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Decline of Norway spruce in the Krkonoše Mts.

O. Mauer, E. Palátová

Department of Forest Establishment and Silviculture, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

ABSTRACT: The paper summarizes results from the analyses of Norway spruce (*Picea abies* [L.] Karst.) stands managed by the Forest Administration in Horní Maršov, Krkonoše National Park (KRNAP), which are affected by decline and by yellowing of the assimilatory apparatus. Forest stands included in the analyses were aged 10–80 years and originated from both artificial and natural regeneration. Analyses of root systems were combined with analyses of soil chemical properties and assimilatory organs, weather conditions and emissions. The analyses showed that affected trees had small and malformed anchoring root systems with a lower number of horizontal roots and a lower number of fine roots of lower vitality (high proportion of dead fine roots), which penetrated only through the uppermost humus horizons. Root systems of affected trees are infested by the honey fungus (*Armillaria* sp.), which colonizes anchor roots. Neither root nor bole rots were detected so far.

Keywords: decline; fine roots; honey fungus; malformation; Norway spruce; root system

Forest ecosystems in the borderland mountains of the Czech Republic were affected by large-scale decline and decay in the last decades of the 20th century. Vacek and Podrázský (2007) assumed that forests in the western and eastern part of the Krkonoše Mts. were affected by air pollution and ecological stress from about 1972 and 1959, respectively. According to the authors, the first conspicuous injury to spruce forests in the Krkonoše Mts. was observed after a climatic extreme in March 1977, at the beginning of 1979 and also in connection with the larch bud moth (*Zeiraphera diniana* Gn.) outbreak in 1977–1981. The damage to forests was increasing since then and resulted nearly in a total destruction of forest stands at altitudes above 900 m a.s.l. The most affected were stands of Norway spruce whose representation in the Czech part of the Krkonoše Mts. was 80% (Vacek et al. 2007).

The search for reasons for the injury and decay of forests in the Krkonoše Mts. led to the establishment of permanent experimental plots in different conditions of sites, on which the health condition of woody species and changes in soil characteristics were regularly monitored. Surveys conducted on them in 1976–2006 by Vacek (2000) and Vacek and Podrázský (2007) indicated that damage was increasing with the increasing elevation. Valley floors were less affected than exposed high altitudes and the health of non-autochthonous spruce populations was apparently worse under comparable conditions. Based on the evaluation of permanent research plots, Vacek and Podrázský (2007) distinguished three characteristic periods according to defoliation dynamics. In the period of the first symptoms of damage (1976–1980), the average annual defoliation of spruce stands was 0.4%. In the period of severe damage (1981–1999), the authors recorded an average annual reduction of foliage in spruce ranging from 3.0% to 4.0%. In the period of damage withdrawal (1989–2006), the situation in stands unaffected by bark beetles stabilized or even improved. Annual average defoliation ranged between 0 and 4% or even increased by 1–3%.

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Vacek and Podrázský (2007) maintained that the main reason for forest decline was air pollution in synergy with a number of other biotic pests and abiotic agents. The monitoring of sulphur compounds that was launched upon the occurrence of initial injuries to the spruce stands revealed a rapid increase in sulphur compound concentrations after 1980. Lokvenc et al. (1992) informed that SO_2 concentrations reached on long-term average 25 $\mu g \cdot m^{-3}$ and monthly averages of daily concentrations ranged from 6 to 118 $\mu g \cdot m^{-3}$. Mazurski (1989) found similar values in the Polish Sudetic Mts. and warned against danger from increasing emissions of nitrogen oxides and considerable dust deposition. After 1991, the SO_2 concentrations fell both in summer and in winter below the value referred to as a lower limit for damage to spruce (Schwarz 1996). Therefore, the author concluded that the period of direct damage to spruce forests by sulphur oxides passed over. Similarly, the concentrations of sulphur, nitrates, ammonium ions and selected heavy metals in rainfall, monitored by Budská et al. (2000) in 1983–1999 exhibited a decreasing trend from the long-term point of view. Monitoring of the chemistry of atmospheric precipitation on the Polish side of the Krkonoše Mts. in 1994–2004 conducted by Twarowski et al. (2007) brought a clear evidence that rainfall acidity decreased. Sulphur dioxide depositions dropped by 60%, and the contents of phosphorus and cadmium in precipitation decreased by 24% and 30%, respectively. Hošek et al. (2007) studied substance flows in throughfall and in the open area concluding that as compared with 1994, sulphur depositions decreased by 2006 from 50–80 $kg \cdot ha^{-1} \cdot year^{-1}$ to 12–26 $kg \cdot ha^{-1} \cdot year^{-1}$. The authors maintained that the last years showed only fluctuations with no significant systematic trends. Nitrogen depositions did not exhibit any unambiguous trend over the whole period of study and ranged from 17 to 35 $kg \cdot ha^{-1} \cdot year^{-1}$ with the variability between individual years being significantly higher than in the case of sulphur. The total acidifying input decreased; however, the current nitrogen deposition exceeds twice the critical load for spruce forests. In spite of the fact that the sulphur deposition fell significantly, the total critical load of sulphur and nitrogen in the territory of the Krkonoše National Park is significantly exceeded, mainly due to nitrogen depositions. The authors assume that with respect to stagnating or increasing depositions of N-compounds, no favourable development can be expected in the years to come.

Although the above-cited sources agree upon the statement that the condition of spruce forests in the Krkonoše Mts. has markedly improved, in the last approximately eight years, damage to the spruce forests appeared again, which affects trees of all age classes including trees from self-seeding. The injury manifests by the yellowing or rusting of needles and proceeds from the oldest needle years and from the stem base to the treetop. Needles with changed colour do not fall rapidly; they can last on the branch even several years. In one stand, we can see healthy and declining trees growing next to each other with stands from artificial regeneration showing mostly the decline of trees from a height of ca 3 m and trees from self-seeding declining even at an aboveground part height of 1 m. Since many expert works suggest that the decline of trees may be induced by changes on their root systems (Mauer, Palátová 1988, 1996a; Mauer et al. 2004, 2008), the goal of this paper was to assess development and health condition of the root system in Norway spruce grown in the region of the Krkonoše Mts. and its role in forest decline.

MATERIAL AND METHODS

Basic methodological approaches

- The analyses included Norway spruce (*Picea abies* [L.] Karst.) stands aged 10–80 years near Horní Maršov (Forest Administration in Horní Maršov, Forest District of Dolní Lysečiny). The objective was to make a comparison (within one forest stand or one forest site) of the development and health condition of root systems in declining and healthy trees of the same height. Healthy trees (with defoliation or colour alteration of assimilatory organs up to 10%) were the controls; declining trees were considered those with defoliation or colour change of the assimilatory apparatus amounting to 40–60%. The analyzed forest stands were pure Norway spruce stands of identical density, growing on a mild slope (gradient up to 10%). Partial analyses included only non-marginal and by wildlife undisturbed trees in the main level. The minimum number of trees analyzed in each stand situation (healthy tree, injured tree) was six. Characteristics of forest stands are presented in Table 1.

Analyses of aboveground parts

- The characteristics measured on the aboveground part of each analyzed and assessed tree

Table 1. Characteristics of analyzed forest stands

Forest stand designation	Stand number	Forest type	Altitude (m) a.s.l.	Age	Pollution damage zone
10 healthy, 10 injured	622A10/1a	6K1	800	6	C
15 healthy, 15 injured	622A2	6K1	800	17	C
30 healthy, 30 injured	622A3	6K1	800	37	C
40 healthy, 40 injured	617C3 a	6K1	850	31	C
80 healthy	616F8/1c	6K1	900	78	B
80 injured	617B8/1b	6K1	850	77	B
Healthy self-seeding, Injured self-seeding	622B12/1b	6K1	750	7	C

were: total length (from ground surface up to terminal tip), stem diameter $d_{1.3}$, length of terminal shoots in 2005, 2006, 2007, length of needles (measured at a half of the last increment on the branch of the whorl concerned). The occurrence of bole rot and infestation of the aboveground part by biotic agents were determined on cross-sections of all trunks. Tables of results from the analyses show arithmetic means of the particular parameters and their standard deviations. Significance of results of was tested by the *t*-test with the significance of results being expressed graphically: – insignificant difference, + significant difference at $\alpha = 0.05$.

Analyses of root system architecture and health condition

All root systems were lifted by hand (archaeological technique). The characteristics determined in them after cleaning were the number and diameter of horizontal skeletal roots (diameters were measured at a distance of 10 cm from the stem base in trees from self-seeding, 20 cm in 10-year old trees, 40 cm in 15-year old trees, 60 cm in 40-year old trees and 80 cm in 80-year old trees); number and diameter of anchoring roots (diameters were measured at 5 cm from the setting point); number and diameter of substitute taproots, i.e. primary root branches shooting from anchoring roots (diameters were measured at 5 cm from the setting point). Measured values were used to calculate Area Index (hereinafter Index P, in the tables of results Ip) as the ratio of the sum of root cross-sectional areas (in mm^2) to the height of trees (in cm). The parameter evaluates a relation between the root system development and the aboveground part development. The higher the value of Index P, the larger the tree root system.

Rooting depth was measured as a perpendicular distance from the ground surface to the deepest reaching root part. The incidence of root rots was determined in a lengthwise section through each root. The regularity of the root network distribution was determined according to the maximum angle between horizontal skeletal roots (the largest angle between two adjacent skeletal roots). The greater the angle (especially over 90 degrees), the worse the root system distribution, and there exists a threat of the mechanical instability of a tree. In all root systems we further determined the number of non-skeletal roots shooting from the stem base, length of horizontal skeletal roots (measured from the stem base to the tip of horizontal skeletal roots), occurrence of malformations into a tangle, damage to roots by biotic agents and incidence of the honey fungus (*Armillaria* sp.) according to resin exudations.

Analyses of fine roots

Biomass of fine roots (< 1 mm)

In each analyzed stand, thirty soil cores were lifted (separately for healthy and affected trees) with a soil sampler of 5 cm in diameter. The cores were sorted out according to soil horizons and homogenized. Studied were all humus horizons as a whole (denoted as Humus) and mineral layer 0–10 cm under humus horizons (denoted as Mineral). For the analyses, six samples were taken from the homogenates, each of 100 ml bulk volume. Fine roots were separated, cleaned by hand, dried and weighed.

Vitality of fine roots

In each analyzed forest stand, five soil cores 20 × 20 cm were taken from humus horizons (separately for healthy and injured trees), from which fine roots were separated by hand, cleaned and homogenized. The vitality of fine roots was determined by the method of 2,3,5 triphenyltetrazolium-chloride reduction (Joslin, Henderson 1984). Results obtained from the processing of samples were subjected to correlation analysis and vitality percentage was calculated (% of vitality is in direct correlation with the proportion of dead fine roots). Tables of results from the analyses of root systems show arithmetic means of the particular parameters and their standard deviations. Significance of results was tested by the *t*-test with the significance of results being expressed graphically: – insignificant variance, + significant variance at α = 0.05.

Chemical analyses, climatic conditions, pollution deposition

Standard chemical analyses of soil and assimilatory apparatus were conducted in selected forest stands for a complex assessment of the situation. Pits for soil analyses were always dug directly under declining or healthy trees and needles for foliage analysis were also sampled from these trees. The samples were taken at the beginning of October 2008. Weather conditions in 1988–2006 were evaluated from data provided by a monitoring station of the Czech Hydrometeorological Institute in Pec pod Sněžkou (816 m a.s.l.). Development of the deposition flows of sulphur, nitrogen and hydrogen ions in 2002–2006 was determined on the basis of a model calculation from the gaseous concentrations of SO_2, NO_x and from their dry and wet deposition flows.

RESULTS

All affected trees show statistically significantly lower terminal increment and lower needle length. All injured trees and nearly all healthy trees are infested by the honey fungus; the injured trees show more roots (exclusively anchors) infested by the honey fungus (Table 2). Neither the injured nor the healthy trees exhibited root or bole rots.

No significant differences were recorded in the number and diameter of anchoring roots and substitute taproots either at the rooting depth of horizontal skeletal roots, anchoring roots or substitute taproots or at the rooting depth of the deepest reaching root. However, all injured trees had a shorter length

Table 2. Biometric parameters of the above-ground part and honey fungus incidence (mean values ± SD) of healthy and injured Norway spruce trees of different age in selected stands of Krkonoše Mts. National Park

Forest stand designation	Above-ground part length (m)	$d_{1.3}$ (cm)	Terminal increment (cm)			Length of needles (mm)	Honey fungus	
			2007	2006	2005		(%) of infested trees	No. of infested roots (pc·tree^{-1})
10 healthy	2.78 ± 0.24	3.12 ± 3.01	29.5 ± 6.4	37.2 ± 3.8	39.0 ± 3.3	18.7 ± 2.2	17	1.0 ± 0.0
10 injured	2.70 ± 0.44	3.16 ± 0.69	15.8 ± 7.6^{+}	19.4 ± 7.8^{+}	18.4 ± 3.7^{+}	12.2 ± 1.4^{+}	100	3.2 ± 1.5
15 healthy	6.29 ± 0.65	7.82 ± 0.77	50.6 ± 17.0	60.2 ± 7.2	55.6 ± 5.6	18.4 ± 1.8	100	2.0 ± 1.4
15 injured	5.75 ± 0.72	6.60 ± 0.54	17.2 ± 8.2^{+}	22.8 ± 10.4^{+}	20.8 ± 5.4^{+}	13.0 ± 1.0^{+}	100	5.6 ± 1.9^{+}
30 healthy	8.60 ± 0.84	12.12 ± 0.50	71.5 ± 18.0	76.2 ± 16.5	83.3 ± 11.5	19.5 ± 1.9	100	2.0 ± 1.8
30 injured	8.23 ± 0.68	9.92 ± 0.46	57.0 ± 10.2^{+}	54.7 ± 12.6^{+}	59.0 ± 20.4^{+}	18.0 ± 0.8^{-}	100	5.3 ± 1.7^{+}
40 healthy	14.95 ± 1.22	14.27 ± 1.15	28.3 ± 7.6	45.0 ± 13.2	48.7 ± 16.4	19.0 ± 1.7	100	2.3 ± 2.3
40 injured	13.50 ± 0.75	12.73 ± 0.75	20.7 ± 12.9^{+}	17.7 ± 12.6^{+}	25.7 ± 11.3^{+}	16.9 ± 2.0^{+}	100	4.7 ± 2.1^{+}
80 healthy	25.30 ± 1.12	28.12 ± 1.71	33.0 ± 4.7	32.7 ± 4.7	40.0 ± 6.9	18.2 ± 0.9	100	12.3 ± 5.0
80 injured	24.30 ± 1.38	27.50 ± 1.32	20.7 ± 8.1^{+}	19.0 ± 6.5^{+}	36.0 ± 9.5^{-}	16.6 ± 1.5^{+}	100	21.7 ± 8.1^{+}
Healthy self-seeding	1.73 ± 0.38	3.67 ± 0.33	28.3 ± 6.1	20.0 ± 7.8	20.6 ± 2.2	16.3 ± 0.5	0	0.0 ± 0.0
Injured self-seeding	1.59 ± 0.21	3.57 ± 0.19	20.0 ± 7.9^{-}	13.5 ± 4.0^{-}	15.1 ± 3.8^{+}	13.1 ± 0.7^{+}	80	1.7 ± 0.9

$^{-}$Insignificant difference; $^{+}$significant difference (α = 0.05)

Table 3. Root system architecture of healthy and injured Norway spruce trees of different age in selected stands of Krkonoše Mts. National Park

Forest stand designation	Number of MSR (pcs)	Average length of MSR (cm)	Average diameter of MSR (mm)	Number of non-skeletal roots (pcs)	Maximal angle between MSR (degrees)	Tangle (% of trees)	Ip values		
							only MSR	only anchors and subst. taproots	whole root system
10 healthy	11.2 ± 3.9	UE	11.1 ± 5.9	19.7 ± 5.9	105 ± 34	100	5.25 ± 0.40	0.74 ± 0.10	5.62 ± 0.30
10 injured	4.0 ± 2.2^{+}	UE	11.6 ± 7.9^{-}	9.4 ± 3.2^{+}	132 ± 31^{-}	100	2.63 ± 1.83^{+}	0.96 ± 0.41^{-}	3.67 ± 2.15^{+}
15 healthy	23.8 ± 3.5	UE	15.9 ± 9.9	31.8 ± 6.1	52 ± 27	100	11.00 ± 3.67	1.97 ± 1.50	12.97 ± 4.26
15 injured	10.4 ± 2.3^{+}	UE	15.0 ± 8.6^{-}	12.2 ± 3.2^{+}	88 ± 24^{+}	100	4.26 ± 1.41^{+}	0.95 ± 0.57^{-}	5.02 ± 1.49^{+}
30 healthy	31.5 ± 1.7	UE	18.9 ± 9.5	28.3 ± 8.6	30 ± 8	100	13.60 ± 2.55	2.75 ± 1.05	16.36 ± 4.38
30 injured	19.5 ± 3.9^{+}	UE	17.0 ± 9.1^{-}	11.2 ± 4.9^{+}	42 ± 12^{-}	100	7.17 ± 1.61^{+}	1.01 ± 0.87^{+}	8.10 ± 2.19^{+}
40 healthy	13.0 ± 3.6	371 ± 71	25.4 ± 15.9	6.3 ± 1.5	80 ± 36	100	6.18 ± 0.93	4.63 ± 4.10	10.81 ± 3.62
40 injured	9.3 ± 1.2^{+}	302 ± 58^{+}	16.8 ± 8.2^{-}	6.0 ± 3.0^{-}	100 ± 40^{+}	100	1.94 ± 0.95^{+}	3.96 ± 1.47^{-}	5.91 ± 0.73^{+}
80 healthy	21.2 ± 3.8	765 ± 124	51.9 ± 25.7	0.0 ± 0.0	23 ± 5	50	22.66 ± 5.79	39.37 ± 11.85	61.53 ± 16.85
80 injured	22.3 ± 10.4^{-}	483 ± 87^{+}	32.5 ± 16.4^{-}	0.0 ± 0.0	38 ± 21^{-}	100	8.92 ± 2.41^{+}	22.39 ± 2.51^{+}	31.32 ± 4.91^{+}
Healthy self-seeding	6.2 ± 2.7	212 ± 43	12.6 ± 7.1	9.2 ± 1.8	146 ± 40	0	6.26 ± 3.40	5.90 ± 1.69	12.17 ± 4.49
Injured self-seeding	2.8 ± 0.7^{+}	147 ± 21^{+}	9.5 ± 4.7^{-}	6.6 ± 2.8^{+}	205 ± 69^{-}	0	1.59 ± 0.97^{+}	5.11 ± 1.83^{-}	6.70 ± 1.50^{+}

MSR – Main skeletal roots; Ip – Area index (calculated as a ratio of the sum of root cross-sectional areas (in mm^2) to the height of trees (in cm); $^{-}$insignificant difference; $^{+}$significant difference ($\alpha = 0.05$); UE – unestimated

of horizontal skeletal roots. Younger healthy trees exhibited more non-skeletal roots shooting from the stem base; older stands showed no significant differences. Healthy and affected trees do not differ in the size of the maximum angle between horizontal skeletal roots. With the exception of trees from self-seeding, most healthy and all injured trees are malformed into a tangle (Table 3; Figs. 1–3).

All injured trees have smaller root systems by up to 50% (Ip values of the whole root system). Differences are particularly conspicuous in the proportion of horizontal skeletal roots. In the majority of cases, their Ip value does not exceed even 50% of the Ip value in healthy trees, the differences being induced either by lower abundance or lower diameter of horizontal skeletal roots of the injured trees

Fig. 1. Architecture of the root system aged 15 years (left: healthy; right: injured)

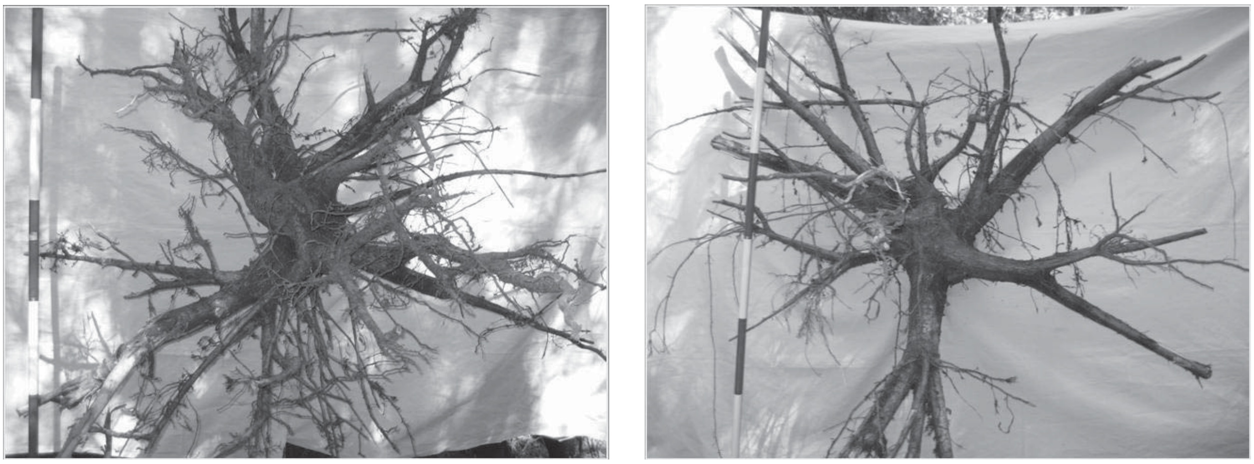

Fig. 2. Architecture of the root system aged 40 years (left: healthy; right: injured)

(Table 3). All injured trees have lower biomass and lower vitality of fine roots (Table 4).

Chemical soil analyses did not reveal any essential differences between the healthy and injured forest stands. The sites are acidic with lower nutrient contents; with the exception of aluminium content, none of the studied parameters reached critical values. The content of Al assumes critical values in all analyzed stands (esp. in stands designated as 40 injured, 80 injured and 80 healthy). Chemical analyses of assimilatory organs showed that both injured forest stands had reduced Mg contents with no other essential differences being found between the healthy and the injured stands in the contents of all other monitored elements.

The behaviour of deposition flows of sulphur, nitrogen and hydrogen ions was monitored in order to assess the existing air pollution stress in the Krkonoše Mts. With respect to the bedrock and the sulphur consumption by the coniferous stand, a critical dose of annual sulphur deposition (15 kg $S \cdot ha^{-1}$) was used for the studied territory. The critical dose of sulphur deposition flow was exceeded in the throughfall deposition in the whole period of study while in the open area it was so only in 2003 (Fig. 4). The critical load of nitrogen depositions in coniferous forests ranges from 10 to 15 kg $N \cdot ha^{-1} \cdot year^{-1}$. For the territory under study, we used a critical dose of throughfall nitrogen deposition at 10 $kg \cdot ha^{-1} \cdot year^{-1}$. This critical dose was exceeded in the whole period of study (Fig. 4). To resolve a relation between the health condition of forest stands, environment acidification due to the input of acid throughfall deposition and damage to soil, we used a critical dose of 1,463 mol $H^{+} \cdot ha^{-1} \cdot year^{-1}$, which was exceeded in the whole period of study (Fig. 5).

As the growth and vitality of trees are considerably affected also by climatic conditions, we monitored weather conditions in the period of 1988 to

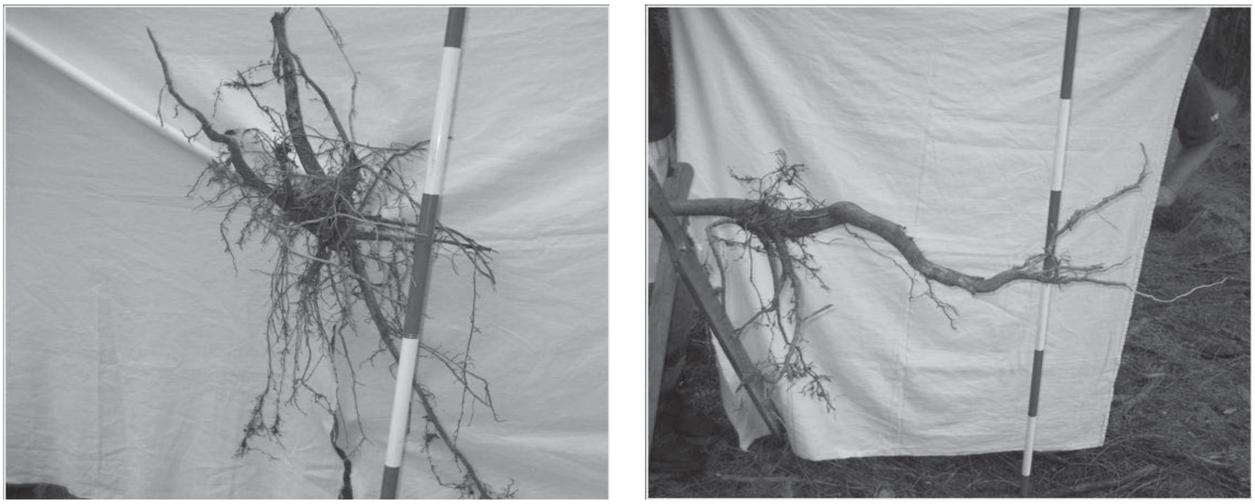

Fig. 3. Architecture of the root system from self-seeding (left: healthy; right: injured)

Table 4. Biomass and vitality of fine roots

Forest stand designation	Sampling date	Biomass of fine roots (g·100 ml^{-1})			Vitality of fine roots
		humus	mineral	total	
30 healthy	September 2007	0.741 ± 0.011	0.091 ± 0.005	0.832 ± 0.014	100
30 injured		0.756 ± 0.010^{+}	0.088 ± 0.004^{+}	0.664 ± 0.008^{+}	64
40 healthy		1.013 ± 0.055	0.216 ± 0.003	1.229 ± 0.056	100
40 injured		0.750 ± 0.010^{+}	0.056 ± 0.005^{+}	0.806 ± 0.005^{+}	46
80 healthy	July 2008	0.598 ± 0.011	0.095 ± 0.008	0.693 ± 0.013	100
80 injured		0.336 ± 0.010^{+}	0.072 ± 0.002^{+}	0.408 ± 0.009^{+}	87

$^{-}$Insignificant difference, $^{+}$significant difference (α = 0.05)

2006. Fitted annual series showed the occurrence of warming, especially in the growing season, and higher total precipitation amounts were also recorded. However, the weather course was considerably fluctuating and critical months were April and June, which were distinctly warmer at the end of the period (differences between temperature values in 1988 and 2006 fitted by a linear regression line in April and June were 1.6°C and 2.4°C, respectively) with a high deficit of rainfall (differences between precipitation values in 1988 and 2006 fitted by a linear regression line in April and June were –56 mm and –26 mm, respectively). Negative ought to be considered also the fact that profound and rapid air temperature changes occur in winter with heavy frosts following the periods of warming above +5°C.

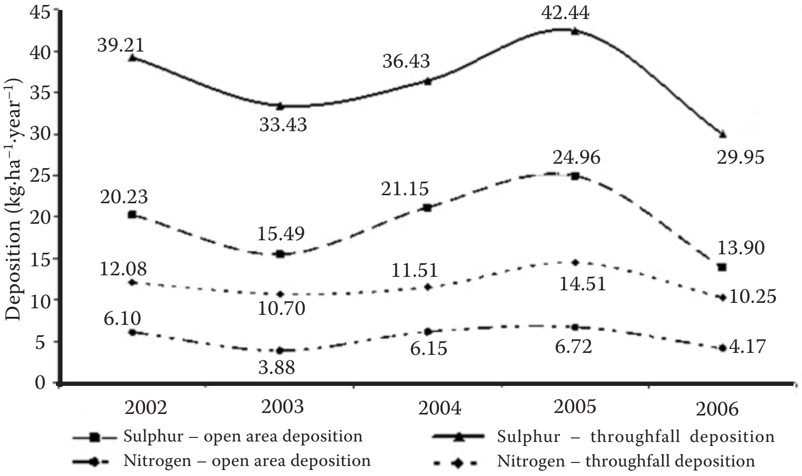

Fig. 4. Annual sulphur and nitrogen depositions in the open area (unstocked forest land) and their throughfall flows

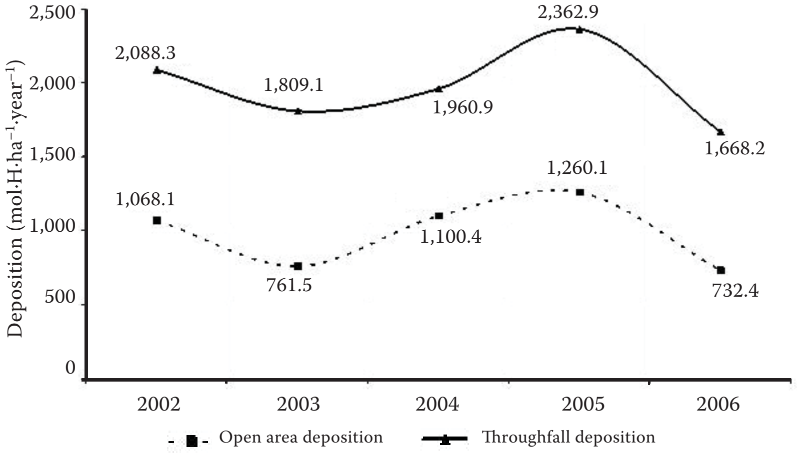

Fig. 5. Annual acid depositions (hydrogen ions) in the open area (unstocked forest land) and their throughfall flows

DISCUSSION

The assessment of permanent experimental plots showed that the condition of spruce stands in the Krkonoše Mts. markedly improved since the end of the 1990s (Vacek, Podrázský 2007). In spite of this fact, local injuries to the stands were recorded in the last approximately eight years, which affect trees of all age classes including those from self-seeding. The injury visually manifests as yellowing or rusting of needles. Colour change of needles proceeds from the oldest needle years and from the stem base to the treetop. In one stand, we could find healthy and declining trees growing next to each other. Our analyses indicated (Table 2) that the affected trees had a considerably lower increment of the aboveground part and shorter needles. Needles with the changed colour do not fall rapidly but they can remain on the branch even several years. The injury does not result in snags and severely injured trees are removed within the planned tending measures.

Our surveys showed that the damage is not due to biotic agents. Although the honey fungus was found in the analyzed forest stands, it has not induced any serious rots of roots or bole so far and other diagnostic symptoms (resin exudations not exceeding 2 cm^2, no syrrocium nor resin exudations on the stem) also suggested that its incidence can be considered “normal” in the pure spruce stands. The injured trees are rather surprisingly heavily infested by bark beetles; if some infestation by this pest was detected, the affected trees appeared visually healthy. We did not find any outbreaks of any other biotic pests.

The area with affected forests has relatively distinct boundaries – injured forest stands occur in forest type group 6K (predominantly 6K1), while the injury does not occur in adjacent forest type groups 6S and 6P. Healthy and injured trees grow on similar soil types – on deep sandy soils highly permeable to water, which differ in the thickness of humus horizons, reaching over 10 cm in the healthy stands and not exceeding 7 cm in the injured stands.

The analyses did not demonstrate any essential differences in soil chemistry under healthy and injured forest stands. However, the sites in question were distinctly acidic with low trophicity in all cases. Except for the content of aluminium, no other monitored parameters showed critical values. The high aluminium content results from high acidity of the site, which may further increase because according to Hošek et al. (2007) the total critical load of sulphur and nitrogen is still significantly exceeded in the Krkonoše Mts. (despite the demonstrable reduction of sulphur depositions, which reduced the total acidification input), mainly due to nitrogen depositions, which according to the authors exceed twice the critical load for mountain spruce forests. Our surveys also showed that throughfall depositions of nitrogen and sulphur exceeded the set up critical doses in the whole period of study.

Further to natural processes of acidification, depositions of sulphur and nitrogen also contribute significantly to soil acidification, the most serious consequences of which are the leaching of base cations (mainly Mg and Ca) from the soil complex, decreased pH value and consequent mobilization of aluminium and metals from clay materials. Ulrich et al. (1979) published a hypothesis about the role of free Al in the decline of forest trees. Many authors experimentally demonstrated later that high concentrations of Al^{3+} might induce damage to the root system. Apart from the direct effect on root tissues, Al may adversely affect the uptake of Mg and Ca. Geburek, Scholz (1989) call it the aluminium-induced Mg and Ca deficiency. The low supply of base cations combined with high aluminium concentrations create an environment unfavourable to roots and that is why according to Fritz et al. (2000) the root system regeneration occurs in horizons with a minimum aluminium load and with a better supply of nutrients, i.e. in humus horizons. Fine roots of healthy spruce trees are normally concentrated in humus horizons Of and Oh and in the upper mineral soil to a depth of 10 cm with a maximum of their occurrence in the layer of 0–5 cm (Murach 1984). A greater part of the fine roots of healthy spruce trees analyzed by us was in humus horizons; however, the fine roots of injured trees occurred only in the upper layer of humus horizons. Injured trees had significantly lower biomass of fine roots, whose vitality was impaired.

The analyses of assimilatory organs did not demonstrate an insufficient supply of basic biogenic elements – nitrogen, phosphorus and potassium – to healthy or damaged trees or an increased content of sulphur. Injured trees only showed reduced Mg content in needles. External symptoms of damage to assimilatory organs also suggested the deficiency of this element. The role of the supply of base cations to tree species in relation to decline was paid great attention by a number of authors (Schulze et al. 1989; Hüttl, Schaaf 1997). Many authors observed the low Mg supply on acidic soils. Landmann et al. (1997) maintained, however, that it was difficult to find a correlation between the results of soil and leaf analyses. In many cases, a close correlation was found between the content of exchangeable Mg in soil and its content in needles. However, this held true generally for the whole stand rather than for individual trees. The authors also point out that in the same Mg-deficient site, we can often find green trees growing just next to trees with a distinctly changed colour of the assimilatory apparatus. Mg content in needles below 0.3 mg·g^{-1} DM indicates a severe Mg deficiency. In this condition, when the needles show conspicuous yellowing, their photosynthetic potential may be considerably suppressed. However, this need not necessarily lead to higher mortality. According to the authors, the development of chlorosis symptoms at a lower Mg supply may depend on climatic and genetic factors. Experiments with the clone material of spruce exposed to an insufficient supply of magnesium and water (Makkonen-Spiecker, Evers 1993 ex Ende, Evers 1997) demonstrated that yellow needles became green again if the spruce trees were given a sufficient water supply during the period of drought. The authors also found out that the change in colour occurred at different Mg contents in the needles. Some spruce clones remained green even with a content of 0.26 mg Mg·g^{-1} DM of 1-year old needles while the needles of other clones showed distinct yellowing symptoms on the same substrate and with the same supply of water. One of the studied clones even exhibited the higher Mg content in yellow needles than in green needles. Based on the obtained results, the authors presume a possible influence of genetic and climatic factors on the development of yellowing symptoms. The authors also present other results supporting their conclusions about a potential role of genetic constitution in yellowing symptoms.

The uptake of a required amount of individual biogenic elements is conditioned not only by their sufficient reserve in the soil environment in available form and by the sufficient size and functionality of the root system, but also by the moisture content of soil. A change in water supply may also affect the total amount of nutrient uptake because water flow is necessary for the movement of nutrients in soil. The amount of available nutrients in the vicinity of roots decreases in consequence of the reduced water flow in soil (Mengel, Kirkby 1978). Palomäki et al. (1995) observed a moderate reduction of N, K, Mg and Ca contents in spruce needles exposed to drought. Thiec-le et al. (1995) informed that e.g. Ca uptake by needles depended on the supply of soil moisture. The Ca concentrations in needles decreased in very dry periods and increased in the periods of sufficient precipitation. Blanck et al. (1995) experimentally demonstrated the reduced content of Mg in the needles of trees exposed to drought stress. Blanck et al. (1988), Thiec-Le et al. (1995) and Fürst (1995) recorded a significant reduction of P and K contents under the influence of drought. In central Europe, drought is considered the main factor inducing Mg deficiency. Most authors are of the opinion that the reserve of available Mg becomes depleted in dry periods and thus the supply of this element is insufficient. According to Landmann et al. (1997), the improvement of Mg nutrition, which follows humid years, supports this interpretation. Hippeli, Branse (1992 ex Landmann et al. 1997) found a close linear correlation between the amount of rainfall during the growing season and the Mg concentration in needles. The effect of drought may be particularly severe if the amount of available Mg is low. Hilebrand (2003) maintained that the reserve of Mg mainly on acidic soils markedly decreased due to acidification and that the element cycling was disrupted. According to this author, a higher amount of Mg occurs in the upper organic floor. However, it does not get to the mineral soil but is rather taken up by roots which are present within the upper floor layer. If the moisture content is sufficient, Mg can get to the roots readily. In the dry period, its amount may be insufficient because only very little dissolved Mg is in the upper floor layer, which is easy to dry out and in the mineral soil of higher moisture content it is not available. He assumes that the symptoms of Mg deficiency correspond to such a situation (e.g. yellowing of spruce in mountains that appears mainly in relatively dry growing seasons). Humus horizons of higher thickness may represent also a more abundant source of Mg and because they are capable of accumulating more water at the same time, they become an important factor in the hydric regime of the site.

Our analyses revealed a significant change in weather conditions in the last years; annual air temperatures increased markedly. Although the total annual precipitation amounts increased in 1988–2007 (with rainfalls being often torrential), water deficits are observed to occur in the months of April and June. Halásová et al. (2007) arrived at a similar conclusion. A negative factor impairing the vitality of trees should is also that considerable warming to above +5°C in winter months is often followed by the arrival of relatively heavy frosts (with temperature differences being even 15°C).

The mosaic occurrence of Norway spruce yellowing may relate to the size of tree root systems. As compared to the visually healthy trees, the analyses of the root system architecture showed a lower number and shorter length of horizontal skeletal roots in the injured trees while the rooting depth of horizontal skeletal roots did not differ. It followed from our results that injured trees from both the artificial regeneration and the self-seeding had a smaller root system at all times (lower Ip value). Although the root system size might also have been affected by site heterogeneity (especially in respect of trophicity), a decisive role was played by root system malformations into tangle evoked by improper biotechnique of planting. This deformation prevented the development of horizontal skeletal roots and impaired the vitality of trees due to the later mutual strangulation of roots (which was also reflected in their smaller diameter and length increments). Although the spruce has a great capacity of developing adventitious roots and thus it can replace roots missing in the root network (Mauer, Palátová 1992, 1996b), their establishment requires favourable conditions (stem base covered with litter, sufficient moisture, temperature and absence of light). The low thickness of humus horizons does not ensure the development of new adventitious roots.

Based on the analyses of root systems, assimilatory apparatus of both injured and visually healthy trees, chemical soil analyses, assessment of the deposition flows of sulphur and nitrogen, and weather conditions in the period 1988–2008, we can judge about the reasons for Norway spruce decline in the region concerned. Predisposition factors for the injury are mainly root system deformations at planting, increasing acidification of soil and its low trophicity, and a triggering factor of the injury is the change weather conditions. Other contributing factors include high soil permeability for water and low thickness of humus horizons. The trees are further weakened physiologically by conspicuous warming with water deficit during the growing season and by temperature fluctuations in winter (the injury has a character of needlecast in younger stands).

The regeneration of the root system and hence of the aboveground part may occur on the site concerned provided that the load of Al is reduced, the supply of nutrients (primarily Mg) increased and the soil moisture is increased in the zone of the growth of fine roots. The course of weather (precipitation amount) cannot be influenced; nevertheless, our analyses showed that the thickness of humus horizons above 10 cm might contribute to water accumulation. The thickness of humus horizons can be increased only through long-term measures. The measures can include the even distribution of logging residues across the site, which would however increase a possibility of bark beetle outbreaks, or the sowing of herbs with voluminous aboveground parts and root systems – such as lupine (if the plot is not to be fenced, great damage by game can be expected).

The low thickness of humus horizons unambiguously predetermines the use of a shelterwood system (planting under canopy). The removal of injured spruce trees leads to further drying out and mineralization of humus horizons, which manifests in faster damage to hitherto healthy trees. Only dead standing trees should be removed.

Chemical conditions of the site can be improved by fertilization. In this concrete case, we would recommend lime fertilizer with a high content of magnesium (lime dolomite). The fertilization has to be applied as a whole-area treatment, gradual and repeated one, because a rapid change in pH and Mg content would adversely affect not only the growth of roots but also the whole ecosystem.

Norway spruce is declining on concerned site the. Should the site conditions remain unchanged, the assumption that the current plantations and younger stands will survive until exploitable age is not realistic. A possible solution consists in the change of the tree species composition. Sycamore maple cannot be planted due to the lack of humus. With the use of European beech and silver fir, we could face the same growth problems as with Norway spruce in spite of the fact that the current young beech plantations have grown relatively successfully so far (as well as Norway spruce plantations of the same age). It cannot be expected that the beech would root through deeper soil horizons because even the root system of spruce reaches the parent rock. In the sense of forest precautions, the most appropriate method would be a change in the composition to the benefit of species with broad ecovalence and a high soil-improving effect such as common birch, European mountain ash or European aspen. After some 10 years (depending on weather development), a proposal for their reconstruction to the benefit of spruce and beech can be prepared.

There are in general two realistic forestry procedures following from the above facts for the solution of this situation. One of them consists in a further underplanting of spruce after the change in soil chemistry by fertilization and in an increased proportion of beech (ca up to 50%). The underplanting of beech should be done in the injured spruce stands with no regard to their current age but the beech must be consistently protected from damage by game. The second realistic forestry approach is a temporary change in the tree species composition to the benefit of preparatory species with a good soil-improving effect. It is important that no clearcut comes to existence and that all plantations are implemented without root system deformations.

CONCLUSIONS

The paper analyzes the development and health condition of the root system in Norway spruce affected by the decline and yellowing of assimilatory apparatus in forest stands managed by Forest Administration in Horní Maršov, KRNAP. Our analyses included forest stands aged from 10 to 80 years originating from both artificial and natural regeneration. Root system analyses were combined with analyses of chemical soil properties, assimilatory organs, weather course and emissions. Conclusions from the analyses are as follows:

- Affected forest stands occur on strongly acidic, oligotrophic and highly water-permeable sites.
- The area is under permanent impacts of increased sulphur and nitrogen depositions and the soil acidification further continues. Magnesium is a deficient element in the nutrition. The weather conditions have markedly changed in recent years – warming and great temperature fluctuations are observed in winter and precipitation deficits are recorded mainly in April and June.
- Injured trees have small and malformed anchoring root systems with a low number of horizontal roots.
- Injured trees have less abundant fine roots of lower vitality (high proportion of dead fine roots) and penetrate normally only through the uppermost humus horizons.
- The root system of affected trees is infested by the honey fungus, which colonizes only anchor roots. Neither root nor bole rots were detected so far.

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References

Blanck K., Matzner E., Stock R., Hartmann G. (1988): Der Einfluß kleinstandörtlicher bodenchemischer Unterschiede auf die Ausprägung von Vergilbungssymptomen an Fichten im Harz. Forst und Holz, ***43***: 288–292.

Blanck K., Lamersdorf N., Dohrenbusch A., Murach D. (1995): Response of Norway spruce forest ecosystem to drought/rewetting experiments at Solling, Germany. Water, Air and Soil Pollution, ***85***: 1215–1256.

Budská E., Franče P., Světlík I. (2000): Monitoring of atmospheric deposition in the area of the Krkonoše Mountains. Opera Corcontica, ***37***: 47–54. (in Czech)

Ende H.P., Evers F.H. (1997): Visual magnesium deficiency symptoms (coniferous, deciduous trees) and treshold values (foliar, soil). In: Hüttl R. F., Schaaf W. (eds): Magnesium Deficiency in Forest Ecosystems. London, Kluver Academic Publishers: 3–22.

Fritz H.W., Jentschke G., Godbold D.L. (2000): Feinwurzelunteruchungen in versauerten Fichtenbeständen. Allgemeine Forstzeitschrift der Wald, ***55***: 788–791.

Fürst A. (1996): Blatt- und Nadelanalytische Untersuchungen im Rahmen des Waldschaden-Beobachtungssystems – Ergebnisse 1989 bis 1993. FBVA-Berichte, ***93***: 101–109.

Geburek T., Scholz F. (1989): Response of *Picea abies* L. Karst. provenances to aluminium in hydroponics. In: Genetic of Air Pollutants in Forest Tree Populations. Springer Verlag, Berlin–Heidelberg: 55–65.

Halásová O., Hančarová E., Vašková I. (2007): Temporal and spacial variability of selected climatologic and hydrological elements in the Giant Mountains in the time period 1961–2000. Opera Corcontica, ***44***: 171–178. (in Czech)

Hilebrand E. (2003): Neuartige Waldschäden – Realität oder Sturm im Wasserglas? Allgemeine Forstzeitschrift Der Wald, ***58***: 1311–1313.

Hošek J., Schwarz O., Svoboda T. (2007): Results of ten-year measurements of atmospheric deposition in the Giant Mountains. Opera Corcontica, ***44***: 179–191. (in Czech)

Hüttl R.F., Schaaf W. (1997): Magnesium Deficiency in Forest Ecosystems. London, Kluver Academic Publishers: 362.

Joslin J.D., Henderson G.S. (1984): The determination of percentages of living tissue in woody fine root samples using triphenyltetrazolium chloride. Forest Science, ***30***: 965–970.

Landmann G., Hunter I.R., Hendershot W. (1997): Temporal and spatial development of magnesium deficiency in forest stands in Europe, North America and New Zealand. In: Hüttl R.F., Schaaf W. (eds): Magnesium Deficiency in Forest Ecosystems. London, Kluver Academic Publishers: 3–22.

Lokvenc T., Dušek V., Jurásek A., Lokvenc T., Martincová J., Podrázský V., Vacek S., Haniš J., Minx A., Dušek M., Schwarz O. (1992): Reforestation of the Krkonoše Mts. Opočno, Správa KRNAP Vrchlabí a VÚLHM Výzkumná stanice: 111. (in Czech)

Mauer O., Palátová E. (1988): Effect of acid air pollutants on the root system development in Norway spruce (*Picea* *abies* [L] Karst.). Acta Universitatis Agriculturae, Facultas Silviculturae, ***57***: 105–120.

Mauer O., Palátová E. (1992): The effect of different methods and types of planting on the development of Norway spruce (*Picea abies* [L.] Karst) root system. Lesnictví-Forestry, ***8***: 193– 203. (in Czech)

Mauer O., Palátová E. (1996a): Results of some rhizological studies in Krkonoše Mts. region. In: Vacek S. (ed.): Monitoring, Research and Management of Ecosystems in Krkonoše Mts: 142–146. (in Czech)

Mauer O., Palátová E. (1996b): Morphogenesis of the Norway spruce (*Picea abies* [L.] Karst.) root system from natural regeneration up to 30 years of stand age. Lesnictví – Forestry, ***42***: 116– 127. (in Czech)

Mauer O., Palátová E., Rychnovská A. (2004): Root system and Norway spruce decline. In: Root System – the Basis of Tree. MZLU v Brně: 64–74. (in Czech)

Mauer O., Palátová E., Pop M. (2008): Root system emergence and health condition in Norway spruce (*Picea abies* [L.] Karst.) affected by yellowing of assimilatory apparatus in the region of the Krušné hory Mts. Folia Oecologica, ***35***: 39–50.

Mazurski K.R. (1989): The air pollution of the Polish Sudets. Opera Corcontica, ***26***: 51–59. (in Polish)

Mengel E., Kirgby E. A. (1978): Principles of Plant Nutrition. Bern, International Potash Institute: 593.

Murach D. (1984): Die Reaktion der Feinwurzeln von Fichten (*Picea abies* Karst.) auf zunehmende Bodenversauerung. Göttinger Bodenkundliche Berichte, ***77***: 128.

Palomäki V., Holopainen J.K., Holopainen T. (1995): Effects of drought and waterlogging on ultrastructure of Scots pine and Spruce needles. Trees, ***9***: 98–105.

Schulze E.D., Lange O.L., Oren, R. (1989): Forest Decline and Air Pollution. A Study of Spruce (*Picea abies*) on Acid Soils. Ecological Studies 77. Berlin, Springer Verlag: 475.

Schwarz O. (1996): Results of sulphur compound concentration measuring in the Krkonoše Mts. In: Vacek S. (ed.): Monitoring, Research and Management of Ecosystems in Krkonoše Mts.: 4–10. (in Czech)

Thiec-Le D., Dixon M., Garrec J.P., Le-Thiec D. (1995): Distribution and variation of potassium and calcium in different cross sections of *Picea abies* (L.) Karst. needles and *Fagus sylvatica* (L.) leaves exposed to ozone and mild water stress. Annales des Sciences Forestieres, ***52***: 411–422.

Twarowski R., Gendola T., Liana E., Wostek-Zagraba K. (2007): Deposition of pollutants from atmosphere with precipitation in the Giant Mountains in the years 1994–2004. Opera Corcontica, ***44***: 213–225. (in Polish)

Ulrich B., Matzner R., Khanna P.K. (1979): Deposition von Luftverunreinigungen und ihre Auswirkungen in Waldökosystemen im Solling. Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen forstlichen Versuchsanstalt, Frankfurt am Main, Sauerländer Verlag, Bd. 58: 291

Vacek S. (2000): Healthy state of forest stands on permanent research plots in the Giant Mountains. Opera Corcontica, ***36***: 536–541. (in Czech)

Vacek S., Podrázský V. (2007): Healthy status development of forest stands on permanent research plots in Giant Mountains. Opera Corcontica, ***44***: 493–498. (in Czech)

Vacek S., Simon J., Minx T., Podrázský V., Balcar Z. (2007): Structure and development of forest ecosystems in the Giant Mountains. Opera Corcontica, ***44***: 453–462. (in Czech)

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Corresponding author:

doc. Ing. RNDr. Eva Palátová, Ph.D., Mendelova Univerzita v Brně, Ústav zakládání lesa a pěstění lesů, Zemědělská 3, 613 00 Brno, Česká republika
tel.: + 420 545 134 132, fax: + 420 545 134 125, e-mail: evapal@mendelu.cz