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Indication of Environmental Changes in Mountain Catchments by Dendroclimatology

Jiří VRTIŠKA[1], Josef KŘEČEK[1] and Roberto TOGNETTI[2]*

[1]Department of Hydraulics and Hydrology, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic; [2]Department of Biosciences and Territory, University of Molise, EFI Project Centre on Mountain Forests (MOUNTFOR), Molise, Italy

**Corresponding author: jiri.vrtiska@fsv.cvut.cz*

Abstract

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In the Czech Republic, mountain watersheds are mostly forested with dominant Norway spruce (*Picea abies*) plantations. The aim of this paper is to analyse changes in radial growth and xylem anatomy of Norway spruce trees in the upper plain of the Jizera Mountains, related to changes in climate (air temperature, precipitation), air pollution and acid atmospheric deposition. Data of two neighbouring climate stations were used to detect trends in air temperatures and precipitation. At elevations of 745–1060 m a.s.l., the ring-width growth was significantly affected by mean annual temperature, while impacts of elevation and precipitation were not significant. In the period 1975–1995, the detected drop in tree radial growth (ca 60% of the normal period, prior to the peak of acid atmospheric deposition) corresponded to the increase in atmospheric SO_2 concentrations and acid atmospheric deposition. The number of cells in tree rings decreased by ca 30–40% in comparison with the normal period, but the mean size of cells did not change significantly. In the last 20 years, increasing radial growth has been detected simultaneously with rising air temperature, and density of cells decreased by 30% in early wood, and by 10% in late wood, increasing the total number of cells in tree rings by ca 10% in comparison with the normal period. Integrated effects of climate and non-climate variables on the variation of tree radial growth in the Jizera Mountains reflected the legacy of acid atmospheric deposition in the forest ecosystem.

Keywords: acid atmospheric deposition; climate change dendrochronology; mountain watersheds; wood anatomy

Mountain regions are very sensitive to climate change (Kohler & Maselli 2009), which adds to a rapid change in climatic conditions with elevation across very short geographical distances. Elevation-dependent warming can accelerate the rate of change in mountain ecosystems and hydrological regimes. Indeed, mountain watersheds are generally more dynamic and more fragile than lowland systems (Chen *et al.* 2011). Natural disturbances, related to climate and land-use changes, influence the dynamics of mountain forest ecosystems, both at the local and at the regional level (Kulakowski *et al.* 2017; Vacchiano *et al.* 2017). In the complex biophysical mountain context, the dynamics of natural disturbances and their impacts on forest structure and tree growth are not fully understood yet. Furthermore, natural and anthropogenic disturbances may combine influencing forest ecosystems in complex ways. Assessing the relative influences and combined impacts of natural and anthropogenic disturbances is crucial for preserving the provision of ecosystem services against the backdrop of their intrinsic variability.

In addition to natural disturbances and climate change, air pollution and atmospheric deposition influence tree growth and development. Permanent plots have been established in Europe (Schopp *et al.* 2003; Schwarz 2009) with the aim of providing representative data on the spatial and temporal variability of forest conditions (Ferretti *et al.* 2015). Data on air quality, pollutant deposition, soil chemistry, and the crown condition can be compared with tree growth to quantify the responses of forest ecosystems to environmental changes, as well as impacts on goods and services provided by mountain forests (Vizzarri *et al.* 2015). Recent increasing rates of tree mortality and associated changes in tree growth reported for many forest ecosystems have been associated with the progressive increase in air temperatures and drought stress (Allen *et al.* 2010). Although the impact of air pollution on tree growth is of difficult interpretation (Cocozza *et al.* 2016a), and there is not a clear trend of defoliation on most of the European monitoring plots, marked growth reductions have been found for conifers, and trees that died from competition (Cailleret *et al.* 2017), as well as crown condition declines (Carnicer *et al.* 2011).

In the Czech Republic, the impacts of climate warming on catchment hydrology have already been observed (Kalvová & Nemešová 1997), particularly as changes in snow characteristics: a drop in seasonal water equivalent and a reduction of both the number of days with snow cover and snow depth maxima. In the 1990s, the atmospheric deposition of sulphate in the Czech Republic decreased significantly (Křeček & Hořická 2001), but spruce forests (Norway spruce, *Picea abies* (L.) Karst.) still show high levels of defoliation, among the highest in Europe (Fabiánek *et al.* 2012; Pokorný & Stojnič 2012), as a consequence of persistent effects of air pollution and other factors driven by climate change (insect outbreaks, drought spells). The synergistic effects of air pollution legacies and climate change stress can lead to extensive decline and dieback of Norway spruce forests in mountain regions of the Czech Republic (Vávrová *et al.* 2009; Křeček *et al.* 2010; Vacek *et al.* 2013).

Increasing sensitivity in the tree radial growth of Norway spruce induced by climate change has been observed in response to late-spring high temperature in central Norway (Solberg *et al.* 2002) and to late-summer low precipitation in the Alpine region (Büntgen *et al.* 2006). These shifts occurred in areas with optimum growth conditions for the species. Cocozza *et al.* (2016b) observed that Norway spruce trees at a high altitude show anatomical traits that suggest preferential investment in avoiding the cell wall collapse and xylem cavitation in comparison with those at a low altitude that display a higher rate of cell production (Italian Alps). Summer drought, interacting with predisposing factors (site conditions, stand management, population genetics), produces long-lasting effects on xylogenesis of defoliated trees that may fail to recover previous growth rates, becoming more prone to die. A deeper understanding of climate-growth relationships for Norway spruce is, therefore, needed to reveal relevant patterns in temporal variability of growth responses to climate that may result in decreasing vitality and increasing decline of this important forest tree species (Čermák *et al.* 2017).

In the 1970s and 1980s, the watersheds of the Jizera Mountains in northern Bohemia, Czech Republic, underwent forest dieback as a consequence of acid atmospheric deposition (mainly sulphate from lignite combustion) and inappropriate forestry practices (Křeček & Hořická 2001). Our experimental plots were established in the Jizera Mountains to provide a measure of resilience in this model disturbance-prone Norway spruce forest. Our aims were to (1) identify possible relationships between atmospheric deposition legacy and radial growth response, (2) determine which climatic variables have influenced the radial growth of Norway spruce in the Jizera Mountains, and (3) investigate the temporal dynamics of these relationships. We addressed the post-decline growth responses at inter- (ring width) and intra-annual (wood anatomy) scales. We hypothesized that the most stressed trees have the lowest growth rates and the highest sensitivity to summer drought, i.e., the lowest post-decline resilience capacity.

MATERIAL AND METHODS

Study area. This study was performed in the upper plain of the Jizera Mountains (50°40'–50°52'N, 15°08'–15°24'E), in northern Bohemia (Czech Republic), (Figure 1). This 200 km^2 headwater catchment area is located at an elevation ranging around 800 m a.s.l., which has a humid temperate climate (subarctic region of the Köppen climate zone). The mean annual precipitation ranges from 1290 to 1400 mm, the mean annual air temperature from 4 to 5°C, and the average maximum snowpack depth is about 120 cm (the snow cover usually lasts from the beginning of November to the end of April), Tolasz (2007). The risk of acidification in the Jizera Mountains is enhanced by the granite bedrock and shallow podzolic soils of a low buffering capacity. The upper watersheds are fully forested; however, during the 19th century, the mixed forest of native tree spe-

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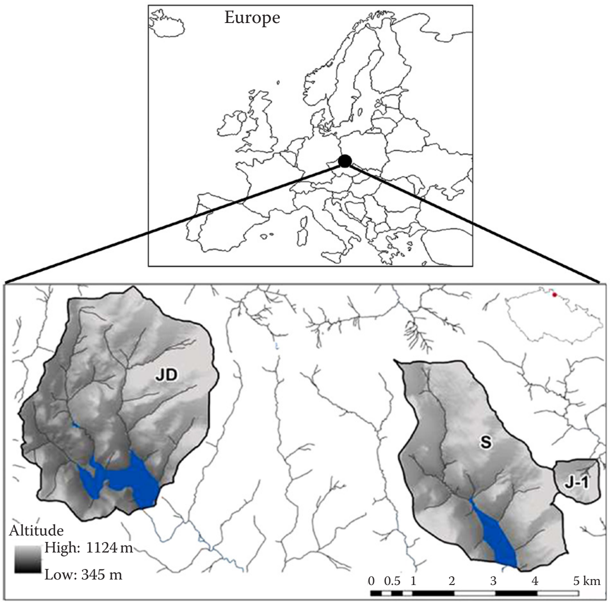

Figure 1. The study area

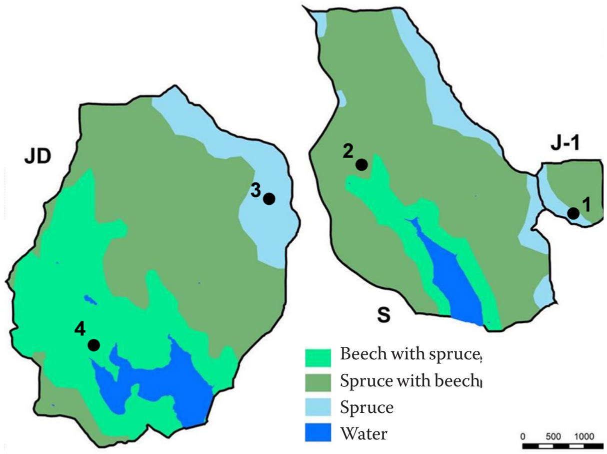

Figure 2. Sampling plots (1–4) and climax zones

cies (*Fagus sylvatica* L., *Picea abies*, and *Abies alba* Mill.) was converted to Norway spruce plantations (almost 90% of forest stands) of lower ecological stability (Křeček & Hořická 2001). Four mature spruce stands in three different forest climax zones (Figure 2) were considered in this study.

Tree rings. In 2015, tree cores (5 mm in diameter) of Norway spruce trees in headwaters of the Jizera Mountains (elevation from 730 to 1060 m a.s.l.) were sampled with the Pressler borer (Fritts 1976) at the standard height of 1.3 m. In total 58 core samples were taken in four mature stands (areas of 30 × 30 m) (Table 1). The selection of trees for sampling concentrated on dominant living trees meeting the following criteria: age of more than 50 years, stand mean height, uniform crown without visible injuries. Two cores per tree were extracted on the trunk. Preparation of core samples included gluing and polishing the surface for a better visibility of tree rings (Warren 1990). Ring-width series were measured with a LINTAB measuring table (Rinntech, Heidelberg, Germany) with a precision of 0.01 mm in the Laboratory of Dendrochronology (Faculty of Science, Charles University in Prague). Ring-width series were synchronised, cross-dated and standardised using the PAST software (Warren 1990).

Wood anatomy. For a deeper understanding of radial growth responses of Norway spruce to atmospheric deposition and environmental disturbances, anatomical analysis of tree-ring micro-sections was undertaken (Gärtner *et al.* 2015). This procedure enables to examine quantitative wood anatomy of single cells of tree cores. Only tree cores with the most evident decreasing trend of tree-ring width were included. The standard technique of sample preparation (Gärtner *et al.* 2015) included 24 h water bath, repeated cutting to reach a continuous plane surface on the top. The final slide was cut with the required thickness of 15 μm. The slides were covered by safranin and cleaned to improve visualisation of individual cells. In total, 28 tree-ring profiles were successfully prepared for microscopic analyses, which enabled quantifying anatomical wood features using images with a high resolution of (2592 × 1944 dpi). Cell number and density were detected by ImageJ (open source Java image processing programme, Schneider *et al.* 2012).

Environmental traits. Basic forest characteristics of monitored plots (mean age, crown closure, mean height and vitality) were estimated by the ground survey using standard techniques according to Wenger (1984). The vitality of trees was estimated as the reciprocal value of electrical resistance in xylem, measured a shigometer (Wilson 1983).

Data of two neighbouring standard weather stations of the Czech Hydrometeorological Institute (Bedřichov and Desná-Souš) (Table 1) were used to evaluate trends in mean annual air temperatures and precipitation sums by the CTPA (technique detecting trends in time series, WMO 2001).

Table 1. Characteristics of relevant climate stations

Station	Location (coordinates)	Elevation (m a.s.l.)	Observation (years)
Desná-Souš	50.789 N, 15.319 E	772	1951–2016
Bedřichov	50.815 N, 15.137 E	777	1938–2016

Table 2. Basic statistics of standard dendrochronology in forest stands (1–4)

	TRI			
	1	2	3	4
Mean	1.03	0.91	1.02	1.06
SD	0.13	0.28	0.17	0.20
SEM	0.02	0.03	0.02	0.02
Minimum	0.54	0.42	0.62	0.74
Maximum	1.27	0.97	1.38	1.51
Median	1.03	0.87	0.95	0.98
Passed normality test	yes	no	no	no

TRI – tree-ring index; SD – standard deviation; SEM – standard error of the mean

Table 3. Changes in the tree-ring index in periods A, B and C (Kruskal-Wallis test of compared medians)

Stand	Periods	Median	Mean rank difference	*P* value
1	A versus B	1.03, 0.64	38.29	< 0.001
	A versus C	1.03, 1.42	–45.21	< 0.001
	B versus C	0.64, 1.42	–83.50	< 0.001
2	A versus B	0.91, 0.63	26.95	< 0.01
	A versus C	0.91, 1.37	–43.47	< 0.001
	B versus C	0.63, 1.37	–70.42	< 0.001
3	A versus B	1.01, 0.67	42.00	< 0.001
	A versus C	1.01, 1.36	–47.07	< 0.001
	B versus C	0.67, 1.36	–89.08	< 0.001
4	A versus B	1.06, 0.65	52.11	< 0.001
	A versus C	1.06, 1.48	–46.15	< 0.001
	B versus C	0.65, 1.48	–98.26	< 0.001

A – normal growth; B – reduced growth; C – intensive growth

Atmospheric concentrations of SO_2 and NO_x were adopted from the standard observation network of CHMI (2016): AIM stations Desná-Souš (LSOU-1022) and Kořenov-Jizerka (LJIZ-1047), SO_2 measured by UV fluorescence every ten minutes, and NO_x by chemiluminescence in hourly intervals. Depositions of sulphur and nitrogen were observed and extrapolated over the study area by Křeček *et al.* (2017).

Statistical analysis. The Kruskal-Wallis test was used, considering the non-parametric distribution statistically significant when $P < 0.05$, in order to test the similarity of different samples (time series) Motulski and Searle (1998). Detecting trends in time series was performed by the CTPA program (WMO 2001), based on the identification of a trend component and its subtraction from the analysed series (parameters of the trend line calculated by using the least squares method). Trend testing included tests of trend existence, trend appearance, and change in trend slope.

RESULTS

Dendrochronology. Mean time series of standardized tree-ring chronologies (tree-ring index, TRI) in the four studied mature Norway spruce stands are given in Figure 4 and basic statistics of the analysed data in Table 2. We were able to identify three different periods: normal growth (A; prior to the peak of acid atmospheric deposition), reduced growth (B; below the growth of the 'normal' phase A), and intensive growth (C; exceeding the growth of the 'normal' phase A). Significant differences between periods A, B and C were confirmed by the Kruskal-Wallis test of compared medians (Table 3). The length of period B varied between 18 and 20 years (beginning in 1977–1978, and ending in 1995–1996).

Wood micro-sections. Analyses of wood micro-sections in tree cores are shown in Figure 4. Three main phases were compared here again according to the detected changes in tree-ring growth (Figure 3, Table 3): normal period (prior to acidification) A, period of an extreme acidification B, and period of recovery C.

The cell number in tree rings of period B decreased by 27–36% in comparison with the normal period A, but, in both periods A and B, the mean size of cells (and their density) was found equal (Table 4). In

Table 4. The density of cells in analysed tree rings (SEM values varied between 1.1 and 1.2)

Period	No. of cells/0.01 mm^2								
	A			B			C		
	mean	min	max	mean	min	max	mean	min	max
Early wood	36	28	40	34	26	40	25	20	29
Late wood	78	62	86	77	62	83	70	59	78

A – normal growth; B – reduced growth; C – intensive growth; SEM – standard error of the mean

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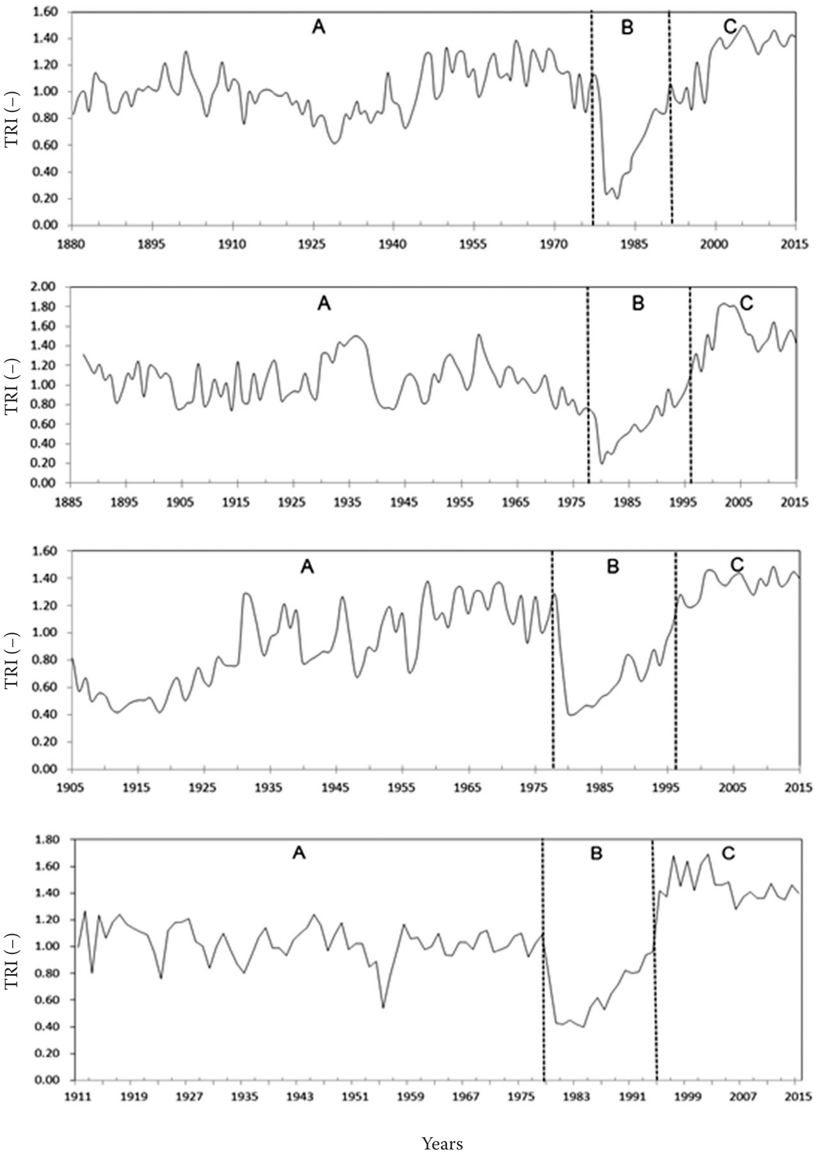

Figure 3. Mean average standard chronology in the studied spruce stands (1–4, from the top)

TRI – tree-ring index; A – normal; B – reduced; C –intensive growth periods

period C, the mean density decreased by 30% in early wood, and by 10% in late wood, and the total number of cells in tree rings increased by 10% against the (normal) period A (Tables 3–4).

Changes in climate. Basic statistics of the mean annual air temperature (T_a) and annual precipitation (P_a), observed at the climate stations Bedřichov and Desná-Souš, are given in Table 5, and trends in time series in Figures 5–6.

While annual precipitation did not show any significant trend (Figure 6), significant upward shifts were observed in mean air temperatures (both stations, Figure 5): test values T = 2.43 and 4.55 (Tcrit = 2.0, $P = 0.05$, regression parameters being $a = 4.89$ and 4.56, $b = 0.01$ and 0.03, respectively for site B and D). For the Bedřichov (B) station, the mean tempera-

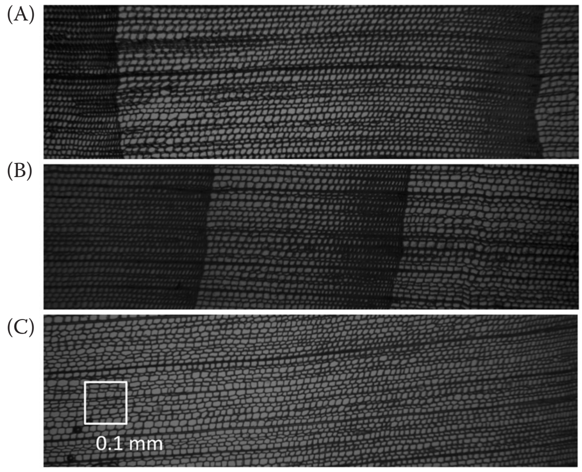

Figure 4. Microsections of tree rings: normal, 1958 (A); extreme acidification, 1982 (B); recovery, 2009 (C)

Table 5. Basic statistics of mean annual air temperatures T_a and annual precipitation P_a of the stations Bedřichov (B) and Desná-Souš (D)

	T_a (B)	T_a (D)	P_a (B)	P_a (D)
	(°C)		(mm)	
Mean	5.10	4.91	1215	1349
SD	0.38	0.77	218	203
Variation coefficient	0.07	0.157	0.18	0.15
Asymmetry coefficient	0.36	–0.20	0.20	0.28
Excess coefficient	3.78	2.58	3.48	3.22
Autocorrelation of the 1st order	0.15	0.35	0.10	–0.05
Passed normality test	yes	yes	yes	yes

SD – standard deviation

ture increased more intensively since 1985 ($a = 6.5$, $b = 0.034$). In the last twenty years (1996–2015), the mean annual temperature increased by 17% against the previous period 1938–1995 (5.35 versus 4.56°C).

A significant correlation between tree-ring index and mean annual air temperature (correlation coefficient $r = 0.35$, $r_{cri} = 0.19$, $P = 0.05$) was observed, while this was not the case of cumulative annual precipitation ($r = -0.09$). However, TRI time series in the (normal) period A did not show any significant trend.

Forest characteristics and acid atmospheric deposition. Characteristics of the studied mature Norway spruce stands are shown in Table 6: including elevation (E), slope (S), exposure (F), mean height of trees (H), canopy density (crown closure C) and vitality (R).

Contents of SO_2 and NO_x in the air at Jizerka Station (Figure 1) in 1980–2015 are reported in Figure 7. In 1982–1992, mean annual concentrations of SO_2 exceeded the serious threshold of 20 μg SO_2/m^3 for forests (Posch *et al.* 2001), while concentrations of NO_x were below the critical value (30 μg NO_x/m^3). Open field depositions of sulphur (S-SO_4) and nitrogen (N-NO_3 and N-NH_4), registered in the bulk at the Jizerka catchment (Křeček *et al.* 2017), correspond to contents of SO_2 and NO_x in the air (correlation coefficients $r = 0.87$ and 0.48, respectively, $r_{crit} = 0.32$, $n = 34$, $P = 0.05$) following the 1985 Helsinki Sulphur Protocol (NIVA 2013). The deposition of sulphur showed a decreasing trend, with gradient of –0.12 ($T = 20.3$, $T_{crit} = 2.1$, $P = 0.05$), WMO (2001), while a minor pattern ($T = 0.69$) was identified in the deposition of nitrogen. Subsequently, during 1982–2015, mean annual pH values of precipitation moved up,

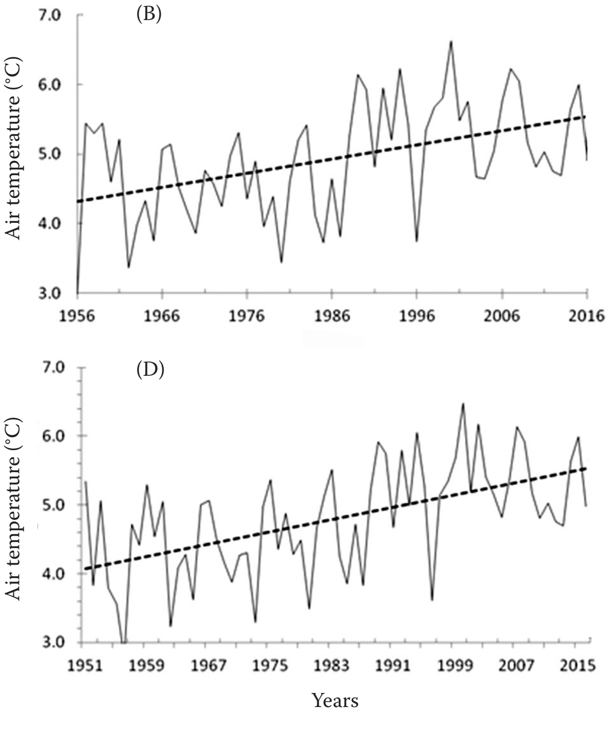

Figure 5. Trends in time series of the mean annual air temperature observed at Bedřichov (B) and Desná-Souš (D)

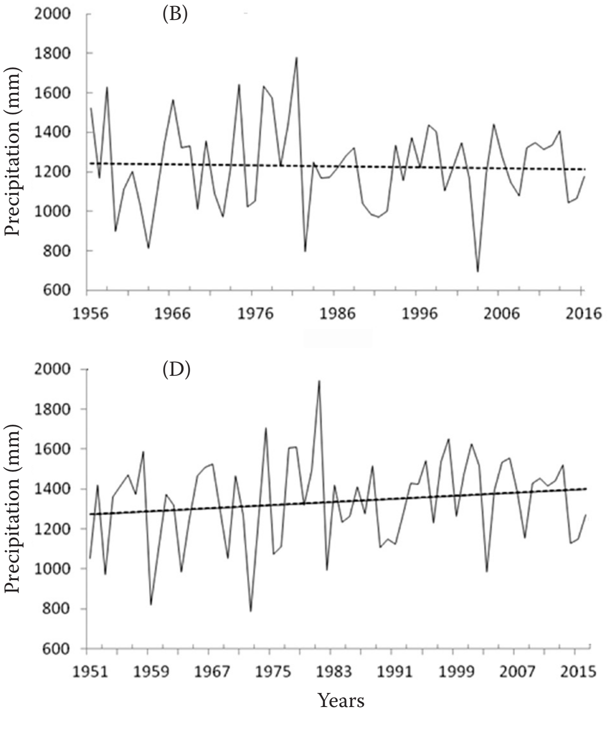

Figure 6. Trends in time series of annual precipitation at Bedřichov (B) and Desná-Souš (D)

Table 6. Characteristics of the studied stands (1–4)

Plot	Elevation (m a.s.l.)	Slope (°)	Exposure (–)	Canopy density (–)	Mean hight of trees (m)	Electric resistance in xylem (kΩ)
1	975	5	NW	0.74	19.3	16.8
2	1060	12	SW	0.64	18.6	22.0
3	820	24	SE	0.94	23.8	17.0
4	745	2	SW	0.92	24.4	15.3

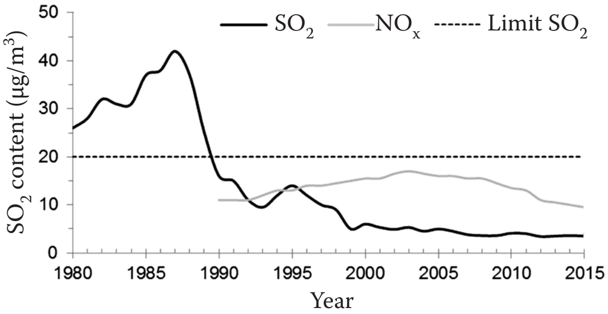

Figure 7. Contents of SO_2 and NO_x in the air, Jizerka, 1980–2015

from 4.2 to 5.3, and the pH-adequate annual open field flux of H^+ in precipitation decreased from 90 to 5 mg/m^2/year.

It is evident (correlation matrix, Table 7) that the growth of Norway spruce trees was significantly affected by changes in air concentrations of SO_2 (including consequences of the acid atmospheric deposition) and mean annual air temperatures. The effect of elevation, canopy density, and vitality in the studied area was not significant. Values of electrical resistance R (15–22 kΩ, observed in 2015) did not show any significant effect on tree-ring statistics.

DISCUSSION AND CONCLUSIONS

Tree-ring growth was found highly responsive to temperature (particularly in the period April-August, with the positive relationship, not shown), as observed for cambial activity and xylem formation of Norway spruce in temperate mountain areas (Cocozza *et al*. 2016a, b). In 1996–2015, increasing tree radial growth paralleled rising mean air temperature. The effect of elevation, canopy density, and tree vitality in the studied area was not significant. Similar increasing ring-width increments in the last decades were detected simultaneously in several different geographic regions in coincidence with higher air temperatures (Kramer 1986; McLaughin *et al*. 2002; Pretzsch 2009), air temperature being generally the major driver of tree growth in temperate forest ecosystems. According to scenarios of future in the period 2071–2100 (Christensen 2005; IPCC 2007), variation in both temperature and precipitation may lead to changes of the climax zonation in the Jizera Mountains.

Table 7. Correlation matrix

	TRI	SO_2	T_a	P_a
TRI	1	–0.77	0.35	–0.09
SO_2	–0.77	1	–0.24	0.05
T_a	0.35	–0.24	1	–0.32
P_a	–0.09	0.05	–0.32	1

TRI – tree-ring index; SO_2 – content of SO_2 in the air; T_a – mean annual air temperature; P_a – annual precipitation

The relatively high average annual precipitation in the Jizera Mountains, and the lack of correlation between precipitation and tree-ring growth can be related to the adequate moisture for tree growth at the study site. However, the lack of correlation between temperature and precipitation may indicate the possible occurrence of periods of water limitation. Although the influence of precipitation was not significant, if evaporative demand continues to rise because of increasing temperature (IPCC 2007), trees growing in these temperate mountain environments may undergo growth reductions. Temperate forests have already shown major growth declines and high mortality levels induced by extreme drought events (Allen *et al*. 2010).

Warming temperature after 1996 may have increased the tree growth by extending the duration of temperatures favourable for the tree growth in an area like the Jizera Mountains, with adequate moisture. However, an alternative explanation of increasing ring-width growth of Norway spruce in 1996–2015 can be the fertilization effect exerted by atmospheric nitrogen deposition, affecting the photosynthetic processes. Indeed, in 1980–2015, Norway spruce trees in the studied area have been exposed to almost uniform deposition of nitrogen

(Křeček *et al.* 2017), exceeding 2–3 times the value of 1 g/m^2/year (i.e., 71 meq/m^2/year), which is considered as an empirical critical load for forests in central Europe by Bobbink and Roelofs (1995). The continuous rise in atmospheric CO_2 concentration and O_3 level can be also reflected in complex changes in tree radial growth and water use efficiency.

Results of this study confirmed an important role of the air pollution (SO_2 and NO_x) and acidification on tree-ring formation (Bytnerowicz *et al.* 2007). NO_x and SO_x are the primary sources of precipitation acidity. In the period of extreme acidification (1977–1995), tree-ring growth was significantly reduced (to ca 60% of the normal period), the size and density of cells did not change; while in the recent recovery period (1996–2015), the density of cells decreased by ca 30% in early wood, and by ca 10% in late wood (the size of cells increasing). Variations in carbon investment in xylem tissue (conduits) of trees indicate either plasticity or vulnerability to varying environmental conditions. Indeed, responses of Norway spruce to pollution and climate cannot be easily disentangled in this mountain environment. Yet, the analysis of functional and structural traits may provide insights into the sensitivity and resilience of stem radial increment of Norway spruce to changing environmental conditions (Mäkinen *et al.* 2002) and hydrological behaviour of headwater catchments.

In conclusion, complex interactions among climate, soil, and disturbance factors may have influenced the tree-ring growth of Norway spruce, determining the resilience of this species to pollution legacy in the Jizera Mountains. Overall, annual stem radial increment of Norway spruce can be regarded as the combined impacts of temperature, acid precipitation, and atmospheric pollutants. Indeed, the nitrogen content from acid precipitation might stimulate the annual radial growth of trees overriding the expected detrimental effect. The decreased concentration of SO_2 due to the European Sulphur Protocol (NIVA 2013) and corresponding national policy were effective in reducing the negative effects of acid deposition on tree growth. The effect of precipitation acidity on patterns of tree radial growth of Norway spruce probably reflected changes in forest biogeochemical cycles and soil nutrient dynamics. Anyway, long-term impacts of altered environmental conditions on forest structure and functions are a difficult interpretation, though their prediction can be conveniently improved by the combined use of tree-ring data and wood anatomy.

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