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EFFECTS OF LIMING AND NPK-FERTILIZATION ON THE SOIL AND FINE ROOTS IN A NORWAY SPRUCE STAND, NÍZKE TATRY MTS

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Abstract

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The main objective of the paper is the quantification of liming (CaO + MgO) and/or NPK-fertilization effects on soil chemical properties and fine root parameters in an 85-year-old Norway spruce (*Picea abies* L. Karst.) stand in the Nízke Tatry Mts, Central Slovakia. The analyses of pH and soil solution Ca/Al molar ratio were carried out two and six years after applying the “amelioration materials” onto the soil. Fine roots in the soil depths of 0–5, 5–15 and 15–25 cm were included in the analyses, and their biomass, necromass, length, surface area and number of root tips were measured. Two years after the liming, values of pH and Ca/Al molar ratio increased significantly only in the top 5 cm of the soil. Six years after the treatment, pH and Ca/Al molar ratio changed also in the soil depth 5–15 cm. NPK-fertilization did not modify the values remarkably. Biomass of fine roots, their length, surface area and number of root tips were stimulated by the liming six years after the application. The NPK-fertilization increased quantity of very fine root necromass. Thus, the fertilization was considered less efficient in stimulating fine root biomass than liming. Mutual combination of liming and NPK-fertilization did not show any additional effects on fine root biomass. Vertical distribution of fine roots was only slightly modified by the application of the lime and/or fertilizer as compared to the control plot.

Key words: acidic soil, Ca / Al ratio, fine roots, *Picea abies*, soil amelioration

Introduction

Inputs of acidifying compounds, especially of nitrogen and sulphur, proved to be a principal factor in forest health decline in most countries in Europe (Flückiger, 1989). Noxious atmospheric substances damaged forest trees either directly via the aboveground parts, mainly foliages, or indirectly via the soil and root systems. Even though these polluting elements decreased in the Central Europe dramatically since the end of 1980s, negative effects of their depositions in the forest soil are still evident. The fine roots are known as the most sensitive tree component to variety of stresses (Kozlowski, Pallardy, 1997). Several works showed significant changes in fine root mass and their chemical properties due to soil acidification and consequent toxic effects of aluminium (Al), as well as reduction of the available pool of base cations – especially calcium (Ca) (Dahlgren et al., 1991; Majdi, Persson, 1995). Hirano et al. (2007) after reviewing a large number of Japanese publications summarized that often the reduction in the root biomass occurred prior to that in the aboveground biomass under acidic soil conditions. In spite of the mentioned fact, the monitoring of health status of forests is still focused mainly on the tree crown level and forest soil properties, neglecting the rhizosphere of the trees.

Amelioration of chemical properties of the soil via liming has been practised mainly in Central and Northern Europe since the 1980s (Ulrich et al., 1979). Most authors have shown a positive influence (Vacek et al., 2006), but a few demonstrated a combination of some positive and negative effects of liming (Nilsen, 2001; Saarsalmi, Mälkönen, 2001). As forest liming effects on forest ecosystems are still controversial, very diverse policies for its application exist, for example, in the German states (Huber et al., 2004) and this practice is forbidden by law in Switzerland (Genenger, 2001). Utilization of fertilizers with nitrogen (N), phosphorus (P) and potassium (K) is even more questionable than liming. Increased N input into terrestrial ecosystems has been caused by a variety of human activities. On the other hand, P and K often occurred under physiologically optimal concentration for instance in needles of Norway spruce (*Picea abies* L. Karst.) in Central Europe (Stefan et al., 1997). Except few results from long term effects of liming or acidification experiments (e.g. Huber et al., 2006), we are still lacking field-measured data concerning chemical changes in the soil and physiological responses in trees followed after amelioration treatments (Jentschke et al., 2001).

The recent soil survey in Slovakia showed that around 25% of forest soils currently display a very acid reaction (pH < 4.5); 40% of soils records acid (pH 4.5–5.5), 17% moderately acid (pH 5.5–6.5), 5% neutral (pH 6.5–7.2), and 13% moderately alkaline (pH 7.2–8.0) reaction (Moravčík et al., 2006). The repetitive measurements taken over last decade do not confirm progressing acidification of the forest soils. However, in some regions of Slovakia, soils with low buffering capacity might still suffer from high acidification load. The data in the framework of the International Co-operative Programme (ICP) – Forests showed that a Norway spruce is the most damaged tree species in Slovakia. For instance in 2006, the average defoliation was 27.2% for Norway spruce and 23.1% for all tree species together (Pajtík, personal communication). The defoliation of Norway spruce manifested slightly improving trend within the last decade. In any case, serious damage is still observed in the spruce forests especially in those growing in the sixth and seventh altitudinal vegetation zones where soils are more sensitive to acidification than the soils in the lower altitudes (Minďáš et al., 1999). These ecosystems often named as "mountain forests" occur in the altitudes between app. 900–1400 m a.s.l.. They represent 228,000 ha, i.e. cca 12% of the total forest area of Slovakia. The forests are valuable from the commercial (wood production) point of view, but mainly for public-beneficial functions (e.g. water management, soil erosion control, nature conservation, tourisms). In the 1980s and 1990s, many thousands hectares of the spruce forests grown on acidified soils in Slovakia were treated, mostly by dolomite lime spreading from aeroplanes or helicopters. The treatments have been occasionally carried out till present day without making serious analysis of their effects to the forest ecosystems.

Considering all above-mentioned facts, we conducted studies on the mountain Norway spruce forest growing on acidic soil. Effects of simulated liming and/or fertilization on soil chemistry and selected parameters of fine roots in the particular soil layers were researched two and six years after accomplishing the treatments.

Methodology

To facilitate studying the amelioration effects of lime and fertilizer on soil and rhizosphere in a Norway spruce forest we conducted the experiment in Sopotnická dolina valley, locality Studienec (48°47´ N, 19°23´ E, 1180 m a. s.l), the south-western part of the Nízke Tatry Mts, Central Slovakia. The forest soil on the site has been classified as a Dystric Cambisol, the parent material was a slope deposit of granodiorit. The humus has been classified as a mull-like moder. The content of coarse fragments is relatively high and fluctuated between 35% in the A horizon to 85% in the deeper parts of the C horizon (below 70 cm). The mean slope was around 40%, eastern aspect.

The experiment stand was prevalently even-aged, app. 85-year-old, with Norway spruce as a dominant tree species (70%) and mixture of broadleaved species, especially European beech (*Fagus sylvatica* L.). Mean diameter at breast height was app. 35 cm, height 24 m, standing volume 290 m^3 per ha. Except at the stand edges, where a few forbs and grasses occurred, almost no other plants grew in the stand because of the closed canopy.

According to our pre-trial observations in the spring of 2000, the defoliation in the crowns of nearly all spruces oscillated between 25–35% (according to the ICP – Forests classification, see also http://www.icp-forests.org), putting the stand on the threshold between classes "slightly" and "moderately" damaged trees, i.e. the spruces manifested symptoms of "early stage" of decline.

In the spring of 2000, four rectangular research plots sized 60 m^2 were established in the Norway spruce stand. The series of the plots was placed parallel along an *isophyse* leaving a buffer zone between two neighbouring plots of 3 m. The first plot was limed (code L thereafter). The liming was carried out by an application of a material with a commercial name "Varinit", which is a very fine milled mixture of calcium/magnesium carbonate slag and dolomite limestone (CaO + MgO content is 48−52%, 12% of which is Mg). Varinit was applied manually on the ground surface in amount of 0.66 kg/m^{-2}. Next plot was fertilized (code F thereafter) with 0.12 kg m^{-2} of an NPK fertilizer with the ratio of N, P and K in the fertilizer of 8:14:22 (expressed on weight base). The third plot received a combination of both Varinit and NPK fertilizer in the same amount as the previous two plots (code L + F thereafter). The fourth, control plot (code C thereafter), was neither fertilized not limed. The applied doses of Varinit (i.e. 6.6 t/ha base) and NPK fertilizer (1.2 t ha^{-1}) correspond to upper quantities used in the forestry practice in Slovakia.

The quantifications of the fine root parameters and soil chemical properties were done two years and six years after performing the soil amelioration, specifically in the last week of June 2002 and June 2006. The soil coring method using a metal auger with an inner diameter of 6.0 cm was used. The high proportion of stones, increasing with the soil depth, allows penetrating only down to 25 cm. Thus, fifteen soil cores were randomly taken from the each plot on every occasion. The soil cores were divided into three depths; 0−5 cm (excluding litter and fermentation layer), 5−15 cm and 15−25 cm. The subsamples, 360 pieces in total, were transferred into plastic bags and stored in a deep-freezer at −20 °C before further processing.

Spruce fine roots (up to 2 mm in diameter) were hand-picked from the samples. Root characteristics such as colour, resilience, wood structure, existence of root hairs were used to distinguish spruce roots from those of other plants which occasionally occurred in the samples. Roots classified as living characterized high resilience, firm and good adhesion between the stele and cortex. Dead spruce roots were quantified only in the year 2006. Live spruce fine roots collected in 2002 were carefully washed by water and dried to constant weight at 70 °C for 24 hours. Dry matter was weighed with a precision of 0.1 mg. Dry matter of the fine roots was calculated on a square meter basis.

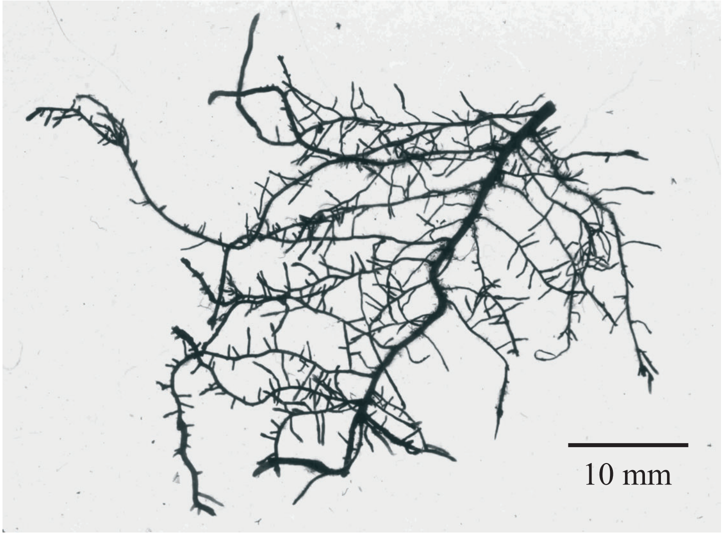

Fig. 1. Spread and scanned cluster of very fine roots (diameter under 1 mm) of Norway spruce extracted from the soil depth 5–15 cm in the control plot.

The fine roots of spruce originating from the sampling in 2006 were subjected to more detailed studies than those sampled in 2002. They were divided into two diameter classes of < 1 mm and 1–2 mm. The roots < 1 mm (i.e. "very fine") in a fresh status were scanned by a scanner EPSON Expression 10000 (Fig. 1). The images of the roots were analyzed by the WinRHIZO software (Regent Instruments Inc., Quebec, Canada). The outputs of the analysis were: root length, root surface and number of root tips for the each root sample. The parameters were expressed on a square meter basis. The roots were dried and their dry matter was weighed. Specific length (cm g^{-1}), specific surface area (cm^2 g^{-1}) and tip density (pieces g^{-1}) were calculated for the each root sample.

In both sampling seasons 2002 and 2006, randomly selected subsamples of the soil cores representing four spots from the each depth and each treatment (totalling 96 samples) were subjected to the chemical analysis. Particularly, soil pH - H_2O, and the soil solution Ca/Al molar ratio was used to evaluate changes on soil properties due to the treatments.

Data on the root biomass and necromass, root length, root surface area, number of root tips, specific root length, specific surface area, tip density, soil pH and Ca/Al molar ratio were processed by analysis of variance. Tukey´s HSD test was used for mean separation of treatments at the 5% level always specifically concerning the particular soil layers.

The term "biomass" is used in the text for dry matter of live roots, "necromass" of dead roots, and the term "mass" covers both live and dead roots. "Fine roots" are classified as those with a diameter up to 2 mm and "very fine roots" as those <1 mm in diameter.

Results

The biomass density (if expressed per soil volume unite; data not shown) of fine roots was the largest in the top 5 cm of the soil and the least in the soil depth 15–25 cm for all treatments in both studied years. For instance in the case of the C plot, the biomass density in

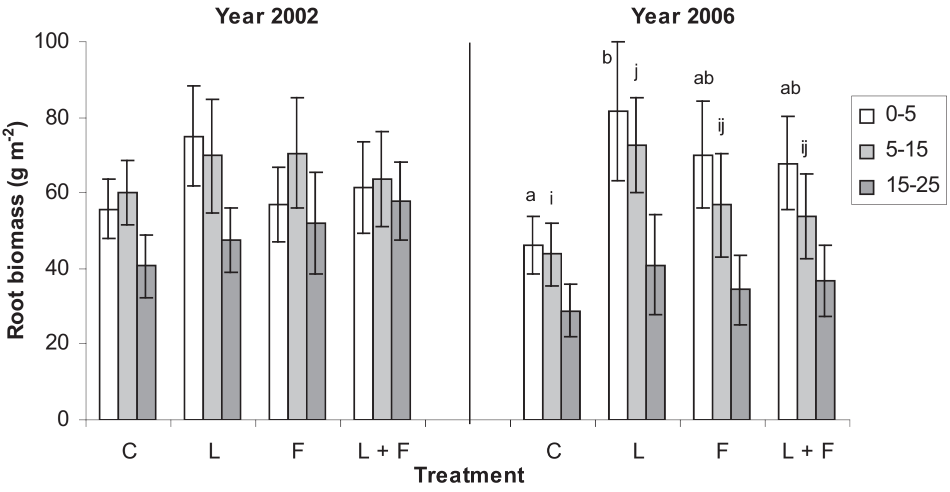

Fig. 2. Fine root biomass of Norway spruce in the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the soil depths 0–5, 5–15 and 15–25 cm.

Note: Mean values and standard errors are shown. Statistically significant differences between the treatments separately for each year are marked by using different letters (Tukey HSD test, $\alpha \le 0.05$). The letters a, b indicate the soil depth 0–5 cm, the letters i, j conform to the soil depth 5–15 cm; columns without any letters or those with the same letters are not significantly different.

the top 5 cm was approximately double and triple in comparison with the depths 5–15 cm and 15–25 cm, respectively.

On the C plot, fine root biomass in 2002 was 56, 60 and 41 g m^{-2}, for the soil depth 0–5, 5–15 and 15–25 cm respectively (Fig. 2). In 2006, the values were slightly lower, reaching 46, 44 and 29 g m^{-2}, in the same soil depths. In fact, certain stimulating tendency on fine root biomass, however not statistical significant, due to the treatments, was found already two years after establishing the experiment. This trend was more expressive after six years. The most evidently increased fine root biomass was found in the soil depths 0–5 and 5–15 cm in the case of liming (Fig. 2). Sustaining effects were indicated, although not statistically significant, also for the F plot and L + F plot, mainly in the topsoil. In the 2006, the biomass of fine roots had very similar quantities and vertical distributions on the F and L + F plots.

In 2006, both the biomass and necromass of very fine roots were studied. However, the dead roots with the diameter of 1–2 mm were not included in this analysis, because many samples did not contain any necromass. To make interpretation of the results less complex, only masses of very fine roots for the entire soil profile 0–25 cm are shown. All treatments tended to increase both biomass and necromass of very fine roots (Table 1). However, significant difference in biomass was found only after liming and in necromass only after fertilizer application. After summing biomass and necromass, root quantity was significantly larger on the plots receiving any of the treatments against the C plot.

T a b l e 1. Biomass and necromass of very fine Norway spruce roots in the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the soil profile 0–25 cm.

Plot	Biomass (g m^{-2})	Necromass (g m^{-2})	Biomass + necromass (g m^{-2})
C	60.3^{a} ± 5.4	23.2^{a} ± 4.0	83.5^{a} ± 9.2
L	80.6^{b} ± 7.2	24.9^{ab} ± 5.1	105.5^{b} ± 12.4
F	73.0^{ab} ± 7.9	39.8^{b} ± 7.1	112.8^{b} ± 15.0
L + F	75.4^{ab} ± 8.7	29.0^{ab} ± 6.7	104.4^{b} ± 15.4

Note: mean values and standard errors are shown. Means with the same letters (ab or b), separately for particular parameters (within column), are not significantly different; Tukey HSD test, α ≤ 0.05.

Length and surface area of very fine roots (< 1 mm) increased due to the application of all the treatments, however this was significant only in the L plot (Table 2). Numbers of root tips were stimulated remarkably by the liming and liming + fertilization. Very similar results were found for the specific parameters, which were all enhanced by the treatments. Specific length of very fine roots, specific surface area, and tip density increased significantly by liming (Table 3). In addition, the tip density markedly increased due to the combination of liming and fertilization.

T a b l e 2. Length of very fine Norway spruce roots, their surface area and number of root tips in the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the soil profile 0–25 cm.

Plot	Length of roots (m m^{-2})	Surface area of roots (m^{2} m^{-2})	Number of root tips (pc m^{-2})
C	505^{a} ± 71	0.96^{a} ± 0.18	162,080^{a} ± 20,574
L	729^{b} ± 102	1.50^{b} ± 0.25	238,224^{b} ± 27,579
F	655^{ab} ± 109	1.20^{ab} ± 0.21	204,913^{ab} ± 24,576
L+F	664^{ab} ± 99	1.30^{ab} ± 0.22	228,160^{b} ± 26,117

Note: mean values and standard errors are shown. Means with the same letters (ab or b), separately for particular parameters (within column), are not significantly different; Tukey HSD test, α ≤ 0.05.

T a b l e 3. Specific length of very fine Norway spruce roots, their specific surface area and root tip density in the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the soil profile 0–25 cm.

Plot	Specific length of roots (cm g^{-1})	Specific surface area of roots (cm^{2} g^{-1})	Root tip density (pc g^{-1})
C	837^{a} ± 29	159^{a} ± 7	2,687^{a} ± 108
L	904^{b} ± 36	186^{b} ± 9	2,956^{b} ± 147
F	897^{ab} ± 38	164^{ab} ± 11	2,808^{ab} ± 155
L+F	880^{ab} ± 33	172^{ab} ± 11	3,026^{b} ± 157

Note: mean values and standard errors are shown. Means with the same letters (ab or b), separately for particular parameters (within column), are not significantly different; Tukey HSD test, α ≤ 0.05.

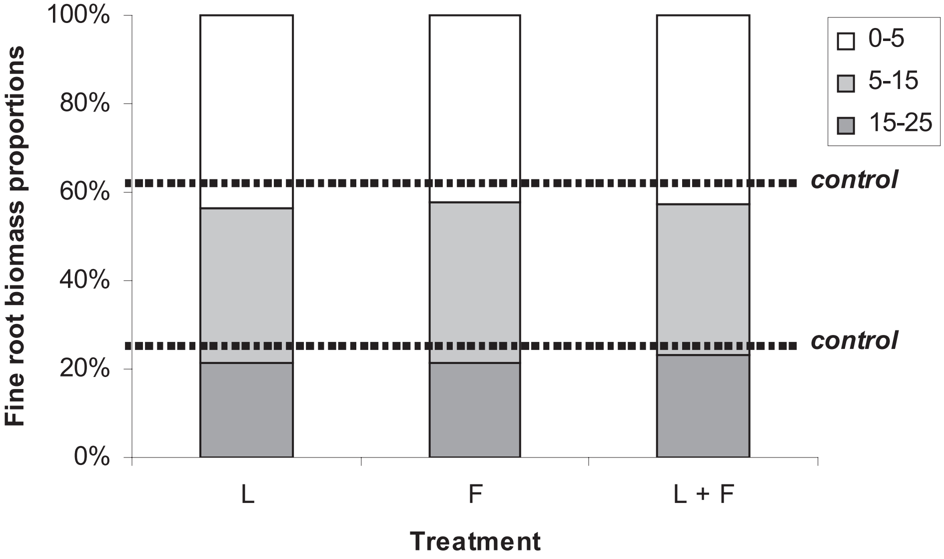

Fig. 3. Proportions of fine root biomass of Norway spruce in the soil depths 0–5, 5–15 and 15–25 cm on the limed (L), fertilized (F) and limed + fertilized (L + F) plots compared with the control plot (dotted line) in 2006. Differences between the plots were not significant.

Data related to the vertical distribution of fine roots in 2006 showed only negligible differences between the treated plots and the C plot (Fig. 3). The largest, but not statistically significant differences were between the C plot and L plot. Here, 38.9% and 43.6% of fine roots in the C plot and the L plot respectively were distributed in the top 5 cm of the soil.

In 2002, the values of the soil pH were evidently modified in the topsoil by the applied treatments and there were significantly increased pH values also in the soil depth 5–15 cm in the L and L + F plots (Fig. 4). However, in Slovakia generally recognized critical level of the pH value 4.1 for Cambisol (Minďáš et al., 1999) was markedly exceeded only for the topsoil in the L and L + F plots. This trend was confirmed after six years, when there was a clear increase of the pH values over the critical threshold in the soil depth of 0–15 cm in the L and L + F plots.

In 2002, the values of Ca/Al molar ratios were largely increased in the topsoil on the L + F plots and mainly on the L plot (Fig. 5). The straight fertilization did not cause any significant changes in this parameter. In 2006, the increases of the Ca/Al molar ratio were further enhanced the most evidently in the topsoil of the L and L + F plots. On these plots, a very sharp effect appeared also in the in the soil depth of 5–15 cm, and significant changes were recorded for the soil depth 15–25 cm. The results were compared with a critical value for soil solution Ca/Al molar ratio equals 1.0 (e.g. Hirano et al., 2007). While in 2002, the liming and fertilizing + liming increased the ratio over the threshold only in the topsoil by 2006 this increase was found also in the soil depth 5–15 cm.

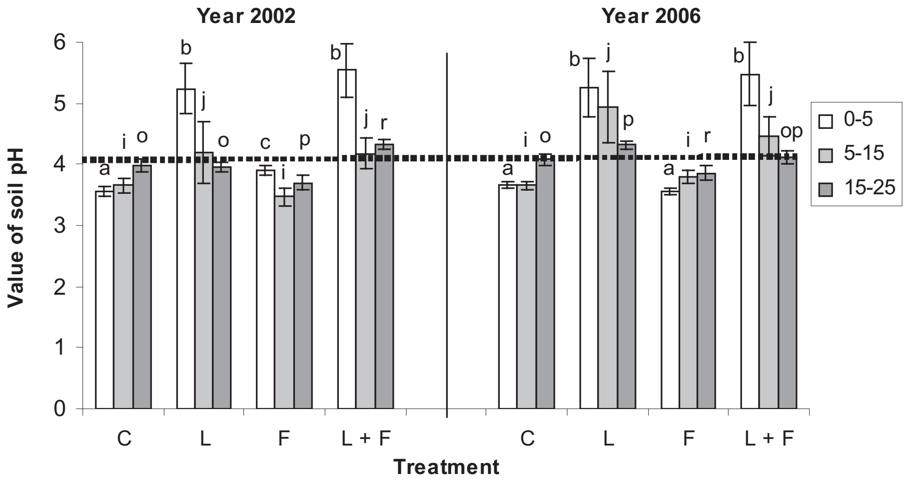

Fig. 4. Values of soil pH on the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the depths 0–5, 5–15 and 15–25 cm. Critical value of pH (4.1) is described by the dotted line.

Note: Mean values and standard errors are shown. Statistically significant differences between the treatments separately for each year are marked by using different letters (Tukey HSD test, α ≤ 0.05). The letters a, b, c indicate the soil depth 0–5 cm, the letters i, j conform with the soil depth 5–15 cm, and o, p, r are for the soil depth 15–25 cm; columns with the same letters are not significantly different.

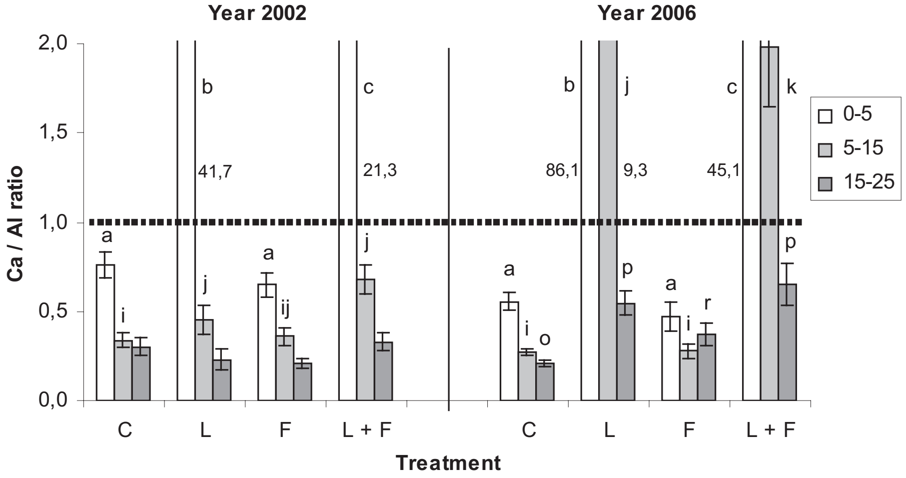

Fig. 5. Values of Ca / Al molar ratio in the soil on the control (C), limed (L), fertilized (F) and limed + fertilized (L + F) plots in the depths 0–5, 5–15 and 15–25 cm. Critical value of Ca / Al ratio (1.0) is described by the dotted line.

Note: Mean values and standard errors are shown. The numbers by the columns show values exceeding 2.0. Statistically significant differences between the treatments separately for each year are marked by using different letters (Tukey HSD test, α ≤ 0.05). The letters a, b, c indicate the soil depth 0–5 cm, the letters i, j, k conform with the soil depth 5–15 cm, and o, p, r are for the soil depth 15–25 cm; columns with the same letters are not significantly different.

Discussion

Chemical properties recorded at the experimental site, i.e. on the C plot, especially the low pH (e.g. 3.6 in the topsoil) and low Ca/Al molar ratio (e.g 0.3 in the soil depth 15–25 cm) were considered as unfavourable for spruce fine root growth. Among others, negative effects of soil acidification are decreasing rooting in the subsoil and possibly enhanced susceptibility to wind and frost in a Norway spruce (Jönsson et al., 2004; Mayer et al., 2005). Well-known is harmful effect of low pH value and Al toxicity to fine roots and mycorrhizal fungi (e.g. Göransson, 2006). A low Ca/Al molar ratio in the soil has been shown to inhibit both root growth and the uptake capacity of base cations by the roots due to competition for the biding sites on the root surface (Marschner, 1986). Heim et al. (1999) showed that the principal part of the Al supplied to a Norway spruce root is immobilised in the root apoplast. Thus, its concentration should be preferably measured in the roots or possibly in the soil than in the needles. Hirano et al. (2007) suggested soil solution Ca/Al molar ratio in roots should be considered in long-term monitoring sites to predict the effects of soil acidity.

Our results showed the highest fine root density in the topsoil, a fact which has both positive and negative consequences. A negative one is that the uppermost soil layer is the most exposed to stresses such as acidification, drought and temperature extremes. On the other hand, a shallow distribution of fine root biomass allows for a relatively fast access to nutritional compounds in the case of surface application of soil-improving materials. In our experiment, the fine root biomass was slightly stimulated after two years and strongly stimulated six years after liming, which can be interpreted as a positive effect. Fertilization effect of NPK was characterised with increasing the quantity of very fine root necromass. Although the NPK application stimulated production of very fine roots, at the same time it enhanced their susceptibility to environmental stresses or decreased their lifespan. After Keeney (1980), most ecosystems have usually been N limited, for instance in boreal and temperate forests. On the other hand, trees are adapted to N limitation rather than to N excess, which can lead to nutrition imbalances and contributes to further soil acidification. In our experiment, combination of liming and NPK-fertilization did not show any additional effects, to the contrary, a slight decrease of the positive effect of liming on root growth (standing biomass) due to its combination with NPK-fertilization could be suspected. It is likely that once certain thresholds of soil chemical properties are met (e.g. pH value of 4.1 and Ca/Al of 1.0), fine roots have reasonably favourable growth conditions and further improvement of these does not have a significant effect. However, we could not conclude that increases of the pH and Ca/Al values over the critical thresholds always were resulted in significant increase of fine root biomass. Thus, probably a certain delay for fine root restitution after an ameliorating treatment can be expected. Positive effects of ameliorative materials on tree fine roots were showed by numerous authors. For instance, Adams, Hutchinson (1992) recorded significant stimulating effects of P-addition on maple fine root growth. Konôpka, Tsukahara (2001) recorded positive consequences of NPK and Mg-fertilizer on fine root production in a pine stand. Particularly, ambiguous results are from the N-addition experiments. Hendricks et al. (1993) reviewed the papers focused on N treatment effects to tree fine roots finding all kind of results: stimulative, insignificant or even suppressive on fine root mass quantity. Nilsson, Wiklund (1995) experimentally proved that a fertilizer including all necessary macronutrients except N was efficient in restoring nutrient balances in Norway spruce in southern Sweden. Hence, they recommended N-free fertilizers to be applied in acidified spruce forests.

Our results showed a very slight modification in vertical distribution of fine roots due to the amelioration of soil. Especially liming brought some, but not significant, redistribution of fine roots in term of increasing their proportion in the topsoil. Huettl, Zoetl (1993) hypothesized that soil amelioration measures can lead to superficial formation of tree roots. Theoretically, this can cause increased susceptibility of fine roots to a variety of climatic stresses and possibly worsening the anchorage of coarse roots resulted in escalated risk to tree uprooting.

Alongside frequently used basic quantitative indicators (biomass, necromass), observations from the monitoring of soil conditions via chemical, morphological or physiological parameters of tree fine roots can be of interest. Some of these have recently been reviewed by Hirano et al. (2007). The authors conclude that even if the root biomass and root elongation are not effected by Al, the changes in the root morphology can be noticeable. This fact strongly supports the proposition that the response of the root morphology is a more sensitive indicator of soil acidification and Al stress than the root biomass. Our very fine root parameters based on absolute values (length, surface area and number of tips) are strongly linked to the biomass amount. Thus, their potential changes due to the treatments might reflect more quantitative modifications on very fine root biomass than conversions on morphological features. Hence, more interesting results are those concerning specific parameters, particularly specific length, specific surface area and tip density. These clearly expressed modifications in fine root morphology due to the treatments. Especially the liming mitigated the soil acidification that probably might increase values of specific length, specific area and root tip density. The result corresponds to the conclusion of Hirano et al. (2007) that soil acidification can cause abnormalities in root morphology as fine roots tended to be thicker, shorter, and less branched than those grown under regular conditions. Ostonen et al. (1999) termed these sorts of specific parameters as eco-morphological and showed their relationship with soil conditions and soil types.

Conclusion

Our study showed that two years after the liming, values of pH and Ca/ l molar ratio increased significantly only in the top 5 cm of the soil. Six years after the treatment, pH and Ca/Al molar ratio changed also in the soil depth 5–15 cm. NPK-fertilization did not modified the values remarkably. Biomass of fine roots, their length, surface area and number of root tips were stimulated by the liming six years after the application. The NPK-fertilization increased quantity of very fine root necromass. The fertilization was considered less efficient in stimulating fine root biomass than liming. Thus, liming might a suitable amelioration material for this sort of spruce stands in conditions of the Nízke Tatry Mts.

On the other hand, we would like to point out that large-scale application of amelioration materials in forests may be also associated with certain ecological risks. The most frequently observed negative phenomena were: emission of CO_2 due to loss of organic matters, NO_3 leaching and even tree growth reduction (Vejre et al., 2001), higher risk of enhanced susceptibility to frost, drought, windfall, and decreased biodiversity (Huettl, Zoetl, 1993; Mayer et al., 2005). Thus, application of amelioration materials would be used only on extremely acidified sites. Available biological approaches of soil amelioration, e.g. planting tree species with positive effects on forest soils before establishing a desired forest stand, would be preferred.

Translated by the authors

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