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ORIGINAL PAPER

Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts.

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Abstract
The negative effect of air pollution on mountain spruce stands culminated in the 70s – 90s of the 20th century, when an extensive dieback and disturbance of stands occurred in the Krkonoše Mts., the Czech Republic. Dendrochronological analysis was used on ten permanent research plots established in 1976–1980 to document the dynamics of radial increment of Norway spruce (*Picea abies* [L.] Karst.). The objective was to determine the effect of SO_2, NO_X and O_3 concentrations and precipitation and temperatures on spruce radial growth in climax forests, waterlogged forests and cultivated forests. The results document the strong depression of diameter increment in the period 1979–1991 caused by synergism of climatic extremes and high SO_2 pollution in the 80s and 90s of the 20th century. After 2000 climate had prevailing effect on radial growth. Spruce increment was in positive correlation with temperature, particularly with temperature in the growing season and annual temperature of the current year. In general, temperature had a more significant effect on increment than precipitation, mainly in climax and peaty spruce stands. Diameter increment was in significant negative correlation with SO_2 and NO_X concentrations in all types of stands. Overall, peaty spruce stands were the most vulnerable to air pollution stress. Low radial increments were caused also by climate extremes, historically by strong frosts and winter desiccation in early spring, nowadays in time of climatic changes by extreme drought. Spruce stands have the ability of quickly responding by tree-ring width to both negative and positive impulses related with air pollution and climate.

Key words: *Picea abies*; dendrochronology; SO_2 concentration; climate factors; Central Europe

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1. Introduction

The effect of air pollutants on mountain spruce stands in Central Europe had been observed since the 50s of the 20th century and culminated in the 70s – 90s of the 20th century (Vacek et al. 1996; Modrzyński 2003; Hůnová et al. 2004; Vacek et al. 2017a) while this effect has persisted to a smaller extent until now (Godek et al. 2015; Kolář et al. 2015; Vacek et al. 2015). The impacts of the extensive forest decline in the Sudetes Mts. system and especially in the Black Triangle area will be observable for many decades (Kandler & Innes 1995; Grodzińska & Szarek-Lukaszewska 1997; Lozenz et al. 2008). A great expansion of the power generation industry along the frontiers of Germany, the Czech Republic and Poland and the prevailing airflow from the west caused a substantial increase in air pollution in the area of interest of the Jizerské hory, Krkonoše and Orlické hory Mts. (Grübler 2002; Vacek et al. 2003, 2007; Blaś et al. 2008; Vacek et al. 2013a; Kolář et al. 2015). Large plots of mostly spruce stands above 1,000 m a.s.l. suffered great damage or died in these areas and due to air pollution disturbance ca. 21,000 ha of stands were felled there (Vacek et al. 2007). Similar destruction of forest ecosystems occurred also in the Polish part of the Sudetes Mts. range (Slovik et al. 1995; Modrzyński 2003; Godek et al. 2015). Such damage was aggravated by strongly acid deposition often related with frequent occurrence of horizontal precipitation and limited buffering capacity of Podzols on the bedrock built of granite, mica schists and phyllites (Hruška & Cienciala 2003; Podrázský et al. 2003; Vacek et al. 2006; Matějka et al. 2010). This air pollution disaster was an impulse for a radical reduction of the air pollution load, mainly of SO_2 concentrations, after 1989 (Vacek et al. 2007; Stjern 2011; Lomský et al. 2012).

Very high concentrations of emissions and especially of SO_2 had a great impact on the radial growth of the

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studied peaty spruce stands as a consequence of huge physiological stress because these stands are located at the boundaries of their ecological valence (Vacek et al. 2015). Tree-ring width is considerably reduced by heavy air pollution (Sander & Eckstein 2001; Wilczyński 2006) that can result even in a complete disintegration of forest stands in extreme cases (Lomský & Šrámek 2002). The variability of tree-ring width is also influenced by other environmental agents, mainly climatic factors (temperature, precipitation, wind, wet snow, icing, winter desiccation), insect pests (*Ips typographus*, *Ips duplicatus*, *Zeiraphera griseana*, *Cephalcia abietis*, *Pachynematus montanus*), fungal pathogens (*Armillaria mellea*, *Heterobasidion annosum*, *Ascocalyx abietina*), etc. (Schweingruber 1996; Vacek et al. 2007; Štefančík et al. 2012; Trotsiuk et al. 2014). Among the climate factors air temperature is very important for the growth of Norway spruce (*Picea abies* [L.] Karst.) at mountain and high-altitude locations (Büntgen et al. 2007) while it is mentioned as one of the crucial factors of an increase in forest stand increment (Linder et al. 2010). Air temperatures can increase the radial growth of spruce if summer is warm and the growing season is longer (Vaganov et al. 1999; Vacek et al. 2015). Other factors influencing increment and related with climate change at the same are variations in sum of precipitation, increase in atmospheric CO_2 (Churkina et al. 2007; Eastaugh et al. 2011) and increased N depositions (de Vries et al. 2009). However, these factors need not always lead to an increase in increment, but they can sometimes cause its decrease (Etzold et al. 2014).

Growth responses to the above-mentioned environmental agents are sufficiently prompt to be a suitable indicator of forest ecosystem degradation (Godek et al. 2015; Parobeková et al. 2016). The impacts of ongoing climate changes have already been supported by empirical evidence from long-term permanent research plots that has indicated an increase in stand productivity in central and eastern Europe in the latest years (Hlásny et al. 2014; Lindner et al. 2014; Pretzsch et al. 2014; Král et al. 2015; Vacek et al. 2015). This has also been supported by dendrochronological studies that document the radial growth of Norway spruce at high-altitude locations of central Europe (Savva et al. 2006; Büntgen et al. 2007; Treml et al. 2012; Král et al. 2015). More frequent various types of disturbances are a consequence of ongoing climate changes (Splechtna et al. 2005; Seidl et al. 2014; Panayotov et al. 2015). Thus ongoing climate changes may significantly influence growth trends of trees and document their growth response to these changes (Grace et al. 2002; Di Filippo et al. 2012; Pretzsch et al. 2014), therefore the effect of climate changes on forest productivity is traditionally the focus of foresters' interest (Bontemps & Bouriaud 2013; Hlásny et al. 2017). Nevertheless, temporal anomalies in climate can be separated within growth trends as they are similar in all stands of the same tree species in the given area, whether under the influence of air pollution or not, similarly like in biotic pests (Vinš & Mrkva 1973; Ferretti et al. 2002; Sensuła et al. 2015). This is probably the reason why forest stand productivity was studied particularly at smaller spatial scales (Bošeľa et al. 2013; Socha et al. 2016). This study should help elucidate this relatively extensive problem in specific conditions of the Krkonoše Mts. because in spite of better knowledge of the warming effect there are still many questions to be answered (Bošeľa et al. 2016). In addition, particular studies of climate impacts on tree growth substantially differ in the type of data and statistical methods used (Peters et al. 2015).

The objective of the present research is to evaluate the impact of air pollutants and climate factors on the radial growth of climax spruce forests, peaty spruce forests and cultivated spruce stands at sites of acidophilic mountain beech forests in the Krkonoše Mts. The paper covers the following questions: (1) How have air pollutants and climate influenced the radial growth of climax, peaty and cultivated types of spruce stands?; (2) What was the effect of SO_2, NO_X and O_3 concentrations on the radial growth of various types of spruce stands?; (3) How have average monthly air temperatures and monthly sum of precipitation influenced the radial growth of various types of spruce stands since 1975? The greatest effect of air pollutants and climate extremes is assumed in peaty spruce stands and the smallest effect in cultivated spruce stands at sites of acidophilic mountain beech forests.

2. Material and methods

2.1. Study area

The territory of interest consists of 10 permanent research plots (PRP) located in the Krkonoše National Park, in the northern part of the Czech Republic at the frontier with Poland. Within an extensive network of PRP the selected plots were originally established in 1976–1980 when on the other spruce PRP all trees died due to an extreme air pollution disaster. The bedrock of the territory of interest is composed of granite, mica schist and phyllite. The prevailing soil type on PRP is Podzol, Cryptopodzol and Organosol. Average annual sum of precipitation is between 800 and 1,400 mm and average annual temperature is in the range of 3–6 °C (Vacek et al. 2007). Growing season lasts 70–120 days in dependence on the altitude above sea level (710–1,250 m a.s.l.) with average precipitation around 670 mm and temperature of 9 °C. Fig. 1 illustrates the localization of PRP and Table 1 shows basic site and stand characteristics of PRP. These PRP are typical of climax spruce forests, peaty spruce forests and spruce stands at sites of acidophilic mountain beech forests in the Krkonoše Mts.

From the aspect of emissions, SO_2 concentrations had increased since 1972 in connection with the operation of large power stations EPO II in Poříčí near Trutnov and Polish power station Turow, burning low-quality brown coal with a high content of sulphur (Vacek et al. 2007). In

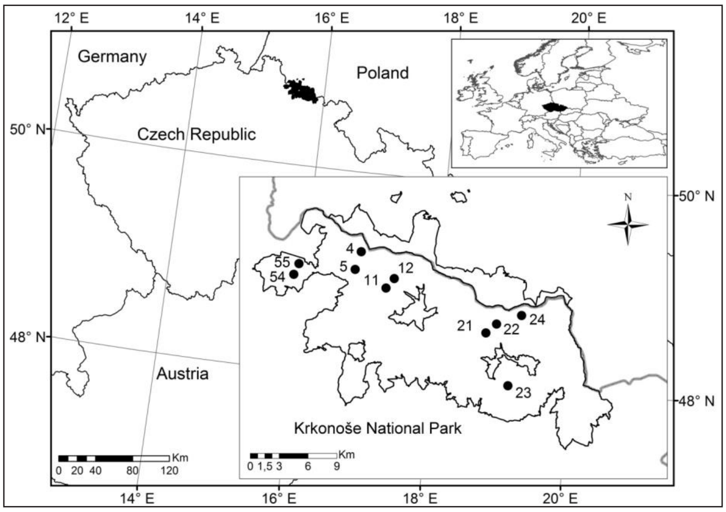

Fig. 1. Location of Norway spruce forest stands on permanent research plots in the Krkonoše Mts.

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

ID	GPS	Altitude [m]	Exposition	Slope [°]	Forest site type[1]	Geology	Soils	Air pollution threat zones[2]	Age [year]	Mean breast diameter [cm]	Mean height [m]	Volume [m^3 ha^{-1}]
						Climax spruce stands						
5	50°45´69´´N 15°30´68´´E	1,130	N	17	8G	Granite	Gley	B	251	64.0	20.8	296
11	50°44´99´´N 15°33´81´´E	1,220	NE	29	8Z	Granite	Podzol	A	228	47.6	14.3	114
12	50°45´02´´N 15°33´83´´E	1,170	NE	26	8Z	Granite	Podzol	B	228	54.6	21.2	167
21	50°43´18´´N 15°42´45´´E	1,230	S	21	8Z	Schist	Podzol	B	142	47.8	21.9	548
22	50°43´62´´N 15°43´51´´E	1,160	E	32	8Y	Schist	Podzol	B	157	39.0	21.4	387
24	50°43´89´´N 15°45´29´´E	1,250	SE	20	8Z	Schist	Podzol	B	199	49.3	22.2	314
						Peaty spruce stands						
4	50°46´62´´N 15°30´54´´E	1,180	SW	12	8R	Granite	Organosol	A	231	46.7	21.4	181
23	50°39´54´´N 15°44´63´´E	1,190	NE	4	8R	Gneiss	Organosol	B	195	33.0	22.2	180
						Cultivated spruce stands						
54	50°45´59´´N 15°24´29´´E	710	NE	6	6K	Phyllite	Crypto-podzol	C	113	22.1	12.1	300
55	50°46´14´´N 15°25´06´´E	720	NE	8	6K	Phyllite	Crypto-podzol	C	120	29.2	18.2	407

Explanatory notes: Forest site type[1] according to Czech forest ecosystem classification (Viewegh 2003) used from the Forest Management Institute: 8G – Nutrient-medium wet spruce forest (*Piceetum paludosum mesotrophicum*), 8Z – Rowan-spruce forest (*Sorbeto-Piceetum humile*), 8Y – Skeletal spruce forest (*Piceetum saxatile*), 8R – Raised bog spruce forest (*Piceetum turfosum montanum*), 6K – Acidic spruce-beech forest (*Piceeto-Fagetum acidophilum*); Air pollution threat zones[2]: A – period of forest disintegration – 20 years, B – 40 years, C – 60 years, D – 80 years.

the period from 1980 to 1991 average annual SO_2 concentrations were in the range of 10 to 35 µg m^{-3} and maximum daily concentrations varied from 60 to 280 µg m^{-3} (Drda 1994; Král et al. 2015). A substantial decrease in SO_2 concentrations in the air occurred at the end of the 20th century when the range from 5 to 20 µg m^{-3} was reached (Schwarz 2001). Currently, average concentrations of SO_2 and NO_X are around 3 and 8 µg m^{-3}, respectively, and the O_3 exposure index AOT40F is 25,000–28,000 ppb h^{-1}.

2.2. Data collection

Data for the analysis of growth relations were acquired by taking cores at a height of 1.3 m with the Pressler borer (Mora Sweden) from 30 living dominant and codominant spruce trees that were randomly selected (RNG function in Excel) on each plot of 50×50 m in size (0.25 ha). The samples were taken in upslope/downslope direction in autumn 2015. In a laboratory tree-ring widths were measured to the nearest 0.01 mm with Olympus binoculars on a LINTAB measuring table and recorded by the TsapWin programme (© Rinntech).

To derive stress factors related with air pollutants and climate recorded data from air quality monitoring stations and from meteorological stations were used. Available data from the Desná-Souš Station (772 m a.s.l.; GPS 50°47´21´´N, 15°19´11´´E) were used for an analysis of the air pollution situation according to SO_2 (1975–2015), NO_X concentrations (1992–2012) and AOT40F

(1996–2012). For this evaluation average annual and maximum daily values of SO_2 and NO_X concentrations given in μg m^{-3} and in ppb h^{-1} for AOT40F were employed. The effect of climate with respect to temperature and precipitation conditions was evaluated on the basis of data from meteorological station in Pec pod Sněžkou (1975–2015; 656 m a.s.l.; GPS 50°18´24´´N, 16°21´07´´E). Data on average annual temperatures, growing season temperatures, temperatures in particular months, minimum and maximum temperatures, annual sum of precipitation, sum of precipitation in growing season, precipitation in particular months, minimum and maximum precipitation in 1975–2015 were used to describe the development of temperature and precipitation conditions.

2.3. Data analysis

The studied forest stands were divided into three basic groups: climax spruce forests, peaty spruce forests and cultivated spruce forests at sites of acidophilic mountain beech forests. Tree-ring increment series were individually crossdated (to remove errors caused by missing tree rings) using statistical tests in the PAST application (Knibbe 2007) and subsequently they were subjected to visual inspection according to Yamaguchi (1991). If a missing tree ring was revealed, a tree ring of 0.01 mm in width was inserted in its place. Individual curves from PRP were detrended and an average tree-ring series was created in the ARSTAN programme (© Cook, Tree Ring Laboratory). Negative exponential spline and year splines were used for detrending (Grissino-Mayer et al. 1992). The analysis of negative pointer years was done according to Schweingruber (1990) and Desplanque et al. (1999). For each tree the pointer year was tested as an extremely narrow tree ring that does not reach 40% of the increment average from the four preceding years. The occurrence of the negative year was proved if such a strong reduction in increment occurred at least in 20% of trees on the plot. To express the relationship between climate characteristics (monthly average temperatures and sum of precipitation in particular years) and radial increment the DendroClim software was used (Biondi & Waikul 2004). To analyse the effect of overall meteorological conditions on radial growth, Sielianinov hydrothermal coefficient (K; share of monthly sum of precipitation and average air temperatures) was used (Radzka & Rymuza 2015). To determine the combined effect of average annual temperature and annual sum of precipitation on diameter increment of spruce, regression quadratic model was used.

Data from the evaluation of diameter increment in relation to air pollution and climate factors were statistically processed by the Statistica 12 programme (© Statsoft, Tulsa). The data were tested for normal distribution by the Kolmogorov-Smirnov test. Differences in radial increment were tested by one-way analysis of variance (ANOVA). Subsequently, the differences were tested by post-hoc HSD Tukey's test. Average tree-ring series from PRP were correlated with climate data (precipitation, temperatures in 1975–2015 from the Pec pod Sněžkou Station) and air pollution data (SO_2 concentrations in 1977–2015, NO_x concentrations in 1992–2012 and AOT40F in 1996–2012 from the Desná-Souš Station) by the particular months and years. The principal component analysis (PCA) was run in CANOCO 5 programme (© Leps & Smilauer) to assess the relationship between the radial growth of climax, peaty and cultivated spruce forest stands, maximum and average concentrations of SO_2, precipitation and average temperatures all the year round, in the growing season (from April to September), out of the the growing season (from October of previous year to March of current year), in June to July and in January to March of the current and preceding year. Prior to the analysis the data were logarithmized and standardized. The results of multivariate PCA were visualized in an ordination diagram.

3. Results

3.1. Dynamics of radial growth of spruce forest stands

Comparison of the average tree-ring curves for the ten PRP shows a good fit between them (t-tests ≥ 7.1, Fig. 2). This consistency allowed the compilation of a local standard chronology for the spruce stands in the Krkonoše Mts. After the division of tree-ring width curves into three periods according to air pollution load (before 1960–1978, during 1979–1991 and after SO_2 load in 1991–2015), there were significant differences between these periods ($p<0.001$). Significantly lower increment was observed during air pollution load ($p<0.001$), when annual diameter growth reached only 49% of common growth in peaty stands, 58% in climax stands and 71% in cultivated stands.

The generally highest fluctuations in radial growth expressed by SD (standard deviation) were determined in peaty stands (mean±0.24) occurring at the boundary of ecological minimum while the relatively balanced growth curve was constructed for climax stands (mean±0.17). Specifically, the highest fluctuations in diameter increment (mean±0.43) were observed on climax PRP 11 situated in extreme climatic conditions of the timberline ecotone and turbulent space of the anemo-orographic system in the Labský důl locality. A pronounced effect of air pollutants and a decrease in radial growth persisted in peaty spruce forest for the longest time (1976–1992), but in cultivated spruce forest they persisted for the shortest time (1979–1989; Fig. 2). On the other hand, the regeneration trend in cultivated spruce forests after 1989 was not so pronounced. Its moderate stabilization was observed, but with many fluctuations, which was caused by frequent attacks of bark beetles in these two allochthonous stands, mainly in 1993–1997 and 2005–2007.

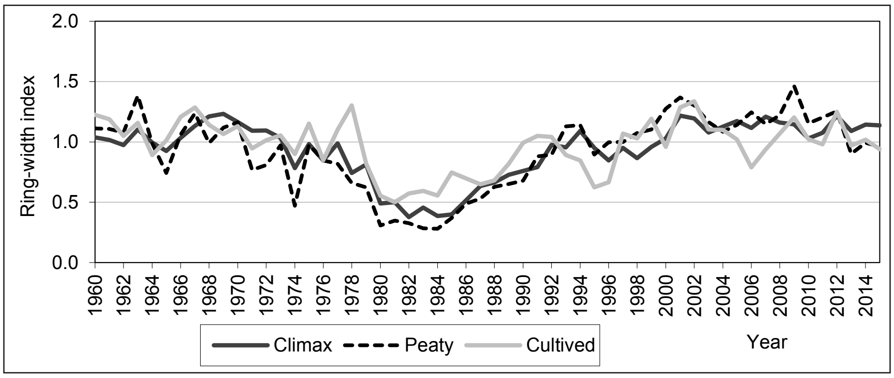

Fig. 2. Standard average tree-ring chronology for climax, peaty and cultivated spruce stands in the Krkonoše Mts. after removing the age trend in Arstan software.

The years 1980 and 1982 were found to be negative pointer years with very low radial increment in climax spruce stand, the years 1974 and 1980 in peaty spruce stand and only the year 1981 in cultivated spruce stand. Besides the period of an extreme air pollution load, low radial increments were caused by climate extremes, especially by extreme frosts and winter desiccation in early spring. With respect to temperatures the negative year 1980 was the coldest year in the history of climate measurements (3.4 °C, average of 1975–2015 – 5.0 °C) along with the coldest April (0.8 °C, average of 1975–2015 – 3.7 °C). In cultivated spruce stand, from the aspect of altitude above sea level with precipitation deficit, the negative year is potentiated by very low precipitation in the growing season (383 mm, average 558 mm). Currently (since 2013), an increment reduction is also caused by the low sum of precipitation in the growing season and by bark beetle feeding enhanced by drought.

3.2. Effect of climate factors and air pollution on radial growth of Norway spruce

Average diameter increment in 1975–2015 significantly more positively correlated with monthly temperatures than with precipitation (Fig. 3). Temperature exerted the highest effect on radial growth in climax spruce forests (6 significant months). Specifically for PRP, climate factors had the lowest influence on peaty spruce stand on PRP 4 (2 values), but they exerted the highest influence on climax spruce stand on PRP 11 in the timberline ecotone strongly influenced by a hilltop phenomenon (8 values) where the highest positive value of the correlation was determined in April of the current year ($r = 0.56$).

Considering the effect of monthly temperatures, average diameter increment was in positive correlation with June and August temperatures of the preceding year and with temperatures in February, March and in the growing season of the current year. The highest positive effect of temperatures on radial growth was observed in April ($r = 0.43–0.45$) and in June ($r = 0.30–0.44$; Fig. 3). In the relationship between monthly sum of precipitation and radial growth there was a significant negative correlation only with precipitation in April of the current year ($r = -0.29 – -0.39$).

The main factor influencing the diameter increment of spruce in study area according to regression quadratic model was identified the temperature (Fig. 4). Annul average temperature had significantly higher effect on radial growth compared to annual sum of precipitation. Diameter increment only slightly increased with increasing precipitation, while optimal growth was observed in

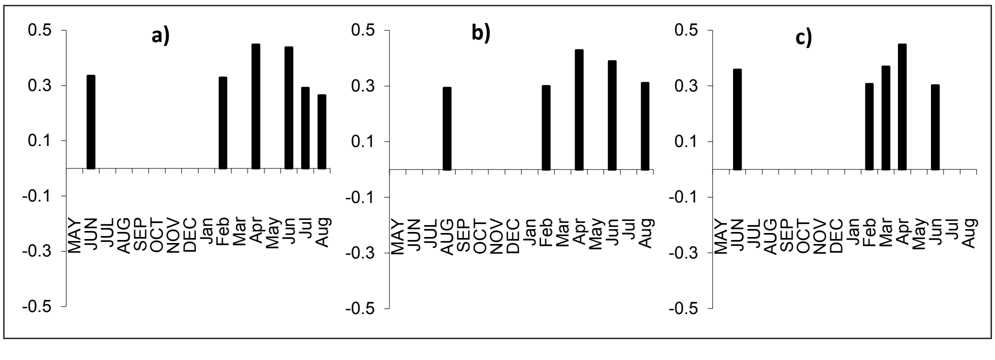

Fig. 3. Coefficients of correlation of the regional residual index tree-ring chronology of spruce with average monthly temperature from May of the preceding year to August of the current year in the period 1975–2015 in a) climax stands, b) peaty stands and c) cultivated stands; statistically significant ($p < 0.05$) values are highlighted in black (positively). Capital letters indicate the months of the preceding year and the lower-case letters the months of the current (given) year.

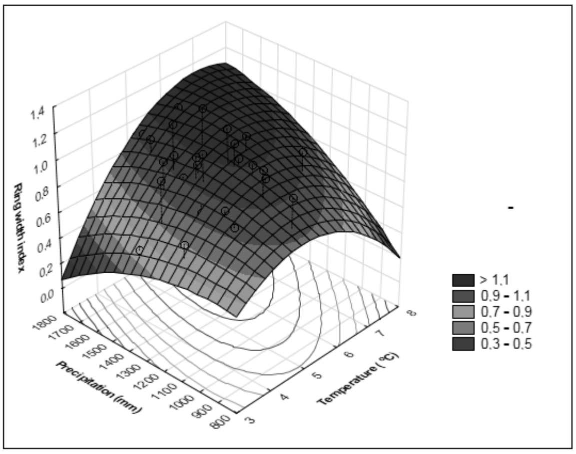

Fig. 4. Response of mean ring width index of spruce to annual sum of precipitation and annual mean temperature for all stands (regression quadratic model, years 1975–2015).

the range of annual air temperature from 5 to 6.5 °C. Only a small difference was found between variants of spruce stands, while the lowest effect of temperature on the growth was observed in a cultivated stand. According to hydrothermal index K, climate (combination of temperature and precipitation) had the significant positive impact on radial growth in April of the current year in peaty ($r = 0.40$, $p < 0.01$) and climax stands ($r = 0.36$, $p < 0.05$).

Correlations between the radial growth of climax, peaty and cultivated spruce forests and climate and air pollution factors are illustrated in Table 2. Of all studied factors maximum and average SO_2 concentrations had the highest negative effect on spruce radial growth ($p < 0.001$). Specifically for PRP, SO_2 concentrations had the highest negative effect on radial growth in peaty spruce stand on PRP 4 and on the growth of climax spruce stands on exposed PRP 11 and on waterlogged PRP 5 ($p < 0.001$), while the lowest effect was found out on PRP 54 ($p > 0.05$). NO_X concentrations were also in significant negative correlation with spruce radial growth. The exposure index AT40F had a negative effect on spruce radial growth, but it was not statistically significant ($p > 0.05$). The effect of temperature on spruce radial growth was significant. The highest effect on radial growth ($p < 0.001$) was exerted by average annual temperature and by average temperature out of the growing season of the current year. The radial growth of climax and peaty spruce stands was in strong correlation with average temperatures in June and July ($p < 0.001$). However, the precipitation did not have any significant effect on the radial growth of spruce stands ($p > 0.05$).

3.3. Interactions between radial growth of spruce, climate and SO_2 concentrations

The results of PCA are represented in an ordination diagram in Fig. 5. The first ordination axis explains 52.4% of data variability, the first two axes together explain 82.6% and the first four axes 92.4%. The x-axis illustrates the radial growth of spruce stands along with SO_2 concen-

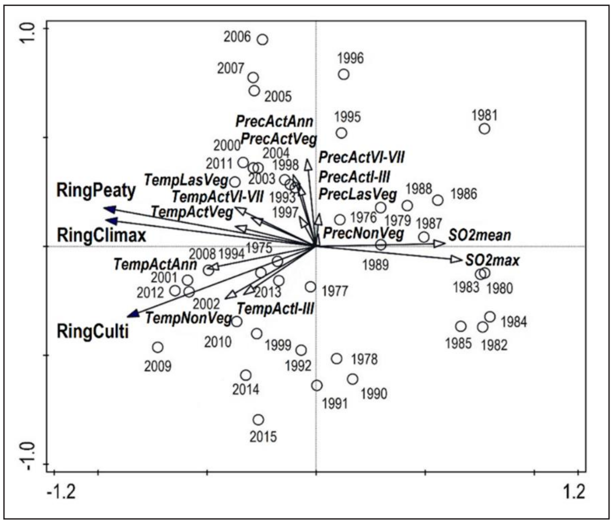

Fig. 5. Ordination diagram of PCA showing relationships between climate data (Temp – mean temperature, Prec – precipitation, Act – current year, Las – preceding year, Veg – growing season, NonVeg – non-growing season, I–III, VI–VII – months), SO_2 concentrations (mean – mean annual concentration, max – maximum concentration) and tree-ring width (Ring – tree-ring width) of climax, peaty and cultivated stands; codes – indicate years 1977–2015.

Table 2. Correlation matrix describing interactions between the radial growth of various spruce stands, precipitation and temperature (1975–2015) and concentrations of SO_2 (1975–2015), NO_X (1992–2012) and AOT40F (1996–2012). Significant correlations are designated by * ($p < 0.05$) and ** ($p < 0.01$).

Ring width index	SO_2 conc.		NO_X conc.		AOT40F	Temp.			
	mean	max	mean	max		ActAnn	ActVeg	LasVeg	NonVeg
	[µg m^{-3}]				[ppb h^{-1}]	[°C]			
Climax stands	−0.39**	−0.59**	−0.58*	−0.56*	−0.30	0.53**	0.42**	0.29	0.42**
Peaty stands	−0.48**	−0.62**	−0.61**	−0.63**	−0.33	0.45**	0.38*	0.33*	0.32*
Cultivated stands	−0.31*	−0.48**	−0.64**	−0.58*	−0.36	0.36*	0.14	0.16	0.44**

	Temp.		Precp.						
	ActI–III	ActVI–VII	ActAnn	ActVeg	LasVeg	NonVeg	ActI–III	ActVI–VII	Ring width
	[°C]		[mm]						
Climax stands	0.34*	0.46**	0.09	0.11	0.09	0.00	0.17	0.01	1.00**
Peaty stands	0.26	0.39**	0.09	0.10	0.07	0.01	0.15	−0.00	1.00**
Cultivated stands	0.34*	0.10	−0.04	0.05	0.09	−0.09	−0.06	−0.02	1.00**

Explanatory notes: $SO_2(NO_X)$mean – mean annual SO_2 (NO_X) concentration, $SO_2(NO_X)$max – maximum SO_2 (NO_X) concentrations, AOT40F – ozone exposure, TempActAnn – mean annual temperature of the given year, TempAct(Las)Veg – mean temperature in the growing season of the given (previous) year, TempNonVeg – mean temperature in the non-growing season, TempActI-III(VI–VII) – mean temperature in January–March (June–July) of the given year, PrecActAnn – annual sum of precipitation of given year, PrecAct(Las)Veg – sum of precipitation in the growing season of the given (previous) year, PrecpNonVeg – sum of precipitation in the non-growing season, PrecActI–III(VI–VII) – sum of precipitation in January–March (June–July) of the given year.

trations and the second y-axis represents the precipitation amount. SO_2 concentrations (average and maximum ones) are negatively correlated with spruce radial growth, especially in peaty and climax spruce stands. Spruce increment is in positive correlation with temperature, mainly with average temperature in the growing season and average annual temperature of the current year. Overall, the effect of temperature on increment is more significant in comparison with precipitation. Precipitation out of the growing season was the smallest explanatory variable in the diagram. In the first half of the studied period (the 80s and 90s of the 20th century) the increment was strongly influenced by SO_2 concentrations while in the second half of the studied period (after 2000) there was a closer correlation between increment and temperature.

4. Discussion

After the start of great air pollution stress in the Krkonoše Mts. in the late 70s and in the early 80s of the 20th century the synergism of air pollution, climate extremes and biotic pests caused substantial deterioration of the health status of spruce forests, which is evident not only on the foliage of these stands but also on the dynamics of radial growth (Král et al. 2015).

The regional standard tree-ring chronology in the Jizerské hory Mts. indicates a slow decrease in radial increment in 1979–1987. The situation was similar in mature spruce stands in mountain areas in the north of the Czech Republic (Sander et al. 1995; Kroupová 2002; Vejpustková et al. 2004; Kolář et al. 2015; Král et al. 2015; Vacek et al. 2015). These authors concluded that a heavy pollution load of mainly SO_2 emissions in the 70s and 80s of the 20th century in combination with climate factors was a cause of the increment decrease. Since the mid-1990s a gradual increase in radial increment has been observed until now. This period has been characterized by mild winters without great temperature extremes, relatively high temperatures in the growing season, more or less normal precipitation and also by a decrease in air pollution but with high NO_X depositions (Vejpustková et al. 2004). In our case the period of increased increment was interrupted by its pronounced decrease in the period 2008–2015.

A low radial increment was confirmed by the analysis of negative pointer years. In 1979 it was a consequence of the fast temperature drop at the turn of 1978/1979, when the temperature dropped by nearly 30 °C within 24 hours; in 1980–1986 it was due to the synergism of air pollution and climate stress, and in 1996 and 2010 it was mainly a result of winter desiccation of the assimilating organs in early spring (necrotic disorders of great extent).

Similar results of the pattern of diameter increment and its response to climate factors were obtained in the Orlické hory Mts., in peaty spruce forests in hilltop parts (1,035–1,075 m a.s.l.) and also in spruce stands in the environs of the Anenský vrch Hill at an altitude of 830–910 m (Rybníček et al. 2009; Vacek et al. 2015). Similarity mainly lies in an increment decrease from the 1970s approximately to the mid-1980s and in its increase in the 1990s of the 20th century. Some negative pointer years, 1979 and 1981, were identical.

By 1977 there was a clear relationship between the occurrence of negative pointer years and climate extremes when the forest stands respond more or less to the specific site and stand conditions in higher parts of the Krkonoše Mts. Similarly like in the Krkonoše Mts. in 1977–1992, this period was critical for spruce stands also in Jizerské hory Mts. in 1979–1986, in Orlické hory Mts. in 1979–1987 and in Krušné hory Mts. in 1977–1989. According to Kroupová (2002) increments of spruce were extremely low (a decrease by 50% on average) in the Krkonoše and Jizerské hory Mts. in 1979–1989. A high frequency of disorders in tree-ring formation was observed. The negative effect of air pollution stress was repeatedly proved in many other papers (e.g. Feliksik 1995; Juknys et al. 2002; Bošela et al. 2014; Vacek et al. 2017b). In the second half of the nineties of the 20th century radial increment was gradually increasing. An evident increase in spruce radial increment in that period was reported from the Orlické hory Mts. (Rybníček et al. 2009; Vacek et al. 2015; Králíček et al. 2017), from the Krkonoše Mts. (Kolář et al. 2015; Král et al. 2015) and from the western Polish Beskids by (Wilczyński & Feliksik 2005). The curves of regional standard chronology from our monitoring in the Krkonoše Mts. are consistent in principal features with the findings of Král et al. (2015), Kolář et al. (2015) from the Krkonoše Mts. and of Šrámek et al. (2008) from the Silesian Beskids. Bošeľa et al. (2016) also documented an increase in stand productivity in the whole of Central Europe in the second half of the 20th century, but they identified the years 1976 and 2003, when there was a very dry period with a negative impact on increment.

The interpretation of radial increment correlations with average monthly temperatures and precipitation is rather complicated because the growth process is influenced by a number of factors, particularly in peaty spruce stands in conditions of extreme frost hollows. A positive effect of rainfall in July of the preceding year and temperatures in July of the current year on radial increment can be explained by conditions in the period when a great part of radial increment is produced. This is consistent with the conclusions of Hlásny et al. (2017), who stated that increment of spruce was influenced mainly by rainfall in June at lower locations and by temperature at high altitudes above sea level.

A positive effect of temperatures in June and July, like in our study, was well documented in Norway spruce at many other mountain and high-altitude locations (Savva et al. 2006; Büntgen et al. 2007; Rybníček et al. 2010; Treml et al. 2012). July has been the warmest month of the year at these locations for a long time. Hence temperatures do not constrain the growth if the water reserve in soil is sufficient. If the water amount is reduced, stress as an increment decrease is usually manifested a year later. Similar results showing a positive effect of temperature in July and August on spruce growth were also obtained in foothills spruce forests in the Western Carpathians (Bednarz et al. 1999), in spruce forests on northern slopes of the Krkonoše Mts. (Sander et al. 1995; Král et al. 2015), in spruce stands in the Orlické hory Mts. (Rybníček et al. 2009; Vacek et al. 2015) and in the Polish Tatras (Feliksik 1972) or in spruce stands in Norway (Andreassen et al. 2006). Positive correlations of spruce radial growth with summer temperatures were also found out at lower altitudes above sea level in the French Alps (Desplanque et al. 1999) or in the Polish Beskids (Feliksik et al. 1994). The relationship between radial growth of spruce and temperature with precipitation during the growing season was described in a similar way in Germany by Kahle & Spiecker (1996), Dittmar & Elling (2004), in Finland by Mäkinen et al. (2001), in Switzerland by Meyer & Bräker (2001), within Central Europe by Zimmermann et al. (2015) and in Poland by Koprowski & Zielski (2006). The latter authors stated that along with climate factors (precipitation and temperature) the radial growth was also influenced by fructification, increased CO_2 level in the atmosphere, nitrogen compounds and UV radiation. Other factors influencing increment are competition (Rohner et al. 2016), nutrient availability (Weber et al. 2015) and biotic agents (Rolland et al. 2001).

The effect of October temperature of the preceding year is usually related with an extension of the short growing season. October and November can provide conditions allowing the root growth in the soil with hitherto favourable temperature above the frost point, supporting needle maturation, shoots and buds (Fritts 2001; Oberhuber 2004; Savva et al. 2006; Rybníček et al. 2010; Treml et al. 2012).

A negative effect of rainfall on radial increment in April of the current year in peaty spruce stands in the Krkonoše Mts. was reported by Král et al. (2015). According to Primicia et al. (2015) these relationships are substantially influenced by the stand structure. We observed this situation on plots that were most severely affected by air pollution and bark beetle disturbance in the late seventies and in the first half of the eighties of the 20th century. These were peaty spruce stands and forest stands in the timberline ecotone. Similar findings from mountain spruce stands at the timberline were reported by Vacek et al. (2010) and Treml et al. (2012) from the Sudetes Mts. range and by Parobeková et al. (2016) from the Low Tatras.

Climate changes and air pollution are integrating influences that affect in forest ecosystems species composition and species distribution, soil environment, health status, water availability and tree growth (Bytnerowicz et al. 2007), which is quite explicitly obvious from results of our study. Thus climate changes and particularly higher temperatures have clear impacts on the whole ecosystem. Higher temperature affects sum of precipitation and modifies the stand production and increases the weathering rate, which enhances the vulnerability of forest ecosystems (Posch 2002). The long-term climate data in the Krkonoše Mts. document that since the beginning of observations average annual temperature has increased by 1.0–1.5 °C and average annual sum of precipitation has decreased by 80–130 mm (Czech Hydrometeorological Institute). It is also necessary to take into account that the proportion of horizontal precipitation has declined considerably since the 1980s due to the destruction of studied forest stands, from 25% to 15% (Vacek et al. 2007). Rising annual temperature increases not only evaporation but also water transpiration by the assimilating organs (Vacek et al. 2015). In general, there occurs a substantial decrease of the water amount in the total water balance, and in some seasons of the year it causes water deficit and reduction in spruce increment (Kmet' et al. 2010; Vacek et al. 2013a, 2013b).

Climate changes can also make the problems of soil acidification worse because they increase the production and subsequent deposition of HNO_3 and NO into soils. They also participate in an increase in the portion of NH_3 converted into ammonium sulphate, which can lead to further soil acidification (Sanderson et al. 2006). The influence of climate changes on growth has a generally positive impact on the increment of forest stands investigated in our study, but on condition that water is not a strongly limiting factor. This finding is consistent with the results of Laubhann et al. (2009), when based on a multivariate analysis the authors found out a statistically significant effect of climate warming on 152 spruce stands across Europe. Solberg et al. (2009) confirmed a positive effect of an increase in temperature on spruce growth if the growth was not limited by water deficit. It explains why worse water availability on the studied plots has caused a decrease in the increment of the studied stands after 2008. Before that year the presented results of this study, if taking into account development after a heavy air pollution stress, are consistent with the expected increased increment due to rising temperature (Myneni et al. 1997; Ceppi et al. 2012). Nevertheless, an increment decrease observed in our study after 2008 is relatively significant and it was highly probably caused by diminished water availability, which was confirmed by Schuster & Oberhuber (2013), who supposed the sum of precipitation, particularly the total precipitation amount in the months of May and June, to be the main factor correlating with radial growth. Radial growth is much more constrained in older trees at diminished water availability (Pichler & Oberhuber 2007) because ecophysiological studies have demonstrated that changes in the tree size are related with changes in physiological processes taking place in trees during their senescence (Mencuccini et al. 2005). Currently, the studied spruce forest stands are influenced mainly by the increasing air temperature (Mérian & Lebourgeois 2011; Bennet et al. 2015). However, a greater constraint stemming from diminished water availability is usually manifested as a limiting factor mainly in lowlands although surprisingly it can also become a limiting factor at higher altitudes where particularly temperature is usually a limiting factor (Etzold et al. 2014). In connection with diminished water availability and more frequent and longer-lasting spells of drought there subsequently arises a risk of bark beetle attacks to spruce stands, which further deteriorates the health status of stands and in extreme cases the complete dieback of tree layer may occur (Kovářová & Vacek 2003; Krejčí et al. 2013).

5. Conclusion

In 1979–1991 in the Krkonoše Mts. the health status of spruce stands and their vitality were considerably deteriorated as a consequence of the synergism of climatic and air pollution stress, especially of high SO_2 concentrations. Since the second half of the nineties of the 20th century the health status of spruce stands has been relatively stabilized, with regard to both their radial increment and the trends of living tree foliage. Forest sanitation in adjacent forest stands contributed to the stabilization of these stands when insect pests, especially the eight-toothed spruce bark beetle, were radically eliminated. Nowadays, the studied mountains stands are influenced mainly by increasing temperature and climatic anomalies. From the analysis of air pollution, climatic and growth factors in the Krkonoše Mts. results, that there still exist predisposing factors that within synergic effects have a potential to evoke gradual decline or dieback of the studied stands. In future the rigorous respect of natural processes in these stands during their management can contribute to the alleviation of negative effects of expected climate changes. In conclusion, the dendrochronological analysis is a useful tool for the evaluation of various disturbances within temporal growth trends.

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