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ORIGINAL PAPER

Effect of soil chemical properties on growth, foliation and nutrition of Norway spruce stand affected by yellowing in the Bohemian Forest Mts., Czech Republic

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Abstract In 1998, a fertilizer experiment aiming to investigate the effects of slow-release N, P, K and Mg fertilizer (SILVAMIX Mg NPK®) on a 60-year-old spruce stand with symptoms of yellowing was established. In this paper, trees were selected to investigate the relation between annual diameter increment, yellowing, foliation, needle and soil chemical properties: ten from the fertilized treatment (F), ten green trees from the control (CG) and ten yellow trees from the control (CY). CG and CY trees were growing in close proximity at a distance of only several meters apart under the same soil conditions. In treatment F, increased annual diameter increment, improved foliation, needle Mg concentration, plant-available Mg and P concentrations in the soil and absence of yellow trees were recorded 7 years after a single application of the fertilizer. During the last 15 years, annual growth increment and foliation of CY trees have continuously decreased while relatively stable values were recorded for CG trees and increased for F trees. In 2006, CG and CY trees differed significantly in Mg concentration in needles, foliation, yellowing and annual diameter increment. Although differences in soil chemical properties between CG and CY treatments were not significant, lower concentrations of plant-available Mg^{2+} and higher concentrations of H^{+} and Al^{3+} were found in soils under CY trees. There was a negative correlation between soil concentration of Mg and yellowing, but this correlation was relatively weak, indicating that there is no simple relation between soil and needle concentrations of Mg. In the investigated locality, the “new type” of yellow tree decline has been a long-term gradual process.

Keywords Magnesium deficiency and nutrition · *Picea abies* · Fertilizer experiment · New type of forest decline · Diameter increment

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Introduction

Yellowing that starts from the needle tip and from older to younger needles is a characteristic symptom of magnesium deficiency in Norway spruce. Although spruce yellowing has been known for more than 200 years and was depicted by old painters (see Jandl et al. 2001), the first large-scale spread of this so-called “new type of disease” was reported in mountain regions of Central and West Europe in the 1980s, particularly on acid soils of low base saturation at altitudes above 700 m. Direct and indirect effects of air-deposited sulfur and nitrogen compounds were recognized as the main cause of imbalances in spruce nutrition leading to yellowing and consequent forest decline (Šrámek et al. 2008; Feger 1997; Roberts et al. 1989; Rehfuess 1987). Excess supply of nitrogen compounds directly promotes biomass production, and a shift from N to Mg growth limitation and air-deposited anions (particularly NO_3^- and SO_4^{2-}) indirectly trigger leaching of base cations from the soil profile, making them unavailable for root uptake (Novotný et al. 2008; Huber et al. 2004; Armbruster et al. 2002; Feger 1997; Katzensteiner et al. 1992a). Several authors have also ascribed yellowing at least partly to historical land use leading to nutrient depletion (Katzensteiner et al. 1995) or the negative effects of increased concentration of ozone under limited Mg availability (Siefermann-Harms et al. 2005).

In response to fear of large-scale "new type" forest decline, amelioration of yellowing by application of various Mg fertilizers has received much attention in recent decades, mainly in Austria (Jandl et al. 2001; Katzensteiner et al. 1992b), the Czech Republic (Lomský et al. 2006; Šrámek et al. 2006; Podrázský et al. 2003), France (Mohamed et al. 1993) and Germany (Huber et al. 2006a, b; Schaaf and Hüttl 2006; Huber et al. 2004; Hüttl and Schneider 1998; Evers and Hüttl 1990). The following generalizations are based on such studies: (1) Fertilization immediately increases the concentration of bases in soil solution and in many cases the concentration of nitrate and the pH value of the soil solution as well. (2) Increased concentrations of bases are recorded in upper soil layers of ameliorated plots for many years following application of fertilizers. (3) Content of Mg ions in needles generally improves above the limit of deficiency of 0.7 mg g^{-1} of dry matter foliage. (4) Foliation improves and yellowing retreats within several months of fertilization. (5) In many cases, fertilization increases the diameter growth of trees in the long term.

In stands affected by yellowing, healthy and declining trees can often be found in close proximity under the same climatic and soil conditions (Kandler and Miller 1990; Köstner et al. 1990). Nechwatal and Osswald (2003) found a positive correlation between fine root density and crown transparency and between the degree of yellowing and needle content of Mg. Although growing on the same substrate, green trees showed better Mg nutrition than yellow trees, indicating that poor fine root status contributes to Mg deficiency in yellowing spruce. The results of their study further indicate that needle yellowing in stands of the Bavarian Forest Mts. was at least partly mediated by fine root disorders and that fine root damage in yellowing trees was caused by soilborne micro-organisms, most likely fungi. On the Czech side of the Bavarian Forest (Šumava Mts. or Bohemian Forest in Czech or English, respectively), an experiment to ameliorate Mg deficiency was established in 1998 (Vacek et al. 2006). An immediate decrease in yellowing and stabilization of foliation was recorded in a 60-year-old spruce stand after a single application of slow-release N, P, K and Mg fertilizer. In the control, the percentage of yellow trees and the severity of yellowing gradually increased and foliation decreased during the 6 years of the investigation. Declining trees were in close proximity to healthy trees although the climatic and soil conditions were apparently the same or similar.

In this study, ten yellow (control yellow, CY) and ten green trees (control green, CG) in the control treatment as well as ten trees in the fertilized treatment (fertilized, F) were selected to test the relationship between diameter growth, yellowing, foliation, needle chemical properties and soil chemical properties. Collection of such data was motivated especially by the conclusion of Nechwatal and Osswald (2003) that soil chemical properties were the same for yellow and green trees growing in close proximity, and the poorly documented effect of yellowing on diameter growth. The aim of this study was to answer the following questions: (1) Is there any residual effect of fertilizer application on annual diameter increment, foliation, yellowing, needle and soil chemical properties after 7 years? (2) Is there any difference in annual diameter increment, needle and soil chemical properties between green and yellow trees growing in close proximity in the control treatment? (3) Is there any relation between annual diameter increment, yellowing, foliation, needle chemical properties and soil chemical properties?

Materials and methods

Study site and description of fertilizer experiment

The study was performed in the beach-spruce altitudinal vegetation zone of the Bohemian Forest Mts., in the borderland between the Czech Republic, Austria and Germany (48°49′31.33″N, 13°50′10.89″). The average annual precipitation in the area is 1,091 mm and the mean annual temperature is 4.2°C. The altitude of the study site is 920 m asl and it lies on a moderate north-facing slope (up to 3°). The soil type is mountain peat podzol developed on granite parent rock poor in calcium and magnesium (mean content of Ca was 0.9% and mean content of Mg was 0.2%; Stejskal 1968). The mean pH(H_2O) of upper soil layers ranged from 3.5 to 4.

In 1998 when the experiment was established, the stand age was 60 years. Spruce yellowing had been regularly observed in the selected stand several years before establishing the experiment but had not reached a critical level leading to forest decline. A pair of neighboring 50 m × 50 m plots with 206 living spruces was selected in 1998 based on their homogeneity in spruce yellowing symptoms, stand characteristics and environmental conditions. One plot was the control (C treatment) without any experimental manipulation, while fertilizer was applied to the second

Table 1 Chemical composition of slow-release fertilizer with commercial name SILVAMIX Mg NPK® used in the experiment

Composition	%
Nitrogen total (N)	10.0
Nitrogen from urea formaldehyde (N)	6.0
Nitrogen from urea formaldehyde that is soluble in cold water (N)	1.6
Nitrogen from urea formaldehyde that is only soluble in hot water (N)	2.7
Nitrogen from urea formaldehyde that is insoluble in hot water (N)	1.7
Nitrogen from urea formaldehyde that is insoluble in cold water (N)	4.4
Ureic nitrogen [$CO(NH_2)_2$]	4.0
Phosphorus soluble in neutral ammonium citrate and in water (P_2O_5)	13.0
Water soluble phosphorus (P_2O_5)	12.0
Water soluble potassium (K_2O)	6.5
Magnesium total (MgO)	16.0
Sulfur (S)	0.4

plot in spring 2000 (F treatment) at a rate of 96.5 kg ha^{-1} Mg, 54 kg ha^{-1} K, 57 kg ha^{-1} P and 100 kg ha^{-1} N. Slow-release fertilizer (commercial name SILVAMIX Mg NPK®) was used (chemical composition is given in Table 1). N, P and K elements were applied together with Mg.

Estimation of yellowing and foliation

Yellowing was estimated visually as the percentage of yellow needles on each investigated tree and foliation as the percentage of needles remaining from the supposed amount on healthy trees in each autumn from 1999 to 2005. All data were collected by an experienced and well-trained researcher.

Needle sample collection and chemical analysis

In autumn 2006, two tree climbers collected twigs from 30 selected trees. Twigs were taken from sun-exposed part of crowns from the third whorl from the tree tip. Needles from twigs were sampled separately for the individual trees and for current (I age class) and 1-year-old needles (II age class). Concentrations of elements were determined by atomic adsorption spectrometry and spectrophotometry after sample desiccation and decomposition in $H_2SO_4 + H_2O_2$.

Analysis of annual diameter increment

In January 2008, tree cores were collected from 30 trees to analyze annual tree ring width. Two cores were taken at breast height (1.3 m) from each sample tree for diameter growth analysis.

Cores were smoothed in the laboratory and the width of individual tree rings was measured to the nearest 0.01 mm using the Kutschenreiter digital positiometer. Each tree ring series was visually cross-dated and checked. Then the average ring-width series was calculated for each treatment. All samples were dominant or co-dominant trees with similar growth conditions in terms of sun radiation exposure and neighboring-tree competition.

Soil sample collection and chemical analysis

Soil cores were taken as a mixture of four sub-samples collected from four directions from the perimeter of the crown of selected trees. Soil cores were taken from the humus horizon (Ah) after removing upper litter (L, F and H) horizons. This sampling strategy was used to detect differences in soil chemical properties in the zone of high fine root density of selected trees. In addition, the Ah horizon is generally most affected by soil acidification. Thirty soil samples were collected, one for each selected tree. Soil samples were then oven-dried at 105°C and sieved (<2 mm). All analyses were performed in an accredited national laboratory according to the Mehlich III method to predict plant-available Ca, K, Mg and P (Mehlich 1984). Total nitrogen content was analyzed according to the Kjeldahl method with adsorption complex characteristics according to Kappen (cation exchange capacity, CEC; base saturation, BS; hydrolytical acidity, HA). To measure pH(H_2O), 5 g of soil was mixed with 25 ml of distilled water. To measure pH(KCl), 1 M solution was used and 5 g of soil was mixed with 25 ml of the solution.

Data analysis

A redundancy analysis (RDA) in the CANOCO 4.5 program (ter Braak and Šmilauer 2002) was applied to evaluate all data together. The RDA was used because data sets were sufficiently homogeneous and environmental variables, e.g. fertilizer treatments, were in the form of categorical predictors. Data were standardized for calculation of all data together. A Monte Carlo permutation test with 999 permutations was also used to reveal whether the tested explanatory variables (environmental variables in the CANOCO terminology) had a significant effect on the multivariate data. The result of the RDA analysis was visualized in the form of a bi-plot ordination diagram created by CanoDraw © software. The percentage of the explained variability induced by treatments was used as a measure of explanatory power. After obtaining a significant result in the RDA, individual univariate analyses were performed.

One-way ANOVA in STATISTICA 5.0 software (StatSoft 1995) was used to evaluate the effect of treatment (CY, CG and F) on yellowing, foliation, needle chemical properties and soil chemical properties in 2006. In the case of a significant ANOVA result, Tukey's post hoc comparison test was applied to identify significant differences between treatments. Repeated measures ANOVA was employed to show the development of foliation, yellowing and annual diameter increment during the experiment. A regression analysis in the same program was used to evaluate the relationship between yellowing, foliation, needle chemical properties and soil chemical properties in 2006.

Results

Long-term foliation of selected trees (CG, CY and F treatments) is shown in Fig. 1a. A significant effect of year ($df = 8$, $F = 42.3$, $P < 0.001$), treatment ($df = 2$, $F = 44.2$, $P < 0.001$) and a year × treatment interaction ($df = 16$, $F = 10.2$, $P < 0.001$) on foliation was revealed by repeated measures ANOVA. The significant effect of year indicates inter-annual variation in foliation as well as a tendency for decreasing foliation in all treatments. The significant effect of treatment indicates differences between individual treatments and the interaction of year × treatment indicates non-parallel development of foliation among CG, CY and F treatments. This is most clear for the CY treatment where a steep reduction in foliation was recorded. Differences among treatments were relatively small at the start of the experiment, but substantially increased by 2006, after 9 years of investigation.

Long-term yellowing of selected trees (CG, CY and F treatments) is shown in Fig. 1b. A significant effect of year ($df = 8$, $F = 5.4$, $P < 0.001$), treatment ($df = 2$, $F = 65.7$, $P < 0.001$) and a year × treatment interaction ($df = 16$, $F = 12.2$, $P < 0.001$) on yellowing was revealed. The percentage of yellowing decreased immediately after fertilizer application in year 2000.

Yellowing in CG trees was relatively constant, but yellowing in CY trees substantially increased during the study period.

According to RDA, the effect of treatment was significant and explained 23.1% variability of all collected data ($F = 4.1$, $P = 0.001$). The results of the multivariate analysis were visualized in the form of an ordination diagram (Fig. 2). The advantage of such a diagram is the visualization of all relations among all collected data and their association with individual treatments within one figure. For example, yellowing was negatively correlated with foliation and with concentration of Mg in first- and second-year needles because the vectors indicating these variables lie in opposite directions. To demonstrate that the ordination diagram correctly shows the relation between all analyzed data, the results of the most important correlation analyses are given in Table 2. The length of the vectors indicates their importance for the result of the analysis. It is clear that the largest differences among treatments were found in yellowing, foliation, diameter increment and in concentration of Mg in current and 1-year-old needles. Concentrations of other elements in the foliage had a negligible effect on yellowing or foliation as their vectors were short and directed to different sides of the diagram, e.g., the soil P and Mg vectors to the triangle indicating the position of treatment F. Yellowing of needles was correlated with the following soil properties: CEC, HA, concentration of exchangeable hydrogen (Hs) and aluminum (Als). The concentration of plant-available P and Mg remained high in treatment F along with that of K in treatment CG.

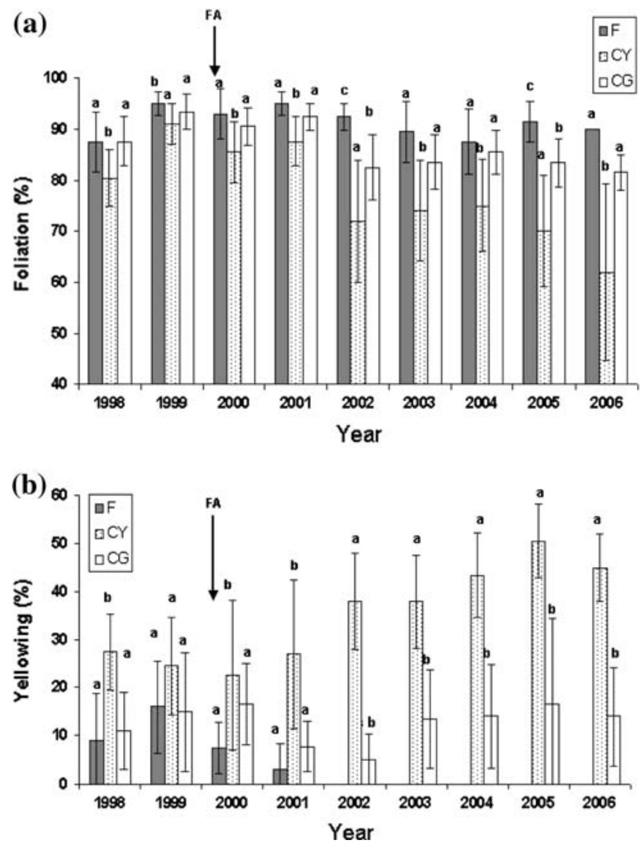

Fig. 1 Foliation (**a**) and yellowing (**b**) of spruce trees as a function of time. Application of slow-release fertilizer (FA) is indicated by *arrow*. *F* trees in fertilized treatment, *CG* trees in control treatment with high foliation and low symptoms of yellowing in 2006, *CY* trees in control treatment with low foliation and high symptoms of yellowing in 2006. *Error bars* indicate standard deviation (SD). Treatments with the *same letter* are not significantly different in each individual year

The effect of the treatment on individual soil chemical properties is shown in Table 3. Significantly increased content of P and Mg was recorded in treatment F 7 years after fertilizer application. On the other hand, HA, CEC, content

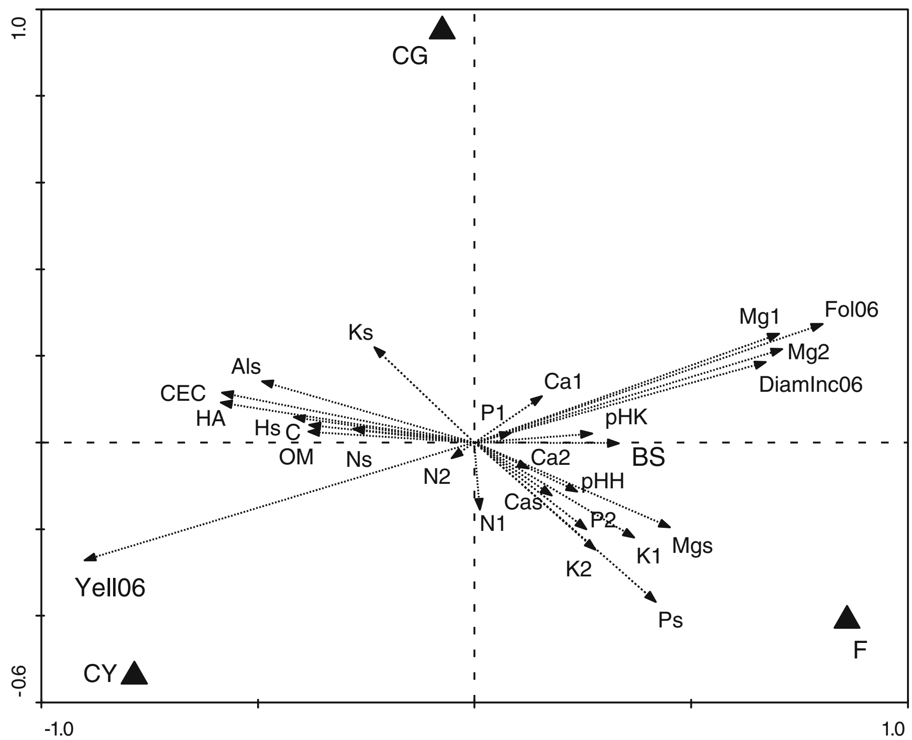

Fig. 2 Ordination diagram showing the result of RDA analysis of soil and foliage chemical properties, yellowing and foliation in 2006. *F* trees in fertilized treatment, *CG* green trees in control treatment, *CY* yellow trees in control treatment, *Yell06* yellowing in 2006, *Fol2006* foliation in 2006, *DiamInc06* diameter increment in 2006. Soil chemical properties: *Ks* exchangeable potassium, *Ps* exchangeable phosphorus, *Cas* exchangeable calcium, *Mgs* exchangeable magnesium, *OM* organic matter, *Ns* total nitrogen, *C* organic carbon, *Als* exchangeable aluminum, *Hs* exchangeable hydrogen, *pHH* pH(H_2O), *pHK* pH(KCl), *CEC* cation exchange capacity, *HA* hydrolytical acidity, *BS* base saturation. Needle chemical properties: *Ca1*, *K1*, *Mg1*, *N1* and *P1* concentration of elements in the first year foliage, *Ca2*, *K2*, *Mg2*, *N2* and *P2* concentration of elements in the second year foliage

of total N and concentration of Al^{3+} were lowest in treatment F. Although differences between CG and CY were not significant, concentrations of K and Mg, pH(KCl) and the base saturation of the soil sorption complex were lower in CY than in CG and vice versa in the case of Al^{3+}, Ca^{2+}, H^{+}, P, organic matter, total N and organic C.

The effect of treatment on needle chemical properties is shown in Table 4. A significantly increased concentration of K and Mg was recorded in both age classes of needles in treatment F. Furthermore, the concentration of Mg was significantly higher in CG than in CY in both age classes of needles. Elemental ratios are given in Table 5. A significant effect of treatment was recorded for the N/Mg ratio in current needles and for N/Mg and K/Mg ratio in 1-year-old needles.

According to repeated measures ANOVA, the effect of treatment ($df = 2$, $F = 13.3$, $P < 0.001$), year ($df = 15$, $F = 13.2$, $P < 0.001$) and the interaction of treatment × year ($df = 30$, $F = 6.8$, $P < 0.001$) on annual diameter increment of trees was significant. Although the diameter increment was the same for all trees in 1992, a reduction was recorded in CY trees, fluctuation was recorded in CG trees and a substantial increase was recorded in F trees (Fig. 3). In the last 3 years of the experiment, the mean annual diameter increment was 3.0, 1.9 and 5.5 mm in CG, CY and F, respectively.

Discussion

Nutrients applied by slow-release N, P, K and Mg fertilizer improved the nutrition of a spruce stand affected by yellowing both quickly and for a long time. Stabilization of foliation and disappearance of yellowing was highly apparent even 7 years after a single application of fertilizer. The long-term effect of applied fertilizers is consistent with results from several fertilizer experiments that have been running in Central Europe for decades (see Prietzel et al. 2008). In similar stands, application of Mg up to 100 kg ha^{-1} can be recommended as a short-term measure with long-term positive effects on spruce stand vitality and stability. This result confirms the Mg application rates recommended by Hüttl and Schneider (1998) and supports conclusions made by Zöttl and Hüttl (1986) that Mg-fertilized stands are more resistant to negative environmental impacts in the long term.

Table 2 Results of correlation analyses of elements concentration in the soil, concentration elements in the assimilatory organs, yellowing and foliation

Indep. var.	Depen. var.	*r*	*P* value
Mgs	MgI	0.078	0.682
Mgs	MgII	0.346	0.061
Ps	PI	0.013	0.546
Ps	PII	0.000	0.912
Ks	KI	0.014	0.538
Ks	KII	0.093	0.102
Ks	Al	0.136	**0.045**
Ks	Ps	0.157	**0.030**
Cas	Mgs	0.508	**<0.001**
Cas	Al	0.036	0.318
Cas	KI	0.267	**0.003**
Cas	pH(KCl)	0.350	**0.001**
pH(H_2O)	Yellowing	0.011	0.580
pH(H_2O)	Foliation	0.0592	0.195
pH(KCl)	Yellowing	0.009	0.613
pH(KCl)	Foliation	0.041	0.281
Al	Yellowing	0.361	**<0.001**
Al	Foliation	0.040	0.290
Mgs	Yellowing	−0.131	**0.049**
Mgs	Foliation	0.080	0.129
HA	Yellowing	0.47	**0.009**
MgI	Yellowing	−0.796	**<0.001**
MgII	Yellowing	−0.795	**<0.001**
Yellowing	Diam. Inc.	−0.688	**<0.001**

Indep. var. independent variable, *Depen. var.* treatment, *s* soil concentration of selected elements, *I* concentration of the element in the current needles, *II* concentration of the element in the first year needles, *HA* hydrolytical acidity, *Diam. Inc.* diameter increment

The immediate positive effect of Mg application on removing foliar Mg deficiency and yellowing of the spruce stand is also consistent with the results reported by Gülpen and Feger (1998).

On the other hand, the state of health of CY trees continued to deteriorate within the study period, i.e. small differences in foliation and yellowing at the start of the study resulted in high differences after 7 years of investigation. The yellowing connected with loss of needles negatively affected annual diameter increment in affected trees in the last years of the investigation. The decline of a spruce stand affected by Mg deficiency is, therefore, a long-term process running step by step for many years. In CY trees, the continuous deterioration in health conflicts with several other studies revealing natural re-greening of formerly yellow Norway spruce stands (see Hüttl and Schneider 1998 and citations therein). Natural re-greening is probably restricted only to specific stands and cannot be generalized for all stands suffering from Mg deficiency. Furthermore, the long-term positive effect of a single Mg application on growth rate is consistent with several other experiments reviewed by Evers and Hüttl (1990) and Gülpen and Feger (1998).

Inter-annual variation in symptoms of yellowing was recorded in CG trees. This is consistent with the results of other authors that revealed high inter-annual variation in nutrition of trees, probably due to weather conditions (Huber et al. 2006a, b). If the weather was warm, it is likely that the improved nitrogen supply and subsequent rapid growth increased the imbalance between N and Mg nutrition. In the investigated locality, Ca deficiency was recorded with Ca concentrations in needles below the optimum 2–3 mg g^{-1} (Hüttl 1986) in all treatments. Despite this, growth was not limited by Ca because the annual diameter increment in treatment F increased under almost the same concentration of Ca in needles as in the CY and CG treatments.

The significantly increased plant-available P and Mg soil concentrations recorded even 7 years after fertilizer application are in accordance with several other authors reporting the long-term residual effect of fertilizer application on P and Mg availabilities in similar soil and climatic conditions.

Table 3 Soil chemical properties of green trees in control treatment (CG), yellow trees in control treatment (CY) and trees in fertilized treatment (F)

Treatment	P (mg kg^{-1})		K (mg kg^{-1})		Ca (mg kg^{-1})		Mg (mg kg^{-1})		Organic matter (%)		$N_{tot.}$ (%)		$C_{org.}$ (%)	
F	27.2[b]	±15.29	199[a]	± 76.61	474.2[a]	±149.89	133.8[b]	±83.01	36.44[a]	±10.48	1.2[a]	±0.22	21.14[a]	±6.08
CG	10.8[a]	±5.67	246.4[a]	±44.72	422.4[a]	±72.76	77[a]	±9.09	42.54[a]	±8.13	1.43[a,b]	±0.19	24.68[a]	±4.72
CY	15.4[a,b]	±7.21	231.4[a]	±49.70	431[a]	±61.54	74.6[a]	±7.05	46.13[a]	±8.47	1.54[b]	±0.19	26.76[a]	±4.91

Treatment	pH H_2O		pH KCl		Al (mmol kg^{-1})		H(mmol kg^{-1})		BS (%)		CEC (mmol 100 g^{-1})		HA (mmol 100 g^{-1})	
F	4.16[a]	±0.19	3.24[a]	±0.28	143.4[a]	±28.15	4[a]	±0.96	21.34[a]	±2.71	55.32[a]	±15.62	43.75[a]	±13.24
CG	4.03[a]	±0.08	3.23[a]	±0.18	186.7[a,b]	±37.58	4.81[a]	±1.53	20.31[a]	±2.57	72.24[a]	±11.02	57.53[b]	±9.16
CY	4.03[a]	±0.15	3.2[a]	±0.15	195.74[b]	±46.91	5.28[a]	±1.20	19.36[a]	±2.07	78.2[a]	±12.36	63.06[b]	±9.81

Treatments with the same letter were not significantly different. ± values represent standard deviation (SD)

BS base saturation, *CEC* cation exchange capacity, *HA* hydrolytical acidity

Table 4 Concentration of nutrients in the current (I) and 1-year-old (II) needles of green trees in control treatment (CG), yellow trees in control treatment (CY) and trees in fertilized treatment (F)

Treatment	NI (mg g^{-1})		PI (mg g^{-1})		KI (mg g^{-1})		CaI (mg g^{-1})		MgI (mg g^{-1})	
F	14.19[a]	±1.16	3.60[a]	±0.91	5.01[b]	±1.05	1.20[a]	±0.33	0.79[a]	±0.10
CG	13.55[a]	±1.50	3.55[a]	±1.50	4.05[a,b]	±0.81	1.18[a]	±0.20	0.73[a]	±0.10
CY	14.03[a]	±1.63	3.55[a]	±1.80	4.15[a,b]	±0.80	1.06[a]	±0.17	0.55[b]	±0.12
Treatment	NII (mg g^{-1})		PII (mg g^{-1})		KII (mg g^{-1})		CaII (mg g^{-1})		MgII (mg g^{-1})	
F	12.93[a]	±1.43	3.70[a]	±0.94	4.54[a,b]	±0.58	1.24[a]	±0.26	0.68[a]	±0.07
CG	12.73[a]	±1.56	2.95[a]	±1.40	3.87[a]	±0.65	1.24[a]	±0.14	0.61[a]	±0.13
CY	13.27[a]	±1.73	2.98[a]	±0.98	4.18[a,b]	±0.63	1.12[a]	±0.22	0.43[b]	±0.16

Treatments with the same letter were not significantly different. ± values represent standard deviation (SD)

Table 5 Elements ratios in the current (I) and 1-year-old (II) needles of green trees in control treatment (CG), yellow trees in control treatment (CY) and trees in fertilized treatment (F)

Ratio	Needle age class	CG	CY	F	Harmonic nutrition
N/P	I	4.5 ± 1.7[a]	5.0 ± 2.3[a]	4.3 ± 1.4[a]	6–12
	II	5.2 ± 2.0[a]	5.0 ± 1.8[a]	3.8 ± 1.2[a]	
N/K	I	3.5 ± 0.7[a]	3.5 ± 0.7[a]	3.0 ± 0.7[a]	1–3
	II	3.4 ± 0.6[a]	3.3 ± 0.6[a]	2.9 ± 0.4[a]	
N/Ca	I	11.7 ± 2.0[a]	13.6 ± 3.0[a]	12.4 ± 2.5[a]	2–20
	II	10.3 ± 1.2[a]	12.4 ± 2.9[a]	10.9 ± 2.3[a]	
N/Mg	I	19.1 ± 4.2[a]	24.7 ± 5.8[b]	18.2 ± 3.0[a]	8–30
	II	22.2 ± 6.0[a]	30.0 ± 7.4[b]	19.1 ± 2.6[a]	
K/Ca	I	3.6 ± 1.1[a]	4.1 ± 1.3[a]	4.4 ± 1.5[a]	0.8–2.4
	II	3.2 ± 0.7[a]	4.0 ± 1.4[a]	3.8 ± 0.9[a]	
K/Mg	I	5.6 ± 1.1[a]	7.4 ± 2.1[a]	6.5 ± 1.8[a]	2.2–6.4
	II	6.6 ± 1.5[a]	9.7 ± 3.0[b]	6.7 ± 1.1[a]	

Treatments with the same letter were not significantly different. ± value represents standard deviation (SD). Values for a ''harmonic nutrition'' were proposed by Hüttl (1991) for current needles

In ecosystems with slow nutrient turn-over and mineralization such as mountain spruce forests, the resilience of the ecosystem after fertilizer application is apparently a long-term process taking more than several years (Gülpen and Feger 1998). In the long-term fertilizer experiments reported by Semelová et al. (2008) and Spiegelberger et al. (2006), the resilience of an alpine grassland ecosystem after final fertilization took more than 60 years. This indicates that a single application of P and Mg fertilizers in mountain areas under extreme soil and climatic conditions can improve plant nutrition for a very long time. For decades, long residual effects of N as well as NPK fertilization were also recorded in spruce plantations at lower altitudes in the Czech Republic (Remeš and Podrázský 2006).

The main aim of this paper was to reveal whether there was a difference in soil chemical properties between CY and CG trees growing in close vicinity. Although differences were not statistically significant, slightly lower concentrations of K and Mg and higher concentrations of H^+ and Al^{3+} were recorded in soils under CY trees. This result can be interpreted in two ways:

1. There were no significant differences in soil Mg availability and other soil chemical properties under CG and CY trees. If this is true, a possible explanation of the differences in Mg concentrations in needles of CG and CY trees is fine roots' status with disorder in CY trees the most probable (see Nechwatal and Osswald 2003). Further, although the depth of the soil profile under both CY and CG trees was the same, CY trees may suffer from drought stress because of more adverse soil physical conditions or the non-site adapted genotype of Norway spruce.
2. The second explanation is that there were differences in the soil availability of Mg and differences in other soil chemical properties between CG and CY trees, but these differences were too small to be statistically significant, but too large to affect spruce nutrition. For example, almost negligible and non-significant differences in soil plant-available P concentrations resulted in two times higher P concentrations in the plant biomass (Semelová et al. 2008). It is possible that only small differences in soil Al^{3+}, H^+, Mg and K

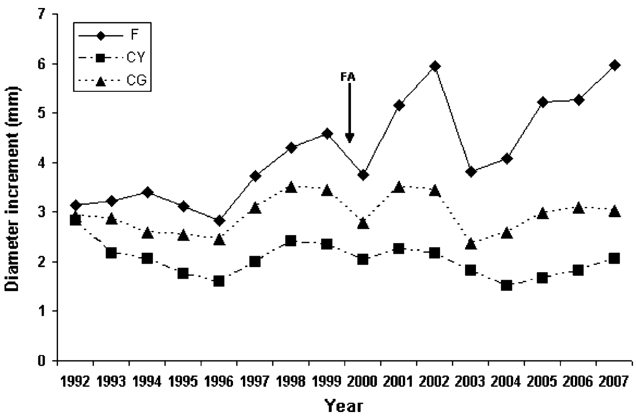

Fig. 3 Annual diameter increment of investigated trees in the years 1992–2007. Application of slow-release fertilizer (FA) is indicated by *arrow*. *CG* green trees in control treatment, *CY* yellow trees in control treatment, *F* trees in fertilized treatment

concentrations can cause large differences in needle Mg concentrations between CG and CY trees.

All explanations must be interpreted with caution as the soil sorption zone of individual trees was probably much larger than the soil sampling area. The aim of soil sampling was to characterize the soil chemical properties in the area of high fine root density of the investigated trees and, therefore, the area with a large effect on tree nutrition. Investigating the soil chemical properties in whole root sorption zones of individual trees would have been extremely difficult and a non-destructive technique was not available.

The high negative correlation between yellowing and foliation and the association between yellowing and a low concentration of Mg in both age classes of needles agree with results obtained by Katzensteiner et al. (1992a) from the Austrian part of the Bohemian Forest. A similar negative correlation between foliation and yellowing was reported by Thomas et al. (2002) for silver fir in the Vosges Mts., and by Nechwatal and Osswald (2003) and Gülpen and Feger (1998) for Norway spruce stands in the Bavarian Forest and the Black Forest, respectively. In CY trees, the mean concentration of Mg in current year needles decreased below the threshold value of 0.7 mg g^{-1} (Hüttl 1986), indicating deficiency. In CG or F trees, the concentration of Mg in current year needles was sufficient and retranslocation of Mg from older to younger needles was apparently much lower than in CY trees. In contrast to Mg and Ca deficiency in the current year needles, the concentration of N and K was sufficient and that of P high above the optimum for all investigated trees (according to threshold values proposed by Hüttl 1986). Evidently, yellowing was connected with Mg deficiency.

There was an obvious positive long-term effect of slow-release N, P, K and Mg fertilizer application on the state of health of the investigated stand as the yellow trees were completely absent from the fertilized treatment 7 years after fertilizer application. The disorder in tree nutrition can be removed by an increase in Mg availability. Although there was a negative correlation between soil concentrations of Mg and yellowing, this correlation was relatively weak, indicating that there was no simple relation between soil and needle concentrations of Mg. Even though soils under CG and CY trees were low in plant-available Mg, the weak correlation indicates that not only soil, but also root status or tree genotype may contribute to the yellowing phenomenon.

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