Long-term influence of applied amphibolite powder on the chemistry of soil supporting Norway spruce plantation

I. Kuneš[1], M. Baláš[1], V. Balcar[2]

[1]*Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic*

[2]*Forestry and Game Management Research Institute, Jíloviště-Strnady, Opočno Research Station, Opočno, Czech Republic*

ABSTRACT: The article assesses the effects of amphibolite applied to the planting holes of spruces on the soil chemistry. The sampling was conducted fourteen growth seasons after the establishment of the experimental spruce plantation. In both treatments (control and amphibolite) the soil samples were taken from the interior of the planting holes as well as from the intact area around the planting holes. Fourteen growth seasons after application the effects of the pulverised amphibolite were not marked despite being detectable. In comparison with the control the soil in the planting holes of the amphibolite treatment showed significantly higher soil reaction, concentration of available phosphorus and partially also concentration of exchangeable Ca. All the significant effects of amphibolite were confined to the soil inside the planting holes. As for the evaluated chemical properties no significant undesirable effects of the amphibolite on soil chemistry were recorded.

Keywords: soil; mountains; acidification; soil chemistry; fertilization; slow-release amendments; *Picea abies*

Soils are the crucial component of forest ecosystems and their condition is closely interlinked with the health of forest stands. Forest ecosystems and forest soils in many regions of the globe were adversely affected by acidic air pollution (De Hayes et al. 1999) and acidification of forest soils is a serious problem also in the Czech Republic (Borůvka et al. 2005).

In fact, in the 1970s and 1980s the mountains situated in the northern part of the Czech Republic (northern Bohemia) experienced an extreme air-pollution load consisting dominantly of SO_2, NO_x (Křeček, Hořická 2006; Hrkal et al. 2009) and particulates that triggered a large-scale forest dieback in the most exposed mountain parts. The spruce stands in the Ore Mts. (Krušné hory) and Jizera Mts. (Jizerské hory) were the most affected ones (Šrámek et al. 2008; Lomský et al. 2011). The naturally acidic and poor forest soils on mountain sites in the region were further acidified by the pollutants with all the adverse consequences such as depletion of base cations, decrease in pH, development of lower quality humus and Al mobilization (Borůvka et al. 2005).

In spite of the significant reduction in the emission of air pollutants after 1989 (Hůnová et al. 2004), some acidification processes still continue in the region up to the present time (Hrkal et al. 2012).

It was often a difficult task to replant the large clear-felled tracts left after the mountain forests disturbed by air pollution. Impoverished and acidified soils as well as harsh climate of open clear-felled areas in the summit mountain parts constituted an extraordinarily unfavourable environment for young forest plantations. A prompt replanting was, however, essential (Kuneš et al. 2013a) to avert an accelerated mineralization of surface hu-

Supported by the Ministry of Agriculture of the Czech Republic, Project No. QH92087, Nadace pro záchranu a obnovu Jizerských hor Foundation, Projects No. ZGP 05/2006 and 090105 and by the Czech University of Life Sciences Prague, Projects CIGA No. 20114314 and No. 20124304

mus and further soil nutrient losses resulting from the absence of a closed forest protecting and sheltering the sites (Vacek et al. 2003; Podrázský 2006). To support the growth and survival of young forest plantation under harsh conditions, some slow-release initial fertilizing improving the soil chemistry was often recommended. In the Czech Republic the use of basic rocks has had a long tradition in counteracting the acidification, amelioration of degraded sites and providing the initial support for forest plantations (Němec 1956; Lhotský et al. 1987; Nárovec, Šach 1994).

Nonetheless, the aerial liming of the forest floor may inadequately increase the decay of surface humus and reduce a humus store in the soil (Kreutzer 1995). Liming can promote a leaching of dissolved organic nitrogen from the uppermost layers of soil (Nilsson et al. 2001) and possibly even result in soil N losses (Persson et al. 1995) in particular if a vital forest stand is absent. From this viewpoint the aerial liming or fertilization of large clear-cut tracts appears risky especially on plots without functioning sheltering forest cover (Nohrstedt 2001; Podrázský, Ulbrichová 2003).

For this reason an experiment was established in the Jizerské hory Mts., in which young Norway spruces were fertilized at planting with an amphibolite powder. The powder was incorporated directly into the soil inside the planting holes of spruces to receive an initial support with minimum risk for environment on the site. The impacts of this treatment on the survival rate, growth and nutrition of the experimental plantation as well as on the biomass and nutrient accumulation of spruce trees were already assessed (Kuneš et al. 2013a, b).

The aim of the present study was to evaluate the influence of the amphibolite powder on soil chemistry inside the planting holes and in the adjacent soil.

MATERIAL AND METHODS

Site. The experiment was installed on a clear-felled area in the Czech part of Jizerské hory Mts. at an altitude of 960 m on a southwest-facing slope of the Střední Jizerský hřeben ridge (lat. 50°49'39''N, long. 15°21'16''E), see e.g. Balcar et al. (2005). The annual mean temperature was 5.1°C (1996–2007) and the annual mean precipitation was 1,093 mm (1994–2007) on the site. The average air SO_2, NO_2, O_3 concentrations in the post-air-pollution period are 4 μg·m^{-3} (2005–2008), 5 μg·m^{-3} (2006–2008) and 102 μg·m^{-3} (2003–2008), respectively (Balcar et al. 2009).

The bedrock was biotitic granite. The soil was determined as a well-drained mountain humus podzol, or Umbri Placic Podzol (FAO 2006). Stratification: L (0–2 cm) integrated into a greensward, F (2–8 cm), H (8–12 cm), Ah (12–13 cm), Ep (13–17 cm), B (17+ cm). The herbaceous vegetation was dominated by *Calamagrostis villosa* (Chaix) J.F. Gmelin. (Kuneš et al. 2006).

Experimental plantation. Four-year-old transplants of Norway spruce (*Picea abies* [L.] Karst.) were planted in the spring of 1994. The plant spacing was 1 × 2 m (Kuneš et al. 2013b). Two treatments are compared in the present study: unfertilized control (CON) and amphibolite treatment (AMT).

In the AMT, 2 kg of finely ground amphibolite powder was incorporated into the soil inside the planting holes (35 × 35 × 25 cm) of each tree, when the experimental plantation was being established. The chemical composition and granularity of the amphibolite powder are summarized in Tables 1 and 2.

Soil sampling. In 2006, we executed a juvenile thinning in the experimental plantation and harvested also several spruce sample trees to analyse them for biomass and nutrients (Kuneš et al. 2013a). The juvenile thinning gave us the opportunity to conduct a detailed soil sampling in the immediate proximity of the harvested trees and take the samples of soil also from the space of planting holes. The soil sampling took place in September 2007. We used a soil corer (penetration rod) with inside diameter of 35 mm and the soil was sampled to a depth of 20 cm.

The sampling was conducted in the space between the NE-SW oriented rows of planted spruces. To evaluate the influence of applied amendment on the soil not only in the planting holes but also in the close surroundings of trees, we sampled the soil

Table 1. Chemical composition of the amphibolite powder

Component	Concentration (%)
CaO	11.11
MgO	7.31
K_2O	0.23
P_2O_5	0.18
Al_2O_3	14.45
Fe_{tot}	12.29
MnO	0.20
S_{tot}	0.18

Table 2. Granularity of the amphibolite powder

Particle size (mm)	Proportion (%)
> 0.6300	0.00
0.0315–0.6300	0.36
0.2500–0.3150	1.08
0.1000–0.2500	7.23
0.0900–0.1000	22.60
0.0710–0.0900	6.78
0.0340–0.0710	16.73
0.0260–0.0340	9.48
0.0180–0.0260	9.29
0.0090–0.0180	12.39
0.0040–0.0090	1.61
0.0035–0.0040	6.69
0.0018–0.0035	3.34
0.0009–0.0018	1.43
< 0.0009	0.99

in the AMT from three different sampling zones. The soil cores from the "A" zone were taken directly from the planting holes. The soil cores from the "B" zone were taken at a distance of 40 cm from the nearest planting hole centre. Finally, the soil cores from the "C" zone were taken at a distance of 80 cm from the nearest planting hole centre.

In the untreated CON we distinguished only two sampling zones: "A" zone (interior of planting holes) and "C" zone (soil outside the planting holes at a distance of 80 cm from the planting hole centres). Altogether we defined 5 combinations of the treatments and sampling zones, let us call them sampling positions for further reference. Fifteen composite samples were taken in each of the five sampling positions. One composite sample consisted of ca 6–8 soil cores (Table 3).

Since the soil inside the planting holes was intermixed by digging the planting holes and planting the spruces (as well as by incorporation of the amphibolite in the AMT), the surface humus and mineral horizons were not distinguished in the sampled cores. To retain uniformity in sampling, the 0–20 cm soil cores thus contained the mineral soil as well as the surface humus except for the L layer in all the sampling positions of the control and amphibolite treatments, respectively. The L layer was removed from the cores because it was inseparably integrated into a greensward.

Because we took the soil cores also outside the planting holes, where the soil horizons were intact, we measured the thickness of surface humus (F+H layers) in each core. In this way we examined whether the thickness of surface humus (the proportion of surface humus and mineral soil) did not significantly differ between the cores taken in particular sampling positions outside the planting holes. The mean thickness of surface humus in the examined sampling positions (AMT-B, AMT-C, CON-C) was comparable and also the statistical analysis did not reveal any significant differences (Table 3). Note to say that the thickness of surface humus in the cores was partly reduced by a compression as the sampling corer was being rammed to the soil. Therefore, the values in Table 3 are lower than the real thickness of intact humus layers described in the previous text concerning the stratification of soil on the site.

Laboratory analyses. Chemical analyses of soil samples were conducted in accordance with standard methods of ICP Forest (Cools, De Vos 2010). The air-dried fine soil consisting of particles less than 2 mm was used for the analyses.

Table 3. List of sampling positions and their codes, number of samples taken in particular sampling positions and mean values of compressed humus layer in particular sampling positions (n = 15)

Treatment		Sampling zone	Code of sampling position	Thickness of compressed* humus layers (cm)	
Control (CON)	A	inside planting hole	CON-A	mean (SD)	–
	C	80 cm from the planting hole centre	CON-C		8.2^{a} (3.20)
Amphibolite (AMT)	A	inside planting hole	AMT-A		–
	B	40 cm from the planting hole centre	AMT-B		8.5^{a} (2.91)
	C	80 cm from the planting hole centre	AMT-C		8.3^{a} (3.25)

letter indexes express the results of statistics: the mean values of compressed humus thickness in particular sampling positions in the area of intact soils (outside the planting holes) are not significantly different from each other at α = 0.05, *humus thickness in the cores was partly compressed by ramification of the sampling corer to the soil

The pH of the soil was potentiometrically measured in the supernatant suspension of 1:5 (volume fraction). This liquid was made up of deionised water for $pH_{(H_2O)}$ or a 0.01 mol·l^{-1} solution of calcium chloride in water for $pH_{(CaCl_2)}$.

The concentrations of C_{tot}, N_{tot} and S_{tot} in soil were determined by a thermal combustion method using VarioMAX CNS (Elementar Analysensysteme GmBH, Hanau, Germany).

Concentrations of the exchangeable basic cations K, Ca and Mg and the exchangeable Al were determined in the 0.1 mol·l^{-1} barium chloride extract of the soil using spectrometry. Savant AA Σ atomic absorption spectrometer (GBC Scientific Equipment Ltd., Braeside, Australia) was used.

To determine exchangeable acidity, the 0.1 mol·l^{-1} barium chloride extract was titrated with a 0.05 mol per litre NaOH solution up to pH = 7.8.

The chemical analyses were conducted in the Laboratories of Forest and Game Management Research Institute (FGMRI Strnady).

Statistical analyses. The chemical soil properties and also the values of the thickness of surface humus in the soil cores were statistically analysed using the Kruskal-Wallis procedure (heteroscedasticity of data) with post-hoc multiple comparisons (Dunn's test). The STATISTICA 8.0 (StatSoft, Inc.) software was used for the statistical procedures, which were described by Hill and Lewicki (2006). The confidence level of 95% was chosen in all statistical tests.

RESULTS

Fourteen growth seasons since planting, the amphibolite powder was still keeping the $pH_{(H_2O)}$ and $pH_{(CaCl_2)}$ in the AMT-A significantly increased compared to the other sampling positions (Fig. 1). This effect of amphibolite on soil pH was confined to the space inside the planting holes. The distance from planting hole centres (sampling zone A vs. B and C) had no effect on soil pH, since otherwise there were no significant differences between the remaining sampling positions (AMT-B, AMT-C, CON-A and CON-C).

As for C_{tot}, N_{tot} and S_{tot}, the statistical analyses did not reveal any significant differences between the compared sampling positions (Fig. 2a). Slightly higher values of all three properties were, however, noticeable for the AMT-B and AMT-C.

In 2007 the amphibolite powder kept the concentration of exchangeable P inside the planting holes (AMT-A) significantly increased in comparison with the other sampling positions (CON-A, CON-C, AMT-B and AMT-C), (Fig. 2b).

Surprisingly, the concentration of exchangeable K inside the planting holes of trees that were fertilized with the amphibolite (AMT-A) was the lowest of all sampling positions, although the differences in K concentrations between particular sampling positions were neither large nor significant irrespectively of the treatment (Fig. 2b).

In terms of statistics, also the exchangeable Mg concentrations did not show any significant differences between the sampling positions (Fig. 2b). Nonetheless, the samples taken outside the planting holes of the amphibolite treatment (AMT-B and AMT-C) showed noticeably increased values compared to both the sampling positions in the control (CON-A and CON-C, respectively).

The concentration of exchangeable Ca (Fig. 3) in the AMT-A was significantly raised in comparison with both the sampling positions situated in the control treatment (CON-A and CON-C). The Ca concentration was increased also outside the planting holes of the amphibolite treatment (AMT-B and AMT-C). In comparison with CON-C (100%) the concentrations in the AMT-B and AMT-C were increased by 31% and 18%, respectively. Nevertheless, the statistics did not interpret the differences among CON-C, AMT-B and AMT-C as significant.

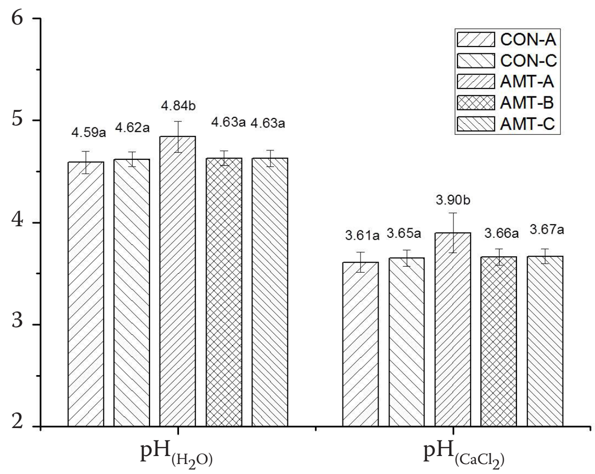

Fig. 1. Soil reaction in the particular sampling positions (see Table 3) in September 2007

CON-A – control sampled inside planting holes, CON-C – control sampled outside planting holes, AMT-A – amphibolite treatment sampled inside planting holes, AMT-B – amphibolite treatment sampled 40 cm from the planting hole centres, AMT-C – amphibolite treatment sampled 80 cm from the planting hole centres; mean values of soil properties in particular sampling positions followed by the same letters are not significantly different from each other at α = 0.05; error bars depict the sample standard deviations

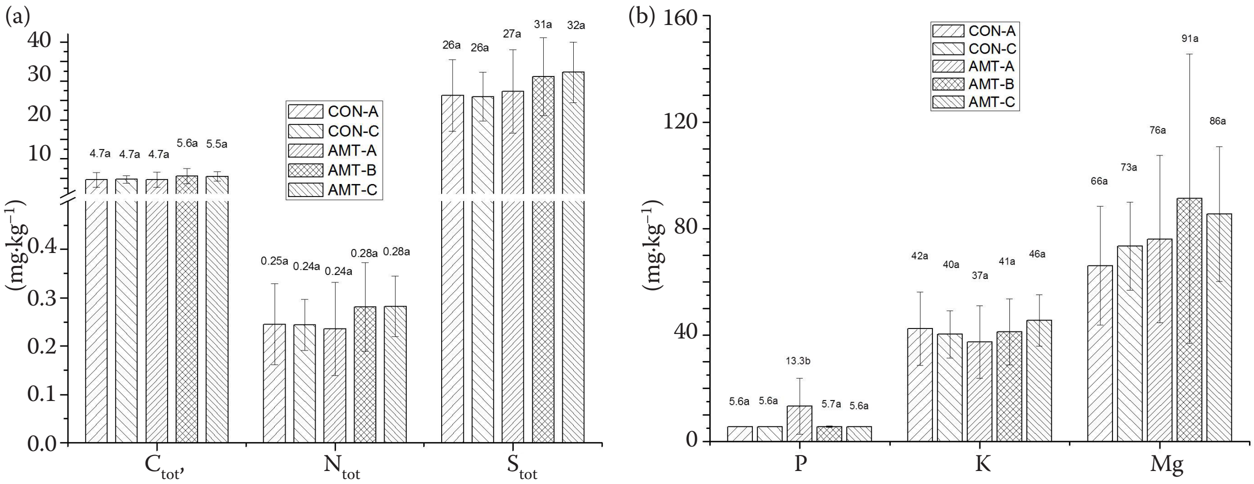

Fig. 2. (a) Total soil carbon, nitrogen and sulphur in the particular sampling positions, (b) available phosphorus (P), potassium (K) and magnesium (Mg) concentrations in the particular sampling positions (see Table 3) in September 2007

CON-A – control sampled inside planting holes, CON-C – control sampled outside planting holes, AMT-A – amphibolite treatment sampled inside planting holes, AMT-B – amphibolite treatment sampled 40 cm from the planting hole centres, AMT-C – amphibolite treatment sampled 80 cm from the planting hole centres; mean values of soil properties in particular sampling positions followed by the same letters are not significantly different from each other at $\alpha = 0.05$; error bars depict the sample standard deviations

Although there was some reduction in exchangeable Al in the AMT-A and AMT-C, the statistical procedures did not classify this reduction in relation to the values recorded in the other sampling positions (CON-A; CON-C and AMT-B) as significant (Fig. 3).

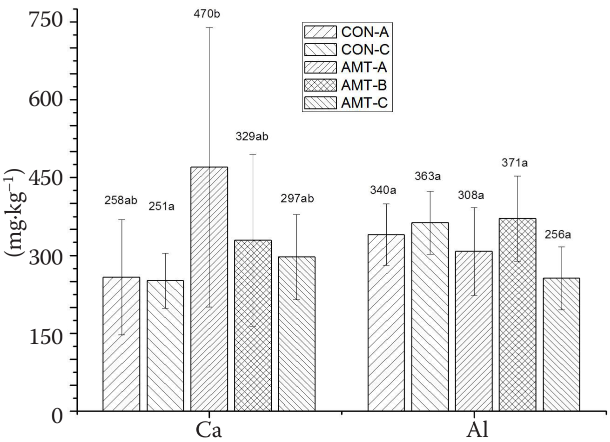

Fig. 3. Available Ca and exchangeable Al concentrations in the particular sampling positions (see Table 3)

CON-A – control sampled inside planting holes, CON-C – control sampled outside planting holes, AMT-A – amphibolite treatment sampled inside planting holes, AMT-B – amphibolite treatment sampled 40 cm from the planting hole centres, AMT-C – amphibolite treatment sampled 80 cm from the planting hole centres; mean values of soil properties in particular sampling positions followed by the same letters are not significantly different from each other at $\alpha = 0.05$; error bars depict the sample standard deviations

DISCUSSION

The significantly increased soil reaction inside the planting holes of the fertilized treatment (AMT-A) documented a long-lasting neutralizing effect of the amphibolite (Fig. 1) influencing the soil chemistry fourteen seasons after the application of the pulverised rock. However, the difference in terms of absolute values of $pH_{(H_2O)}$ and $pH_{(CaCl_2)}$ was not great in 2007, which probably indicated a diminishing of the amendment effects.

There are available still unpublished data on soil chemistry inside the planting holes of an experimental elm (*Ulmus glabra* Huds.) plantation established on the same site that support the diminishment hypothesis. The crushed amphibolite was incorporated into the soil inside the planting holes of elms at the same dose as the amphibolite in our spruce plantation. Four growth seasons since planting the elms, $pH_{(H_2O)}$ inside the fertilized planting holes was by 2 units higher than $pH_{(H_2O)}$ in the untreated control, eight years since planting, the difference was already only 0.71 unit.

It is probable that $pH_{(H_2O)}$ and $pH_{(CaCl_2)}$ in our experiment developed analogously as in the case of elm and the difference between the control and amphibolite was slowly decreasing up to the reported year.

The slightly higher C_{tot}, N_{tot} and S_{tot} concentrations in the intact soil outside the planting holes of the amphibolite treatment (AMT-B, AMT-C) in comparison with the control (CON-A and CON-C) might indicate a raised organic matter accumulation in soil due to an increased litter supply by fertilized trees. The biomass of foliage, branches and twigs and roots was higher in the case of trees fertilized by amphibolite than in the control ones (Kuneš et al. 2013a) and we can therefore expect that also the quantity of the aboveground litter and root biomass and necromass produced by fertilized trees were higher. This assumption is supported also by literature (e.g. Leppälammi-Kujansuu et al. 2013) and suggested by the gently higher thickness of surface humus layer in the soil cores (Table 3). However, since neither the differences in C_{tot}, N_{tot} and S_{tot} concentrations nor the differences in the compressed humus layer were significant, no final conclusions can be drawn at this moment.

The applied amphibolite even fourteen growth seasons since planting kept a significantly raised concentration of available P in the planting holes of fertilized spruces (Fig. 2b). Phosphorus is a limited macroelement in the nutrition of spruces on the experimental site (Balcar, Kacálek 2008; Kuneš et al. 2013b) as well as elsewhere in the Jizerské hory Mts. (Špulák 2009; Lomský et al. 2011). Therefore, this effect of amphibolite might be important despite being limited to the space of planting holes. On the contrary, the confinement of the increased P concentration to the space of planting holes might have been advantageous since the competing weed growing around the planted trees (outside planting holes) could not utilize the raised P supply whereas the spruces, when planted, had P containing amendment at disposal directly in their rhizosphere.

However, we suspect that in 2007 the soil exchangeable P concentration in the planting holes of fertilized trees (AMT-A), despite still being significantly higher than in the other sampling positions, was no longer sufficient to ensure the better nutrition of spruces. Our suspicion is based on the fact that the foliar P concentration of fertilised spruces was not influenced by amphibolite in 2007 and dropped to the deficiency limit (Kuneš et al. 2013b).

Surprisingly, exchangeable K was the lowest in the planting holes of the fertilized trees (AMT-A) from all the sampling positions in both compared treatments, although the amphibolite powder contained K (Fig. 2b). The total amount of K bound in the biomass of trees in the control and amphibolite treatments is not so much different (Kuneš et al. 2013a) to fully explain the differences in the soil exchangeable K concentration. Moreover, the soil inside the planting holes of the control trees showed a higher exchangeable K concentration than the soil around them (an opposite pattern to the amphibolite treatment). The high mobility of K (Binkley 1986) and leaching of the element from the soil and foliage might have played a role as well as different exchangeability of K in different chemistry regimes.

Different chemistry (pH etc.) in the planting holes of trees in the amphibolite treatment might have promoted the fixation of K in the soil and thus perhaps partly reduced the extraction of K by the $BaCl_2$ solution.

Possibly a part of K taken up by spruces from the fertilized planting holes during the years since planting might have been leached from the spruce foliage to the zone around the planting holes. Also the litterfall (needles, twigs) and root necromass containing K from the amendment might have contributed to an increased K concentration around the fertilized planting holes. The belowground litter (the necromass of large quantities of annually dying fine roots) might constitute a significant contribution to biomass and element pools and cycling (Feger 1997).

The differences in exchangeable K between sampling positions were not significant. Therefore, we cannot exclude also the eventuality that the differences simply rest in the variability of soil and laboratory outcomes.

In general and as expected, the concentration of the soil exchangeable Mg in the amphibolite treatment was higher than in the control despite the difference not being significant (Fig. 2b). Nonetheless, the low concentration of Mg in the planting holes of the amphibolite treatment (AMT-A) was rather puzzling, since it was lower than Mg concentration in the surrounding soil. Because the soil inside the planting holes of amphibolite treatment was mixed with the Mg containing amendment, the high variability of Mg content data might be an explanation for this somewhat surprising result. Nonetheless, the Mg uptake by trees and Mg leaching from soil might also have played an important role in this regard. Nihlgård et al. (in Lundell et al. 2001) suggested that the excess of Ca ions from a basic amendment during years since liming can displace the Mg from the exchange sites. The subsequent leaching of Mg during many years of Ca excess might cause the supplies of Mg in the soil to decline (Lundell et al. 2001).

The concentration of soil exchangeable Ca was the highest in the space of planting holes of the amphibolite treatment (AMT-A), see Fig. 3. This finding corresponds with soil pH and documents the long-lasting effects of crushed amphibolite on some soil properties inside planting holes. In fact, the Ca concentration was increased also outside the planting holes of the amphibolite treatment (AMT-B and AMT-C), which indicates an overlap of the direct and indirect treatment effects on the immediate surroundings of the planting holes.

From the bar charts (Fig. 3) it is evident that the exchangeable Ca concentration dropped with increasing distance from the planting hole centres. We suppose that the soil exchangeable Ca concentration in the AMT-B (i.e. ca 40 cm from the planting hole centres and 15–22.5 cm from the planting hole boundaries, respectively) was raised by two mechanisms. On the one hand it was a direct diffusion of Ca ions to the soil in the immediate proximity of the planting holes, and on the other hand it was an indirect input of Ca through a decomposition of the aboveground litter and root necromass of the fertilised spruces. A role was possibly played also by a "contamination" of the site by crushed amphibolite and its dust when the amendment was being applied.

Calcium is generally a less mobile element in comparison with e.g. K or Mg (Binkley 1986; Kreutzer 1995; Ponette et al. 1997). For this reason we suppose that the indirect mechanisms (decomposition of the aboveground and belowground litter) and "contamination" of the site by amphibolite dust since plantation establishment dominantly contributed to the gentle increase of exchangeable soil Ca in the AMT-C sampling position.

Although in 2007 the differences were not significant in terms of statistics, the crushed amphibolite was keeping the concentration of soil exchangeable Al in the planting holes of the amphibolite treatment (AMT-A) gently reduced in comparison with the soil in the planting holes of the control (CON-A), in spite of the fact that the amendment contained Al_2O_3 (Fig. 3). This was probably a result of increased pH and raised concentration of Ca in soil (positive influence of Ca on base saturation). It was documented that the basic amendments containing Ca and Mg are able to reduce the mobility of Al (Kreutzer 1995), although chemical soil properties, various processes in soil and time might play a role in this regard (Guo et al. 2004).

With statistical significance, the amphibolite raised soil pH, concentration of available phosphorus, and concentration of exchangeable Ca. As for other assessed soil properties, fourteen growth seasons since planting, the effect of amphibolite were no longer significant even inside the planting holes.

In general, we can suggest that the influence of the amphibolite applied in 1994 was already vanishing in 2007. This assumption is supported by the comparison of soil chemical properties in the particular sampling positions and considering the growth response of the fertilised spruces in the period from 1994 to 2006 (Kuneš et al. 2013b).

CONCLUSIONS

Fourteen growth seasons after application the effects of the pulverised amphibolite (incorporated into the soil inside the planting holes when the trees were planted) were not marked despite being detectable. In comparison with the control, the soil in the planting holes of the amphibolite treatment showed significantly higher soil reaction, concentration of available phosphorus and partially also concentration of exchangeable Ca. All the significant effects of amphibolite were confined to the soil inside the planting holes. No significant undesirable effects of the amphibolite on the assessed soil properties were recorded. The C_{tot} and N_{tot} concentrations in the intact soil outside the planting holes were even slightly (not significantly) increased in the fertilized treatment. In general the amendment effects seemed to be already vanishing.

Acknowledgements

The study was conducted on the Jizerka research plot established by Forestry and Game Management Research Institute, Strnady. The samples for chemical analyses were prepared at the Truba research station (Czech University of Life Sciences Prague), chemical analyses were conducted in the Department of testing laboratories of the Forestry and Game Management Institute, Strnady. Sincere thanks are accorded to Václav Nárovec for the specified information on the granularity of the pulverised amphibolite.

References

Balcar V., Kacálek D. (2008): Growth and health state of silver fir (*Abies alba* Mill.) in the ridge area of the Jizerské hory Mts. Journal of Forest Science, ***54***: 509–518.

Balcar V., Kacálek D., Kuneš I., Podrázský V. (2005): Jizerka study area. In: Neuhöferová P. (ed.): Forestry Management in the Jizerské hory Mts. Field Trip. Jizerské hory Mts., Czech University of Agriculture Prague and Forestry and Game Management Reseach Institute: 11–19.

Balcar V., Kacálek D., Kuneš I. (2009): Vývoj kultury jilmu horského (*Ulmus glabra* Huds.) v hřebenové poloze Jizerských hor. [Scotch elm (*Ulmus glabra* Huds.) plantations prosperity in ridge part of the Jizerské hory Mts.] Zprávy lesnického výzkumu, ***54***: 3–8.

Binkley D. (1986): Forest Nutrition Management. New York, Chichester, Brisbane, Singapore, John Wiley & Sons: 290.

Borůvka L., Mládková L., Drábek O. (2005): Factors controlling spatial distribution of soil acidification and Al forms in forest soils. Journal of Inorganic Biochemistry, ***99***: 1796–1806.

Cools N., De Vos B. (2010): Sampling and Analysis of Soil. Manual Part X. In: Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Hamburg, UNECE, ICP Forests: 208.

De Hayes D.H., Schaberg P.G., Hawley J., Strimbeck G.R. (1999): Acid rain impacts on calcium nutrition and forest health. Alteration of membrane-associated calcium leads to membrane destabilization and foliar injury in red spruce. BioScience, ***49***: 789–800.

FAO (2006): World Reference Base for Soil Resources 2006. A Framework for International Classification, Correlation and Communication. Rome, Food and Agriculture Organisation of The United Nations: 132.

Feger K.H. (1997): Biogeochemistry of magnesium in forest ecosystems. In: Hüttl R.F., Schaaf W. (eds): Magnesium Deficiency in Forest Ecosystems. Dordrecht, Kluwer Academic Publishers: 67–100.

Guo J., Vogt R.D., Zhang X., Zhang Y., Seip H.M., Tang H. (2004): Ca-H-Al exchanges and aluminium mobility in two Chinese acidic forest soils: a batch experiment. Environmental Geology, ***45***: 1148–1153.

Hill T., Lewicki P. (2006): Statistics: Methods and Applications. Tulsa, Statsoft: 832.

Hrkal Z., Fottová D., Rosendorf P. (2009): The relationship between quality of ground waters and Forest cover in regions affected by high levels of acid atmospheric deposition – a case study of the Krušné Hory Mts., Czech Republic. Polish Journal of Environmental Studies, ***18***: 995–1004.

Hrkal Z., Burda J., Fottová D., Hrkalová M., Nováková H., Novotná E. (2012): Groundwater quality development in area suffering from long term impact of acid atmospheric deposition – the role of forest cover in Czech Republic case study. In: Voudouris K. (ed.): Water Quality Monitoring and Assessment. Shanghai, InTech: 561–584.

Hůnová I., Šantroch J., Ostatnická J. (2004): Ambient air quality and deposition trends at rural stations in the Czech Republic during 1993–2001. Atmospheric Environment, ***38***: 887–898.

Kreutzer K. (1995): Effects of forest liming on soil processes. Plant and Soil, ***168–169***: 447–470.

Křeček J., Hořická Z. (2006): Forests, air pollution and water quality: influencing health in the headwaters of Central Europe's "Black Triangle". Unasylva, ***57***: 46–49.

Kuneš I., Vykypělová E., Möllerová J., Šedlbauerová J., Fritscherová H., Kohoutová J., Benešová T., Zadina J. (2006): Bylinné patro v rámci výsadeb smrku ztepilého na chemicky meliorovaných plochách horského imisního stanoviště Jizerka. [Herb layer community under a young Norway spruce plantation and its response to chemical amelioration at the Jizerka air-polluted mountain site.] Zprávy lesnického výzkumu, ***51***: 219–229.

Kuneš I., Zahradník D., Balcar V., Špulák O., Baláš M., Koňasová T., Kacálek D., Vítámvás J., Jančová A., Nováková O., Millerová K. (2013a): Effects of fertilisation on biomass of Norway spruce on a harsh mountain site. Journal of Forest Science, ***59***: 8–21.

Kuneš I., Baláš M., Balcar V., Kacálek D., Millerová K., Jančová A., Nováková A., Špulák O., Zahradník D., Vítámvás J., Koňasová T. (2013b): Effects of fertilisation on growth and nutrition of Norway spruce on a harsh mountain site. Journal of Forest Science, ***59***: 306–318.

Leppälammi-Kujansuu J., Salemaa M., Kleja D.B., Linder S., Helmisaari H.S. (2013): Fine root turnover and litter production of Norway spruce in a long-term temperature and nutrient manipulation experiment. Plant and Soil, ***374***: 73–88

Lhotský J., Ferda J., Herynek J., Materna J., Pokorný P., Švarc B. (1987): Degradace lesních půd a jejich meliorace. [Forest Soil Degradation and their Reclamation.] Praha, SZN: 240.

Lomský B., Šrámek V., Novotný R. (2011): Changes in the air pollution load in the Jizera Mts.: effects on the health status and mineral nutrition of the young Norway spruce stands. European Journal of Forest Research, ***131***: 757–771.

Lundell Y., Johanisson C., Högberg P. (2001): Ion leakage after liming or acidifying fertilization of Sweedish forests – a study of lysimeters with or without active tree roots. Forest Ecology and Management, ***147***: 151–170.

Nárovec V., Šach F. (1994): Přehled poznatků o využívání silikátových horninových mouček k zúrodňování půd a hnojení lesních kultur v České republice. [Overview on the application of pulverised silicate rocks for soil amelioration and fertilisation of young forest plantations in the Czech Republic.] Opočno, VÚLHM: 18.

Němec A. (1956): Meliorace degradovaných lesních půd. [Reclamation of Degraded Forest Soils.] Praha, SZN: 291.

Nilsson S.I., Andersson S., Valeur I., Persson T., Johan B., Wirén A. (2001): Influence of dolomite lime on leaching and storage of C, N and S in a Spodosol under Norway spruce (*Picea abies* (L.) Karst.). Forest Ecology and Management, ***146***: 55–73.

Nohrstedt H.Ö. (2001): Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of swedish experiences. Scandinavian Journal of Forest Research, ***16***: 555–573.

Persson B., Rudebeck A., Wirén A. (1995): Pools and fluxes of carbon and nitrogen in 40-year-old forest liming experiments in Southern Sweden. Water, Air, and Soil Pollution, ***85***: 901–906.

Podrázský V. (2006): Logging and forest decline effects on the surface humus horizons in the Šumava Mts. Journal of Forest Science, ***52***: 439–445.

Podrázský V., Ulbrichová I. (2003): Surface liming of immission clear-cuts: benefits and risks. Ekológia, ***22***: 277–283

Ponette Q., Dufey J.E., Weissen F. (1997): Downward movement of dolomite, kieserite or a mixture of $CaCO_3$ and kieserite through the upper layers of an acid forest soil. Water, Air, and Soil Pollution, ***95***: 353–379.

Špulák O. (2009): Produkční potenciál mladého porostu smrku pichlavého a akumulace živin v nadzemní biomase. [Production potential of blue spruce young stand and nutrient accumulation in the aboveground biomass]. Zprávy lesnického výzkumu, ***54***: 85–91.

Šrámek V., Slodičák M., Lomský B., Balcar V., Kulhavý J., Hadaš P., Pulkráb K., Šišák L., Pěnička L., Sloup M. (2008): The Ore Mountains: will successive recovery of forests from lethal disease be successful? Mountain Research and Development, ***28***: 216–221.

Vacek S., Podrázský V., Mikeska M., Moser W.K. (2003): Introskeletal erosion threat in mountain forests of the Czech Republic. Journal of Forest Science, ***49***: 313–320.

Received for publication November 21, 2013
Accepted after corrections February 13, 2014

Corresponding author:

Ing. Martin Baláš, Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Department of Silviculture, 165 21 Praha 6–Suchdol; e-mail: balas@fld.czu.cz, mar.balas@seznam.cz