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Changes in the nutrition and health status of young Norway spruce stands in the Krkonoše Mts. in a 17-year period

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Abstract

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For 17 Norway spruce stands located in the Krkonoše Mts. in the Czech Republic a long-term assessment of defoliation, height increment, foliage concentration of nutrients (N, P, Ca, K, Mg) and stress elements (S, F) was carried out. The results show a decrease of defoliation and a slight increase of height increment, which occur in accordance with the decreasing concentration of sulphur in spruce needles. However, neither sulphur concentration nor height increment trends are significant, suggesting that both the main pollution abatement and the growth resumption took place already in the 1990's. During the late 1990's the average spruce defoliation was greater than 35%, while since 2007 it has fluctuated between 18 and 25%, which corresponds with the figures for the forest stands located in the other regions of the Czech Republic. The evaluation of single nutrient concentrations detected occasional deficiencies of P and Mg at individual plots. The good N nutrition (> 15 mg $N \cdot g^{-1}$) in combination with a significantly decreasing trend of P, K and Ca concentrations in Norway spruce needles may potentially constitute a problem in regard to both the future health and the stability of forest stands in the studied region.

Keywords: mountain forest; height increment; defoliation; nutrients; stress elements; nutrient ratio

The Krkonoše Mts. constitute a mountainous region that is located in the north of the Czech Republic and in the south-west of Poland. They form the highest part of the Sudeten Mountain system with the highest Sněžka peak at 1,603 m a.s.l. Geologically, the Krkonoše Mts. were formed in the period of the Proterozoic and Early Palaeozoic eras, with orogeny processes producing the first appearance of the massif called the Krkonoše-Jizera crystalline complex. Mesozoic weathering, Tertiary alpine orogeny, subsequent water erosion and recurrent Quaternary glaciation gradually transformed the natural appearance of Krkonoše into their current form. In the Krkonoše Mts. acidic rocks (crystalline, silicate) prevail over those that we classify as belonging to the group of alkaline (basic) rocks. The acidic rocks include granite, gneiss, mica schists, phyllites and other crystalline schists. These are relatively poor in nutrients and very fertile soils do not develop on such bedrock types (Bašta, Štursa 2013). In terms of geomorphology this area can be divided into two parts: the outer Border (Silesian) ridge and the inner Czech ridge (Plíva, Žlábek 1986). About 70% of the Krkonoše Mts. area is forested prevailingly by Norway spruce (*Picea abies* /Linnaeus/ H. Karsten) stands which replaced original more diverse mountain forests (Hercynian mixed mountain forest). The highest parts of the mountains, above 1,250 m a.s.l., are covered by a subalpine/alpine vegetation zone which, though in the past it was used for hay

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and other agricultural production (Semelová et al. 2008), currently preserves many endemic species. During the second half of the 20th century, as a part of the "Black Triangle", the Krkonoše Mts. were exposed to the adverse effects of air-pollution. The region was not as extremely polluted as the Krušné hory Mts. (Šrámek et al. 2008) or the Jizerské hory Mts. (Lomský et al. 2012) but it does suffer from the synergistic effect of high and long-lasting air pollution and climatic stress that has led to extensive decline and dieback of the forest (Vacek, Podrázský 2007; Vávrová et al. 2009). Signs of air pollution damage had already appeared in the Eastern Krkonoše Mts. in the 1960's and one decade later also in the Central and the Western parts. Significant damage to the spruce stands in the Krkonoše Mts. appeared due to harsh climatic conditions that occurred in March 1977 and also at the beginning of 1979, when it was even intensified by the outbreak of the larch bud moth (*Zeiraphera diniana* Guénée) (Tesař et al. 1982; Vacek et al. 2013). The pollution and also the forest health deterioration had peaked in this area in the late 1980's (Vacek et al. 1999; Cudlín et al. 2000). A sharp drop in the concentration level of principal pollutants in the 1990's formed the prerequisite to the restoration of forest vitality and forest ecosystem stability in this region, where the forests are still being influenced by the ongoing nitrogen deposition (Vacek et al. 2014). The article summarises the development of health, pollution load and nutrition in the Norway spruce stands during the last 20-year period. An assessment of long-term monitored plots provides important information about changes and trends of selected characteristics of the ecosystem state in this region and can help with the preparation and planning of further measures of forest and ecosystem management.

MATERIAL AND METHODS

Research plots. Research plots in the Krkonoše Mts. were established in 1994. They were selected in young Norway spruce stands. The plots (25 × 25 m) are located from the western part (Lysá hora) to the east (Pomezní boudy) of the Krkonoše Mts., trees are individually numbered. The plot location and other characteristics are presented in Fig. 1 and Table 1.

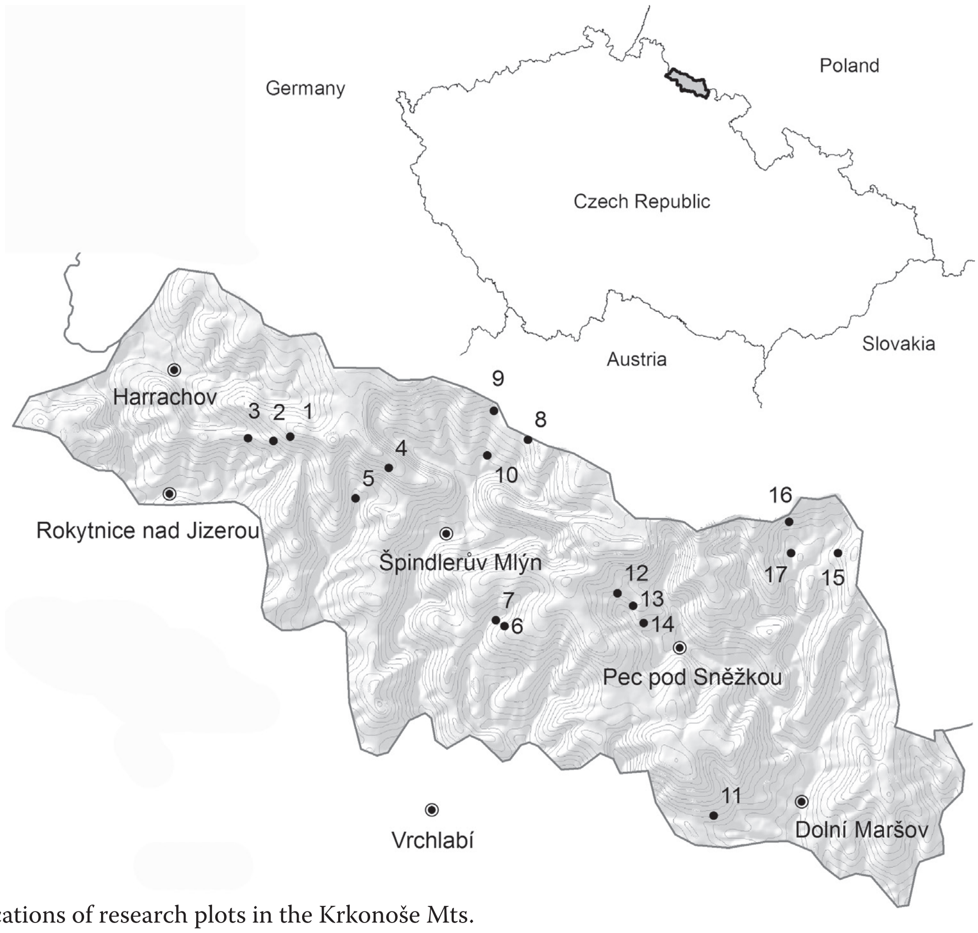


Fig. 1. Locations of research plots in the Krkonoše Mts.

1 – Lysá hora, 2 – Hájenka, 3 – Ručičky, 4 – Zlaté návrší, 5 – Mechové jezírko, 6 – Friesovy boudy, 7 – Klínový potok, 8 – Špindlerovka, 9 – Petrovy boudy, 10 – Jelení boudy, 11 – Jánské lázně, 12 – Richtrovy boudy, 13 – Lesní hora, 14 – Čertovy schody, 15 – Pomezní boudy, 16 – Jelenka, 17 – Poděbradská

Table 1. Research plots in the Krkonoše Mts. (age of the stands and soil pH in 2013)

No.	Locality	Coordinates	Altitude (m a.s.l.)	Exposure	Age (yr)	pH_{KCl} (o/m)	Soil type (according to WRB)
1	Lysá hora	50°45'08"N, 15°30'13"E	1,214	SW	31	2.96/3.46	Albic Podzol
2	Hájenka	50°44'59"N, 15°29'41"E	1,076	SW	52	3.01/3.63	Haplic Podzol
3	Ručičky	50°44'59"N, 15°28'51"E	956	–	47	3.10/3.31	Haplic Podzol
4	Zlaté návrší	50°44'44"N, 15°33'41"E	1,245	SW	41	3.82/3.78	Skeletic Leptosol
5	Mechové jezírko	50°43'59"N, 15°32'43"E	831	SW	33	3.18/3.46	Haplic Podzol
6	Friesovy boudy	50°41'39"N, 15°38'14"E	1,038	NW	51	3.50/3.65	Haplic Podzol
7	Klínový potok	50°41'45"N, 15°37'54"E	880	SE	50	2.77/2.66	Dystric Cambisol
8	Špindlerovka	50°45'42"N, 15°38'16"E	1,223	NW	181	3.31/3.64	Histosol
9	Petrovy boudy	50°46'13"N, 15°37'00"E	1,205	SE	44	3.15/3.42	Histosol
10	Jelení boudy	50°45'15"N, 15°36'55"E	928	SW	56	3.06/3.93	Albic Podzol
11	Jánské lázně	50°38'06"N, 15°46'03"E	783	SE	41	3.03/2.86	Dystric Cambisol
12	Richtrovy boudy	50°42'39"N, 15°41'53"E	1,161	–	46	2.97/3.31	Histosol
13	Lesní hora	50°42'25"N, 15°42'29"E	1,074	SW	34	3.35/3.44	Haplic Podzol
14	Čertovy schody	50°42'05"N, 15°42'53"E	993	SE	45	–/–	Haplic Podzol
15	Pomezní boudy	50°44'04"N, 15°49'09"E	1,037	NW	46	3.13/3.65	Albic Podzol
16	Jelenka	50°44'37"N, 15°47'23"E	1,109	S	40	2.83/2.91	Albic Podzol
17	Poděbradská	50°43'55"N, 15°47'36"E	898	E	53	2.82/3.43	Haplic Podzol

o – organic (humus) layer, m – mineral soil 0–20 cm, WRB – World Reference Base for Soil Resources

Crown condition and growth assessment. Since 1995 the crown defoliation was assessed annually at the end of vegetation season (October-November). Defoliation was evaluated within a diagonal transect, at minimally 30 numbered trees, on a 5% scale in accordance with the methodology of the international co-operative programme on assessment and monitoring of air pollution effects on forests (ICP Forests) (UNECE 2010) which was modified for the young Norway spruce stands (Lomský, Uhlířová 1993). The results are presented as a mean percentage of defoliation for individual plots. The height increment was measured for the group of 20 trees which are included in the crown defoliation assessment. The measuring was initially carried out by means of a Sokkia measuring pole. As the stands were growing, this method had to be changed and since 2006 the Vertex hypsometer (Haglöf, Sweden) has been used.

Foliage sampling. Norway spruce needles were sampled annually in order to analyse both their content of nutrients and their risk elements. This sampling was carried out every autumn (October-November). At each individual plot 10 trees were sampled. From each of the trees one branch was taken from the top part of the crown (i.e. from the third to the sixth whorl). For each plot one pooled sample for current year needles and one pooled sample for one-year-old needles were created. Current year needles were taken during the entire evaluated period between 1994 and 2013; the collection and analysis of one-year-old needles have been implemented since the year 2000.

Laboratory analyses. Samples of foliage were prepared in accordance with the standard methods (UNECE 2010). After their decomposition in a microwave oven, the amounts of K, Ca, Mg, and P in the needles were determined using the inductively coupled plasma optical emission spectroscopy analysis. Nitrogen contents were determined spectrometrically after Kjeldahl digestion. Since the year 2003 the total S and N contents have been determined using the CNS element analyser (LECO Corporation, USA). The fluoride concentration in the solution was measured using a fluoride ion selective electrode.

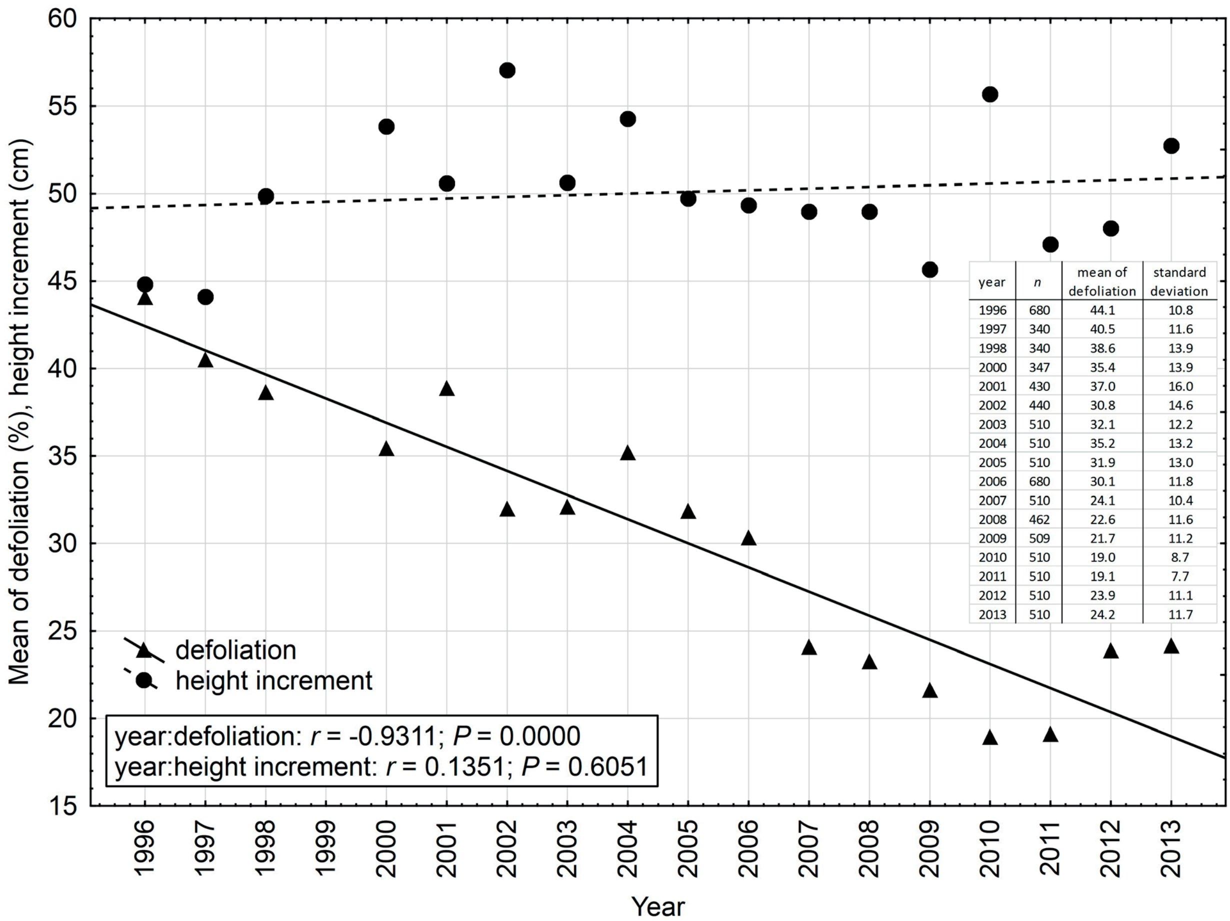
Data analyses. Before any statistical recalculation took place, exploratory data analysis was carried out. For the comparison of individual years graphic methods together with one-factor analysis of variance and two variable comparison tests (i.e. the Fisher-Snedecor F-test for variance and Student's t-test for averages) were used. For the correlation analysis the Pearson R coefficient was used (Meloun et al. 2005). For evaluation of the time trend in regard to defoliation, height increment, element content and to the ratio between nitrogen and main nutrients multiple regression analysis and fixed nonlinear regression were used. All the statistical evaluations were processed using the Statistica CZ software (Version 12, 2013).

RESULTS

Crown condition and height increment

Mean crown defoliation of Norway spruce in 1996 and 1997 was more than 40% (Fig. 2). During the monitoring period a gradual significant decrease of defoliation can be observed (tested by multiple regression analysis and by fixed nonlinear regression). Since 2007 the defoliation mean has oscillated around 20%. This is close to the average Norway spruce defoliation in the Czech Republic, which in 2013 was 10% for less than 60-years-old stands and 32% for older stands. The worst health condition of spruce was recorded at plots located close to the tree limit in the eastern and central parts of the Krkonoše Mts.: Lysá hora (1,214 m a.s.l.), Zlaté návrší (1,245 m a.s.l.) and Špindlerovka (1,223 m a.s.l.), where in 1996 the degree of defoliation exceeded 50%, while in 2013 it still remained higher than 30%. Based on a survey the highest level of forest vitality was identified at different plots in individual years. In general plots with a low degree of defoliation were found at lower altitudes and at more protected sites.

Mean height increment exhibits an opposite non-significant trend compared to defoliation with an increasing tendency during 1996–2013 (Fig. 2). The time trend, however, is not so pronounced, confirming that the increment is influenced more by the course of climatic conditions during individual years. The mean height increment of spruce stands ranged between 20 and 73 cm. The lowest mean increment (14.2 cm) was recorded in 2000 at the Špindlerovka plot; the highest in 2010 at the Mechové jezírko plot (92.5 cm). Figs 3 and 4 show the relationship between crown defoliation and height increment with regard to the plot altitude. A strong and significant correlation between defoliation and altitude ($P < 0.000$) was found during the first seven years of our assessment (Fig. 3), for the last decade 2003–2013 and this relation is significant as well ($P = 0.004$). On the contrary, the negative correlation between height increment and altitude was strongly significant and it was also similar for both of the evaluated time periods during 1996–2002 ($P < 0.000$); since then this relation has been weaker but still significant ($P < 0.000$).



year	n	mean of defoliation	standard deviation
1996	680	44.1	10.8
1997	340	40.5	11.6
1998	340	38.6	13.9
2000	347	35.4	13.9
2001	430	37.0	16.0
2002	440	30.8	14.6
2003	510	32.1	12.2
2004	510	35.2	13.2
2005	510	31.9	13.0
2006	680	30.1	11.8
2007	510	24.1	10.4
2008	462	22.6	11.6
2009	509	21.7	11.2
2010	510	19.0	8.7
2011	510	19.1	7.7
2012	510	23.9	11.1
2013	510	24.2	11.7

Fig. 2. Mean defoliation and mean height increment during the evaluated period
n – number of evaluated trees

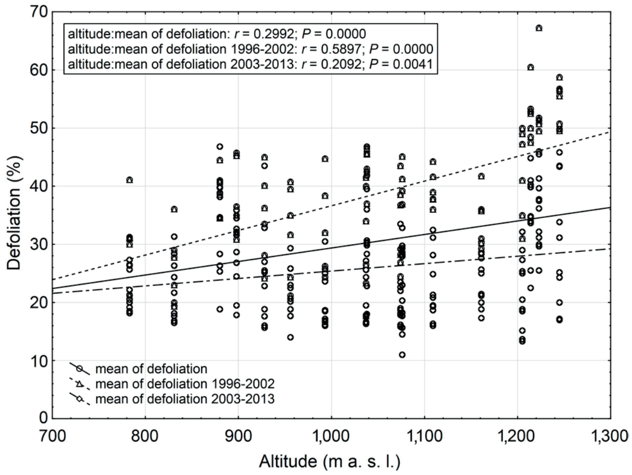


Fig. 3. Relationship between defoliation and altitude during the period of evaluation

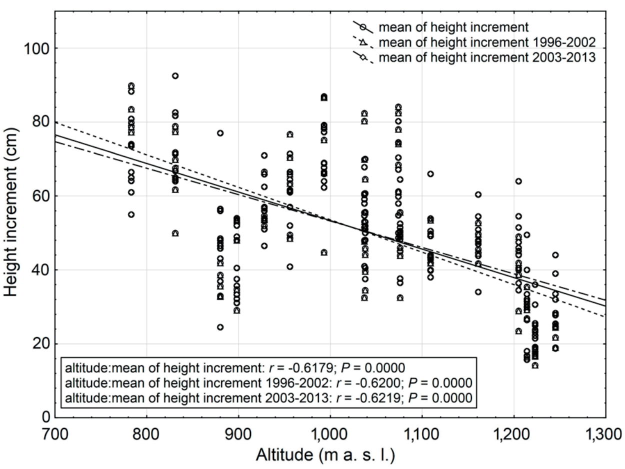


Fig. 4. Relationship between height increment and altitude during the period of evaluation

Foliar analysis – stress elements, mineral nutrition and nutrient ratios

During the period 1996–2013 the sulphur content in current year needles at individual plots varied from 0.79 to 1.79 mg·g^{-1} (Fig. 5). The plots where the long-term mean (1996–2013) in current year needles exceeded the limit of increased concentration (1.20 mg·g^{-1}) are located in the western and the central areas of the Krkonoše Mts. at the middle/higher altitudes: Čertovy schody 1.32 mg·g^{-1} (993 m a.s.l.); Hájenka 1.29 mg·g^{-1} (1,076 m a.s.l.); Mechové jezírko 1.25 mg·g^{-1} (831 m a.s.l.); Petrovy boudy 1.02 mg·g^{-1} (1,248 m a.s.l.). With the exception of 1995 and 1996, the sulphur concentration in general was elevated until 2001.

Since then the data from one-year-old needles has also been analysed. The values are slightly higher than in current year needles and exhibit the same dynamics. Trends of sulphur concentration in both needle year classes are decreasing but not significantly (Table 2).

Fluorine is another element that characterises the air pollution load in central Europe. If its concentration in needles exceeds 5 μg·g^{-1}, then it characterises a high load of spruce stands (Polle et al. 1992). The mean values of F concentration in the Krkonoše Mts. did not exceed the threshold and they were in the range of 0.700 to 2.678 μg·g^{-1} in the current year needles and between 0.857 and 2.149 μg·g^{-1} in the one-year-old needles. For the current year needles we can see a significantly decreasing trend of fluorine (Fig. 5, Table 2), while similar development with a slightly higher concentration has also been recorded for one-year-old needles since 2001. In general, the limit for an increased fluorine concentration (2 μg·g^{-1}) was rarely exceeded. In the years in which the highest mean fluorine concentration was in the needles, this value was exceeded on 7 plots at the most (in 1998) or on 6 plots (in 1996). The plot with the highest long-term mean fluorine concentration in the current year needles is the same as that for sulphur – Čertovy schody with 1.57 μg·g^{-1}.

The lowest level of nitrogen concentration in the current year needles was found in 1996, when the nitrogen concentration lower than 13 mg·g^{-1} was observed at 12 plots (Fig. 5). In the individual years since 1997 not more than 3 of the plots have been below this limit. There were only two plots, both in the eastern part of the Krkonoše Mts., with prevalent low N nutrition: Jelenka with a long-term mean of 13.1 mg·g^{-1} and Poděbradská with 13.7 mg·g^{-1}. On the other hand, the number of plots at which we found good nitrogen nutrition (N > 15 mg·g^{-1}) ranged from 5 to 13 during the period 1997–2013. The slightly increasing trend of nitrogen concentrations in current year needles and also the slightly decreasing trend in one-year-old needles were both statistically insignificant (Table 2).

In individual years the phosphorus concentration varied between 1.03 and 3.66 mg·g^{-1} in current year needles, while in the one-year-old needles it was lower – ranging from 0.82 to 3.06 mg·g^{-1}. The lowest mean phosphorus concentrations (1.29 mg·g^{-1}) were found in the plots that are located closer to the tree limits in the eastern and central areas of the Krkonoše Mts.: Špindlerovka (1.29 mg·g^{-1}), Zlaté návrší (1.33 mg·g^{-1}) and Lysá Hora (1.34 mg·g^{-1}). Phosphorus in both needle year classes exhibits a significantly decreasing trend (Fig. 5, Table 2).

In general, potassium and calcium concentrations in needles fall within the category of sufficient or good nutrition, based on their content of these elements. There are only two values of potassium concentration in the current year needles – 2.92 mg·g^{-1} at Jelenka in 2001 and 2.95 mg·g^{-1} at Poděbradská in 1997 – to be slightly below the deficiency limit (3.00 mg·g^{-1}). In one-year-old needles potassium concentrations varied between 3.48 and 11.67 mg·g^{-1}. Despite these favourable values a significant decreasing trend has been identified in both current and one-year-old needles (Fig. 5, Table 2).

The calcium concentration is usually higher in one-year-old needles. We found a deficit of this element at Lysá hora plot, where the long-term

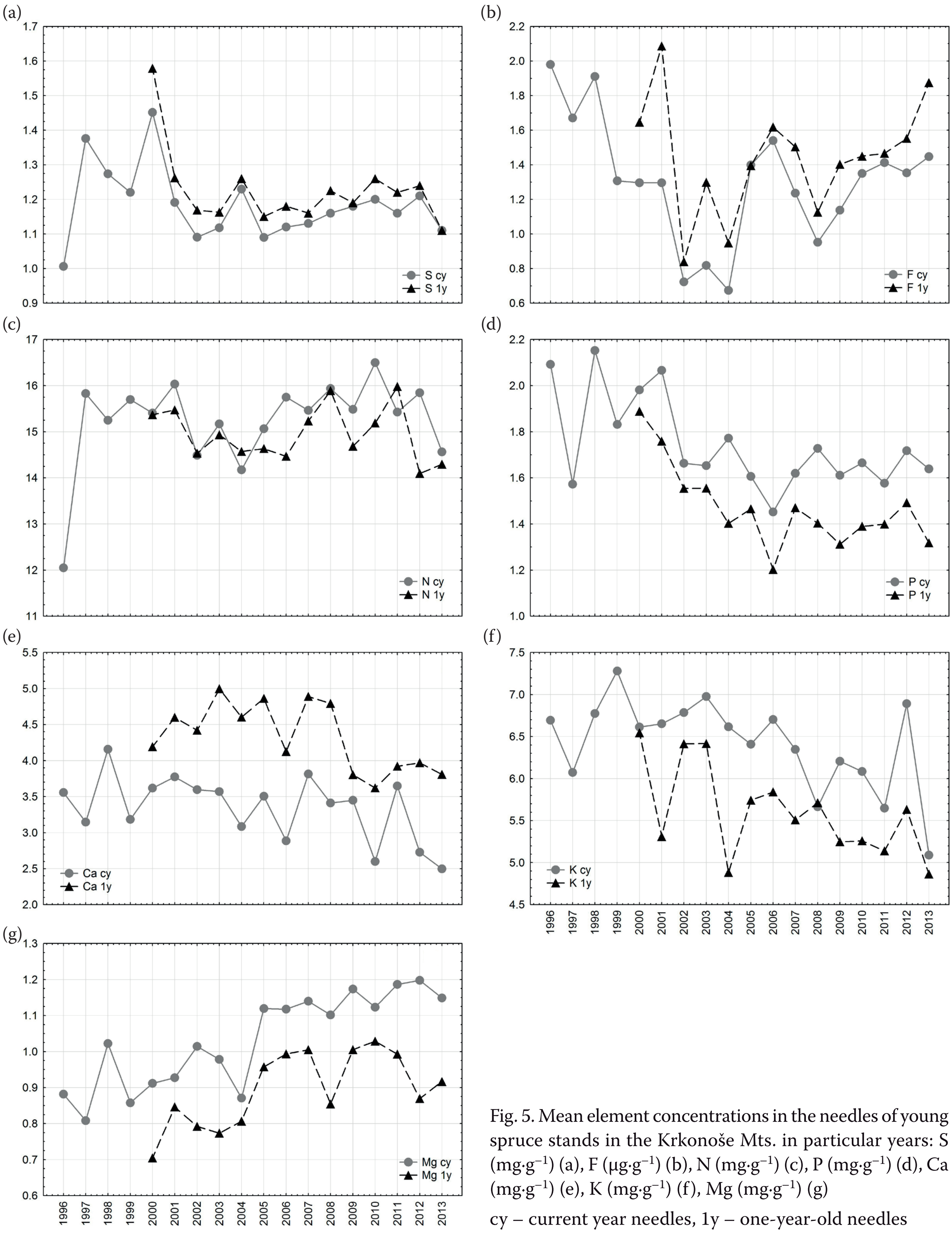


Fig. 5. Mean element concentrations in the needles of young spruce stands in the Krkonoše Mts. in particular years: S (mg·g^{-1}) (a), F (µg·g^{-1}) (b), N (mg·g^{-1}) (c), P (mg·g^{-1}) (d), Ca (mg·g^{-1}) (e), K (mg·g^{-1}) (f), Mg (mg·g^{-1}) (g)

cy – current year needles, 1y – one-year-old needles

(1996–2013) mean for current year needles was only 1.83 mg·g^{-1} and in nine years during the monitoring period 1996–2013 the calcium concentration was below the deficiency limit (1.50 mg·g^{-1}). All the other plots exhibit a good calcium concentration. Similarly to potassium, Ca concentration in needles also exhibits a significantly decreasing trend (Fig. 5, Table 2).

Magnesium is the only base cation with a significantly increasing tendency (Fig. 5, Table 2). Despite this positive trend three plots exhibit a permanent deficit of magnesium in one-year-old needles: i.e. Janské lázně (451 mg·g^{-1}), Zlaté návrší (579 mg·g^{-1}) and Lysá hora (647 mg·g^{-1}).

For an assessment of the ratio between nitrogen and other nutrients the ranges according to Hüttl (1990) and Mellert and Göttlein (2012) have been used. The optimal N/P ratio in foliage should be in the range between 6 and 12. In the current year needles this ratio is within this range, except for the year 1996 (Fig. 6). During the evaluated period there is an evident slight upward trend. In the one-year-old needles the N/P ratio also had an increasing trend with values reaching the upper boundary of the range and thereby described the decreasing concentration of phosphorus in needles.

Table 2. Time trends of element contents in the current year (cy) and one-year-old (1y) needles as detected by means of fixed nonlinear regression

	Multiple R^2	P value	Trend	Significance
N_cy	0.1192	0.1606	↗	ns
P_cy	0.3497	0.0097	↘	***
K_cy	0.3277	0.0130	↘	**
Ca_cy	0.2651	0.0288	↘	**
Mg_cy	0.7535	0.0000	↗	***
S_cy	0.0692	0.2917	↘	ns
F_cy	0.0779	0.2621	↘	ns
N_1y	0.0213	0.6186	↘	ns
P_1y	0.4679	0.0070	↘	***
K_1y	0.3737	0.0202	↘	**
Ca_1y	0.3394	0.0288	↘	**
Mg_1y	0.4185	0.0124	↗	**
S_1y	0.1926	0.1164	↘	ns
F_1y	0.0204	0.6261	↗	ns

ns – not significant, **P < 0.05, ***P < 0.01

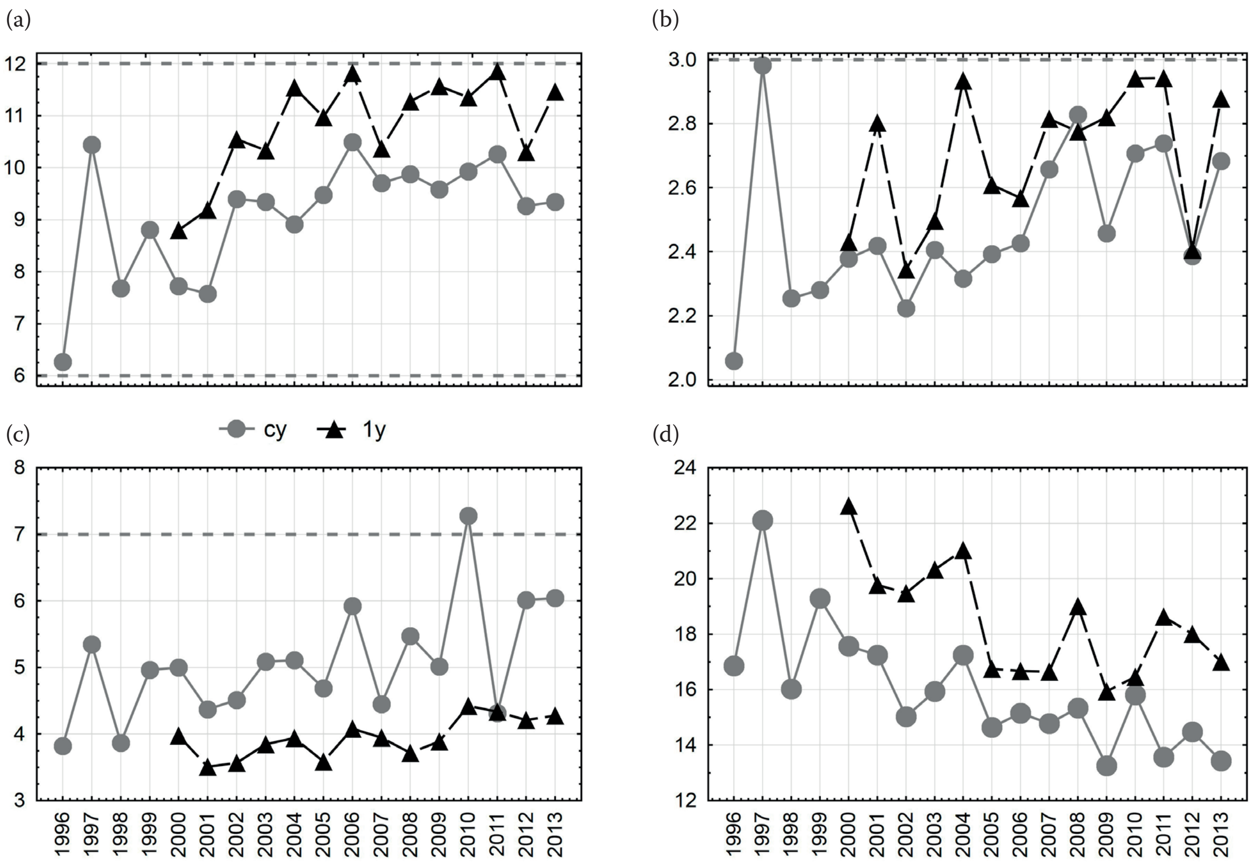


Fig. 6. Ratios of main nutrient concentrations in the needles of young Norway spruce stands in the Krkonoše Mts. in particular years: N/P (a), N/K (b), N/Ca (c), N/Mg (d). Dotted grey lines show an optimum range. For N/K and N/Ca the upper limit is shown

cy – current year needles, 1y – one-year-old needles

The N/K ratio has its optimum between 1 and 3. The values of current year needles lie within this range but during the monitoring period they are increasing towards the upper boundary (Fig. 6). In the one-year-old needles the determined N/K values even exceeded the upper limit in many evaluated plots. Both needle age classes confirmed possible higher nitrogen inputs and decreasing concentrations of potassium in the needles.

The foliar N/Ca ratio optimum value is in the range of 2 to 7. In the current year needles the ratio is within the optimum range, except the year 2010, in the one-year-old needles the ratio is within the optimum range as well (Fig. 6).

The N/Mg ratio has an optimal limit in the range of 8 to 30, while the values determined for both classes of needles are below this limit (Fig. 6) with no detectable trend during the monitoring period.

DISCUSSION

Crown defoliation is affected by many factors such as air pollution, weather conditions, physiological status of trees, habitat and soil conditions (Schulze et al. 2005). It is broadly accepted as a general indicator describing the health status of forest (Eichhorn, Roskams 2013). A rapid decrease of Norway spruce defoliation during the last almost twenty years in the Krkonoše Mts. was reported also by other authors (Vacek, Podrázský 2007) and it certainly represents a positive signal in regard to the forest health development in this region. Annual height increment, on the other hand, exhibits only a slightly insignificant increase. The main resumption of height increment occurred probably already during the 1990's. Since 1998 the height increment has been between 45 and 55 cm, which corresponds with the conditions of mountain sites. The decrease of defoliation can be conclusively connected with the reduction of SO_2 pollution and atmospheric sulphur deposition that took place during the 1990's and then continued at a slower pace until ca. 2010 (Hůnová et al. 2004, 2014). The decrease of SO_2 concentration can also be documented by the insignificant decrease of sulphur content in Norway spruce needles. A similar development was also identified in other mountain areas in the so-called "Black Triangle" region, e.g. in the Jizerské hory Mts. by Lomský et al. (2012) and Šrámek et al. (2013), in the Orlické hory Mts. by Vacek et al. (2014) and in the Krušné hory Mts. by Šrámek et al. (2008) and Lomský et al. (2013). Although fluorine (in the form of hydrogen fluoride) is not generally considered to be a major air pollutant in Europe (Emberson 2003), in the Central European countries, in the second half of the 20th century, it still belonged amongst the important stressors (Uhlířová et al. 1996). The increased concentrations of fluorine in the needles in the "Black Triangle" area are usually connected with the glasswork factories or with the use of low-quality brown coal in power plants and local heating systems (Uhlířová et al. 1996). The degree of fluorine pollution in the Krkonoše Mts. was not comparable with what was determined in the Krušné hory Mts. (Reuter et al. 1997).

Nitrogen concentration fluctuating at ca.15 $mg \cdot g^{-1}$ indicates relatively good nutrition. The increasing tendency of nitrogen contents in current year needles was not significant nor was a decreasing trend in one-year-old needles. The deposition of nitrogen compounds is considerably elevated in the Czech Republic, especially in the mountain regions (Hůnová et al. 2017) and although its absolute amount is slowly decreasing, it still significantly influences processes in forest ecosystems (Ciencala et al. 2016).

The mean phosphorus concentrations were in the range of sufficient nutrition although at individual plots values below the deficiency limit of 1.20 $mg \cdot g^{-1}$ were also found (Mellert, Göttlein 2012). A significant decrease of phosphorus content was found in both current year and one-year-old needles. The decrease is more serious in one-year-old needles, in which the mean concentrations are just above the deficiency threshold and the frequent occurrence of plots with insufficient phosphorus content is high. A low level of phosphorus in needles is related to a restricted intake from acidic soils (Fisher, Binkley 2000). Phosphorus deficiency as a limiting factor in regard to the forest growth in the Bavarian Alps was reported by Mellert and Ewald (2014) regarding Norway spruce and by Ewald (2000) regarding European beech. Talkner et al. (2014) documented a significant decrease of phosphorus nutrition throughout the beech stands in Europe which was also supported in other species by findings of Jonard et al. (2015), who suggested the increased growth resulting from a high level of N deposition and from the global increase of atmospheric CO_2 as being the main driver behind the deterioration of mineral nutrition of trees. This conclusion can be supported by the significant increase of N/P ratio in both needle classes – though it is still within the optimal range (6–12) – indicating decreasing availability and possibly a nutritional imbalance of phosphorus in relation to nitrogen uptake (Hüttl 1990; Drenowsky, Richards 2004; Luyssaert 2004; Ewald 2005).

The mean potassium and calcium concentrations were in the range of good to adequate nutrient supply (Mellert, Göttlein 2012). The overall trend of both cations is however decreasing significantly. This is especially noticeable in potassium – between 2000 and 2013 the K concentration in needles dropped by about 20–25%. The N/K and N/Ca ratios were in the optimal ranges of 1–3 for N/K and 2–7 for N/Ca with significantly increasing trends in both cases. On the other hand, magnesium concentrations were significantly increasing on average from levels that were close to the deficiency limit ($0.8\ mg\cdot g^{-1}$) and entering the range of sufficient nutrition.

In the case of magnesium, which is highly mobile, the concentration in one-year-old needles is a more precise indicator of nutrient imbalance (Hüttl, Schaaf 1997). Thereby the N/Mg ratio was thus consistently decreasing. Similar findings in regard to the temporal trends of N/K, N/Ca (an increase) and N/Mg (a decrease) ratios were reported by Jonard et al. (2015) while the positive change in the foliar Mg concentration was more marked in plots with a low foliar Mg status. These trends of base cations are somewhat contradictory. An increase of magnesium can be explained by either the recovery of forest soils from rapid acidification (which, however, should also be accompanied by better potassium availability) or liming of forest stands (which should be accompanied by better calcium supply). To clarify this particular discrepancy information about the development of soil chemical properties is required (Prietzel et al. 2008).

CONCLUSIONS

In the late nineties the actual crown defoliation of Norway spruce stands in the Krkonoše Mts. was in the range of 35–45%. Our study documents the significant decrease of defoliation to values of ca. 20%, which is where it has oscillated in the last seven years. The similarly positive increasing trend of height increment was not so pronounced – we can assume that it was resumed already in the 1990's, simultaneously with a sharp drop in the SO_2 air pollution. The current health of spruce stands is on the same level not only as in the other mountain regions of the Czech Republic (e.g. Jizerské hory Mts., Krušné hory Mts.) but it also corresponds with the national defoliation average as it is evaluated regularly by the ICP Forest Programme. While at the end of the 20th century the health and productivity of forests in the Krkonoše Mts. were strongly affected by air pollution, now they are mostly influenced by the site quality and meteorological and other environmental factors, which delivers a very positive message. The evaluation of foliar chemistry, on the other hand, points out some potential risks for its future development. Although the nutrient deficiency of magnesium and phosphorus was found rather scarce at individual plots, the concurrent trend of the increasing nitrogen concentration and decreasing phosphorus, potassium and calcium concentrations in spruce needles indicates the ongoing effect of excessive nitrogen deposition. Gradually this can lead to more serious problems such as nutrient imbalance and effects on the mechanical stability of forest stands, particularly in those regions that have a long-term history of acidic deposition and insufficient stocks of base cations in the leached soil environment. In such a situation the regular monitoring of forest health, tree nutrition and soil conditions can provide a beneficial series of data for forest protection, nature conservation and also for other stakeholders.

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