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ORIGINAL PAPER

# Effects of air pollution and climatic factors on Norway spruce forests in the Orlické hory Mts. (Czech Republic), 1979–2014

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**Abstract** The area of the Orlické hory Mts. has been characterised by decline and disturbances of Norway spruce (*Picea abies*/L./Karst.) stands since the 1980s. Currently, only three permanent research plots have been preserved from the original sixteen established plots in this region. In the present study, the health status, as indicated by defoliation, mortality, and stem radial growth, was studied in the peaty and climax spruce ecosystems in the upper elevations of the mountains from 1979 to 2014. This health status was correlated with ambient air pollution ($SO_2$) as well as climate factors (temperature and precipitation). The health status of individual trees on the plots was determined by evaluation of the foliage status, and tree vitality was evaluated by measuring stem radial growth increment. Stress factor analysis showed that high air pollutant concentrations predisposed Norway spruce to stress from climatic events (drought, temperature changes), leading to forest decline. The most serious damage can be attributed to the combination of chemical and climatic stress. Stands with lowered vitality were attacked by secondary biotic pests (particularly bark beetle), resulting in rapid tree mortality. The damage process is marked not only by higher mortality, but also by chlorosis and necrosis of the needles. The stabilised trend in health status of the spruce stands was registered since approximately 1990s. In terms of climatic factors, the weather in June had the most visible influence on radial increment. Low temperatures and high precipitation were the limiting factors for radial growth in studied mountain area.

**Keywords** Stress factors · Sulphur dioxide · Nitrogen air pollution · Ozone · Climate · Central Europe

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## Introduction

Pollution and climate are the major external environmental factors influencing the development of forest ecosystems in Central Europe over the long run (Ulrich et al. 1980). Montane forest ecosystems in particular are constantly exposed to climatic stress in natural conditions and have been severely affected by air pollution over the past 50 years (Vacek et al. 2003). Climatic stress includes water deficit, excessive, or prolonged periods of heat or cold, excessive radiation, and mechanical stress (Tranquillini 1979). The effects of these natural stressors on plants are exacerbated by air pollution, caused by increased concentrations of harmful chemicals in the air and their deposition, and ultimately by affecting the quality of seepage water, nutrient input, nutrient and organic matter balance, and soil chemical conditions (Lochman and Mareš 1995; Boháčová et al. 2010; Lüttge 2014). Changes in climatic factors in forest stands may therefore affect numerous processes in forest ecosystems, where they can have a positive influence (e.g. higher growth increments) or negative influence (all types of forest damage; Spiecker 1990;

Rolland and Lempériere 2004; Paoletti et al. 2010) or both. There is an urgent need to fill in the gaps in understanding of the interactions between air pollution, climate change and forests (Serengil et al. 2011; Matyssek et al. 2012), in order to assess impacts on forest ecosystems at present as well as in the future.

The pathway to any forest decline usually follows three stages. First, the predisposing factors, such as low site quality, limited historical precipitation or older age of forests, set the forest ecosystem on a path of stress. An inciting factor, such as frost, short-term drought, insect defoliation or acid deposition (Kmet' et al. 2010), pushes the ecosystem to the brink. Finally, the contributing factor might be an insect or disease that takes advantage of a tree's weakened state, effectively pushing the ecosystem over the edge (Spetich et al. 2011; Kula et al. 2013).

The most challenging task in the assessment of tree decline and mortality is the retrospective determination of the trees' reactions to individual stressors (Šrámek et al. 2008). Monitoring forest decline is typically a short-term exercise, often initiated only after evidence of symptoms appears and thus capable of rendering only a picture of mortality or initial factors rather than the predisposing factors (Larcher 2001; De Vries et al. 2003). In order to interpret non-specific manifestations of forest decline where synergistic action of a broader range of factors can be reasonably expected, it is necessary to monitor not only the latest and most evident response of trees (e.g. defoliation), but also changes in radial growth. While defoliation and other visible reactions are perceptible only after a delay (Žid and Čermák 2008), growth can show an immediate response. Annual ring analysis may therefore yield evidence over long periods and may be correlated with individual stressors (Fritts 1976; Kroupová 2002; Preusler et al. 2004).

Montane forests, being already in a stressful environment, are highly sensitive ecosystems, exposed to a significant burden from multiple stressors (Buttoud 2000; Bridgmann et al. 2002). In Central Europe, these are chiefly emission impacts (acid deposition, ozone), extreme climate (low temperatures, periods of drought, high winds), and adverse soil conditions (somewhat acidic soils with low biological activity) because they are predominantly more recently formed soils (Kärenlampi and Skärby 1996; Hruška and Ciencala 2003; Gallo et al. 2014). In the Czech Republic, air pollution has been recognised as the main environmental problem since 1950, due to the extremely high $SO_2$ and particulate matter emissions from power plants and other industrial facilities (Moldan and Schnoor 1992). Notably, the $SO_2$ emissions ranked among the most dangerous factors limiting the health status of forests in the entire Central European region (Ulrich 1991), including the Czech Republic, between 1970 and 1990 (Materna 1999; Hůnová 2001). Even after a substantial reduction in air pollutants ($SO_2$, in particular) in the 1990s (Renner 2002; Hůnová et al. 2004), forests in some parts of the Czech Republic are still suffering the effects of past emission-caused damage. Based on the lingering effects on forest growth, Likens et al. (1996) have hypothesised about the long-term residual effect of acid deposition in spruce stands. Sulphur dioxide is not the only source of emission impacts on forest ecosystems, however. Air pollution by $NO_x$ and $O_3$ (ozone) has been perceived as a problem only since the 1990s (Hruška and Ciencala 2003; Hůnová and Schreiberová 2012). In terms of damage to ecosystems, ozone is currently considered as the most harmful ambient air pollutant (EEA 2014). Concentrations of ambient $O_3$ range between 20 and 45 ppb over the mid-latitudes of the Northern Hemisphere (Vingarzan 2004). The long-term trends and analysis of spatial relationships of atmospheric deposition have been published in many works, e.g. Hůnová et al. (2004, 2014); Šrámek et al. (2014). But atmospheric deposition of nitrogen—dry depositions in particular—has most likely been underestimated due to the lack of data on certain forms of nitrogen such as $HNO_3$ and $NH_3$ (Flechard et al. 2011). Recently, in montane Norway spruce (*Picea abies*/L./Karst.) forests, the extent and level of air pollution ($NO_x$ and $O_3$) have been increasing. The considerable damage to these stands and the subsequent sanitary clear-cutting devastated spruce stands in the Krušné hory Mts. (the Ore Mts.), the Jizerské hory Mts., the Krkonoše Mts. (the Giant Mts.), the Orlické hory Mts. (the Eagle Mts.), and the Jeseníky and the Beskydy Mts. (the Beskids). Pollution has caused damage in other regions of the Czech Republic, but with less intensity (Tesař 1993; Boháčová et al. 2010; Vacek et al. 2013; Lomský et al. 2013). A total of 62.5 thousand hectares of clear-cuts resulted from forest decline in the forests of the Czech Republic mountains in the 1970s and 1980s. These forests were reforested mostly with Norway spruce or so-called substitute pioneer tree species (Vacek et al. 2003; Špulák 2012). Numerous experiments sought to increase the stability and vitality of forest stands by applying fertilisers and lime (Vacek et al. 2009; Kuneš et al. 2013) or to restore stands by various reproduction techniques (e.g. Vacek et al. 2012). Visible damage to the forest stands in the study area of the Orlické hory Mts. became evident in 1979 after the Chvaletice and Opatovice power plants were put into full operation. Air pollution and extreme climatic conditions in the 1980s resulted in a very rapid deterioration of the health status of the ridge stands and vast salvage clear-cuts (approximately 2000 ha) at altitudes of over 900 m (Vacek et al. 2003).

The objective of this investigation was to evaluate the trend of the health status (in terms of foliation and tree mortality) and productivity (in terms of stem radial growth) of peat bog and climax spruce stands in the Orlické hory Mts. from 1979 to 2014 in relation to the air pollution burden and climatic environmental factors. Objectives were to (1) identify long-term trends of air pollution indicators, climatic factors, health status, and productivity of Norway spruce stands; (2) determine the response in stand health and productivity to climatic and air pollution factors, and (3) reveal interactions and relationships among all air pollution and climatic factors, stand health status, and productivity indicators.

## Materials and methods

### Description of the study area

The study was conducted in three permanent research plots (PRPs) in the central part of the Orlické hory Mts. and in the northeast of the Czech Republic near the border with Poland. Sixteen PRPs were originally established in 1979, but all trees on 13 of these plots died after extreme pollution-caused stress. The Orlické hory Mts. are chiefly composed of crystalline rocks. The predominant soil types are Cambisols, Crypto-podzols, and Podzols, with sporadic Organosols (Vacek et al. 2003). The average annual temperatures are between 4 and 7 °C, and precipitation between 800 and 1300 mm. The predominant potential natural vegetation is herb-rich beech forest alternating with acidophilic beech wood of the submontane and montane type. Habitats influenced by water are mostly represented by waterlogged and peat bog spruce stands, and climax spruce stands at the highest altitudes (Vacek et al. 2003). PRP 1 is located in a peat bog spruce stand in the Jelení lázeň Nature Reserve, and PRP 2 is in the peat bog spruce stand of the U Kunštátské kaple Nature Monument. PRP 3 is represented by a climax spruce stand located on the summit of the Koruna Mountain. Locations of the PRPs are

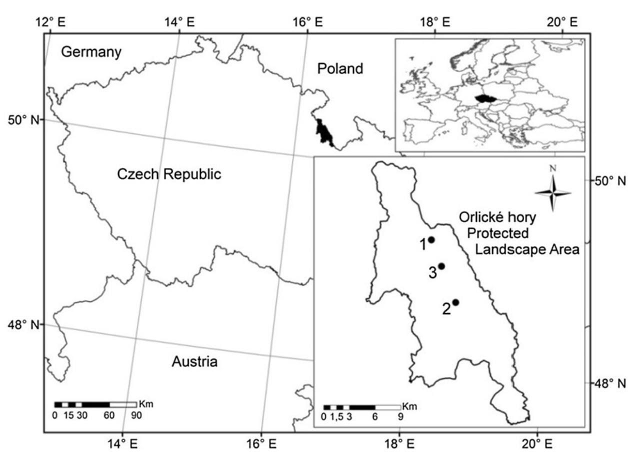


**Fig. 1** Location of the three permanent research plots (PRP 1–3) in which the spruce stands were investigated (PRP 1: 50°18′41″N, 16°23′55″E, PRP 2: 50°14′48″N, 16°27′08″E, PRP 3: 50°17′01″N, 16°25′39″E)

shown in Fig. 1, and Table 1 summarises the details about the plots. Stand characteristics by plot are summarised in Table 2; species' horizontal structure by plot in 1979 and 2014 is shown in Fig. 2.

### Collection of climatic and air pollution data

We used long-term climate and air pollution measurements provided by meteorological and air pollution monitoring stations near the study area.

Temperature and precipitation data were collected at the meteorological station at Deštné v Orlických horách (656 m a.s.l.; GPS 50°18′24″N, 16°21′07″E). Temperature and precipitation trends were based on average annual temperature, vegetation season temperature (April 1–September 30), average temperature in each month, minimum and maximum temperatures, total annual precipitation, total precipitation in the vegetation season (April 1–September 30), and minimum and maximum precipitation from 1961 to 2013. The moisture balance was calculated according to Thornthwaite (Nosek 1972). The evapotranspiration rates were derived from long-term measurements (1976–2013) in a Norway spruce stand located in Deštné v Orlických horách (Kantor 1983). In addition, we evaluated average moisture conditions in the coniferous stands by comparing total precipitation for the May–August period from 1961 to 2013 with the limit of 300 mm total annual precipitation, considered to be the maximum for favourable growth of Norway spruce.

Analysis of air pollution in the Orlické hory Mts. was based on $SO_2$, $NO_x$ and $O_3$ concentrations from data available from the Šerlich station (1011 m a.s.l.; GPS 50°19′41″N, 16°23′05″E), close to the investigated PRPs. Since the measurement time series from this station has been relatively short, we also used data from the Desná-Souš station in the Jizerské hory Mts. (772 m a.s.l.; GPS 50°47′21″N, 15°19′11″E). For the assessment, average and maximum concentrations (in μg $m^{-3}$) and their 95th percentiles for the whole year and for the vegetation season (April 1–September 30) were used. For the assessment of $O_3$ concentrations, the exposure index AOT40 for forests, calculated as the sum of differences between the observed hourly mean concentration and the threshold value of 40 ppb over the vegetation period, was used (UN/ECE 2004; Hůnová and Schreiberová 2012).

### Health status and productivity data collection

The long-term dynamics of the health status of individual trees in the three investigated PRPs has been assessed annually from 1979 to 2014 based on the level of foliation and degrees of defoliation according to the Tesař and Temmlová (1971) classification (Table 3). Then, the

**Table 1** Overview of basic characteristics of the forest stands in this study, 2014

| PRP | Name | Altitude (m) | Aspect | Slope (°) | Forest site type | Species | Age (y) | Diameter (cm) | Height (m) | Volume ($m^3$ $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Jelení lázeň | 1075 | S | 1 | 8R, 8T | *Picea abies* | 68 | 14 | 6 | 67 |
| 2 | U K. kaple | 1035 | SW | 2 | 8R, 8T | *Picea abies* | 84/22 | 12 | 5 | 27 |
| 3 | Koruna | 1095 | E | 7 | 8Z | *Picea abies* | 92 | 29 | 8 | 105 |

Forest site type: 8R—*Piceetum turfosum montanum,* 8T—*Piceetum paludosum oligomesotropicum humile,* 8Z—Sorbo-*Piceetum humile*

average stand foliation was calculated as the arithmetic mean of the foliation values for all trees and the living trees for each PRP. Defoliation (foliation relative to a potential of 100 %), with attention to the cenotic position and the morphological type of the crown, was estimated with an accuracy of 5 %, according to the methodology applied by the ICP-Forests project (Lorenz 1995). Mortality was calculated as the percentage of all trees on the PRP with the degree of defoliation 5 (Table 3).

The long-term productivity dynamics of the PRPs were assessed using measures of radial growth. Data for the radial increment analysis were obtained by collecting cores at a height of 1.3 m using a Pressler auger from 30 living uniform-height and above-height spruce trees in each PRP. The annual ring width was measured to an accuracy of 0.01 mm using an Olympus binocular magnifying glass on a LINTAB measurement table and registered using the TSAPWin software (www.rinntech.com).

### Data analyses

To calculate the stem radial growth, the annual ring increment series were cross-dated individually (to eliminate errors caused by missing annual rings) using statistical tests in the PAST4 application software (Knibbe 2007) and then subjected to visual inspection according to Yamaguchi (1991). If a missing annual ring was found, a ring 0.01 mm wide was inserted in its place. The individual curves from PRP 1–3 were then detrended, and an average annual ring series was created in the ARSTAN software. First, a negative exponential spline was used, and then, the 30-year spline applied (Grissino-Mayer et al. 1992).

In order to determine the response of tree growth to climatic and air pollution factors, the average annual ring series from PRP 1–3 were correlated with climatic (precipitation and temperatures, 1961–2013) and air pollution data ($SO_2$ concentrations, 1971–2013) for each month and year using the DendroClim software (Biondi and Waikul 2004).

In order to determine the response of stand health status to climatic and air pollution factors, the foliation of all trees, the foliation of living trees, tree mortality and radial growth (diameter increment) were tested for correlation with many parameters. For climatic factors, we used annual temperature, temperature in the vegetation season, temperatures in June (July, August) of the given year, temperatures in May–August of the given year, temperatures in May–August of the previous year, annual precipitation, precipitation in the vegetation season, precipitation in January–March of the given year, number of days without precipitation in the period of May–August, precipitation in May–August of the given year, and precipitation in May–August of the previous year. For air pollution factors, the average annual and the maximum annual $SO_2$ concentrations were used. Other air pollution data ($NO_x$ and $O_3$) were disposable for short time period. To test the difference in tree mortality between the three investigated PRPs over time, analysis of covariance was applied with tree mortality as the dependent variable, PRP as the independent categorical predictor, and the time (years) as the independent continuous co-variable. The significantly different results were then tested by the post hoc HSD Tukey test. The tests were carried out in the Statistica 12 package (StatSoft, Tulsa).

In order to examine the mutual relationships and interactions among climatic data (precipitation and temperature in selected critical periods), air pollution (annual average and maximal $SO_2$ concentrations), health status (foliation of living trees, annual mortality), and productivity (ring width), the unconstrained principal component analysis (PCA) in the Canoco for Windows 4.5 software (ter Braak and Šmilauer 2002) was applied. Data were log-transformed, centred, and standardised before the analysis. The results of PCA were visualised in the form of an ordination diagram, with the years displayed (1979–2012) as passive supplementary variables, constructed by the CanoDraw software (ter Braak and Šmilauer 2002).

## Results

### Long-term trends in climate and air pollution

Graphs of temperature and precipitation data for 1961 through 2013 are shown in Fig. 3. The average annual temperature on the study site was 5.6 °C, and the average

**Table 2** Detailed overview of stand characteristics in PRP 1–3

| PRP | Year | $t$ (y) | $d_{1.3}$ (cm) | $h$ (m) | $f$ | $v$ ($m^3$) | $N$ (trees $ha^{-1}$) | $G$ ($m^2$ $ha^{-1}$) | $V$ ($m^3$ $ha^{-1}$) | h:d | PAI ($m^3$ $ha^{-1}$ $y^{-1}$) | MAI ($m^3$ $ha^{-1}$ $y^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1979 | 48 | 10.3 | 5.5 | 0.38 | 0.02 | 552 | 4.6 | 10 | 56.0 | | |
| 1 | 2014 | 70 | 12.6 | 5.5 | 0.45 | 0.03 | 1752 | 22.0 | 54 | 43.3 | 2.0 | 0.76 |
| 2 | 1979 | 104 | 13.9 | 4.9 | 0.42 | 0.03 | 360 | 5.5 | 12 | 35.1 | | |
| 2 | 2014 | 84 | 11.1 | 4.8 | 0.43 | 0.02 | 560 | 5.4 | 11 | 43.5 | 0.6 | 0.13 |
| 3 | 1979 | 77 | 26.5 | 9.9 | 0.43 | 0.24 | 456 | 25.2 | 108 | 37.7 | | |
| 3 | 2014 | 90 | 27.4 | 8.6 | 0.49 | 0.25 | 400 | 23.5 | 99 | 31.5 | 1.4 | 1.10 |

*t*—mean stand age; $d_{1.3}$—mean dbh; *h*—mean height; *f*—form factor; *v*—average tree volume; *N*—number of trees per hectare; *G*—basal area; *V*—stand volume; h:d—slenderness quotient; PAI—periodic annual increment; MAI—mean annual increment

temperature during the vegetation season was 11.6 °C. The average annual temperatures in 1961–2013 show an increase of approximately 2.9 °C per 53 years; those in the vegetation seasons show a growth of approximately 3.1 °C per 53 years. The total annual precipitation rates have decreased by approximately 250 mm per 53 years, and the total precipitation in the vegetation seasons by approximately 110 mm per 53 years. The moisture balance trend for May–August on the Deštné site (Fig. 4) shows that despite high annual variation, there is a linear trend of decreasing precipitation excess by 106 mm per 53 years. There were 2 years (1992 and 2003) in which the moisture balance deficit in the mountain spruce region was extreme, with a particular deficit in the two peat bog spruce stands.

The average total precipitation in May–August on the study site was 457 mm (623 mm in April–September); the average annual total was 1165 mm. The precipitation totals for May–August exceeded 300 mm, the maximum for providing favourable moisture conditions for Norway spruce stands' growth, with an exception of 2 years. In 1992 and 2003, there was a conspicuous decrease in precipitation during the summer months. This decrease led to moisture stress throughout the Orlické hory Mts., as well as in the entire adjacent region of Sudetes. Total precipitation for May–August then dropped by 94 and 36 mm, respectively, below the recognised limit of 300 mm, causing significant moisture stress. In addition, the following years were drier (i.e. with precipitation below the long-term average): 1982, 1983, 1990, 2004, 2008, and 2013.

Concentrations of $SO_2$ and $NO_x$ in the vegetation seasons on the Šerlich and Souš stations are shown in Figs. 5 and 6, respectively. Daily maximum $SO_2$ concentrations decreased from 1994 to 2013, but a dramatic decline occurred specifically up to 1999, and then, the $SO_2$ concentrations remained low and slightly fluctuating. The pattern of maximum annual $NO_x$ concentrations at both stations between 1993 and 2013 was different. On the Šerlich site, maximum annual $NO_x$ concentrations were relatively high in 1995–2000, followed by a decrease, but with considerable fluctuation, whereas on the Souš site the trend was a slight steady decrease after 1997. The development of the exposure index AOT40 for forests in 1996–2013 is shown in Fig. 7. The $O_3$ concentrations were relatively high with marked peaks in 2003 on both sites due to the extremely hot and sunny summer. The Šerlich station also registered high AOT40 values during the study period, namely 24.000 ppb $h^{-1}$ in 2002, 28.000 ppb $h^{-1}$ in 2003 and 23.000 ppb $h^{-1}$ in 2006.

## Dynamics of stand health status

The trends of average foliation and degrees of defoliation of each Norway spruce tree in PRP 1–3 in the Orlické hory

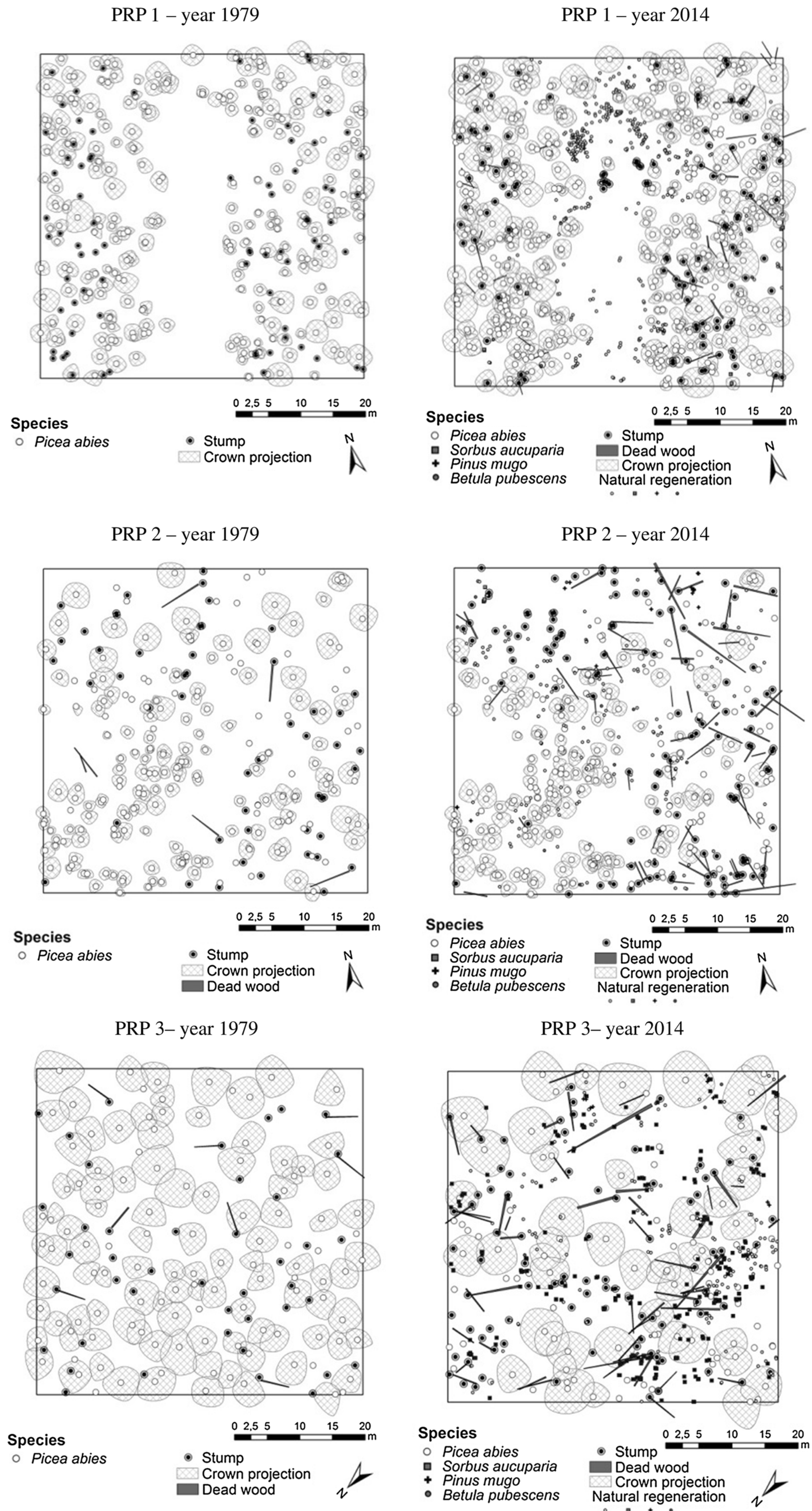


**Fig. 2** Map of the horizontal structure of the stands in PRP 1—Jelení lázeň, PRP 2—U Kunštátské kaple, and PRP 3—Koruna in 1979 and 2014

**Table 3** Overview of characteristics of the health status of forest stands by degree of defoliation and percentage of foliation

| Degree of defoliation | Foliation (%) | Tree characteristics |
|---|---|---|
| 0 | 91–100 | Healthy |
| 1 | 71–90 | Slightly damaged |
| 2 | 51–70 | Medium damaged |
| 3 | 31–50 | Seriously damaged |
| 4 | 1–30 | Dying |
| 5 | 0 | Dead |

Mts. in 1979–2014 are shown in Figs. 8, 9, 10 for each PRP separately. The development of tree mortality showed a different pattern among PRPs. Tree mortality was significantly the lowest for PRP 1 and highest for PRP 3 ($F = 62.4$, $P < 0.001$).

Average foliation of Norway spruce (87 % on PRP 1, 77.5 % on PRP 2, and 78.8 % on PRP 3) and the shares of degrees of defoliation of trees in the peat bog spruce stands (PRP 1 and PRP 2) and climax spruce stand (PRP 3) in 1979 indicate the status at the beginning of the visible macroscopic damage to the assimilation organs of the spruce (sporadic necrosis and chlorosis on PRP 1; sporadic necrosis on PRP 3).

On PRP 1, a foliation decrease occurred in 1980–1991, slight at first in 1980 (average annual defoliation of living trees of 2.0 %, zero mortality), and steep in 1981–1983 (average annual defoliation of living trees of 7.2 %, annual mortality of 3.6 %), and continued at a slower defoliation pace until 1991 (average annual defoliation of living trees of 9.5 % in 1984–1991, annual mortality of 1.0 %). Reflecting a nationwide reduction in emissions, a foliation increase occurred in 1992–1998 (average annual foliation increase in living trees of 3.7 %, annual mortality of 1.2 %). In 1999–2014, the health status of the trees has been almost stabilised, with moderate oscillations (average annual defoliation of living trees of 0.5 %, annual mortality of 0.3 %).

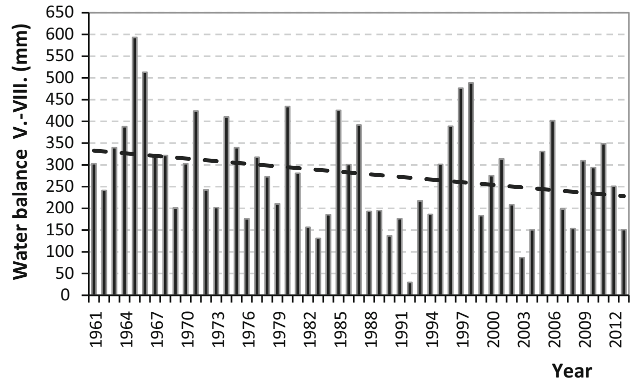


**Fig. 4** Development of water balance on the Deštné site in 1961–2013 (CHMI and FGMRI data)

On PRP 2, a foliation decrease occurred in 1980–1990, slight in 1980 (average annual defoliation of living trees of 0.9 %, zero mortality), but very steep in 1981 (average annual defoliation of living trees of 20.5 %, annual mortality of 0.9 %), and continued at a slower defoliation pace until 1990 (average annual defoliation of living trees of 2.9 % in 1982–1990, annual mortality of 4.7 %). A foliation increase occurred in 1991–1994 (average annual foliation increase in living trees of 5.3 %, annual mortality of 2.2 %). In contrast, a noticeable foliation decrease occurred in 1995 and 1996 (average annual defoliation of living trees of 5.6 %, annual mortality of 0.5 %). Since 1997, tree health status has almost stabilised, with moderate oscillations (average annual defoliation of living trees of 0.1 %, annual mortality of 0.1 %).

On PRP 3, a significant foliation decrease occurred in 1981 and 1982, very steep in 1981 (average annual defoliation of living trees of 10.7 %, zero mortality), and steep in 1982 (average annual defoliation of living trees of

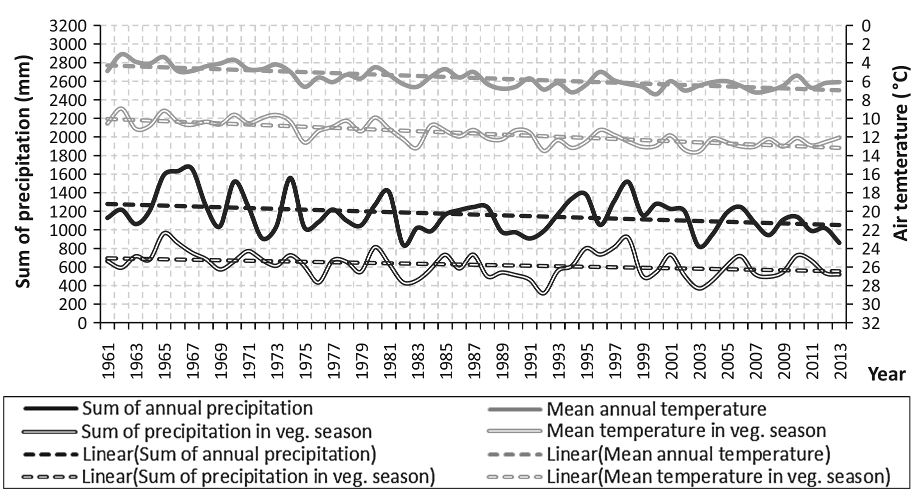


**Fig. 3** Development of mean annual temperatures, mean temperatures in the vegetation season, sum of annual precipitation and sum of precipitation in the vegetation season at Deštné station in 1961–2013 (CHMI data)

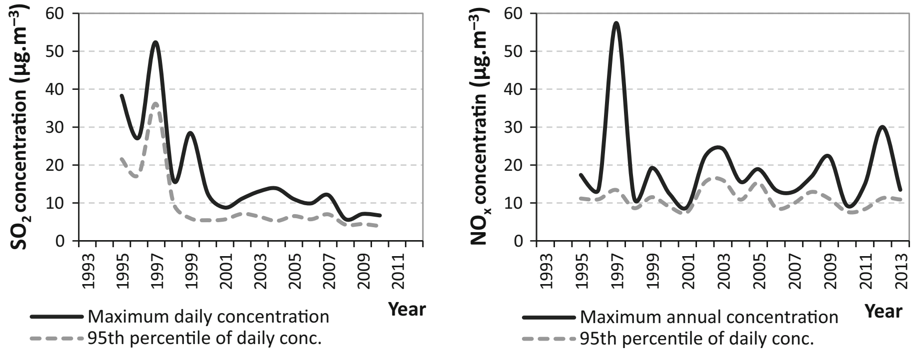


**Fig. 5** Trends in $SO_2$ and $NO_X$ concentrations in vegetation seasons (expressed as the 95th percentiles of daily concentrations and daily maxima) on the Šerlich site in μg $m^{-3}$ (CHMI data)

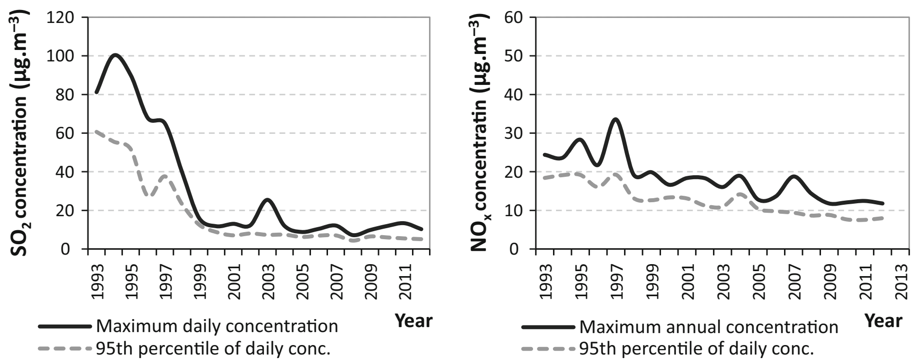


**Fig. 6** Trends in $SO_2$ and $NO_x$ concentrations in vegetation seasons (expressed as the 95th percentiles of daily concentrations and daily maxima) on the Souš site in μg $m^{-3}$ (CHMI data)

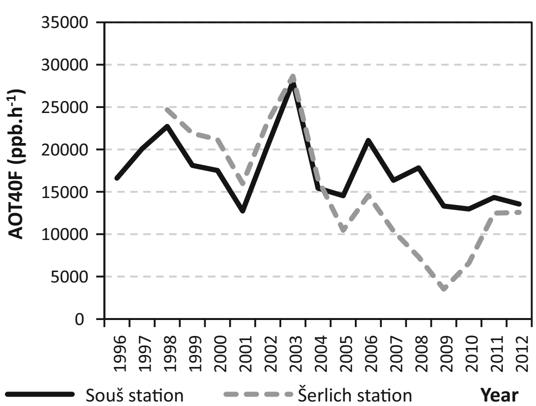


**Fig. 7** Trends in exposure index AOT40 for forests ppb $h^{-1}$ on the Šerlich and Souš sites in 1996–2012 (CHMI data)

5.1 %, zero mortality). Since 1983, tree health status has been almost stabilised, with only moderate oscillations (minimal average annual foliation increase in living trees of 0.04 %, annual mortality of 2.4 %). Very significant mortality rates occurred due to a spruce bark beetle outbreak in 1983–1992 (annual mortality of 6.9 %).

The foliation of all trees showed a positive correlation with the maximum annual $SO_2$ concentrations, a negative correlation with temperatures, and no correlation with precipitation parameters (Table 4). The foliation of living trees showed negative correlations with temperatures only, and average annual mortality of trees showed a positive correlation with $SO_2$ concentrations, a negative correlation with temperatures, and no correlation with precipitation. Annual mortality was positively correlated with $SO_2$ concentrations and negatively with the temperature in June in the current year (Table 4).

## Dynamics of radial growth

Comparison of the average annual ring curves for the three PRPs shows a high rate of agreement among them (*t* tests >7.8, Fig. 11). This consistency permitted the compilation of a local standard chronology for the spruce stands in the ridge parts of the Orlické hory Mts.

The regional standard annual ring chronology indicates a relatively balanced radial increment in 1960–1978, interrupted by a decrease in 1978–1984. The year 1984 started a period of increased radial increment, interrupted again by a decrease in 1996, and then again in 2010 and 2013 (Fig. 12).

The diameter increment in 1979–2013 showed positive correlations with the July and August temperatures of the previous year ($r = 0.33$ and 0.38), with the June, July, and August temperatures of the current year ($r = 0.41$, 0.34 and 0.34) and with precipitation in February and March of

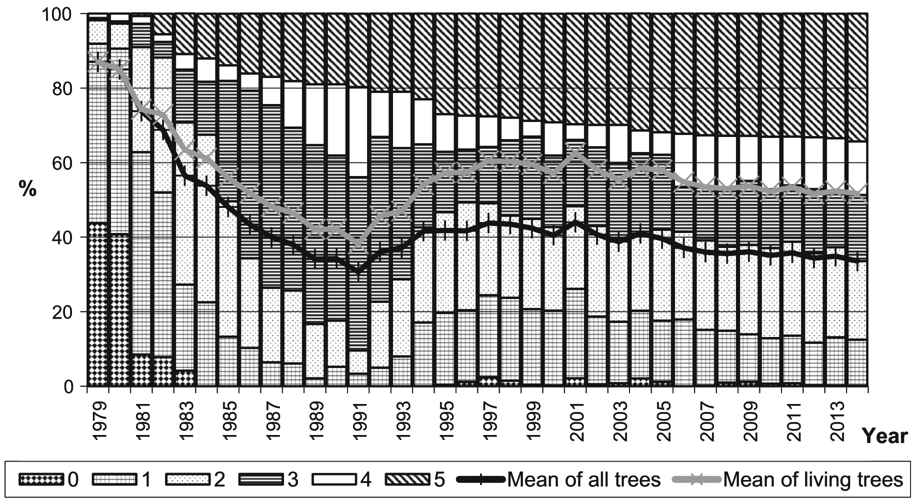


**Fig. 8** Dynamics of average foliation and shares of degrees of defoliation of the spruce in the peat bog spruce stand in PRP 1—Jelení lázeň

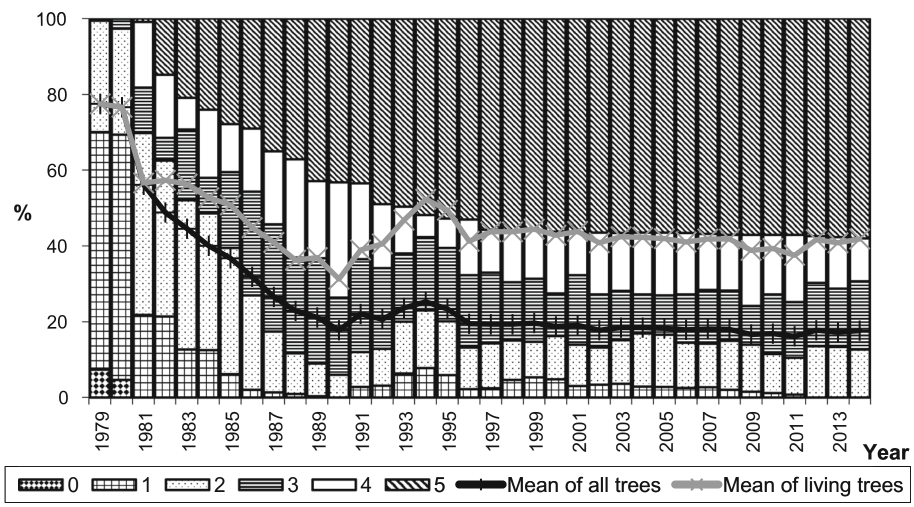


**Fig. 9** Dynamics of average foliation and shares of degrees of defoliation of the spruce in the peat bog spruce stand in PRP 2—U Kunštátské kaple

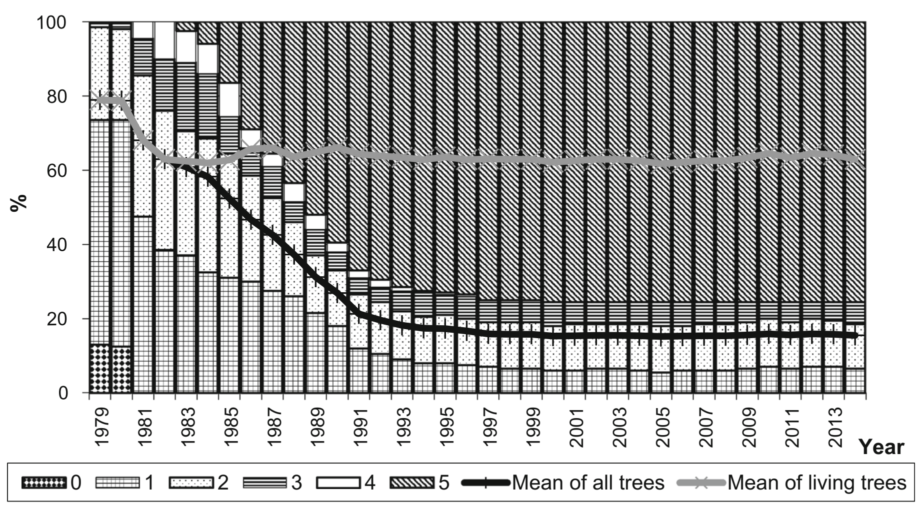


**Fig. 10** Dynamics of average foliation and shares of degrees of defoliation of spruces in the climax spruce stand in PRP 3—Koruna

the current year ($r = 0.30$, 0.32; Fig. 13). Statistically significant negative correlations with precipitation amount in June of the current year were also found ($r = -0.33$; Fig. 13). In addition, diameter increment was positively correlated with temperatures and negatively correlated with precipitation and $SO_2$ concentrations (Table 4).

**Table 4** Correlations between health status and radial growth increment and climatic and air pollution factors in 1979–2013

| | $SO_2$ mean | $SO_2$ max | Temp Ann | Temp Veg | Temp ActVI | Temp ActVII | Temp ActVIII | Prec Ann | Prec Veg | Prec ActI–III | NonPrec Day | TempAct V–VIII | PrecAct V–VIII | Temp Last V–VIII | PrecLast V–VIII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Foliation all trees | 0.14 | **0.28** | **−0.45** | **−0.51** | **−0.21** | **−0.36** | **−0.33** | 0.04 | 0.07 | −0.09 | 0.13 | **−0.42** | 0.05 | **−0.47** | 0.02 |
| Foliation living trees | −0.09 | 0.01 | **−0.27** | **−0.28** | −.0378 | **−0.26** | **−0.21** | 0.11 | 0.14 | −0.03 | 0.08 | **−0.24** | 0.11 | **−0.25** | 0.04 |
| Mortality | **−0.25** | **−0.37** | **0.40** | **0.46** | **0.26** | **0.28** | **0.27** | 0.01 | 0.01 | 0.09 | −0.12 | **0.37** | 0.02 | **0.44** | 0.01 |
| Annual mortality | **0.46** | **0.48** | −0.12 | −0.12 | **−0.22** | −0.09 | −0.11 | −0.13 | **−0.13** | −0.07 | 0.10 | −0.14 | −0.14 | −0.09 | −0.07 |
| Increment | **−0.23** | **−0.23** | **0.31** | **0.28** | **0.22** | 0.19 | 0.12 | −0.09 | **−0.23** | 0.17 | 0.12 | **0.22** | **−0.23** | **0.21** | −0.06 |

Significant correlations ($P < 0.01$) are indicated in bold

$SO_2$ mean—mean annual $SO_2$ concentration, $SO_2$max—maximum day $SO_2$ concentrations, TempAnn—mean annual temperature (°C), TempVeg—mean temperature (°C) in the vegetation season, TempActVI (VII, VIII)—mean temperature (°C) in June (July, August) of the given year, PrecAnn—annual sum of precipitation (mm), PrecVeg—sum of precipitation (mm) in the vegetation season, PrecActI–III—sum of precipitation (mm) in January–March of the given year, NonPrecDay—number of days without precipitation in the period May–August, TempActV–VIII—mean temperature (°C) in May–August of the given year, PrecActV–VIII—sum of precipitation (mm) in May–August of the given year, TempLastV–VIII—mean temperature (°C) in May–August of the previous year, PrecLastV–VIII—sum of precipitation (mm) in May–August of the previous year

### Interactions of air pollution, climate, health status, and radial growth

Results of the PCA are presented in an ordination diagram in Fig. 14. The first ordination axis explains 27 % of the variability in the data, the first two axes explain together 45 %, and the first four axes explain together 65 %. The first axis $x$ represents the trends in the development of health status and annual radial increment together with temperatures in both the current and last years and $SO_2$ concentrations. The second axis $y$ represents precipitation parameters. Foliation of living trees was negatively correlated with the annual ring width and with the temperatures in vegetation season, July, August, and May–August of the current and last year, and with precipitation in January–March of the current year. Annual mortality of trees was positively correlated with maximum and mean annual $SO_2$ concentrations and partly also with the number of days without any precipitation during the year. Health status in terms of living trees' foliation and annual tree mortality was not correlated, or was correlated only very weakly, with any precipitation parameter. With respect to time, health status during the first half of the investigated period (1980s, 1990s) was related more to $SO_2$ concentrations and precipitation parameters, whereas during the second half of the investigated period (after 2000) it was related more to temperature.

## Discussion

### Long-term trends in climate and air pollution

The ridges of the Orlické hory Mts. are characterised by a harsh climate with low temperatures and high total precipitation (see Fig. 3). The ambient temperatures are, however, not a limiting factor for Norway spruce. Total precipitation exceeds 300 mm (the maximum for optimal growth) in the May–August period (Fig. 4), with the exception of 1992 and 2003, when water deficit stress was significant. Similar conclusions were derived by Žid and Čermák (2008) in the upper elevations of the Orlické hory Mts. in the Anenský vrch area.

The relationship between precipitation and temperatures during the vegetation season has been described similarly by Kahle and Spiecker (1996), Dittmar and Elling (2004) for Germany, Mäkinen et al. (2001) for Finland, Meyer and Bräker (2001) for Switzerland, and Koprowski and Zielski (2006) for Poland. The last authors note that radial growth is influenced not only by climatic factors (precipitation and temperature), but also by fructification, increased atmospheric $CO_2$ levels, nitrogen compounds, and UV radiation.

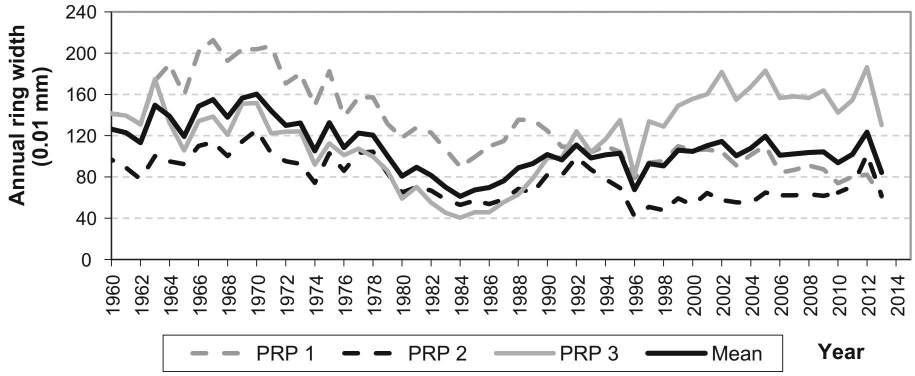


**Fig. 11** Standard annual ring chronology for PRP 1–3 and the entire study area of top parts of the Orlické hory Mts.

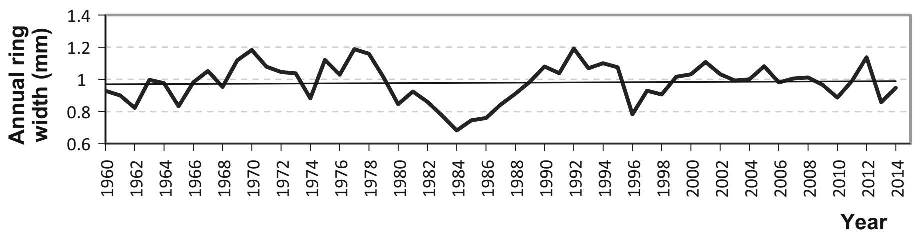


**Fig. 12** Average annual ring increment in the entire study area of top parts of the Orlické hory Mts. after removing the age trend in Arstan software

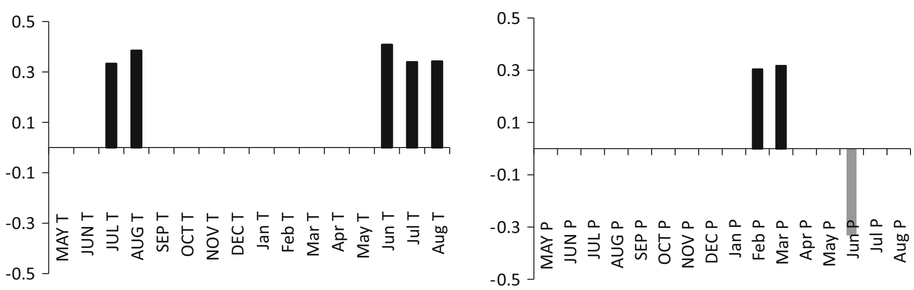


**Fig. 13** Values of correlation coefficients of regional residual index tree–ring chronology with average monthly precipitation and temperature from May previous year (*block letters*) to August of the year in question in the period 1979–2012; values highlighted in *black* are statistically significant ($\alpha = 0.05$). Notes: *capital letters* indicate the months of the previous year and the *normal letters* the months of the current (given) year

The annual $SO_2$ and $NO_X$ concentrations gradually decreased from 1994 to 2013. The values indicate that in 1994–1998, the $SO_2$ concentrations were still high enough to cause acute damage to the assimilatory organs of the spruce (not observed). Damage to the Norway spruce assimilatory organs occurs when $SO_2$ concentrations reach 20 µg m$^{-3}$ and $NO_x$ concentration is about 30 µg m$^{-3}$ (Manninen and Huttunen 2000). Apparently, climate conditions play a crucial role in the damage process. Foliation damage was also observed at lower concentrations of $SO_2$ and $NO_x$, reflecting the synergic effects of air pollution and climatic factors, especially winter desiccation, at altitudes above 900 m a.s.l. in the Krkonoše (cf. Vacek et al. 2007).

The level of air pollutants decreased after 1999, with a slightly fluctuating trend, and no acute damage has ensued. Likewise, the $NO_x$ concentrations were relatively high in 1995–2000, followed by a decrease, again with considerable fluctuation. Figure 4 documents the trend of annual $SO_2$ and $NO_x$ concentrations (the 95th percentile of daily mean concentrations and daily maxima) on the Souš station. A noticeable decrease in the $SO_2$ concentrations occurred in 1999. This figure shows that the annual maximum $SO_2$ concentrations were elevated before 1999 and were presumably a predisposing factor for acute damage to the assimilation organs, acidification of stand soil, and disruption to the soil sorption complex. $NO_x$ concentrations have been decreasing slightly decreasing since 1997. Similar findings were reported for the mountain spruce stands in the Krkonoše Mts. (Vacek et al. 2013; Hůnová et al. 2014).

Ozone represented a significant air pollution factor in the Orlické hory Mts. in summer; its long-term concentrations

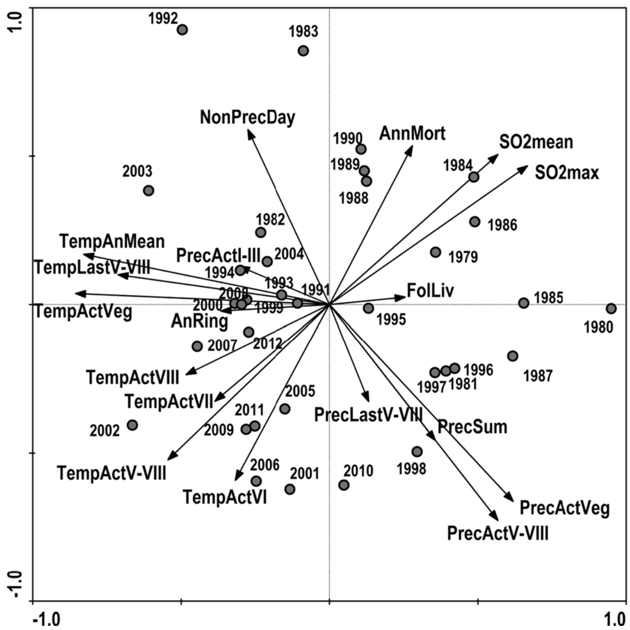


**Fig. 14** Ordination diagram showing results of PCA analysis of relationships among climatic data (Temp—mean temperature, Prec—precipitation, Act—current year, Last—last year, Veg—vegetation season, Sum—summary; *I–III, V–VIII, VI, VII, VIII*—months), $SO_2$ concentrations (mean—mean annual concentration, max—maximum annual concentration), annual mortality of trees (*AnnMort*) and ring width (AnRing—annual ring width); codes *filled circle* indicate years 1979–2012

have exceeded the vegetation protection thresholds (Hůnová and Schreiberová 2012). These thresholds were exceeded particularly during the vegetation season, and the occurrence and duration of the extremely high concentrations were closely linked to the weather trend in the vegetation season. The highest ozone concentrations were detected in 2002 and 2003, along with the highest frequency of exceeding the air pollution limit for the 24-h concentrations and the highest AOT40 rates. Similar results for the Sudetes ranges were found by Šrámek et al. (2007); Hůnová and Schreiberová 2012.

## Dynamics of the stand health status

After an onset of a major air pollution–ecological load in the Orlické hory Mts. in the late 1970s and early 1980s, the interaction of air pollution, climatic extremes, and biotic pests resulted in a dramatic deterioration in the health status of the spruce stands. After pollution-caused stress, only three RPPs situated in extreme habitats from 16 originally plots have been preserved in the present (Vacek et al. 2013). Similar findings in the Orlické hory were made by Žid and Čermák (2008), who showed the dependence of defoliation and yellowing symptoms on slope and aspect of the forest stands. The most severely damaged stands were identified in the summit areas. Number of secondary spruce shoots formed in the current year was positively correlated with the annual $NO_3$ deposition rates.

A similar increase in stand damage (defoliation) with site slope, and particularly with elevation, in climax spruce stands in the Krkonoše Mountains has been documented by Vacek and Lepš (1987, 1996) and Vacek and Matějka (2010). They indicate that the extreme winter desiccation in the early spring of 1981 led to a major increase in damage to spruce stands, caused by physiological weakening of the stands followed by an attack of various insect pests (Larch Tortrix, spruce bark beetle). Trees with inhibited growth were mostly damaged in the first stage of the disturbance; their cenotic position no longer had an effect on their mortality once the air pollution–ecological disturbance had been in place for a while. Moreover, in the north-eastern French Alps, tree sensitivity to climate was found to be greatly enhanced by insect infestation. Such interactions between climatic stress and insect outbreak led to forest dieback in a 15- to 20-year period (Rolland and Lempériere 2004). Similar findings from the Polish part of the Sudetes were made by Mazurski (1986), but he concluded that spruce stands are damaged by air pollution (chiefly acid deposition) because it upsets the nutrient balance in soil. Schulze (1989) expresses an almost identical opinion on the cause of damage to spruce stands in Central Europe; he attributes the considerable acidification in these stands to spruce's ability to intercept a high proportion of airborne acidifying substances. This process results in the strong acidification of soil in spruce stands (Augusto et al. 2002; Szopka et al. 2011). According to Hůnová et al. (2014), the total deposition of acidic substances in forest stands in the Czech Republic is considerably lower today than it was in the 1980s. This is clear for both wet and dry sulphur deposition. Nitrogen deposition does not show clear regional trends. In spite of an overall decrease in acid deposition, forest soils have not been regenerated adequately so far (Borůvka et al. 2005), defoliation is still substantial (Fabiánek et al. 2012), and numerous symptoms of damage to the assimilation organs are connected to nutritional disturbance (Lomský et al. 2012).

## Dynamics of radial growth

The regional standard ring chronology for the Orlické hory Mts. indicates a gradual reduction in the radial increment in 1979–1987. A similar case exists in mature spruce stands in the mountain areas of the north of the Czech Republic (Kroupová 2002; Sander et al. 1995; Vejpustková et al. 2004). According to the authors, the reduced increment was caused by air pollution, chiefly by $SO_2$ air pollution in the 1970s and 1980s combined with climatic factors. Since the late 1990s, this has been followed by a steady increase in radial increment. The period was characterised by mild winters without any substantial temperature extremes, relatively high temperatures in the vegetation season, more or less normal precipitation, and a decrease in air pollution, albeit with high $NO_x$ deposition (Vejpustková et al. 2004). The period of increased increment was interrupted by major decreases in 1996, 2010, and 2013.

The low radial increment was confirmed by an analysis of years with decreases in incremental growth. In 1979, it resulted from a temperature reversal at the turn of 1978–1979, when the temperature dropped by nearly 30 °C within 24 h; in 1982–1986, it was the combined influence of air pollution and climatic stresses; and in 1995 and 2013, the situation chiefly resulted from the winter desiccation of the assimilation organs in early spring (considerable extent of necrotic defects).

Similar results of the diameter increment and its reaction to climatic factors have been reported in the Orlické hory Mts., namely in spruce stands around the Anenský vrch at altitudes of 830–910 m a.s.l. (Rybníček et al. 2009). There is a similarity in the reduced increment between the 1970s and roughly the mid-1980s and its increase in the 1990s. There is also a similarity in the years of substantially reduced growth in 1979, 1981, 1984, and 1986.

Until 1978, there was a noticeable connection between the occurrence of major negative years and climatic extremes, especially in the case of stands on specific sites and in specific stand conditions in the summit areas of the Orlické hory Mts. Similarly, the period of 1977–1989 was also critical for spruce stands in the Krušné hory Mts. An almost identical situation existed in the Jizerské hory Mts. and the Krkonoše Mountains in 1979–1989, demonstrated by extremely low increments (50 % decrease on average) and a high frequency of defective annual ring formation (Kroupová 2002). The negative impact of air pollution on growth increment has been documented often (e.g. Feliksik 1995; Juknys et al. 2002). A gradual increase in the tree growth followed in the late 1990s. The period was characterised by mild winters without any significant temperature extremes, high vegetation season temperatures, approximately normal precipitation, and a decrease in air pollution. A perceptible increase in the radial increment in spruce is documented by Rybníček et al. (2009) for the Orlické hory Mts. and by Wilczyński and Feliksik (2005) for the western Polish Beskids in the same period. The trend curves of the regional standard chronology for our monitoring in the Orlické hory Mts. essentially correspond with the findings of Šrámek et al. (2008) for the Silesian Beskids.

Interpreting the correlations of the radial increment with the average monthly temperatures and precipitations is somewhat complicated, as the growth process is influenced by many factors. The positive effect of the July precipitation in the previous year and the July temperatures in the current year can be explained by conditions in the period in which a substantial part of the radial increment forms. July is typically the warmest month of the year in the area. Therefore, temperatures do not limit growth as long as there is a sufficient water reserve in the soil. If water availability is reduced, stress becomes apparent the following year in the form of reduced increment. Similar results indicating a positive effect of July temperatures on spruce growth have been detected in submontane spruce forests in the Western Carpathians (Bednarz et al. 1999), in spruce stands on the northern slopes of the Krkonoše Mts. (Sander et al. 1995), at altitudes of 830–910 m a.s.l. of the Orlické hory Mts. (Rybníček et al. 2009), in the Polish Tatras (Feliksik 1972), and at high-altitude sites in Norway, Germany, and Finland (Mäkinen et al. 2002; Andreassen et al. 2006). Positive correlations of radial spruce growth with summer precipitation and temperatures have also been found at lower elevations of the French Alps (Desplanque et al. 1999) and in the Polish Beskids (Feliksik et al. 1994). A positive influence of precipitation in July of the previous year on radial increment has also been reported at lower elevations of the Krušné hory Mts. (Kroupová 2002).

## Interactions of air pollution, climate, health status, and radial growth

Climatic factors together with air pollution have showed an important combined effect on the health status and radial growth of peaty bog as well as climax spruce stands in the upper elevations of the Orlické hory Mts. The most notable dynamics was documented in the period 1981–1991. Spruce trees, damaged by the interactive effects of air pollution and climatic extremes, were infested by spruce bark beetle; decline followed (Rolland and Lempériere 2004; Bytnerowicz et al. 2007). The results of multivariate analysis showed that the first half of the investigated period was largely influenced by $SO_2$ concentrations and precipitation parameters, whereas after 2000 temperatures became the primary factor. Annual concentrations of $SO_2$ were negatively correlated with the annual ring width; similarly, other studies reported the negative influence of $SO_2$ on basal area increment (Muzika et al. 2004) or on ring width of *Picea,* especially in mountainous areas (Hauck et al. 2012). Annual ring width was positively correlated with temperatures in May–August of the previous and current years and precipitation in January–March of the current year. Temperatures in June and July positively affect growth with increased elevation (Meyer and Bräker 2001; Andreassen et al. 2006; Hauck et al. 2012). The limiting effect of low temperatures is more significant not only at high-altitude sites, but also at northern latitudes, while the importance of precipitation increased in the south latitudes and at lowlands (Mäkinen et al. 2002). Additionally, in southern Finland precipitation in January was also positively related to increment, but in the peat stands the correlation between precipitation and growth was very weak (Mäkinen et al. 2001). In addition, the annual ring width was negatively correlated with precipitation in May–August of the current year. In contrast, spruce growth on northern Polish sites was positively correlated with rainfall from May to July, but it is caused by water deficiency in that period (Koprowski and Zielski 2006). The relationship between annual mortality and $SO_2$ concentrations was positive, as reported in coniferous forests in southern Germany (Elling et al. 2009), where a negative response (mortality or reduced growth) to increased $SO_2$ concentrations was observed but with quick recovery following a decline in concentration of the pollutant. In contrast, our results suggest that high concentrations of $SO_2$ triggered the deterioration of health status, but no distinct improvement of foliation was documented after the decrease in concentration.

## Conclusion

It can be concluded that climatic factors together with air pollution cause a progressive decline and even dying of spruce stands in the summit areas of the Orlické hory Mts. Until 1978, there was a connection between the occurrence of years with decreased tree growth and climatic extremes, when the stands reacted to climatic extremes by increased defoliation and decreased increment. A major deterioration in the health status of the spruce stands and their radial growth as a consequence of the interaction between the air pollution and climatic stresses occurred in 1979–1987. This outcome is indicated not only by high rates of defoliation or a decrease in radial increment, but first of all it is demonstrated in the 100 per cent mortality on most of the original research plots, which could not be included in the study for this reason. The three remaining plots are more resistant to bark beetle outbreak, probably because they are located on sites with extreme conditions, such as waterlogged soils and a summit position, which may favour resistance. The improved condition of the adjacent stands (due to elimination of insect pests) could contribute to stabilisation of the studied stands as well. Since the late 1990s, the health status of the spruce stands has been stabilised when measured by radial increment and foliation of living trees in the different PRPs. Foliation did not improve visibly after atmospheric pollution decreased. Tree growth increased significantly with increasing temperature, but was only slightly affected by precipitation. It is important to recognise that we had only a small number of different "surviving" plots to analyse in this study.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Andreassen K, Solberg S, Tveito OE, Lystad SL (2006) Regional differences in climatic responses of Norway spruce (*Picea abies* L. Karst) growth in Norway. For Ecol Manage 222(1):211–221

Augusto L, Ranger J, Binkley D, Rother A (2002) Impact of several common tree species of European temperate forests on soil fertility. Ann For Sci 59(1):233–253

Bednarz Z, Jaroszewick B, Ptak J, Szwarzyk J (1999) Dendrochronology of the Norway spruce (*Picea abies* (L.) Karst.) from the Babia Gora National Park, Poland. Dendrochronologia 16(17): 45–55

Biondi F, Waikul K (2004) Dendroclim 2002: AC++ program for statistical calibration of climate signals in tree ring chronologies. Comput Geosci 30(3):303–311

Boháčová L, Lomský B, Šrámek V (2010) Forest condition monitoring in the Czech Republic. Forestry and Game Research Institute, Strnady

Borůvka L, Podrázský V, Mládková L, Kuneš I, Drábek O (2005) Some approaches to the research of forest soils affected by acidification in the Czech Republic. Soil Sci Plant Nutr 51(5):745–749

Bridgmann HA, Davies TD, Jickells T, Hůnová I, Tovey K, Bridges K, Surapipith V (2002) Air pollution in the Krušné hory region, Czech Republic during the 1990s. Atmos Environ 36(21): 3375–3389

Buttoud G (2000) White Book 2000 on Mountain forest in Europe. Saint Jean ď Arvey, EOMF, Kemptville, Ontario

Bytnerowicz A, Omasa K, Paoletti E (2007) Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environ Pollut 147(3):438–445

De Vries W, Reinds GJ, Van Dobben H, De Zwart D, Amlid D, Neville P, Posch M, Auée JCH, Voogd EM (2003) Intensive monitoring of forest ecosystems a Europe, Technical Report. EC, UN/ECE, Brussels

Desplanque C, Rolland C, Schweingruber FH (1999) Influence of species and abiotic factors on extréme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). Trees 13(4):218–227

Dittmar C, Elling W (2004) Radial growth of Norway spruce [*Picea abies* (L.) Karst.] at the Coulissenhieb Site in relation to environmental conditions and comparison with sites in the Fichtelgebirge and Erzgebirge. Ecol Stud 172:291–311

EEA (2014) Air quality in Europe—2014. EEA Report No 5/2014. Copenhagen

Elling W, Dittmar C, Pfaffelmoser K, Rötzer T (2009) Dendroecological assessment of the complex causes of decline and recovery of the growth of silver fir (*Abies alba* Mill.) in Southern Germany. For Ecol Manage 257:1175–1187

Fabiánek P, Hellebrandová K, Čapek M (2012) Monitoring of defoliation in forest stands of the Czech Republic and its comparison with results of defoliation monitoring in other European countries. J For Sci 58(5):193–202

Feliksik E (1972) Dendroclimatic studies on spruce (*Picea excelsa* L.): Part I. Studies of spruce in Gasienicowy Forest in the Tatra Mountains. Acta Agrar Silv, Ser Silv 12:39–70

Feliksik E (1995) Dendrological monitoring of the treat to the forests of Western Beskids created by industrial immissions. Beskids Bull 7:23–34

Feliksik E, Wilczyński S, Wałecka M (1994) Klimatyczne uwarunkowania pryzrostow kambialnych świerka pospolitego (*Picea abies* Karst.) w leśnictwe Pierściec Acta Agrar Silv. Ser Silv 32:53–59

Flechard CR, Nemitz E, Smith R, Fowler D, Vermeulen AT, Bleeker A, Erisman JW, Simpson D, Zhang L, Tang YS, Sutton MA (2011) Dry deposition of reactive nitrogen to European ecosystems: a comparison of inferential models across the NitroEurope network. Atmos Chem Phys 11:2703–2728

Fritts HC (1976) Tree ring and climate. Academic Press, London

Gallo J, Kuneš I, Baláš M, Nováková O, Drury ML (2014) Occurrence of frost episodes and their dynamics in height gradient above the ground in the Jizerské hory Mts. J For Sci 60(1):35–41

Grissino-Mayer HD, Holmes RL, Fritts HC (1992) International tree-ring data bank program library: user's manual. Laboratory of Tree-Ring Research, University of Arizona, Tuscon

Hauck M, Zimmermann J, Jacob M, Dulamsuren C, Bade C, Ahrends B, Leuschner C (2012) Rapid recovery of stem increment in Norway spruce at reduced $SO_2$ levels in the Harz Mountains, Germany. Environ Pollut 164:132–141

Hruška J, Ciencala E (2003) Long-term acidification and nutrient degradation of forest soils—limiting factors of forestry today. Ministry of the Environment, Prague

Hůnová I (2001) Spatial Interpretation of ambient air quality for the territory of the Czech Republic. Environ Pollut 112(2):107–119

Hůnová I, Schreiberová M (2012) Ambient ozone phytotoxic potential over the Czech forests as assessed by AOT40. i-Forest Biogeosci For 5:153–162

Hůnová I, Šantroch J, Ostatnická J (2004) Ambient air quality and deposition trends at rural stations in the Czech Republic during 1993–2001. Atmos Environ 38(6):887–898

Hůnová I, Maznová J, Kurfürst P (2014) Trends in atmospheric deposition fluxes of sulphur and nitrogen in Czech forests. Environ Pollut 184:668–675

Juknys R, Stravinskiene V, Vencloviene J (2002) Tree-ring analysis for the assessment of anthropogenic changes and trends. Environ Monit Asses 77(1):81–97

Kahle HP, Spiecker H (1996) Adaptability of radial growth of Norway spruce to climate variations: results of a site-specific dendroecological study in high elevetions of the Black Forest (Germany). Radiocarbon 38:785–801

Kantor P (1983) Water balance of a mature spruce and a beech stand. Comm Inst For Čechosloveniae 13:111–130

Kärenlampi L, Skärby L (1996) Critical levels for ozone in Europe: testing and finalizing the concepts. University of Kuopio, Kuopio

Kmet' J, Ditmarová Ľ, Priwitzer T, Kurjak D, Baláž P, Blaženec M (2010) Physiological limits—a possible cause of spruce decline. Beskydy 3(1):55–64

Knibbe B (2007) PAST 4: personal analysis system for treering research, Version 4.2., SCIEM, Vienna

Koprowski M, Zielski A (2006) Dendrochronology of Norway spruce (*Picea abies* (L.) Karst.) from two range centres in lowland Poland. Trees 20(3):383–390

Kroupová M (2002) Dendroecological study of spruce growth in regions under long-term air pollution load. J For Sci 48(12):536–548

Kula E, Kajfosz R, Polívka J (2013) Attractiveness of *Picea pungens* to the bark beetle species *Ips amitinus* (Eichh.) and *Pityogenes chalcographus* (L.). J For Sci 59:493–502

Kuneš I, Baláš M, Balcar V, Kacálek D, Millerová K, Jančová A, Nováková O (2013) Effects of fertilisation on growth and nutrition of Norway spruce on a harsh mountain site. J For Sci 59(8):306–318

Larcher W (2001) Ökophysiologie der Pflanzen. Ulmer, Stuttgart

Likens GE, Driscoll CT, Buso DC (1996) Long-term effects of acid rain: response and recovery of a forested ecosystem. Science 272:244–246

Lochman V, Mareš V (1995) Air pollutant fallout in forest ecosystems of the Orlické Mountains and its effect on chemical composition of precipitation, soil and stream water, and on soil development. Communicationes Instituti Forestalis Bohemicae 18:75–95

Lomský B, Šrámek V, Novotný R (2012) Changes in the air pollution load in the Jizera Mts.: effects on the health status and mineral nutrition of the young Norway spruce stands. Eur. J For Res 131(3):757–771

Lomský B, Šrámek V, Novotný R (2013) The health and nutritional status of Norway spruce stands in the Krušné hory Mts. 15 years subsequent to the extreme winter of 1995/96. J For Sci 59(9):359–369

Lorenz M (1995) International co-operative programme on assessment and monitoring of air pollution effects on forests—ICP forests. Water Air Soil Pollut 85(3):1221–1226

Lüttge U (2014) Climate change, air pollution and global challenges. Understanding and perspectives from forest research. J For Sci 60:351–352

Mäkinen H, Nöjd P, Mielikäainen K (2001) Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce [*Picea abies* (L.) Karst.] in southern Finland. Trees 15:177–185

Mäkinen H, Nöjd P, Kahle HP, Neumann U, Tveite B, Mielikäinen K, Röhle H, Spiecker H (2002) Radial growth variation of Norway spruce (*Picea abies* (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. For Ecol Manage 171(3):243–259

Manninen S, Huttunen S (2000) Response of needle sulphur and nitrogen concentrations of Scots pine versus Norway spruce to $SO_2$ and $NO_2$. Environ Pollut 107(3):421–436

Materna J (1999) Development and causes of forest damage in the Ore Mts. J For Sci 45:147–152

Matyssek R, Wieser G, Calfapietra C, de Vries W, Dizengremel P, Ernst D, Jolivet Y, Mikkelsen TN, Mohren GMJ, Le Thiec D, Tuovinen JP, Weatherall A, Paoletti E (2012) Forests under climate change and air pollution: gaps in understanding and future directions for research. Environ Pollut 160:57–65

Mazurski KR (1986) The destruction of forests in the Polish Sudetes Mountains by industrial emissions. For Ecol Manage 17(4):303–315

Meyer FD, Bräker OU (2001) Climate response in dominant and suppressed spruce trees, *Picea abies* (L.) Karst., on subalpine and lower montana site in Switzerland. Ecoscience 8:105–114

Moldan B, Schnoor JL (1992) Czechoslovakia: examining a critically ill environment. Environ Sci Technol 26:14–21

Muzika RM, Guyette RP, Zielonka T, Liebhold AM (2004) The influence of $O_3$, $NO_2$ and $SO_2$ on growth of *Picea abies* and

*Fagus sylvatica* in the Carpathian Mountains. Environ Pollut 130(1):65–71

Nosek M (1972) Metody v klimatologii, [Methods in climatology]. Academia, Prague

Paoletti E, Schaub M, Matyssek R, Wieser G, Augustaitis A, Bastrup-Birk AM, Bytnerowicz A, Gunthardt-Goerg MS, Muller-Starck G, Serengil Y (2010) Advances of air pollution science: from forest decline to multiple-stress effects on forest ecosystem services. Environ Pollut 158(6):1986–1989

Preusler T, Bastrup-Birk A, Beuker E (2004) Manual on methods and criteria for harmonized sampling assessment, monitoring and analysis of the effects of air pollution on forests. Part VII. UN ECE, convention on long-range transboundary air pollution

Renner E (2002) The black triangle area—fit for Europe. Ambio 31:231–235

Rolland C, Lempériere G (2004) Effects of climate on radial growth of Norway spruce and interactions with attacks by the bark beetle *Dendroctonus micans* (Kug., Coleoptera: Scolytidae): a dendroecological study in the French Massif Central. For Ecol Manage 201(1):89–104

Rybníček M, Čermák P, Kolář T, Přemyslovská E, Žid T (2009) Influence of temperatures and precipitation on radial increment of Orlické hory Mts. spruce stands at altitudes over 800 m a.s.l. J For Sci 55(6):257–263

Sander C, Eckstein D, Kyncl J, Dobrý J (1995) The growth of spruce (*Picea abies* (L.) Karst.) in the Krkonoše (Giant) Mountains as indicated by ring width and wood intensity. Ann Sci For 52:401–410

Schulze DE (1989) Air pollution and forest decline in a Spruce (*Picea abies*) forest. Science 244(4906):776–783

Serengil Y, Augustaitis A, Bytnerowicz A, Grulke N, Kozovitz AR, Matyssek R, Muller-Starck G, Schaub M, Wieser G, Coskun AA, Paoletti E (2011) Adaptation of forest ecosystems to air pollution and climate change: a global assessment on research priorities. i-Forest Biogeosci For 4:44–48

Spetich M, Fan Z, Fan X, He H, Shifley SR, Moser WK (2011) Risk factors of oak decline and regional mortality patterns in the Ozark highlands of Arkansas and Missouri. In: Potter KM, Conkling BL (eds) 2012. Forest health monitoring: 2009 national technical report. Gen. Tech. Rep. SRS-GTR-167. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, pp 199–202

Spiecker H (1990) Growth variation and environmental stresses—long-term observation on permanent research plots in south western Germany. Water Air Soil Pollut 54(91):247–256

Špulák O (2012) Aboveground biomass and nutrients in an 18-years-old stand of blue spruce (*Picea pungens* Engelm.) as a substitute tree species. J For Sci 58(6):253–264

Šrámek V, Novotný R, Bednářová E, Uhlířová H (2007) Monitoring of ozone risk for forest in the Czech Republic: preliminary results. Sci World J 7:78–83

Šrámek V, Vejpustková M, Novorný R, Hellebrandová K (2008) Yellowing of Norway spruce stands in the Silesian Beskids—damage extent and dynamics. J For Sci 54(2):55–63

Šrámek V, Fadrhonsová V, Jurkovská L (2014) Ca/Al ratio in Norway spruce fine roots on monitoring plots in the Czech Republic. J For Sci 60:121–131

Szopka K, Karczewska A, Kabała C (2011) Mercury accumulation in the surface layers of mountain soils: a case study from the Karkonosze mountains, Poland. Chemosphere 83(11):1507–1512

ter Braak CJF, Šmilauer P (2002) CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5), Microcomputer Power, Ithaca, New York

Tesař V (1993) Tradition und jetzige Bestreben einer naturnahen Waldwirtschaft in der Tschechischen Republik, [Tradition and nowadays endeavour of near-nature forest management in the Czech Republic]. Actes du 1er Congres européen PRO SILVA, 21.–24. 6. 1993, Besanson, France, pp 219–220

Tesař V, Temmlová B (1971) Olistění stromů jako kritérium pro hodnocení stavu porostů v imisním území, [Foliage of trees as a criterion for evaluating the condition of stands in pollution area]. Lesnictví 17(11):1017–1032

Tranquillini W (1979) Physiological ecology of Alpine timberline, tree existence at high altitudes with special reference to the European Alps, ecological studies 31. Springer, Berlin

Ulrich B (1991) Conclusions from 10 years of research into forest ecosystems and damage to forest. For Holz 46(21):3–12

Ulrich B, Mayer R, Khanna PK (1980) Chemical changes due to acidic precipitation in a loess-derived soils in Central Europe. Soil Sci 130(4):193–199

UN/ECE (2004) Mapping manual revision. UN-ECE convention on long-range transboundary air pollution. Manual on the methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends. http://www.icp-mapping.org

Vacek S, Lepš J (1987) Changes in the horizontal structure in a spruce forest over a 9-year period of pollutant exposure in the Krkonoše Mountains, Czechoslovakia. For Ecol Manage 22(3–4):291–295

Vacek S, Lepš J (1996) Spatial dynamics of forest decline: the role of neighbouring trees. J Veg Sci 7(6):789–798

Vacek S, Matějka K (2010) Health status of forest stands on PRP in the Krkonoše Mts. J For Sci 56(11):555–569

Vacek S, Zingari PC, Jeník J, Vančura K, Simon J, Smejkal J (2003) Mountain forests of the Czech Republic. Ministry of agriculture, Prague

Vacek S, Matějka K, Simon J, Malík V, Schwarz O, Podrázský V, Minx T, Tesař V, Anděl P, Jankovský L, Mikeska M (2007) Zdravotní stav a dynamika lesních ekosystémů Krkonoš pod stresem vyvolaným znečištěním ovzduší. [Health status and dynamics of forest ecosystems under air pollution stress in the Giant Mts.]. Folia forestalia Bohemica, Lesnická práce, Kostelec nad Černými lesy

Vacek S, Semelová V, Remeš J, Podrázský V (2009) Effect of soil chemical properties on growth, foliation and nutrition of Norway spruce stand affected by yellowing in the Bohemian Forest Mts., Czech Republic. Eur J For Res 128(4):367–375

Vacek S, Hejcmanová P, Hejcman M (2012) Vegetative reproduction of *Picea abies* by artificial layering at the ecotone of the alpine timberline in the Giant (Krkonoše) Mountains, Czech Republic. For Ecol Manage 263:199–207

Vacek S, Bílek L, Schwarz O, Hejcmanová P, Mikeska M (2013) Effect of air pollution on the health status of Spruce stands, a case study in the Krkonoše Mountains, Czech Republic. Mt Res Dev 33(1):40–50

Vejpustková M, Zahradník D, Šrámek V, Fadrhonsová V (2004) Growth trends of spruce in the Orlické hory Mts. J For Sci 50(2):67–77

Vingarzan R (2004) A review of surface ozone background levels and trends. Atmos Environ 38:3431–3442

Wilczyński S, Feliksik K (2005) Disturbances in variation of the annual ring width of Norway spruce in the Polish Western Beskids Mountains. J For Sci 51(12):539–547

Yamaguchi DK (1991) A simple method for cross-dating increment cores from living trees. Can J For Res 21(3):414–416

Žid T, Čermák P (2008) Health condition of spruce stands in the Orlické hory Mts. in relation to climatic, anthropogenic and stand factors. J For Sci 53(1):1–12