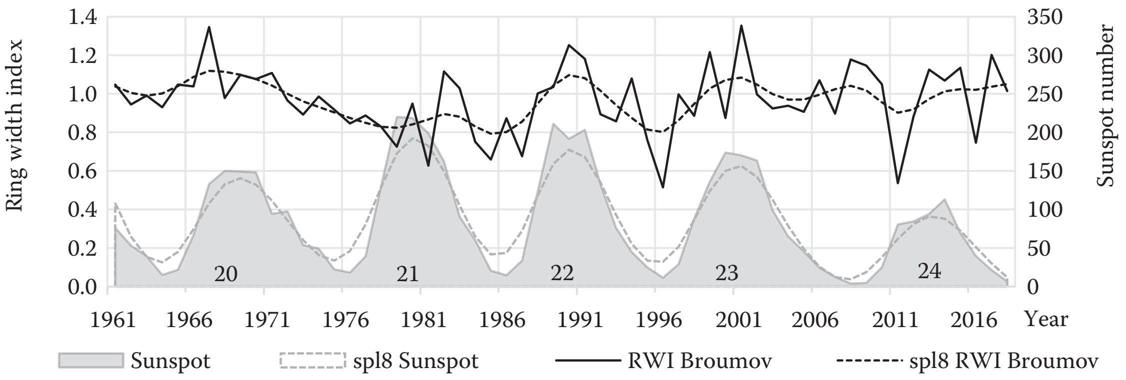

Figure 2. Tree-ring width index of European beech growth and annual number of sunspots in the period from 1961 to 2018

spl8 – eight-year spline; RWI – tree-ring width index; numbers 20, 21, 22, 23 and 24 – solar cycle numbers

SO_2 concentration) lasting from 1970 to 1987 and by heavy spring frosts in 2011. Since 2000, the impacts of global climate change that disturbs the parallelism of European beech radial growth to solar cycles have been increasing. Figure 2 illustrates a long-term effect of solar activity on European beech radial growth, which is well described by eight-year splines where short-term fluctuations in studied data have been removed. The splines demonstrate the parallelism of radial growth and solar activity. Three solar cycles 20, 22 and 23 are almost clearly reflected in European beech radial growth by a higher increment during solar maximum (Figure 2).

Figure 3 illustrates the correlation coefficients of radial growth with annual precipitation and with growing-season temperatures (May–September). Figure 3A documents that the correlations of solar activity, seasonal temperatures and annual precipitation vary during each solar cycle. The air pollution disaster had a negative impact on European beech radial growth in the 70s to the 80s of the 20th century, i.e. during solar cycle 21, but the increment response to precipitation was negative during that cycle (Figure 3). However, the correlation of SO_2 with radial growth during solar cycle 21 is not significant and it even shows positive values. This positive correlation can be caused by the short-term synchronization of data before the culmination

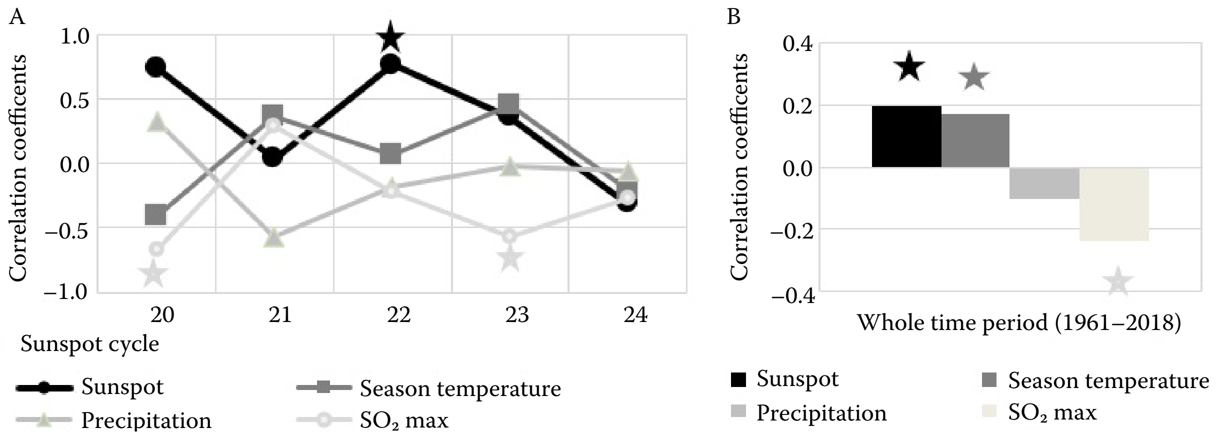

Figure 3. Correlation coefficients (r) of the tree-ring width index with precipitation, seasonal air temperature in the vegetation period, sunspot number and maximum SO_2 concentration; (A) correlation coefficients of the evaluated factors in individual solar cycles; (B) correlation coefficients for the entire time period 1961–2018; the sunspot cycles are defined by the number and year window: 20, 1964–1976; 21, 1976–1986; 22, 1986–1996; 23, 1996–2008; 24, 2008–2018 (statistically significant values are marked with asterisk for A at $P < 0.05$ and for B at $P < 0.20$)

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of SO_2 air pollution in 1987, and even at the same time the correlation with temperatures increased. The correlations of solar activity with radial growth indicate the culmination of coefficients in solar cycle 22. The total correlations demonstrate that the solar activity has the highest correlation coefficient (Figure 3B), but these results indicate a statistically significant result at $P < 0.20$. Our results also confirm the high significant correlation of the SO_2 air pollution load with beech radial growth. The evidence of negative correlation between tree growth and SO_2 concentrations was recorded in Figure 2 (in the years from 1970 to 1987) and Figure 3B, where we recorded the highest negative significant correlation ($r = -0.2386$; $P < 0.20$) with the maximum SO_2 values during the entire time period. Our results also show significant correlations with the maximum values of SO_2 concentrations in Figure 3 during solar cycle 20 and 23. Additionally, we found a significant correlation ($r = 0.315$) of radial growth with maximum values of SO_2 and there was even the significant cross-correlation, where Lag reaches up to –2 years.

The spectral analysis of data (Figure 4) from 1961 to 2018 indicates that every investigated factor repeats statistically significant cycles. Tree-ring width index in Figure 4A contains 3.7- and 7.5–11-year cycles. The results also describe the influence of 11-year and 22-year solar cycles in the data for the number of sunspots (Figure 4B) while the periods from 9- to 13-years are also statistically significant. The seasonal temperature (Figure 4C) contains 3.2- and 6–8-year cycles. Precipitation total in the growing season (from May to September) in Figure 4D repeats cycles after 2.3 and 3.3 years. At the same time, the tree-ring width index of European beech shows a cyclical interrelation between temperatures and solar cycles. Precipitation total in the growing season does not have a directly significant period consistent with the tree-ring width index of European beech.

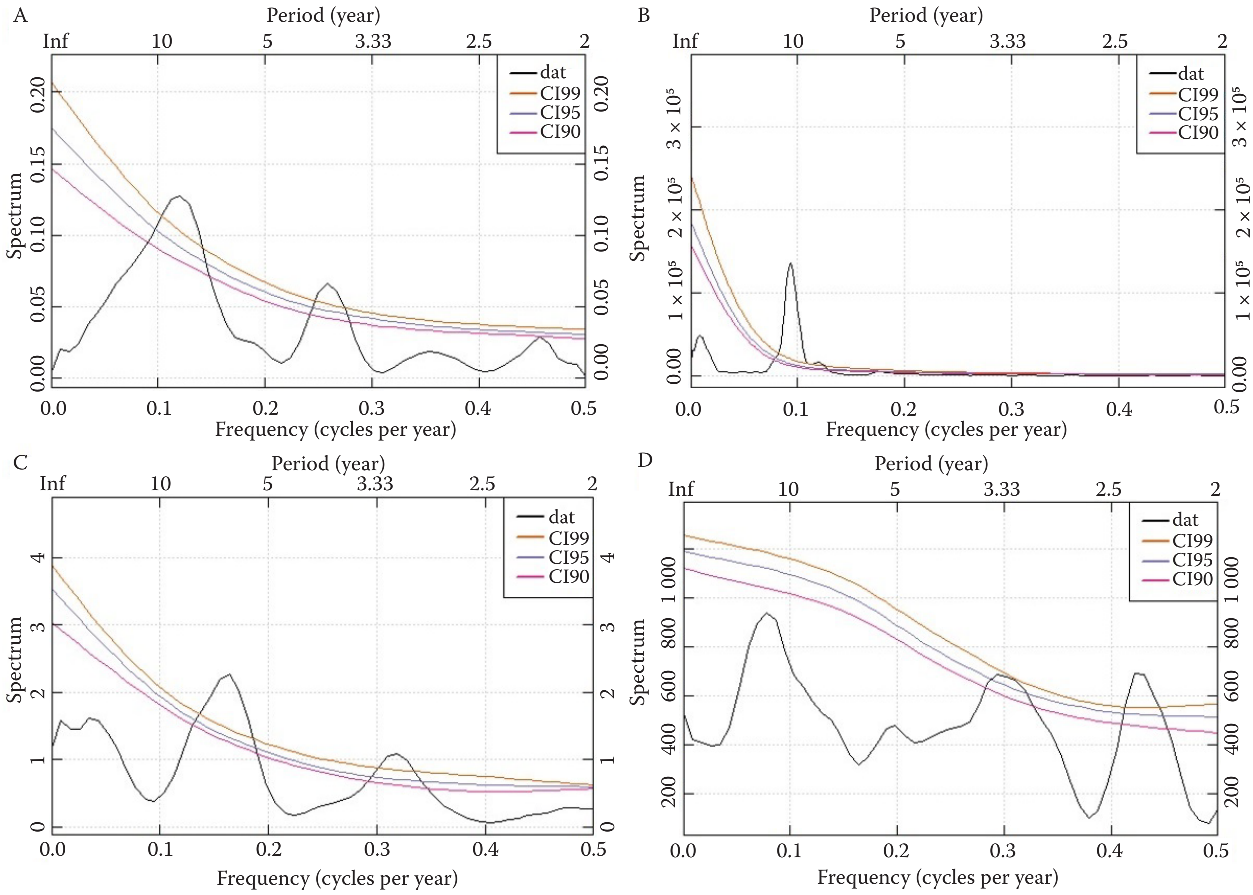

Figure 4. Spectral analysis of data sets in the time period 1961–2018; (A) tree-ring width index of European beech; (B) annual number of sunspots; (C) average seasonal temperature; (D) seasonal precipitation

The lower parabolic line – significant at 90%; the middle line – significant at 95%; the upper line – significant at 99%; inf. – infinity

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DISCUSSION

Solar cycles are associated to climate change and temperature differences on the planet Earth's surface. Solar cycles are assumed to influence temperatures and precipitation indirectly (Šimůnek et al. 2020, 2021). Some studies describe a possible association of low sunspot activity with climatically cold periods on the Earth (Easterbrook, 2016; Lockwood et al. 2017). Other studies even show the link between climate, cosmic rays and solar cycles (Kniveton 2004; Hathaway 2015; Ormes 2018). The influence of solar cycles on European beech radial growth is recorded in 3 of the 5 cycles (20, 22 and 23) (Figure 2), when the tree ring increment rises or falls together with the sunspot number during the approximately 11-year period, which is the sunspot cycle (Hathaway 2015). Our results indicate (Figure 3b) that there is a positive correlation of temperatures and sunspot number with radial growth. Nevertheless, the solar activity need not always be directly contained in tree ring analyses because other natural conditions disturb the parallelism of radial growth to solar cycles.

Radial growth in the period from 1970 to 1987 was influenced by an air-pollution load described by many authors from the Sudetes mountain range (Král et al. 2015; Putalová et al. 2019; Vacek et al. 2019b). The large influence of the SO_2 air pollution load is also evident from Figure 2 (in the years from 1970 to 1987) and Figure 3B, where we recorded the highest negative correlation (r = –0.2386) with the maximum SO_2 values. Our results recorded significant correlations with the maximum annual values of SO_2 concentrations in Figure 3 during solar cycle 20 and 23. This period of extremely high mean SO_2 concentrations was characterized by values reaching 57.4 $\mu g \cdot m^{-3}$ (maximum daily concentration 1 000 $\mu g \cdot m^{-3}$) (Vacek et al. 2020b), while the limit of vegetation damage according to the Czech Air Protection Act is 20 $\mu g \cdot m^{-3}$. Similarly, in the study area of Broumovsko PLA, diameter increment of Scots pine (*Pinus sylvestris* L.) was significantly negatively correlated with SO_2 concentrations in the growing season, especially in June-August and on more exposed sites in the 1980s and 1990s (Vacek et al. 2017). In general, it was proved that in the Orlické hory Mts. not far from here there was a decrease in European beech radial growth during the air-pollution load (Králíček et al. 2017). This paper showed a significant negative effect of maximum daily SO_2 concentration on radial growth of European beech, especially in the growing season.

Late frosts, which are a significant issue in cultivating forests all over Central Europe, are another important factor that disturbs the parallelism of the tree ring curve to solar activity (Gallo et al. 2014). Late frosts can reduce radial growth of European beech by more than 90% and the frequency of frost-related growth minima increases with altitude (Dittmar et al. 2003). The effect of low temperatures at the beginning of the growing season in 2011 was documented (Šimůnek et al. 2019, 2021). The research from European beech forests in Germany also documented the strong negative effects of a severe late spring frost event in early May 2011, following after warm April (Príncipe et al. 2017).

Another significant element diminishing the correlations between solar cycles (Figure 3A) and European beech radial growth in the last two solar cycles (23 and 24) may be the increasing CO_2 concentration in atmosphere that causes an increase in European beech radial growth, which was proved in southern and Central Europe (Rezaie et al. 2018). Simultaneously, global temperature was affected due to increasing CO_2, which disturbed the natural process of solar cycles in relation to climate (Kristoufek 2017). A decreasing correlation could be linked to the effect of solar activity on climate change, where both factors are associated with the changes in the North Atlantic Oscillation (NAO) (Lüdecke et al. 2020). Many studies have also described that the effect of solar activity has an impact on precipitation and temperature (Mauas et al. 2016; Baker et al. 2018). Temperatures on the European continent correlate with NAO mainly during the winter and spring seasons (Lüdecke et al. 2020). Even the wind currents in the highest parts of the atmosphere (jet streams) are linked with solar cycles, where these wind currents are blocked during solar minimum (Adolphi et al. 2014; Gray et al. 2016), which leads to colder winter seasons (Ma et al. 2018).

However, the total correlation (Figure 3B) with radial growth documents that solar activity has the highest positive significant (P < 0.20) correlation coefficient. Our results of positive correlations are supported by the latest research on the beech radial growth from the Krkonoše Mountains, where a high significant correlation with solar cycles was revealed (Šimůnek et al. 2020). This current research is also supported by the results from

https://doi.org/10.17221/94/2020-JFS

southern Italy that also reported the high correlation levels with solar cycle; however, this effect was significantly negative on radial growth in that area (Šimůnek et al. 2021). A long-term influence of solar cycles on the radial growth of Scots pine was investigated in the East European Plain (Matveev et al. 2017) or northwestern Russia, where the sunspot cycles may be imprinted through the spectral composition of solar radiation along with other factors such as cosmic rays or aa index (aa index – summary of the geomagnetic field variations) (Kasatkina et al. 2019).

The spectral analyses of results (Figure 4B) indicate the best known 11-year cycle of solar activity when also the 22-year solar magnetic cycle is important (Livingston, Penn 2009). The spectral analyses of this study suggest similar conclusions like those from northwestern Russia, where the 11-year influence of solar cycles on tree-ring increment of Scots pine was proved (Shumilov et al. 2011; Kasatkina et al. 2019). Our results document that 3.7-year periods are reflected in diameter increment of European beech. Air temperature in the growing season has a higher correlation with the radial growth of European beech (Figure 3) than precipitation total. The prevailing significant positive effect of temperatures from April to August in mountainous areas was confirmed by other studies from the Czech Republic (Šimůnek et al. 2019), Germany (Dulamsuren et al. 2017) or Italy (Skomarkova et al. 2006). A study from Sweden demonstrated a 2- to 3-year delay of seed production behind radial growth and documented a great influence of seasonal temperatures on the seed production of European beech (Drobyshev et al. 2010), which may evoke a theoretical question whether 3-year sunspot cycles are associated with the seed production cycles of European beech. At the same time, the radial growth of European beech (Figure 4) shows a cyclical interrelation between temperature and solar cycles.

CONCLUSION

The analysis of dendrochronological time series from the Broumovské stěny National Nature Reserve indicates an association between radial growth of European beech and sunspot number. Among the studied factors influencing European beech radial growth the highest positive significant total correlation was found out for sunspot number and then for seasonal air temperature. The maximal SO_2 depositions indicate the higher negative correlation coefficient than sunspot number during the entire time period in 1961–2018. Individually correlated solar cycles respond to precipitation total, growing-season air temperatures and sunspot number in a different way. The spectral analysis demonstrates that the radial growth of European beech shows 3.7-year and 7.5- to 11-year cycles when the 7.5–11-year period reflects the interrelation between the cycles of seasonal temperatures and solar activity. In conclusion, this study confirms that radial growth is influenced by solar activity and growing-season temperatures. More studies from different localities are needed to generalize the results. Studies of this type can help forest managers better understand cyclical regularities of forest tree species growth.

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