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Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014

Struktura, vývoj a zdravotní stav smrčin pod vlivem imisí v západních Krkonoších v letech 1979–2014

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Abstract

The structure and health status of waterlogged or peaty spruce (*Picea abies* [L.] Karst.) forests in the summit parts of the Krkonoše Mts. in the Czech Republic were studied in 1979–2014. The objective was to evaluate the stand structure, dead wood, trend of the health status and productivity on four permanent research plots (PRP) in relation to air pollution (SO_2 and NO_x concentrations) and climatic conditions (temperatures and precipitation amounts). Stand structure was evaluated on the base of the measured parameters of individual trees on PRP. The health status of trees was evaluated according to foliage, and their vitality was assessed according to their radial growth documented by dendrochronological analyses. The radial growth was negatively correlated with SO_2 and NO_x concentrations. Stand dynamics during the observation period was characterised by increased tree mortality, the presence of dead wood and reduction of stand density from 1983 to 1992, while the most severe impairment of health status and stand stability occurred in 1982–1987. The foliage mass of living trees has been gradually increasing since 1988, but no pronounced improvement of tree vitality was documented after the decrease in SO_2 concentration. However, particularly physiologically weakened spruce trees were attacked by the European spruce bark beetle (*Ips typographus*). The process of forest damage is manifested not only by foliage reduction but also by symptoms of various necroses on the assimilatory organs. In terms of climatic data, the weather in April had the most important effect on radial growth. Diameter increment showed positive statistically significant correlation with temperature in growing season, but the precipitation effect was low.

Keywords: stand structure; Norway spruce (*Picea abies* [L.] Karst.); air pollutants; growth ring analyses; Sudetes mountain range

Abstrakt

Na čtyřech trvalých výzkumných plochách (TVP) v podmáčených až rašelinných smrčinách (*Picea abies* [L.] Karst.) ve vrcholových partiích Krkonoš v České republice byla v letech 1979–2014 studována struktura a zdravotní stav porostů. Cílem bylo zhodnotit strukturu porostů, odumřelého dřeva, trend vývoje zdravotního stavu a produktivitu ve vztahu ke znečištění ovzduší (koncentrace SO_2 a NO_x), klimatickým podmínkám (teplota a množství srážek). Zdravotní stav stromů na TVP byl hodnocen podle olistění a jejich vitalita byla posuzována podle radiálního růstu doložená dendrochronologickou analýzou. Radiální růst byl v negativní korelaci s SO_2 a koncentrací oxidů dusíku. Ke značnému narušení struktury porostů zvýšenou mortalitou, přítomností odumřelého dřeva a snížením hustoty porostu docházelo v letech 1983 až 1992, zatímco k největším poruchám zdravotního stavu a stability porostů došlo v letech 1982 až 1987. Od roku 1988 již u živých stromů nastalo postupné zvyšování olistění, ale po poklesu koncentrací SO_2 nebylo prokázáno výrazné zlepšení vitality stromů. I nadále však jednotlivé fyziologicky oslabené stromy smrku byly napadány lýkožroutem smrkovým (*Ips typographus*). Proces poškození lesa se zde projevuje nejen poklesem olistění, ale i symptomy různých nekróz na asimilačním aparátu. Z hlediska klimatických dat mělo počasí v dubnu významný vliv na radiální růst. Průměrný přírůst ukázal pozitivní statisticky významnou korelaci s teplotou ve vegetačním období, ale účinek srážek byl nízký.

Klíčová slova: struktura porostů; smrk ztepilý (*Picea abies* [L.] Karst.); imise; letokruhové analýzy; Sudetská soustava

1. Introduction

The ecosystems in higher mountain areas may be more vulnerable to air pollution compared to the ecosystems at lower altitudes. Synergistic effects of high and long-lasting air pollution along with climatic stresses may contribute to an extensive decline of forests in these localities (Vávrová et al. 2009). The occurrence of climate extremes, air pollutants and other abiotic and biotic stress agents were often related to frequent stress symptoms observed in forest ecosystems in Europe especially from 1970 to 1980 (Führer 1990). Rapid expansion of these symptoms, their spatio-temporal distribution and mutual relationship of their impacts on forest communities have led to a description of this status as a syndrome of unknown forest loss (Mueller-Edzards et al. 1997; Badea et al. 2004), sometimes called as "forest decline" (Waldsterben) (Kandler & Innes 1995). It is to note that the effects of all known biotic and abiotic factors cannot fully explain all aspects of this phenomenon (Landmann 1991). Many hypotheses about the causes of ecosystem disturbances were associated with the effects of air pollution and therefore the air pollution was considered as a predisposing and accompanying factor of forest ecosystem disturbance (Lorenz et al.

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1999). Besides, great changes in forest ecosystems under the influence of air pollutants occurred as a result of acidification of the environment (Vacek et al. 2013).

The greatest threat to the Krkonoše forest ecosystems was the industrial air pollution mainly by SO_2, which most severely damaged the Krkonoše forest ecosystems (Vacek & Matějka 2010). In the next years, there was a decrease in the air pollution by SO_2, but in many localities forest stands were greatly damaged and their decline continued. In the mid-nineties of the 20th century there was a frequent dieback of individual trees in 80% of Norway spruce (*Picea abies* [L.] Karst.) stands above 900 m a.s.l., and surviving trees suffered from intensive defoliation (Polák et al. 2007). After the industrial air pollution was reduced, photochemical pollution gained in importance (Stanners & Boreau 1995). It was caused mainly by an increased number of vehicles that produce increased emissions of nitrogen oxides and volatile hydrocarbons. This part of central Europe is affected by increased concentrations of ozone (O_3), which is considered a phytotoxic agent causing damage to vegetation (Bytnerowicz et al. 2003). Ozone can negatively increase the phytotoxic effects of other compounds that contaminate air, mainly sulphur and nitrogen oxides (SO_x and NO_x) (Bytnerowicz et al. 2004). The ozone itself caused very severe damage to forest ecosystems in all Europe (de Vries et al. 2003). Moreover, an increase in the ozone level is assumed in the future (Brasseur et al. 2001).

In spite of the reduction in emissions of industrial air pollutants in the CR that resulted in extensive and very severe disturbances of spruce forests in many localities, relatively high defoliation has been observed in the last years in the CR, Slovakia (Hlásny et al. 2010), and Poland (Vančura et al. 2000). For the most effective management it is necessary to take into account what possible impacts climate changes can have on the growth and mortality of particular tree species (Hanewinkel et al. 2014) because higher frequency and intensity of disturbances are expected due to climate changes (Fuhrer et al. 2006; Jonášová et al. 2010). We used dendrochronological methods to determine the relationship between the growth of trees and environmental conditions and stand dynamics including disturbances. Most commonly, precipitation and temperatures are recorded, and climate data are then analysed for the frequency of extreme years, changes in mean conditions, ranges of long-term variability, and changes in inter-annual variability (Sheppard 2010).

Air pollutants not only influence the health status, biological diversity and ecosystem processes but they can also exert indirect effects on secondary threats to forest ecosystems such as bark beetle attack (Hlásny et al. 2010a) or toxicity of heavy metals in soils (Bytnerowicz et al. 2004). Climatic extremes or pathogenic organisms and general deterioration of soil conditions contribute to greater damage to forest stands (Lomský et al. 2012).

Clouds and fogs that significantly contribute to hydrological and chemical inputs into forest ecosystems (Zimmermann & Zimmermann 2002) have an irreplaceable effect on the transport of substances causing pollution. For this reason the chemistry of fogs and clouds is a useful tool for additional interpretation and identification of the long-term transport of compounds causing pollution. In mountain areas of Europe, fogs and clouds can contain up to 70% of total deposition. It is to note that the deposition of air pollutants through fog is considered as one of the most important factors of forest disturbance in the western Sudetes (Godek et al. 2012). The highest mountain of the Krkonoše Mts. called Sněžka belongs to localities with the highest incidence of fogs in Europe, on average on 296 days a year (Migała et al. 2002). In the Krkonoše Mts., a decreasing annual width of tree-rings as a result of the effect of fogs polluted by phytotoxic compounds was also proved. It causes changes in other characteristics of trees like height increment or total biomass production (Ferretti et al. 2002).

In the framework of the long-term study of forest stands affected by air pollutants it is assumed that other significant stress factors influencing individual trees and whole stands should be excluded with regard to the length of the period. They include mechanical impacts of snow cover, land movements of larger extent, effect of browsing by herbivores, mutual competition and presence of pathogenic fungi and insects (Godek et al. 2012). Based on this assumption, this study is exclusively aimed at the structure and development of mountain spruce forests influenced by air pollutants and other environmental factors, notably the effect of precipitation and temperature. This problem is relatively very extensive with high spatio-temporal variability.

The aim of this study was to evaluate the structure and development of spruce forests influenced by air pollutants on four PRP out of 7 plots in specific conditions of the western Krkonoše Mts. in the Pod Voseckou boudou locality in the time horizon of 35 years. The objectives were to 1) analyse the dynamics and structural changes of waterlogged and peaty autochthonous spruce forests in the period 1979–2014; 2) detect the development of radial growth and health status (foliation) of spruce mountain stands; 3) analyse the effect of air pollution (SO_2 and NO_x concentrations) and climatic factors (temperatures and precipitation) on radial growth; and 4) determine the relationships among stand parameters, structural indices and dead wood in the course of time. The study attempts to contribute to the understanding of the core of the problem, based on the obtained results of management optimisation, mainly regeneration in these or similar forest ecosystems of mountain spruce forests in the Krkonoše Mts. and in other Sudetes mountain ranges.

2. Material and Methods

2.1. Description of study area

The study was conducted in waterlogged or peaty autochthonous spruce forests on 4 PRPs of 50 × 50 m in size (0.25 ha) in the western part of the Krkonoše Mts. National Park. The localisation of PRPs is represented in Fig. 1 and the basic characteristics of PRPs are shown in Table 1. These permanent research plots are typical waterlogged and peaty spruce forests in the western Krkonoše Mts.

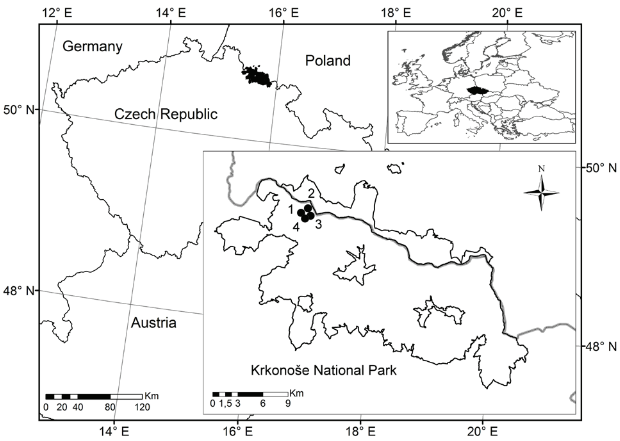

Fig. 1. Localisation of PRPs with waterlogged or peaty spruce forests in the western Krkonoše Mts. (Spatial coordinates: PRP 1: 50°46'39"N, 15°30'33"E; PRP 2: 50°46'43"N, 15°30'40"E; PRP 3: 50°46'38"N, 15°30'43"E; PRP 4: 50°46'37"N, 15°30'35"E).

complex. Average annual concentrations of NO_x and average concentrations of NO_x in the non-vegetation period have been slightly decreasing since 1994. On the contrary, annual maximum concentrations of NO_x have been oscillating considerably.

2.2. Data collection

A theodolite was used to determine the structure of the forest stands in the plots at the time of establishment of 4 permanent research plots (PRP) of 50 × 50 m in size (0.25 ha) in 1979. PRPs were established in the same locality, where monitoring of the health status of forest stands was conducted (cf. Tesař et al. 1971).

Repeated dendrometric measurements were performed every five years. In 2009 and 2014 the FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.) was used to remeasure the positions of old trees and new ingrowth individuals. In the particular measurements the positions of all overstorey trees of diameter at breast height (DBH) above 4 cm were localised. Other measured parameters of the tree layer were heights of the live crown base and crown perimeter. DBH of the trees were measured with a metal calliper to the nearest 1 mm. Tree heights and heights of the live crown base were measured with a Blume-Leiss hypsometer to the nearest 0.5 m (1979) and Vertex laser hypsometer to the nearest 0.1 m (2014). The tree layer was divided accor-

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

PRP	Name of PRP	Species	Age of tree layers	Height [m]	DBH [cm]	Volume [m^3 ha^{-1}]	Altitude	Soil	Exposition	Slope [°]	Forest site type[1]
1	Pod Voseckou 1	*Picea abies*	224/47/11	17	43	179	1180	Gley, histosol	SW	12	8R1, 8G3
2	Pod Voseckou 2	*Picea abies*	224/47/11	12	31	243	1205	Gley, histosol	SW	14	8R1, 8G3
3	Pod Voseckou 3	*Picea abies*	224/47/11	9	24	82	1215	Gley, histosol	SW	8	8R1, 8G3
4	Pod Voseckou 4	*Picea abies*	224/47/11	15	38	273	1185	Gley, histosol	SW	11	8R1, 8G3

Notes: [1]forest site type: 8G – waterlogged spruce forest (*Piceetum paludosum mesotrophicum*), 8R – boggy spruce forest (*Piceetum turfosum montanum*). As for the potential vegetation, in forest type group 8G these are spruce forests of the plant associations *Mastigobryo-Piceetum* Br.-Bl. et Sissingh in Br.-Bl. et al. 1939 and *Calamagrostio villosae-Piceetum sphagnetosum* Hartmann in Hartmann et Jahn 1967 and in FTG 8R it is the plant association *Sphagno–Piceetum* (Tüxen 1937) Hartmann 1953.

Fig. 2 illustrates the trend of air pollution according to SO_2 and NO_x concentrations as measured at the Souš station. The values indicate that SO_2 concentrations were rather high before 1999 to cause acute damage to spruce foliage. A pronounced decrease in SO_2 and NO_x concentrations occurred in 1999. Fig. 2 documents that the annual maximum concentrations were very high before 1999, being a predisposing factor for the origin of acute damage to foliage, stand soil acidification and disturbance of the soil sorption

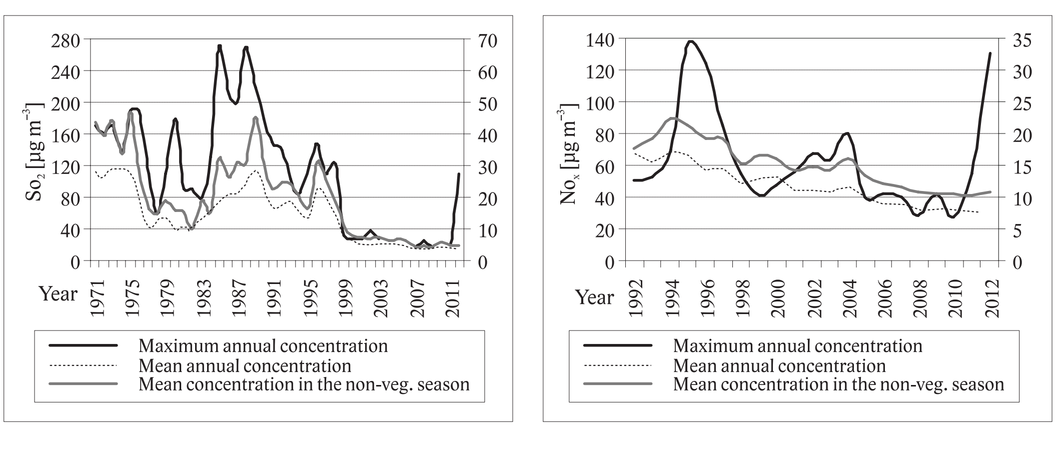

Fig. 2. Trends of average annual concentrations of SO_2 and NO_x, average concentrations of SO_2 and NO_x in the non-vegetation period (right y axis), annual maximum concentrations of SO_2 and NO_x (left y axis) at the Souš station. The values of SO_2 in 1971–2012 (left) and NO_x 1992–2012 (right) are given in μg m^{-3} (data of the Czech Hydrometeorological Institute).

ding to into upper storey (dominant and codominant trees) and lower storey (intermediate and suppressed trees) tree classes. Both qualitative traits and quantitative parameters of deadwood were evaluated. From the quality aspect, tree species and degree of decomposition were determined (five--point scale: 1 – decay-free stem, 5 – final phase of decay; the scale was modified according to Spetich et al. 2002), from the quantity aspect the volume of deadwood and its proportion in the total growing stock of the stand were evaluated.

In 2014, increment cores were taken from 30 codominant trees on each PRP with a Pressler borer at a breast height (130 cm) perpendicularly to the stem axis down- and up--slope.

The dynamics of the health status of autochthonous spruce stands in Pod Voseckou boudou locality in the western part of the Krkonoše National Park was evaluated on 4 PRPs every year in 1979–2014 according to the foliage state of individual trees that was classified into degrees of defoliation – see Tab. 2. The average foliage percentage of forest stand is expressed by two curves (Fig. 9) as the arithmetic mean of the values of foliage percentage of living trees and as the arithmetic mean of all trees on PRP including dead standing trees (cf. Vacek et al. 2013). Defoliation (foliage complement to 100%) with special regard to social status and morphological type of crown was estimated to the nearest 5% and recorded using six degrees of defoliation that correspond to the degrees of tree damage. This method is compatible with the contemporary methodology used in the international project of ICP-Forests and ICP-Focus (Lorenz 1995).

Table 2. Degrees of defoliation and their description.

Degree of defoliation	Foliation [%]	Tree characteristics
0	91 – 100	Healthy
1	71 – 90	Slightly damaged
2	51 – 70	Moderately damaged
3	31 – 50	Seriously damaged
4	1 – 30	Dying
5	0	Dead

2.3. Data analysis

On the particular plots structural and growth parameters, production quantity and quality, structural diversity (horizontal and vertical structure) and complex diversity were evaluated on the base of all individuals of the tree layer. Tree volume was calculated using the volume equations published by Petráš & Pajtík (1991). Forest development stages were classified according to Korpeľ (1989).

Biodiversity was evaluated using these indices: index of diameter differentiation and height differentiation (Füldner 1995), Arten-profil index (Pretzsch 2006) and stand diversity index (Jaehne & Dohrenbusch 1997). These indices were computed to determine the spatial distribution: index of non-randomness (Pielou 1959; Mountford 1961), aggregation index (Clark & Evans 1954) and Ripley's *L*–function (Ripley 1981). The test of significance of the deviations from values expected for the random point distribution was done by Monte Carlo simulations. The mean values of the *L*–function were estimated as arithmetic means from *L*–functions computed for 1999 randomly generated point structures. Tab. 3 shows the criteria of calculated structural indices. These characteristics were calculated using the growth simulator SIBYLA (Fabrika & Ďurský 2005) and PointPro 2.1 software (Zahradník).

Stand density, canopy closure (the sum of the areas of all crown projections / total area of PRP) and crown projection area were derived as a part of the study of horizontal structure on PRP. Situational maps were created in the ArcGIS programme (Law & Collins 2015).

Tree-ring width increment series were individually cross-dated (removal of errors connected with the occurrence of missing tree-rings). The degree of similarity was determined using a statistical test in the PAST application programme (Knibbe 2007) and subsequently subjected to visual inspection according to Yamaguchi (1991). If a missing tree-ring was found out, a tree-ring of 0.01 mm in width was inserted in its place. The ring-width series from PRPs were detrended and ring-width chronologies were created from them in the ARSTAN programme. The modified negative exponential function was applied (Fritts 2001). The standardised ring-width chronologies from PRPs in the Krkonoše Mts. were correlated with climatic data (precipitation, temperatures; 1961–2013 from Harrachov station) and air pollution data (SO_2 and NO_x concentrations; 1971–2014 from Desná-Souš station) by the particular years. To simulate diameter increment in relation to climatic characteristics (precipitation and temperatures of previous year and current year) the DendroClim2002 software was used (Biondi & Waikul 2004).

For further computations, the degrees of defoliation were transformed to percentual values of defoliation (average values for a given degree of defoliation). The evaluation of the health status of Norway spruce trees was based on the trend of the arithmetic mean of foliage percentage of all trees (including standing dead wood) and living trees on PRPs, and the trend in the number of dead trees (totally defoliated trees). For the overall evaluation of the forest condition an average defoliation calculated from all trees including those completely defoliated trees were also calculated.

Table 3. Overview of indices describing the stand structure and their common interpretation.

Criterion	Quantifiers	Label	Reference	Evaluation
Horizontal structure	Index of non-randomness	α (P&Mi)	Pielou 1959; Mountford 1961	Mean value $\alpha = 1$; aggregation $\alpha > 1$; regularity $\alpha < 1$
	Aggregation index	R (C&Ei)	Clark & Evans 1954	Mean value R = 1; aggregation R < 1; regularity R > 1
Vertical diversity	Arten-profil index	A (Pri)	Pretzsch 2006	Range 0–1; balanced vertical structure A < 0.3; selection forest A > 0.9
Structural differentiation	Diameter differentiation	TM_d (Fi)	Füldner 1995	Range 0–1; low TM < 0.3; very high differentiation TM > 0.7
	Height differentiation	TM_h (Fi)	Füldner 1995	
Complex diversity	Stand diversity	B (J&Di)	Jaehne & Dohrenbusch 1997	Monotonous structure B < 4; uneven structure B = 6–8; very diverse structure B > 9

In order to determine the response of the stand health status, air pollution factors (the average annual and the maximum annual SO_2 and NO_x concentrations), the foliation of living trees and radial increment were tested for correlation. The tests were carried out in the Statistica 12 package (Beranová et al. 2012). Unconstrained principal component analysis (PCA) in CANOCO for Windows 4.5 programme (Ter Braak & Šmilauer 2002) was used to analyse the relationships between stand parameters, health status, structural indexes, dead wood and similarity of 4 research plots during the time. The data were centred and standardised during the analysis. The results of the PCA analysis were visualised in the form of an ordination diagram constructed by the CanoDraw programme (Ter Braak & Šmilauer 2002).

3. Results

3.1. Production of mountain spruce forests

Table 4 contains an overview of structural characteristics on the particular studied PRPs. Numbers of living trees (DBH ≥ 4 cm) in the tree layer in 1979 ranged between 408 and 596 trees ha^{-1}, in the observed period they were decreasing, and in 2014 there were 252–280 trees ha^{-1}. The highest decrease in the number of individuals was on PRP 2, from 596 to 280. Relative stand density (SDI) roughly correlates with the number of trees on PRP, when SDI was between 0.30 and 0.83 in 1979 and between 0.22 and 0.46 in 2014. The highest decrease in this index from 0.83 to 0.41 occurred on PRP 1. The values of the average basal area are related to this decrease to a certain extent as they ranged from 17.4 to 61.5 $m^2\ ha^{-1}$ in 1979 and from 13.2 to 34.0 $m^2\ ha^{-1}$ in 2014. The decrease in basal area was highest on PRP 1, from 61.5 to 28.3 $m^2\ ha^{-1}$. A more moderate decrease was also observed on the other PRP. A similar trend was recorded in the standing volume that was in the range of 85–426 $m^3\ ha^{-1}$ in 1979 and in the range of 63–233 $m^3\ ha^{-1}$ in 2014. The highest decrease in the standing volume occurred on PRP 1, from 426 to 195 $m^3\ ha^{-1}$, while on PRP 4 the standing volume moderately increased. Periodic annual increment was 1.5–3.3 $m^3\ ha^{-1}\ y^{-1}$ in 1979 and mean annual increment was 0.6–2.3 $m^3\ ha^{-1}\ y^{-1}$, i.e. it decreased by 2014 (PAI 1.0–2.1 $m^3\ ha^{-1}\ y^{-1}$ and MAI 0.5–1.4 $m^3\ ha^{-1}\ y^{-1}$).

Diameter frequencies of the tree layer and the relation of DBH to tree height on PRPs in 1979 and 2014 are illustrated in Figs. 3 and 4, respectively. A comparison of the histograms of diameter frequencies in 1979 and 2014 shows that a major part of weaker (growth-suppressed) trees died during the period of air pollution disaster and in 2014 the growth of individuals in thinner diameter classes was already obvious. Only minimum changes were revealed in the relation between DBH and tree height in the forest stands on PRPs in 1979 and 2014.

Table 4. Structural characteristics of living trees on PRPs in 1979 and 2014.

PRP	Year	Age [y]	*dbh* [cm]	*h* [m]	*v* [m³]	*N* [trees ha⁻¹]	*BA* [m² ha⁻¹]	*V* [m³ ha⁻¹]	*PAI* [m³ ha⁻¹ y⁻¹]	*MAI* [m³ ha⁻¹ y⁻¹]	*TVP* [m³ ha⁻¹]	*CC* [%]	*CPA* [ha]	*SDI*
1	1979	182	42.4	17.00	0.97	436	61.5	426	3.3	2.34	426	68.4	1.15	0.83
	2014	203	36.7	13.08	0.72	268	28.3	195	1.9	1.05	212	42.6	0.55	0.41
2	1979	152	27.7	11.74	0.33	596	35.8	198	2.9	1.30	198	48.2	0.66	0.57
	2014	182	35.6	14.18	0.60	280	27.8	170	1.9	1.44	242	38.9	0.49	0.40
3	1979	141	23.8	8.96	0.21	392	17.4	85	1.5	0.60	85	35.5	0.44	0.30
	2014	157	25.6	8.95	0.24	256	13.2	63	1.0	0.54	82	26.6	0.31	0.22
4	1979	171	33.8	14.03	0.56	408	36.6	229	2.4	1.34	229	49.5	0.68	0.54
	2014	202	41.5	16.14	0.92	252	34.0	233	2.1	1.40	273	48.7	0.67	0.46

Notes: Age average stand age, *dbh* mean diameter at breast height, *h* mean height, *v* average tree volume, *N* number of trees, *BA* basal area, *V* stand volume, PAI periodic annual increment, *MAI* mean annual increment, *TVP* total volume production, *CC* canopy closure, *CPA* crown projection area, *SDI* stand density index.

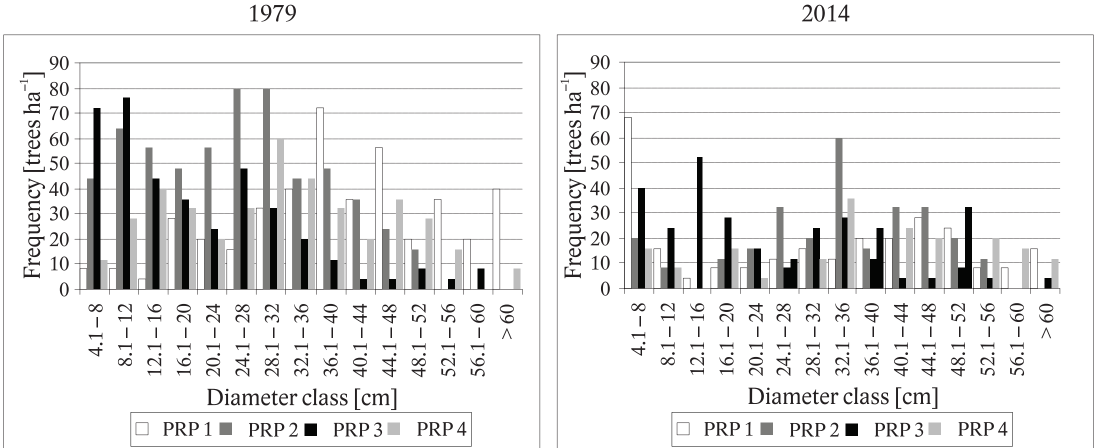

Fig. 3. Histogram of diameter classes in spruce stands on PRPs in 1979 and in 2014.

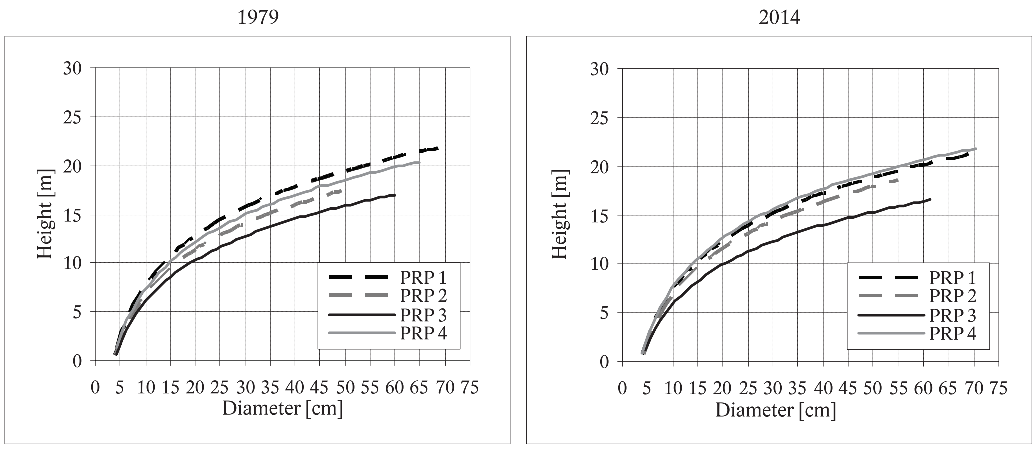

Fig. 4. The relation between diameter at breast height and tree height in spruce stands on PRPs in 1979 and 2014.

3.2. Tree layer diversity

Table 5 shows the horizontal structure of the tree layer on PRPs in 1979 and 2014 and its layout is represented in Figs. 5 and 6. According to all indices, the aggregated distribution of trees on the plot is clearly prevailing on PRPs, while the random distribution of trees on PRP 1 was exceptional in 2014, as shown by the Clark-Evans index. The aggregated distribution of trees on the plot is also indicated by the *L*–function, at a smaller spacing of trees (mostly less than 3 or 4 m), the exception was PRP 3, when in 1979 it was within 7.5 m and in 2014 aggregation was already observed in all cases. Table 5 shows structural indices of tree layer on PRPs for 1979 and 2014. In the studied years the vertical structure according to

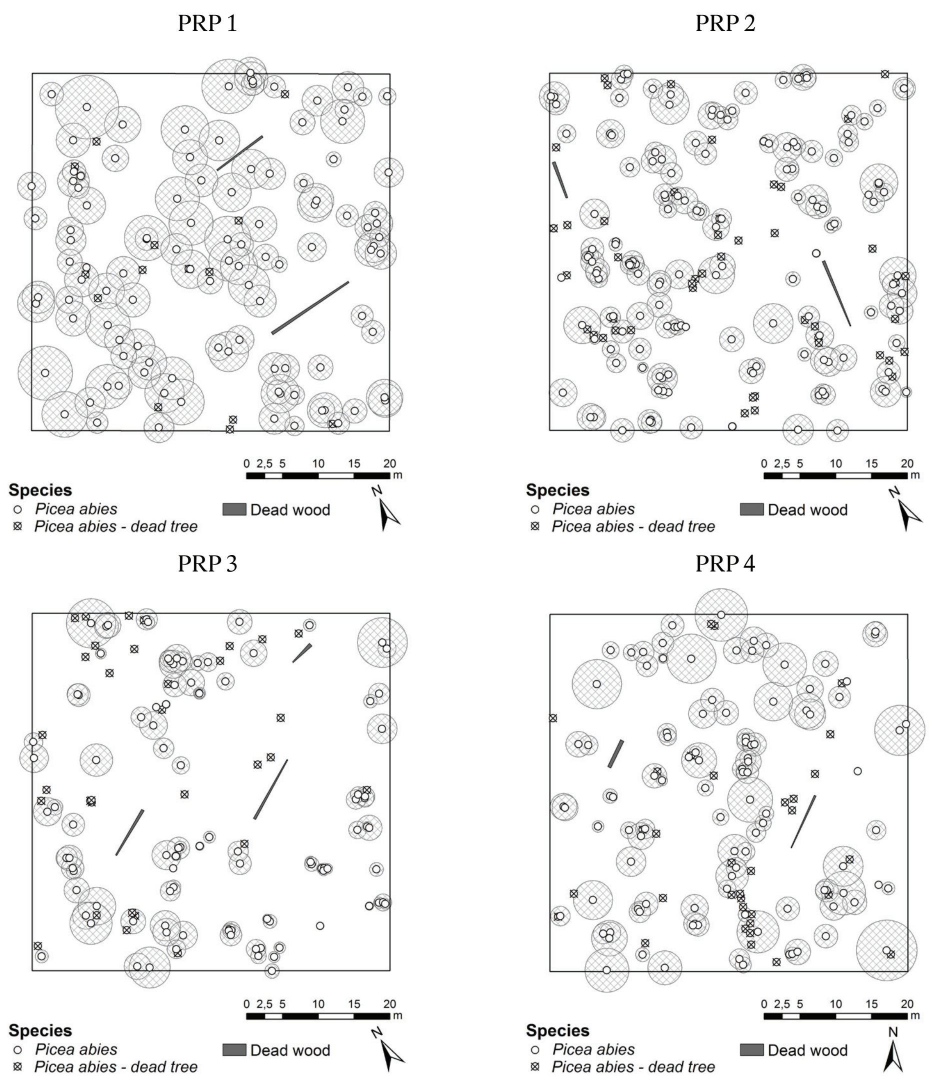

Fig. 5. Horizontal structure of waterlogged spruce stands on Pod Voseckou PRP in 1979.

Table 5. Indices describing the diversity of tree layer on PRPs in 1979 and 2014.

PRP	Year	Indices					
		α (P&Mi)	R (C&Ei)	A (Pri)	TM_d (Fi)	TM_h (Fi)	B (J&Di)
1	1979	1.231	0.978	0.904	0.278	0.241	5.726
	2014	1.108	1.019	0.920	0.363	0.354	5.953
2	1979	1.596*	0.746*	0.700	0.413	0.346	6.699
	2014	1.655*	0.655*	0.614	0.382	0.355	6.345
3	1979	2.248*	0.635*	0.583	0.371	0.317	6.347
	2014	1.952*	0.703*	0.644	0.354	0.350	6.351
4	1979	1.347	0.821*	0.756	0.394	0.302	6.055
	2014	1.083	0.882*	0.808	0.367	0.321	6.209

Notes: α index of non-randomness, *R* aggregation index, *A* Arten-profil index, TM_d diameter differentiation index, TM_h height differentiation index, *B* stand diversity index; *statistically significant for horizontal structure ($p > 0.05$).

the Arten-profil index was a selection structure on PRP 1, on PRP 2 and 3 the structure was moderately or largely diversified and on PRP 4 it was largely diversified. The stand diversity index of some PRPs indicates a uniform structure while the structure of other PRPs is non-uniform. The Füldner index of height and diameter differentiation indicates low structural differentiation on PRP 1 in 1979, while in 2014 it was already a stand with intermediate structural differentiation. Intermediate height and diameter structural differentiation was found on PRP 2, 3 and 4 both in 1979 and 2014. Crown differentiation was low on all studied PRPs.

In 2014, the optimum phase on PRP 4 was without regeneration, PRP 2 was dominated by the phase of initial disintegration with the phase of initial regeneration, on PRP 1 the phase of initial break-up with advanced phase of regeneration was present, and on PRP 3 the advanced break-up phase and growing-up phase overlapped (Fig. 6).

3.3. Diameter growth and relations to climate

The standardised annual ring chronology (Fig. 7) shows a moderate trend in radial growth, specifically a slight decrease in 1950–1978. In this period there are significant declines in growth in the years 1965 and 1974. This period is followed by a period of stagnation 1978–1991, when the trees had minimal diameter increments. Since 1991 the radial growth gradually increased, the period 2006–2014 is characterised by large fluctuations with significant declines in growth in 1996, 2004, 2010 and in the last two years. On the other hand, the radial growth in this period was greatest within the studied period. The correlations of diameter increment with average monthly

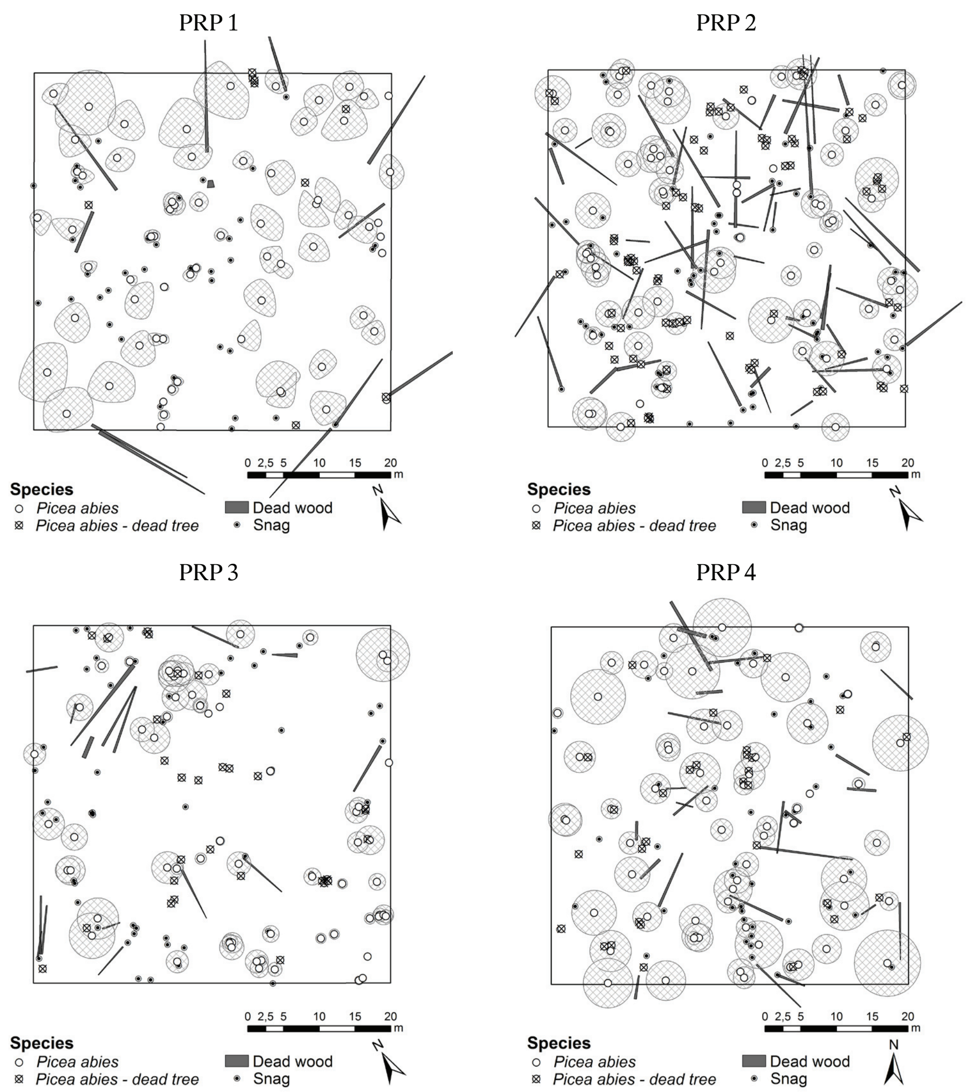

Fig. 6. Horizontal structure of waterlogged spruce stands on Pod Voseckou PRP in 2014 .

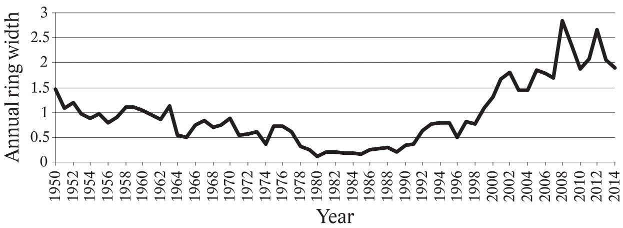

Fig. 7. Standardised ring-width chronologies.

temperatures and precipitation indicate some statistically significant values. In the Krkonoše Mts. diameter increment in 1976–2010 shows statistically significant positive correlations ($\alpha = 0.05$) with temperatures in June, July, August and in January of the preceding year (r = 0.37, 0.29, 0.31, 0.32 and 0.56) and with temperatures in May, June, July and August of the current year (r = 0.56, 0.45, 0.38 and 0.31). Statistically significant negative correlations with precipitation amount in May of the current year were also found (r = −0.3; Fig. 8).

3.4. Health status of spruce stands

The development of average foliage percentage and the proportion of defoliation degrees in an autochthonous spruce stand on PRP 1 – Pod Voseckou boudou showed that Norway spruce suffered from strong defoliation in 1981–1987 (Fig. 9). After 1988, the foliage percentage was relatively stabilised, but there were smaller oscillations especially in 1993, 2000 and 2001. A moderate increase in Norway spruce defoliation was observed also in 2007. In 2012, as a result of intensive regeneration processes the average foliage percentage largely increased in all trees with different health condition and healthy trees started to occur again.

A similar foliage trend like on PRP 1 was found on PRP 3 in the foliage of both living trees and all trees. The foliage of living trees on another two PRPs (2 and 4) was very similar, but it was slightly better in all trees because after 1995 and 1996 the trees did not die due to the feeding of the European spruce bark beetle. This trend of mortality (the percentage of standing dead trees to the total number of all trees in the current year) is documented in Fig. 10.

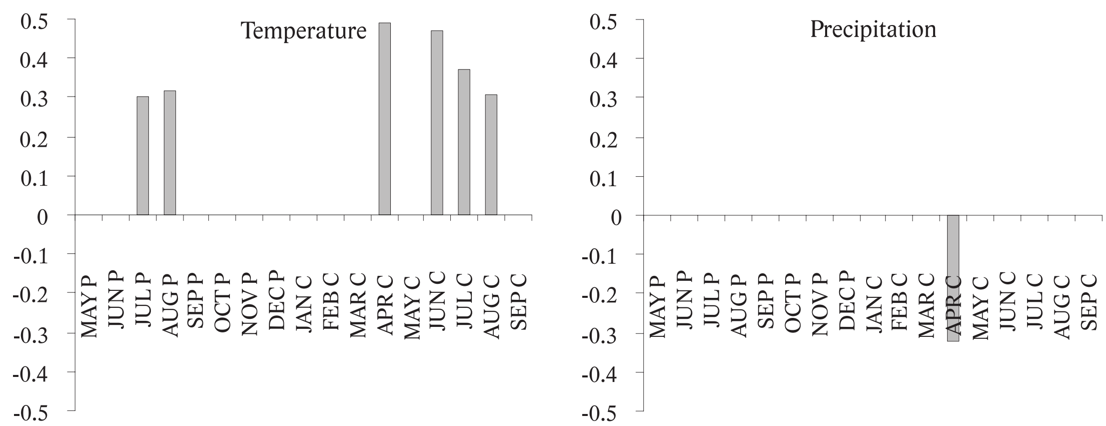

Fig. 8. Coefficients of correlation of regional residual index tree-ring chronology with average monthly temperature and precipitation from May of the previous year (P) to September of the current year (C) in the period 1976–2010. Only correlation coefficients with statistically significant values ($\alpha = 0.05\%$) are displayed.

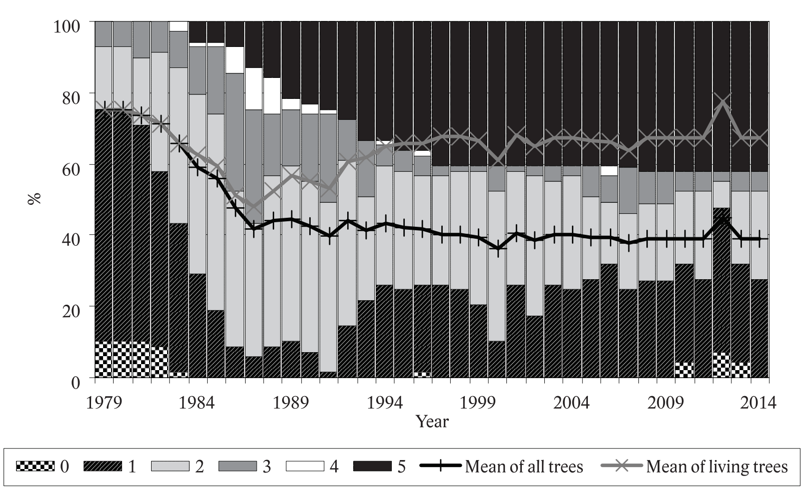

Fig. 9. Dynamics of average foliage percentage and the proportion of degrees of spruce defoliation in an autochthonous spruce stand on PRP 1 – Pod Voseckou boudou in 1979–2014.

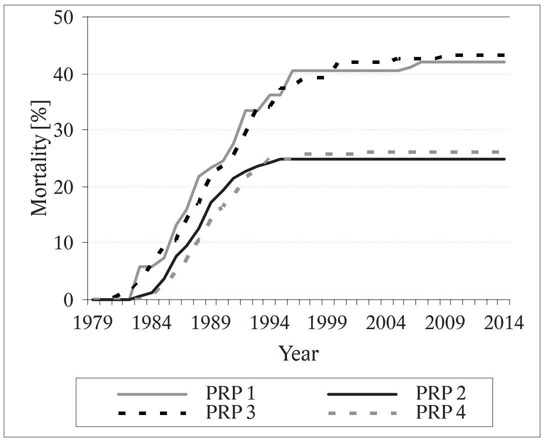

Fig. 10. Trend of mortality of trees on PRPs in 1979–2014.

3.5. Deadwood

Table 6 shows the characteristics of deadwood on PRPs in 1979 and 2014. The total volume of deadwood was in the range of 27.2–50.1 m³ ha⁻¹ in 1979, and from 41.1 to 146.6 m³ ha⁻¹ in 2014. The largest increase in deadwood was observed on PRP 2, the smallest on PRP 4. The proportion of deadwood in the total standing volume of forest stand (living and dead trees) was 6–29% in 1979 and 22–46% in 2014. With regard to decay classes, degree 3 accounted for the highest proportion in standing deadwood on PRPs, 42–69% in 1979 and 64–84% in 2014. In lying deadwood more advanced stages of decay prevailed. In 1979, only degrees 4 and 5 occurred on the plots due to the extraction of usable wood. In 2014, degree 3 with 33% and 78% prevailed on PRP 1 and PRP 3, respectively, while degree 4 with 37% was dominant on PRP 2, and degree 5 with 52% on PRP 4. The horizontal distribution of standing and lying deadwood was random on PRPs.

3.6. Stand structure, productivity, health status and air pollutants interactions

The results of the PCA analysis are presented in the form of the ordination diagram in Fig. 11. The first ordination axis explains 48%, the first two axes together 72%, and the first four axes together explain 94% variability in the data. The I. axis represented structural indexes. The II. axis represented number of trees, total mortality of trees and volume of dead wood. Total mortality was positively correlated with the volume of dead wood and increased in time, while these parameters were negatively correlated with the number of trees. Arten-profil index was positively correlated with Clark-Evans aggregation index, while these parameters were negatively correlated with stand diversity index and diameter differentiation. These parameters were independent from the time. DBH was positively correlated with tree height and partially with volume, crown closure and crown projection. These parameters are dependent on the age of trees. The dynamics of the parameters in the course of 35 years was remarkable especially for PRP 1 and PRP 2 as their marks of each record are relatively distant from one another, whereas the marks for PRP 3 and 4 were relatively close together in the diagram. The plots differed from each other, when PRP 1 which represents the initial break-up stage with mature regeneration occupied the extreme right part of the diagram typical for higher height, diameter and volume and lower stand diversity index and diameter differentiation, while PRP 3 which represents the advanced stage of break-up with growing-up occupied the extreme left part of the diagram. PRP 4 represents the optimum stage in the middle of the diagram.

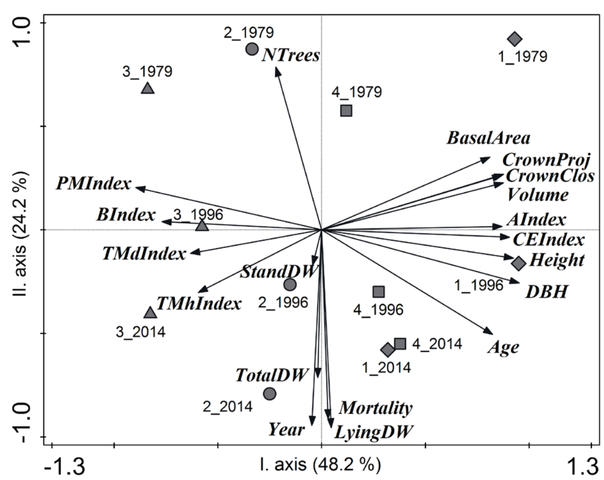

Fig. 11. Ordination diagram showing results of PCA analysis of relationships among tree characteristics (*N trees* number of trees, *DBH, Height, Basal Area, Volume, CrownClos* Crown closure, *CrownProj* Crown projection area, *Age*), structural indexes (*CE index* Clark-Evans aggregation index, *PM index* Pielou-Mountford index of non-randomness, *A index* Arten-profil index, *TMd index* diameter differentiation index, *TMh index* height differentiation index and *B index* stand diversity index), health status (total *Mortality*), dead wood parameters (*Total DW, Lying DW, Stand DW*) and time (*Year*). Code abbreviation: identification of PRP + year.

Table 6. Deadwood characteristics on PRPs in 1979 and 2014.

PRP	Year	Standing DW			Lying DW			Total DW		
		[pcs ha⁻¹]	[m³ ha⁻¹]	%	[pcs ha⁻¹]	[m³ ha⁻¹]	%	[pcs ha⁻¹]	[m³ ha⁻¹]	%
1	1979	42	22.2	82	8	5.0	18	50	27.2	6
	2014	36	17.2	30	52	39.1	70	88	56.3	22
2	1979	141	38.4	94	8	2.6	6	149	41.0	17
	2014	288	72.9	50	204	73.8	50	492	146.6	46
3	1979	96	29.4	85	12	5.2	15	108	34.6	29
	2014	124	19.1	47	64	22.0	53	188	41.1	40
4	1979	99	45.6	91	8	4.5	9	107	50.1	18
	2014	120	39.9	57	92	30.2	43	212	70.1	23

The radial growth showed negative correlation with mean annual mortality of trees, mean and maximum SO_2 and NO_x concentrations and no correlation with mean foliage of living trees and mean annual defoliation (Table 7). The foliation of living trees showed positive correlations only with mean annual defoliate and no significant relationship with air pollutants. Mean annual mortality was positively correlated with SO_2 and NO_x concentrations and negatively with mean radial increment (Table 7).

matic factors and they can cause undesirable effects such as acidification or eutrophication, and finally they can decrease overall biodiversity (Clark & Tilman 2008). High nitrogen depositions also contribute to nutrient imbalance (Braun et al. 2010) and to an increased risk of pest infestation (Grulke et al. 2010). At a similar developmental trend that occurred in the Krkonoše Mts. in the first half of our research all these factors could potentially influence forest ecosystems in the Krkonoše Mts. very negatively.

Table 7. Correlation matrix describing interactions between growth, health status and air pollutants.

	Ring width	SO_2 mean	SO_2 max.	NO_x mean	NO_x max.	Foliage of living trees	Defoliate annual	Mortality annual
Ring width	1.000							
SO_2 mean	**−0.822****	1.000						
SO_2 max.	**−0.834****	**0.943****	1.000					
NO_x mean	**−0.918****	**0.806****	**0.756****	1.000				
NO_x max.	**−0.767****	**0.618****	**0.713****	**0.675****	1.000			
Foliage	0.176	−0.187	−0.103	−0.378	0.001	1.000		
Defoliate	−0.157	0.144	0.127	0.100	0.085	**0.562***	1.000	
Mortality	**−0.492***	0.586**	**0.511***	**0.505***	0.272	−0.284	0.175	1.000

Note: * Statistically significant at the level $p < 0.05$; ** statistically significant at the level $p < 0.01$.

4. Discussion

The health status of spruce forests in the Krkonoše Mts. is highly differentiated (Vacek & Matějka 2010) although in our study dealing with autochthonous waterlogged or peaty spruce stands in the western Krkonoše Mts. the differences between the plots were not as large as in the eastern Krkonoše Mts. (cf. Vacek et al. 2007). Our results document that in the studied period the most severe defoliation occurred on PRPs in 1981 – 1987. Distinctly higher defoliation than on PRP 2 and 4 was observed on PRP 1 and 3. Similar results from European mountain regions that are exposed to an increased air-pollution stress were reported by Augustin et al. (2005) or by Lorenz et al. (2006). According to Vacek et al. (2013) moderately different development of the health status on PRP in the Krkonoše Mts. can be explained by several factors: aspect, forest type characteristics, tree species composition, autochthonous or allochthonous origin and forest management practices in the past. Paoletti et al. (2010) studied other stress factors that can influence the health status; in their opinion, the combination of seasonal variability in air pollution, water availability, changed nutrient content in the soil and increased CO_2 content is crucial for forest ecosystems.

Our study indicates that NO_x and SO_2 concentrations were rather high before 1999 and since then they have decreased; particularly in the second half of the studied period the stabilisation and in some cases moderate improvement of the health status of forest stands occurred as shown by their foliage. Such a trend is very important for further development of the Krkonoše forests because as stated by Paoletti et al. (2010) nitrogen and its compounds, their deposition and effects on forest ecosystems are a very urgent issue with a number of negative influences. Markedly excessive values of nitrogen can be integrated with other contaminants and cli-

The relations between the critical values of acid deposition and forest ecosystem degradation, which can also be seen from our study, are documented in other studies (Lomský et al. 2012). Nevertheless, the ecological interactions between critical values and other environmental factors such as CO_2 and O_3 concentrations, effects of insects, pathogens, drought or extreme temperatures as well as the effect of management have not been sufficiently elucidated until now (McNulty & Boggs 2010).

In the last several years, the influence of climate on diameter increment of forest stands has been a frequently studied subject (Piermattei et al. 2014). Therefore, our study also focused on the evaluation of diameter increment, its dynamics and relation to climate. In the period of 1976–2010, we observed statistically significant positive correlations of diameter increment with temperature in the studied months of both the preceding year and the current year. Negative significant correlations with precipitation amount in May of the current year were also found. This contradicts the results reported by Duchesne & Houle (2011), who stated that at precipitation-sensitive site high humidity on rainy days and relatively low solar radiation promote stem increment, while relatively low humidity and a high level of solar radiation reduces increment. Because there is a moderately decreasing trend of ground water level in spruce forests in the Krkonoše Mts. (Vacek et al. 1994; Vacek &Matějka 1999), this finding could in future also apply to these stands. A reduction in tree-ring width in relation to climatic factors in the Krkonoše Mts. in the 80s and 90s of the 20th century was reported by Sander et al. (1995). Mäkinen et al. (2001) studied radial increment in dependence on temperature and precipitation in 13 heavily damaged and 12 healthy Norway spruce stands in southern Finland. They found a considerable reduction in growth since the late eighties of the last century when in damaged stands summer temperatures were in negative correlation with spruce growth. Elevated temperatures in the summer of the preceding year reduced the growth in the summer of the next year. The tree-ring width analysis confirmed a close positive correlation with precipitation amount in June of the current year. Nevertheless, Etzold et al. (2013), who studied the influence of climate on the growth of Swiss forests, stated that the differences in increment might be caused by a number of factors that minimise the influence of climate on increment when particularly the effect of disturbances and pathogens is mentioned that will result in a decrease in stand density and higher increment of the remaining trees. The tree-ring analysis revealed that the dominant trees showed great enhancement of radial growth after the decline of SO_2 concentrations compared with the period before the start of the air pollution disaster. These differences are caused by the decreased stand density, or decreased spatial competition, increased deposition of nitrogen in the soil and lower ground water level in mountain spruce forests in the Krkonoše Mts. (Vacek et al. 1994; Vacek & Matějka 1999).

The structure of the studied stands and their long-term development under the influence of air pollution are other attributes that were investigated and that should contribute to deeper knowledge of this problem in central Europe because this subject was studied in similar site conditions in such a long time horizon only by a few authors. It is essential to thoroughly understand forest stand development and interactions between developmental processes (Klopčič & Bončina 2011). This is especially true in the cases, where risk assessment and prevention is important (Paoletti et al. 2010). As for the particular studied attributes of horizontal and vertical structure and structural diversity of investigated stands, they are in line with the results from similar site conditions presented by Vacek et al. (2010).

Deadwood is another aspect of mountain forests that was monitored in this study. As reported by Zielonka (2006), deadwood is a very important component of forest ecosystems and it is also a very important reservoir of nutrients in the forest soil (Harmon et al. 1986). The total volume of deadwood on the studied PRP increased in the studied period and at one locality it even exceeded the value of 130 m^3 ha^{-1} (146.6 m^3 ha^{-1}), which was presented by Christensen et al. (2005) as the average value of European near-natural forests. Similar values like in the studied localities were obtained on the basis of 40-year development by Vacek et al. (2015), who reported average values of 193.3 m^3 ha^{-1} and 96.2 m^3 ha^{-1} from two localities in the Krkonoše Mts. The spatial distribution of deadwood in the studied localities is random, similarly like in localities studied in Germany by von Oheimb et al. (2005) or in the Carpathians (Janík 2013).

4. Conclusion

The analysis of the effect of air pollution and climatic factors on the structure and health status of waterlogged or peaty spruce forests in the western Krkonoše Mts. showed that there occur predisposition factors that have a potential to cause gradual decline or death of spruce forests due to their synergistic interactions. A pronounced worsening of the health status of autochthonous spruce forests and their vitality due to the synergism of air pollution and climatic stress occurred in 1980–1987. This was proved not only by high values of defoliation but also by a dramatic decrease in radial increment. The main causes of the decline in increment were high concentrations of SO_2 and significant temperature fluctuations. In this period there were pronounced changes in the structure of forest stands, including the ratio of living to dead trees. Since 1988 the health status of spruce forests has been relatively stabilised as for the trend of foliage of living trees on PRPs and since 1992 as for their radial increment. Apart for the negative correlation of radial growth with SO_2 concentrations, tree growth also significantly increased with decreasing NO_x concentration. Tree growth was significantly correlated with temperature in the growing season, but was only slightly negatively affected by precipitation. Last of all, the improved stand hygiene in adjacent forests contributed to the stabilisation of these stands when insect pests, especially the European spruce bark beetle, have been substantially eliminated. To improve the ecological stability of mountain forests we recommend active silvicultural management supporting the complexity of forest stands with abundant natural and/or artificial regeneration. Based on our research results, it is expected that climate change may increase the regeneration success and thus the recovery capacity of mountain spruce forest ecosystems. Nevertheless, in the following years it is necessary to pay attention to consequent use of sanitation principles, because trees physiologically weakened by pollution are often attacked by European spruce bark beetle.

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