The health and nutritional status of Norway spruce stands in the Krušné hory Mts. 15 years subsequent to the extreme winter of 1995/96

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ABSTRACT: Since 1994, the nutritional status and the air pollution load have been evaluated on 20 research plots, located in young Norway spruce stands in the ridge area of the Krušné hory Mts. The most recent acute damage to the spruce stands, in the winter of 1995/96, was connected with a long-lasting inversion situation in the eastern area of the Krušné hory Mts. Today, the health status of the spruce stands, expressed in terms of the crown defoliation, has recovered and is comparable to that found in other regions of the Czech Republic. The sulphur and fluorine content of the needles has decreased significantly. The long-term negative effect of acid deposition that contributes to the degradation of forest soils remains an important part of stressors acting on forest ecosystems in the region. In recent years, nitrogen and sulphur concentrations in the needles have increased slightly again. A long-term tendency towards a decrease in the phosphorus, calcium and potassium content of the needles was detected.

Keywords: forest health; tree nutrition; air pollution; Ore Mts.

The forest stands of the Czech Republic are constantly influenced by anthropogenic factors. The effect of air-borne pollutants such as sulphur dioxide, fluorine or nitrogen oxides and of acid deposition has had a substantial influence on the forest vitality and productivity in the "Black Triangle" – the mountain area on the borders between the Czech Republic, Germany and Poland (Lomský et al. 2001; Fiala et al. 2002; Zimmerman et al. 2002; Fottová 2003; Šrámek et al. 2008a). Damage to the forest stands caused by sulphur dioxide was already perceptible in northwestern Bohemia at the beginning of the 20th Century (Stoklasa 1923). In the seventies, when the sulphur emissions culminated, the Norway spruce stands in the ridge area of the Krušné hory Mts. were strongly affected over an area of ca 40,000 ha (Materna 1988; Lomský et al. 2002). Desulphurisation of the most important pollution sources at the turn of the 1980's and 1990's has gradually lowered the sulphur dioxide load significantly (Kubelka 1993) and this has resulted in the improvement of the forest health. This positive trend was interrupted in the winter of 1995/96, during which an extensive decline in the forest was recorded in the ridge part of the Krušné hory Mts., over an area of about 12,000 ha. This damage was caused by direct effects of a high concentration of sulphur dioxide that had accumulated during an extraordinarily long-term period of meteorological inversion. At the same time a sharp drop in the air temperature was also recorded, accompanied by hard frost cover on trees (Lomský, Šrámek 1999). Extreme air-borne pollutant concentrations resulted in a very high amount of sulphur and fluorine in the needles of trees (Lomský et al. 1996; Lomský, Šrámek 2004). The drying and falling of needles, resulting in high crown defoliation, reached a level of over 60% in the damaged forest stands. In some cases only 10% of vital buds were recorded and their vitality decreased in accordance with the age of the stand

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(Lomský, Šrámek 1999). During the subsequent period the spruce stands successfully regenerated (Lomský et al. 2002).

Another type of deterioration was observed in the western Krušné hory Mts. The long-term effects of acid deposition connected with base cation leaching, granite bedrock poor in base cations, massive washing of the soil horizon after winter at the turn of the century resulted in the historically repeated yellowing of Norway spruce stands (Hadaš 2006; Šrámek et al. 2008a). The yellowing of the stands in all age categories was connected with a base cation deficiency – primarily of magnesium and of calcium – in the forest soil and in the needles. This type of damage affected about 8,000 ha of forest stands (Šrámek et al. 2001; Lomský, Šrámek 2004). Based on Government Resolution No. 532/2000, during the period from 2000 to 2004 liming and fertilising of the forest stands were carried out in the Krušné hory Mts. forests. Dolomite lime was applied, together with a liquid magnesium fertiliser and dry fertilisers (Lomský et al. 2006; Podrázský 2006; Šrámek et al. 2006). The ameliorative methods including biological and chemical amelioration and reduced air pollution pressure have contributed to stand regeneration and enabled the transformation of existing transitory stands into stands composed of the target tree species (Slodičák et al. 2008; Šrámek et al. 2008b).

The purpose of this article is to assess the changes in forest health and in tree nutrition and growth as they were recorded in the Norway spruce in the Krušné hory Mts. during the fifteen years following the disastrous winter of 1995/96.

MATERIAL AND METHODS

Krušné hory Mountains

The Krušné hory Mountains at the border between the Czech Republic and Saxony cover an area of 180,015 ha. This long and rather flat-topped mountain range is formed in a NE-SW direction. It is about 130 km long and, on the Czech side, only about 6–19 km wide. The mountain plateaus slope moderately towards the NW, while, on the other hand, the SE slopes are quite steep, dropping to the Czech brown-coal basins. The degree of forestation in the Krušné hory Mts. is about 67% (ÚHÚL 2002). Geologically, the Krušné hory Mts. could be divided into two different sections, with the highest peak, Klínovec, in the centre. The northeastern Krušné hory Mts. are formed mainly of gneiss and granulite with a few basalt penetrations on a limited scale (0.9%). The southwestern area is formed of phyllites and granites which are very poor in CaO, MgO, P_2O_5. The differences between the western and the eastern areas of the Mountains have already been described by many authors (Materna 1986, 2002; Kubelka 1993; Jirgle 1995; Lochman 1996; Lomský et al. 1996, 2002). According to the taxonomic classification system of the Czech Republic (Němeček et al. 2001; Kozák et al. 2010) the most frequent soil types in Krušné hory Mts. are Podzols represented in about 43.7% of the area followed by Cambisols over 39.8% of the area (Kulhavý et al. 2008).

The Krušné hory Mts. is the region of Europe most affected by air pollution. Between the 1960's and the 1990's the effect of air pollutants, in synergy with the climate changes, resulted in the widespread disintegration of forest ecosystems on the mountain plateau. More detailed information concerning the Krušné hory Mts. forest region can be found in publications by Plíva and Žlábek (1986) and Vacek et al. (2003).

Research plots

Research plots were installed in the Krušné hory Mts. in young Norway spruce (*Picea abies* [L.] Karst) stands up to 40 years old in 1994 (Lomský, Uhlířová 1993). In 1996, the monitoring system was completed, creating a transect from Cínovec to Horní Lazy in the Slavkovský les region. The plots have an area of 25 × 25 m. The individual trees are numbered and their defoliation and annual increment are assessed on an annual basis (Lomský 2006). The plot locations and additional characteristics are shown in Fig. 1 and Table 1.

Crown condition and growth assessment

From 1995 onwards, defoliation of the tree crown was assessed annually at the end of the vegetation season (October–November). The defoliation of minimally 40 numbered trees was evaluated within a diagonal transect, on a 5% scale, in accordance with the ICP Forests methodology (UNECE 2010a), modified for young Norway spruce stands (Lomský, Uhlířová 1993). These results are presented for individual plots as mean percentages of defoliation.

Height increment was measured annually in the autumn in a set of 20 trees that were included in the crown defoliation assessment. Measuring was originally carried out using a Sokkia measuring pole (Sokkia, Tokyo, Japan). As the stands grew, the method had to be changed; since 2006 the Vertex hypsometer (Haglöf, Långsele, Sweden) has been used.

Table 1. Characteristics of research plots in the Krušné hory Mts.

	Locality	Stand	Age (years)	Altitude	Forest type	Stress zone	Soil type	Exposition	JTSK coordinates	
									Y	X
1	Cínovec	605 Ca4	< 40	820	7K3	A	PZhm	NW	777321.9	965822.9
2	Lounská	504 F1c	< 20	840	7G3	A	GLmt	NW	781962.6	967792.6
3	Klínovčík	503 Ba05b	< 40	810	7S1	B	KPmb	W	782765.9	968545.5
4	Fláje	110 C4	< 40	750	7K4	B	KPmo	SW	791175.4	968867.6
5	Klíny	602 B4	< 20	800	7K3	A	PZhm	0	796352	972834.5
6	Nová Ves	440 C4	< 20	680	7G3	A	GLmt	NW	800460.9	975175.4
7	Rudolice	56C 3a	< 40	780	7K3	A	PZhm	0	806475.6	978025.3
8	Kálek	70 C1	< 20	815	7K3	A	PZhm	SW	809840.9	979101.5
9	Načetín	7 B2b	< 20	795	7K3	B	PZhm	0	816671.8	977359.6
10	Sv. Šebestián	528 A12/3	< 20	810	8R3	A	OR	N	819017.9	982045.6
11	Skelný vrch	521 F3	< 20	875	7K3	A	PZhm	NE	822108.5	984114.8
12	Přísečnice	415 C14/03	< 40	875	7K1	A	KP	NW	839595.9	993239.2
13	Výsluní	411 D2	< 20	810	6K4	A	KP	SW	821557.6	987059.2
14	Kovářská	162 D3b	< 20	800	7G1	B	GL	SE	832271.9	987283.6
15	Špičák	170 E2a	< 20	895	7K3	A	PZhm	N	832156.2	989113
16	Loučná	267 C4	< 20	990	7K1	B	KP	NW	5587800	3356300
17	Klínovec	708A15/01c	< 20 coppice	1,230	8Z4	B	PZhh	SW	840306.3	994054.3
18	Přebuz	102 E4	< 20	885	7M3	B	PZoh	0	864532.6	993937.8
19	Studenec	637 C4	< 20	645	6K4	B	KP	N	873910.6	1005682.8
20	Lazy	72 B2	< 20	850	5K1	B	KAmo	N	868093.3	1006629.5

Foliage and soil sampling

Sampling of the needles to define their nutrient level and air pollution load was undertaken every autumn (October–November), together with the assessment of the crown condition. 10 trees were sampled on individual plots. One branch of the top part of the crown (from the third to the sixth whorl) was taken from each of them. For each plot a pooled sample of the current year needles and a pooled sample of one-year-old needles were created. These foliar samples were prepared in accordance with the ICP Forests methodology (UNECE 2010b).

Soil samples were taken at four-year intervals in 1995, 1999, 2003 and 2007. Individual samples of the upper organic layer and of the mineral soil from a depth of 0–30 cm were taken individually. The sampling was carried out diagonally throughout each plot; the samples from three sampling spots were pooled prior to their analysis. The preparation of the samples from the surface organic (humus) layer and the mineral soil was carried out in accordance with the ICP Forests methodology (UNECE 2010c).

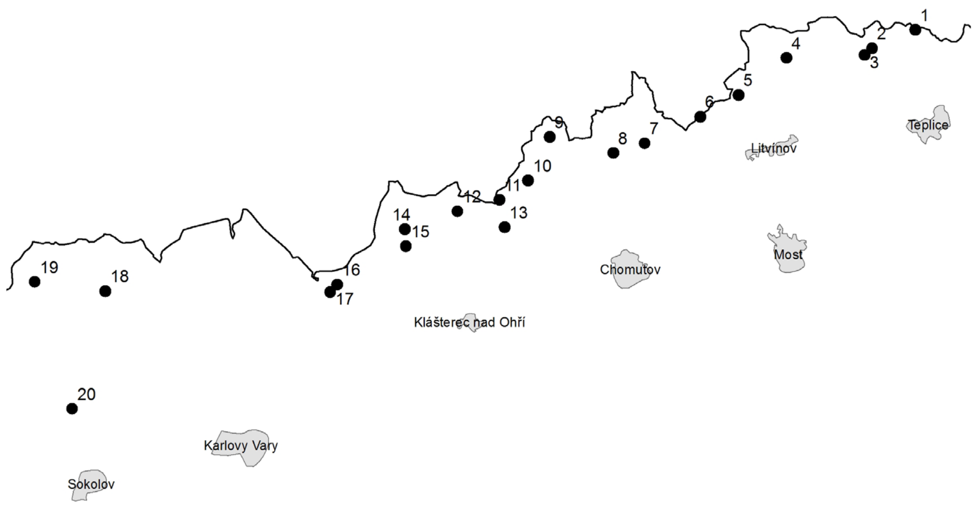

Fig. 1. Location of the research plots in the Krušné hory Mts.

Laboratory analyses

Samples of the foliage, humus and mineral soil were prepared in accordance with the standard methods (UNECE 2010b,c; Tomíček 1958). After decomposition in a microwave oven the content of K, Ca, Mg, Al, Fe, Mn, Zn and P in needles was determined using ICP-OES. The active pH – $pH_{(H_2O)}$ and exchangeable $pH_{(KCl)}$ in the soil samples were determined. In 1995 and 1999 nitrogen content was detected spectrometrically by kjehldalisation and the amounts of oxidable carbon by iodometric titration after oxidation using a chrome-sulphur mixture. Since 2003 the total C and N contents have been determined using the Leco CNS element analyser (LECO, Michigan, USA). The quantity of exchangeable elements in the extract was determined by the use of ammonium chloride and the total element amounts by using *Aqua regia* in an AAS. The available phosphorus was analysed spectrophotometrically (CFA Skalar) after being dissolved in $HCl+H_2SO_4$.

Data analysis

The results of foliage and soil chemistry were compared with the classification published by Bergmann (1993) and with the other classification systems (Šrámek et al. 2009). Prior to statistical recalculation exploratory data analysis was carried out. A comparison was carried out in regard to the individual years during the period investigated using graphic methods (box graphs, categorised point graphs), one-factor analysis of dispersion and methods for comparing the independence of selected sets of data (*F*-test for dispersion, *t*-test for averages). For the correlation analysis the Pearson *R* coefficient was used (Meloun, Militký 2002). Nonlinear regression was used for evaluation of the time trend using an element content module. All the statistical data evaluation was carried out using the STATISTICA 10 (SPSS, Tulsa, USA).

RESULTS AND DISCUSSION

Forest health status and growth of tress on the plots investigated in the Krušné hory Mts.

The defoliation data (Fig. 2) confirms that the health condition of the Norway spruce stands distinctly deteriorated following the disastrous winter of 1995/96 (Lomský, Šrámek 1999). The mean defoliation ranged between 33 and 78%. Most severely damaged were the Skelný vrch, Fláje and Lounská plots and the

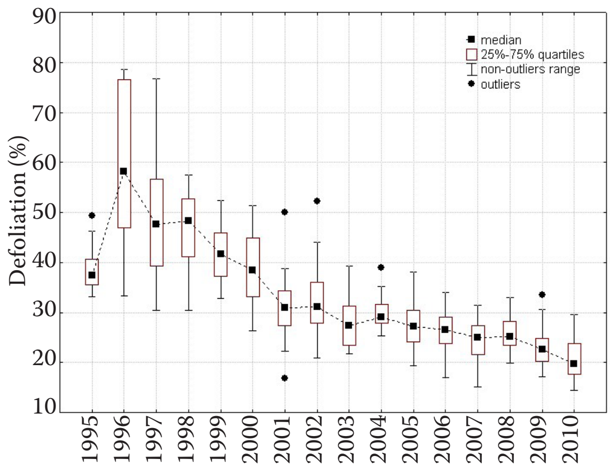

Fig. 2. Mean crown defoliation in 1995–2010

mean defoliation of the entire region was 59%. The health status of the Norway spruce stands has improved during subsequent years, thanks to favourable climatic conditions and a relatively low air pollution load. By the year 2000 the total mean defoliation of all the plots had already decreased to 39.2%; on some of the plots, however, it still exceeded 50%. On most of the plots the mean defoliation was around 40%. Fig. 3 shows that the eastern area of the Krušné hory Mts. was damaged more severely. By 2005 the maximum defoliation of the spruce stands did not exceed a level of 40%, while the mean defoliation level for all the plots was 27.6%. A further decrease in the mean defoliation level to 20.8% in 2010 has confirmed that the health status of the spruce stands is similar to that in the surrounding regions of Central and Western Europe (UNECE 2008; Boháčová et al. 2009, 2010). The balanced vitality of the forests over the mountain range could also be recognised by the similar degree of defoliation in the eastern like in the western area of the Krušné hory Mts.

Mature spruce stands respond to SO_2 air pollution by slower growth in height (Spiecker 1999).

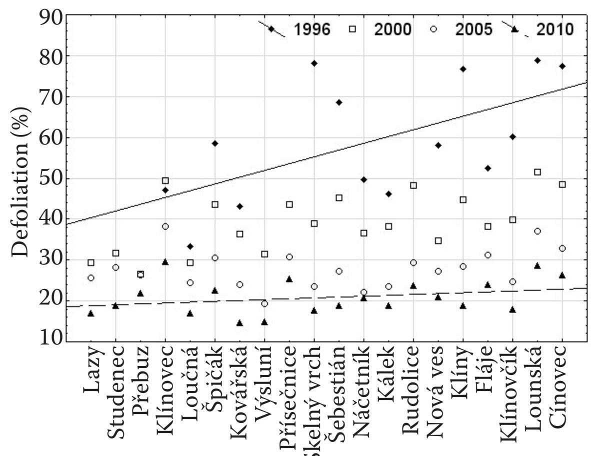

Fig. 3. Development of defoliation on individual plots in 1996, 2000, 2005 and 2010

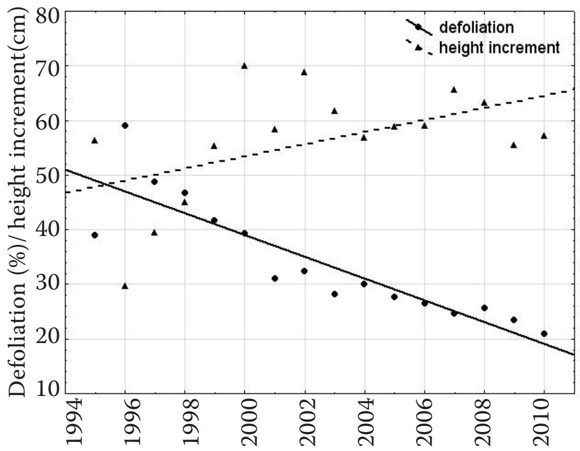

Fig. 4. Mean of Norway spruce defoliation and height increment values in the Ore Mts in 1995–2010

For two years at least, the loss of needles also affected the height growth of the young spruce stands (Kriegel 2001). This condition is also confirmed by an assessment of the growth in height in the Krušné hory Mts. Height growth (annual height increment) had decreased significantly after the winter 1995/96; the eastern area of the Krušné Hory Mts. had been affected more severely. The height increment recovery continued for three years at least while the regeneration of the foliage of the stands was also linked to it. The highest increment was recorded in 2000; during subsequent years it was about 60–70 cm and this trend remained virtually steady (Fig. 4).

Changes in concentrations of stress elements and principal nutrients in the needles

High concentrations of sulphur dioxide and of hydrogen fluorine had a devastating effect during the winter of 1995/96. Their presence was also confirmed by the higher amounts of sulphur and fluorine in the Norway spruce needles (Lomský et al. 1996; Lomský, Šrámek 2004). Until 2002 a significant downward trend was perceptible in the concentration of sulphur in both needle year-classes (Fig. 5). After the winter of 1995/96 sulphur content in the current-year needles ranged from 1,300–2,000 mg·kg^{-1}, i.e. it was distinctly elevated (Tesař et al. 1982; Materna 1986; Stefan et al. 1997; Renou-Wilson, Farrell 2007). In spite of the ongoing installation of desulphurisation technologies at the sources of the highest degrees of emission, in 2000 sulphur concentrations in the first needle year-classes in some of the plots were comparable to those of 1996. A more significant decrease in sulphur concentrations was recorded only in the subsequent period; in 2005 the mean concentrations were 1,000–1,500 mg·kg^{-1}.

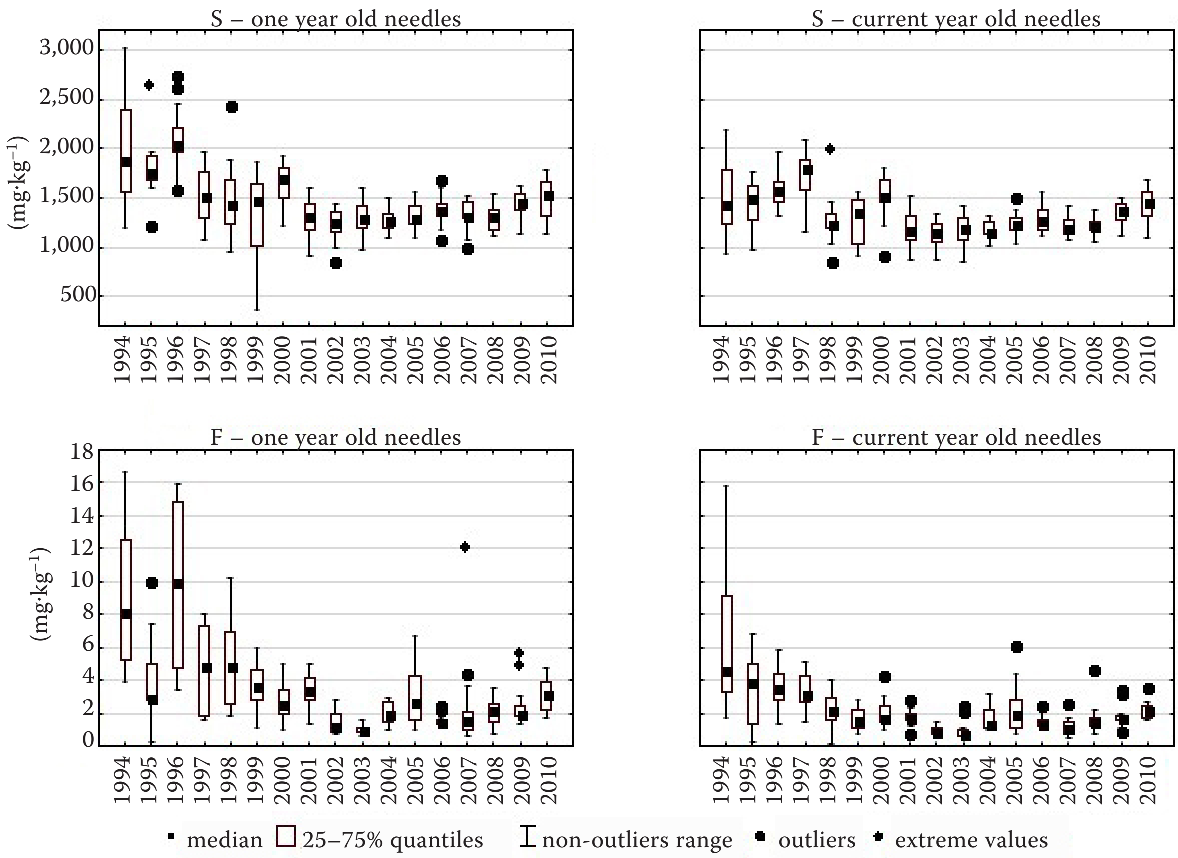

Fig. 5. Mean annual content of sulphur and fluorine in the current year and one-year-old needles

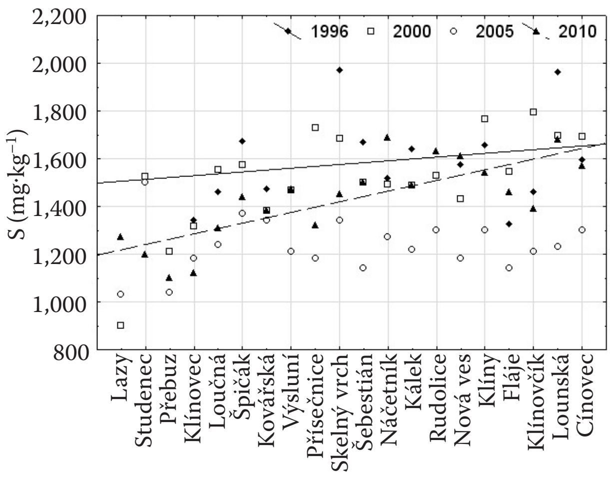

Fig. 6. Sulphur concentration in the current year needles in the plots and years investigated

In spite of the fact that the concentration of SO_2 in the air has been very low in recent years, a slight increase in the mean sulphur concentration in the needles has been perceptible during the last two years. This could be connected with the increasing usage of brown coal in the local heating systems. The air pollution load as evaluated by the sulphur needle content was lower in the western area of the Krušné hory Mts. throughout the entire monitoring period (Fig. 6).

Fluorine has been the second most significant pollutant in the Krušné hory Mts. region (Lomský, Šrámek 2002). After the winter of 1995/96, at most of the sites monitored (Fig. 5) the fluorine content of one-year-old needles significantly exceeded the toxicity limit of 5 mg·kg^{-1} (Polle et al. 1992; Lomský et al. 1996). The most loaded and affected localities in regard to sulphur pollution were Špičák, Skelný vrch and Lounská. During the subsequent period a decrease in fluorine concentration was recorded with only scarce exceedance of the level of 4 mg·kg^{-1}. In 2000 the mean fluorine concentration for all the plots monitored was less than 2 mg·kg^{-1}. In recent years the fluorine concentration seems to have been increasing slightly, though in the years 2005 and 2010 it was remarkable (a mean concentration of 2.15 mg·kg^{-1} and of 2.17 mg·kg^{-1}, respectively).

The nitrogen content in the current-year needles was between 1.1 and 2.1%, covering the entire range between deficiency and an abundant nutrition supply (Fig. 7). The overall trend of nitrogen levels suggested a slight increase but this trend is not statistically significant (Table 2). Following a moderate decrease in the late nineties, since 2003 an increase can be seen again. The nitrogen content of the needles in 2010 is higher than it was after the winter of 1995/96, noticeably so on the plots situated in the eastern area of the Krušné hory Mts.

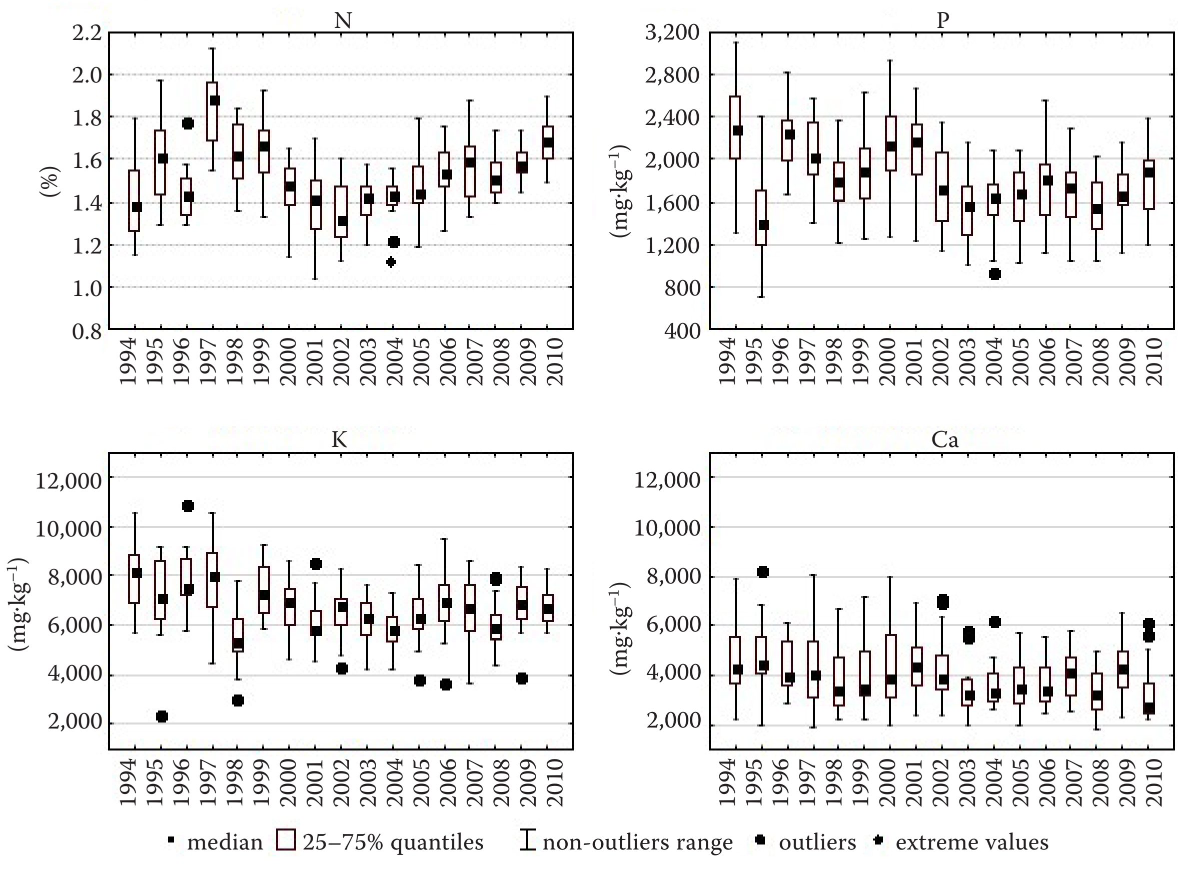

Fig. 7. Annual values of nitrogen, phosphorus, potassium and calcium content in the current year needles

Table 2. Statistical evaluation of time trends in element contents in Norway spruce needles

	Needle class	P	Significance level	Trend
N	cy	0.9657	ns	↗
	1y	0.1910	ns	↗
P	cy	0.0806	*	↘
	1y	0.1835	ns	↘
K	cy	0.0655	*	↘
	1y	0.0130	**	↘
Ca	cy	0.0507	*	↘
	1y	0.0318	**	↘
Mg	cy	0.0015	***	↗
	1y	0.0295	**	↗
S	cy	0.0598	*	↘
	1y	0.0056	***	↘
F	cy	0.0022	***	↘
	1y	0.0041	***	↘

cy – current year needles, 1y – one-year-old needles, ns – not significant, *significant at $\alpha < 0.1$, **significant at $\alpha < 0.05$, ***significant at $\alpha < 0.01$, ↗ indicates increase, ↘ indicates decrease

The phosphorus content of the current-year needles was practically identical between 1996 and 2000, ranging between 1,200 and 2,900 mg·kg^{-1} (Fig. 7), i.e. from deficiency level to favourable nutritional supply (Polle et al. 1992; Bergmann 1993). After a moderate decrease in the phosphorus concentration, a slight increase in the mean values from 1,300 to 1,800 mg·kg^{-1} has been observed since 2003. The phosphorus concentration in the needles was higher in 1996 than it was in 2010, with the values decreasing towards the eastern area of the Krušné hory Mts. In 2010 the values were balanced.

The mean potassium content of the current-year needles was around 6,000 mg·kg^{-1} (Fig. 7), characterizing sufficient nutrition by this element. Neither in 1996 nor in the subsequent period any deficit in the concentration of potassium in the Norway spruce needles has been recorded. A slightly downward trend in the potassium content was recorded both for the current year's and the one-year-old needles (Table 2).

The mean content of calcium fluctuated between individual years and showed a slight decreasing tendency in both needle year-classes (Fig. 7, Table 2). The lowest value (2,000 mg·kg^{-1}), at the threshold of deficiency, was measured in the current-year needles at Klínovec in 2000, and on the plots in Přebuz and in Fláje in 2005. The calcium content of the needles is lower in the western part of the Krušné hory Mts.; in 2010 a moderate decrease could be observed in comparison with the status in 1996.

Over the long perspective there is a tendency towards an increase in magnesium content in both needle year-classes (Fig. 8). This trend is highly significant for the current-year needles (Table 2). In 1996, on 7 of the plots, magnesium concentrations were below the deficiency limit (700 mg·kg^{-1}); the mean magnesium content was 783 mg·kg^{-1}. In 2000, the number of plots evidencing a deficiency of magnesium dropped to just two (Klínovec and Přísečnice). On the rest of the plots their magnesium concentrations were mostly good to very good, and the mean concentration increased to 1,043 mg·kg^{-1}. In 2005 only one plot (Klíny) was below the magnesium deficiency threshold, and the mean concentration for the transect of the plots was 967 mg·kg^{-1}. In 2010 a magnesium deficiency was found in Cínovec. The total mean concentration for the Krušné hory Mts. has increased to 1,095 mg·kg^{-1}.

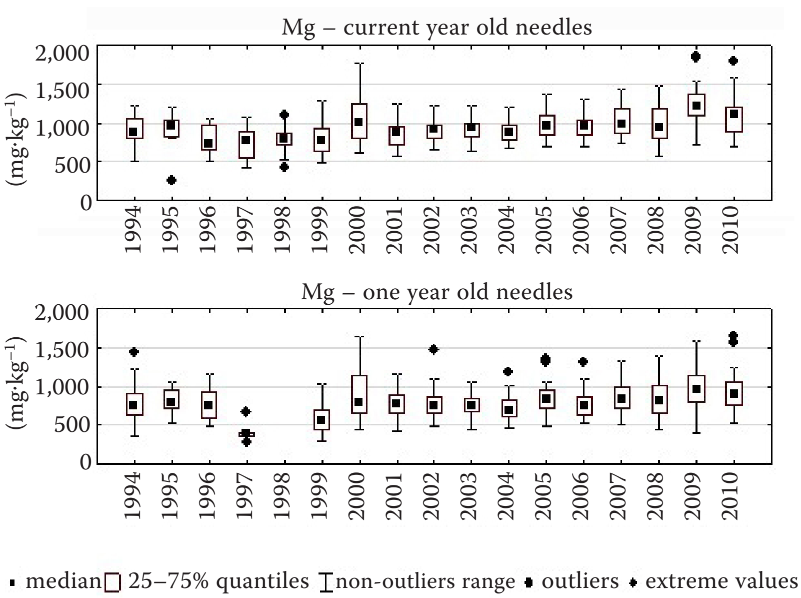

Fig. 8. Annual values of magnesium content in the current year and one-year-old needles

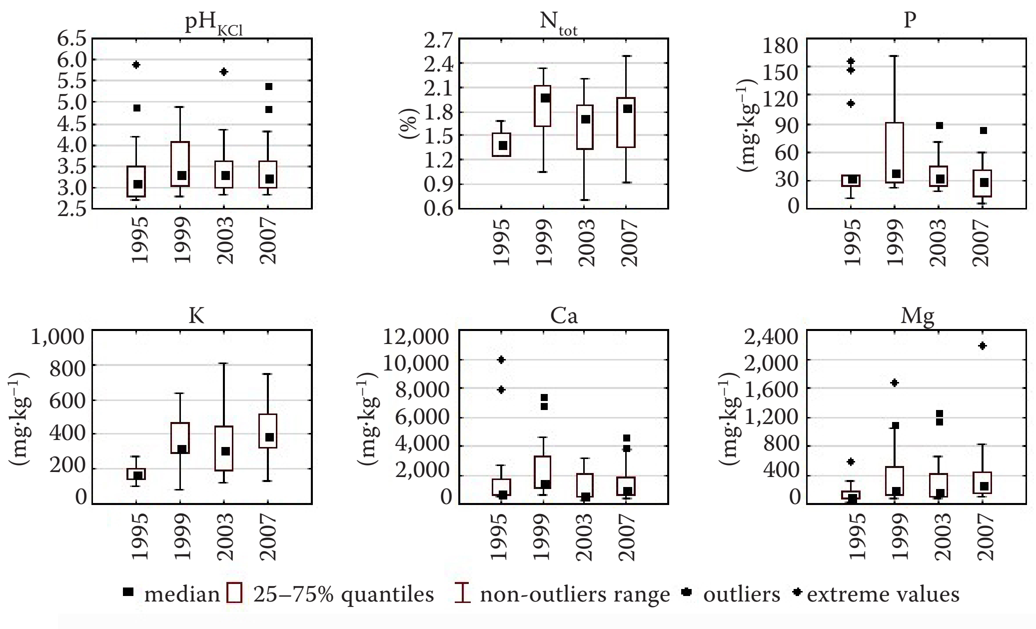

Fig. 9. pH values and nutrient concentrations in the upper humus layer on the plots investigated in the Krušné hory Mts.

The highest concentrations were found in the central area of the mountains. The increase in magnesium content is most probably connected with the liming that was carried out in the eastern part of the Krušné hory Mrs., starting in 2000 (Podrázský et al. 2003; Šrámek et al. 2006, 2008b).

Changes in the soil chemistry

Soil analyses have confirmed the same trend in the development of the nutrient level that was found in the leaf analyses. The soil taken from each of the plots showed an acid reaction. The pH$_{(KCl)}$ values in the humus layer were mostly between 2.8 and 3.7, and in the mineral soil they were between 2.8 and 3.8 (Figs 9 and 10), which corresponds with the range reported from other investigations conducted in the same region (Materna 2002; Klimo et al. 2006). In 1995 nitrogen content in the humus horizon showed a mean value of 1.45%; in subsequent surveys its mean value has ranged between 1.66 and 2.00% (Fig. 9). In the mineral soil nitrogen content with a mean value of 0.34% was found in 1995. In next surveys nitrogen content was lower than 0.30% but no significant temporal trend was detected (Fig. 10).

Since 1999 phosphorus concentrations in both the humus and the mineral horizons have been decreasing gradually. A significant trend was found in the mineral soil, in which the phosphorus content decreased from 35 mg·kg^{-1} in 1999 to only 5 mg·kg^{-1} in 2007 (Fig. 10). These results correspond with decreasing P nutrition in the needles. Ongoing acidification and a higher nitrogen input into the ecosystem can result in an unbal-

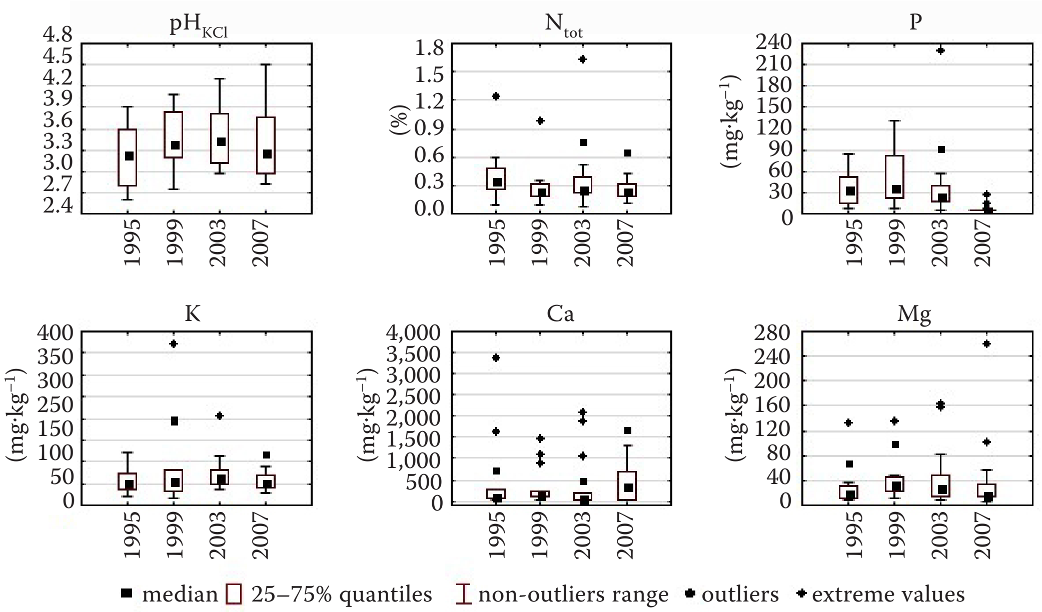

Fig. 10. pH values and nutrient concentrations in the mineral soil on the plots investigated in the Krušné hory Mts.

anced N/P ratio (Prietzel, Stetter 2010), which was also confirmed in other regions, e.g. in the Jizerské hory Mts. (Lomský et al. 2012). Potassium content in the humus layer, on the other hand, increased significantly – from 170 mg·kg^{-1} in 1995 to more than 400 mg·kg^{-1} in 2007 (Fig. 9). In the mineral soil K content reached over 50 mg·kg^{-1}, characterised as a medium supply. No temporal trend was detected for potassium in the mineral soil (Fig. 10). The calcium content in the humus layer is characteristic by a high level of supply and most probably this is influenced by the liming of forests. In the mineral soil calcium content increased significantly in 2007 (Fig. 10). Liming has also affected magnesium concentrations in the humus layer. The concentration has increased from 108 mg·kg^{-1} (in 1995) to 267 mg·kg^{-1}, characterising a high level of supply. This finding is in accordance with the recorded increase in the concentration of magnesium in the needles. The liming applied has not yet been reflected in the mineral soil; the highest contents of 35 and 32 mg·kg^{-1} were recorded in 1995 and 2007. These values characterise a low supply level of magnesium. That the effect of liming on the mineral horizons can be anticipated with a certain delay was confirmed in respect of the Krušné hory Mts., and also for other forest regions (Podrázský 2006; Šrámek et al. 2012).

CONCLUSIONS

During the last fifteen years a significant change in the spectrum of pollutants can be identified. The direct effects of SO_2 and of hydrogen fluorine were minimised, as can be confirmed by the significantly lowered sulphur and nitrogen content in the Norway spruce needles. On the other hand, the sulphur and fluorine contents have increased slightly in the youngest needle year-classes, which can be connected with the increased use of brown coal with high sulphur content in the local heating systems. This trend should be carefully monitored in the future. The health condition of the Norway spruce stands, strongly affected during the winter of 1995/96, has improved and is comparable with that in other regions in the Czech Republic. The long-term history of acid deposition has created a permanent risk for the forest ecosystems in the Krušné hory Mts., contributing to the degradation of the forest soils which are poor in base cations and phosphorus. During the last decade the concentrations of nitrogen, magnesium and calcium in the needles and soil have increased, while, on the other hand, the tendency of a long-term decrease in the quantities of phosphorus, calcium and potassium was found.

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