Effects of fertilisation on growth and nutrition of Norway spruce on a harsh mountain site

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ABSTRACT: We evaluated the potential of crushed amphibolite and artificial slow-release N-P-K-Mg fertiliser to stimulate the survival, growth and nutrition of Norway spruce planted on an acidified air-polluted mountain site. Control plots and treatments with slow-release fertiliser (SRF) and amphibolite (AMT) were installed. In the SRF, forty grams of tabletted amendment were applied in the close vicinity of the trees. In the AMT, two kilograms of amendment were incorporated into the soil inside the planting hole of each tree at planting. The SRF application resulted in a significant growth stimulation of spruces. The growth stimulation by amphibolite was perceptible but not significant; this amendment, however, significantly reduced mortality. None of the amendments induced marked changes in foliar nutrient concentrations.

Keywords: fertilization; nutritional status; *Picea abies*; survival

The mountain forest ecosystems in northern and north-western Bohemia (Czech Republic) were heavily disrupted by air pollution during the 1970s and 1980s (Filipiak, Ufnalski 2004; Vacek 2003). The forests stands in the most exposed summit parts of the air-polluted mountains often succumbed to combined anthropogenic and environmental stresses (Kandler, Innes 1995; Křeček, Hořická 2006) and large clear-felled tracts arose as a result of damage to forests and efforts to utilise timber from the affected stands. The enormous deposition levels of S (Hrkal 2004; Jezierski et al. 2006) and to also N compounds (Křeček, Hořická 2006) emitted by thermal power plants in the "Black Triangle" region have been considered to be the trigger mechanism of that large-scale disaster disintegrating the mountain forests in the area. Desulphurisation of power plants and attenuation of heavy industry in the 1990s resulted in a reduction of S load in the region (Filipiak, Ufnalski 2004; Hrkal et al. 2009) and improved the prospects for surviving forests as well as new plantations.

To avert excessive mineralisation of surface humus and soil nutrient losses (Podrázský 2006) a prompt replanting of the clear-felled tracts was essential.

The depleted acidified soils and harsh microclimate of clear-felled tracts in the mountain environment made replanting of these tracts very difficult. To address this problem, several field experiments were established to evaluate the potential of fertilisation for promoting the growth and survival of various tree species during the critical initial phase after their planting on such sites (Balcar,

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Kacálek 2008; Balcar et al. 2011; Kuneš et al. 2011; Koňasová et al. 2012).

Our study evaluates the effects of (a) slow-release fertiliser based on Ureaform (Alexander, Helm 1990) and potassium-magnesium phosphates and (b) finely ground amphibolite powder on vitality, growth and foliar nutritional status of a young Norway spruce plantation in the harsh environment of an air-polluted mountain site.

The assessed hypothesis is that the application of amendments directly to the trees might promote the survival and growth of spruce plantation and thus expedite its canopy formation on a site prone to losses of soil organic matter.

MATERIALS AND METHODS

Site description

The referred experiment was installed on a clear-felled area in the Czech part of the Jizerské hory Mts. at an altitude of 960 m a.s.l. on a southwest-facing slope of the Střední Jizerský hřeben ridge (50°49'39''N,15°21'16''E). The annual mean temperature was 5.1°C (1996–2007) and the annual mean precipitation was 1,093 mm (1994–2007) on the site (Balcar, Kacálek 2008).

The bedrock is formed of biotitic granite. The soil was determined as a mountain humus podzol (Umbri Placic Podzol according to the FAO terminology). The soil is well-drained. Stratification: L (0–2 cm), F (2–8 cm), H (8–12 cm), Ah (12–13 cm), Ep (13–17 cm), B (17+ cm).

The average air SO_2, NO_2, O_3 concentrations in the post-air-pollution period are 4 μg·m^{-3} (2005 to 2008), 5 μg·m^{-3} (2006–2008) and 102 μg·m^{-3} (2003–2008), respectively (Balcar, Kacálek 2008).

Experimental plantation and biometric measurements

The experiment consists of 9 plots (10 × 10 m) arranged in a Latin square design with three treatments and three replications. On each plot, there were 50 four-year-old transplants of Norway spruce (*Picea abies* [L.] Karst.) planted at a spacing of 1 × 2 m in the spring of 1994. The planting stock originated from the Beskydy Mts. (northeastern Moravia, Czech Republic). Treatment no. 1 was control (CON) with no amendments applied, treatment no. 2 was slow-release fertiliser (SRF), and treatment no. 3 was amphibolite treatment (AMT).

In the SRF, four tablets (40 g altogether) of the Silvamix Forte® slow-release fertiliser (Ecolab Znojmo Ltd., Znojmo) were applied per each tree in the spring of 1997 (i.e. 3 years after planting). The fertiliser contained 17.5% of P_2O_5, 10.5% of K_2O, 9.0% of MgO and 17.5% of N compounds (60% of total nitrogen derived from methylene urea, P and K present in potassium-magnesium phosphate). The characteristics of the methylene urea-based fertilisers were described e.g. by Jahns et al. (1999). The SRF tablets were regularly placed in a circle around the trees, approximately 30 cm from the stem and 5–10 cm under the soil surface.

In the AMT, 2 kg of finely ground amphibolite powder were incorporated into the soil inside a planting hole (35 × 35 × 25 cm) of each tree, when the experimental plantation was established. We received some new authentic information on the origin, granularity and chemical composition of the used amphibolite (Nárovec 2013, personal communication). The amphibolite originated from a quarry in Libodřice (Central Bohemia), nonetheless, it was pulverised in a mill in Kunčice nad Labem (Northern Bohemia) to achieve a higher degree of fineness. Therefore, the granularity of the amphibolite powder was finer than reported in some earlier studies and the amphibolite parameters presented e.g. by Kuneš et al. (2013) should be revised here.

As for granularity, the particles over 0.63 mm in diameter absented and the pulverised amphibolite contained 1.44% of particles 0.25–0.63 mm, 7.23% of particles 0.1–0.25 mm, 22.6% of particles 0.09–0.1 mm, 6.78% of particles 0.071–0.09 mm, 16.73% of particles 0.034–0.071 mm and 45.22% of particles below 0.35 mm.

The amphibolite from Libodřice contained 11.1% of CaO, 7.31% MgO, 0.23% K_2O, 0.18% P_2O_5. It is probable that the amphibolite from Libodřice was contaminated by another amphibolite from Markovice near Čáslav, which was experimentally pulverised in the mill immediately before, and also by limestone.

Measurement accuracy

The tree heights were measured to the nearest 1 cm and crown diameter to the nearest 10 cm. The stem base diameter was measured with an accuracy of ±1 mm. The crown and stem base diameter were measured twice in two perpendicular directions and the mean was used for further calculations.

Sampling of assimilatory tissues

The nutritional status of plantations was assessed by means of foliar analyses of current-year needles. The sampling was carried out in the dormant (off-season) period. One annual (current-year) shoot from the sunned part of a crown was taken per each healthy tree in a particular treatment. The shoots were then pooled in the composite samples representing the compared treatments, dried and their needles after shedding were analysed. In the laboratory the needles were dried at 70°C until constant weight and afterward the concentrations of N, P, K, Ca, Mg and S in dry mass were determined. The applied analytic chemical methods were shortly summarised by Kuneš et al. (2012).

Assessment of nutritional status

For the purpose of our study the criteria defined by ICP Forests (Boháčová et al. 2003) were used for N, P, K, Ca and Mg. The limits presented by Granhus and Braekke (2001) were used for S.

Macronutrient ratios were evaluated using criteria summarised by de Vries (1998).

Statistical analysis

Mortality rates were assessed by means of a binomial test with subsequent multiple comparisons described e.g. by Anděl (1998).

Height increment, stem-base diameter and crown diameter were statistically analysed using the Kruskal-Wallis procedure with post-hoc multiple comparison (Dunn's test). The STATISTICA 8.0 (StatSoft, Inc., Tulsa, USA) software was used for this statistical procedure, which was described in detail by Hill and Lewicki (2006). The statistically processed files of mensurational characteristics consisted only of the data relating to the trees alive in the autumn of 2006. Data belonging to the trees dead in 2006 were retrospectively excluded.

Trends in the nutrition of plantations were evaluated using the linear-regression lines smoothing the macronutrient concentrations and macronutrient ratios recorded within a treatment in the years of sampling. For each macronutrient (or macronutrient ratio) and treatment, the existence of a significant divergence of the time axis and regression line representing a development in macronutrient concentration (or in macronutrient ratio) was examined. A proved divergence between the time axis and regression line of a certain macronutrient (or macronutrient ratio) gives a proof of a significantly increasing or decreasing linear trend of the macronutrient (or macronutrient ratio) in time. The methods were described by Anděl (1998) and were executed by S-Plus 6.1 (Insightful Corp., Reinach, Switzerland) software. The confidence level of 95% was chosen in all statistical tests.

RESULTS

Mortality rates

The lowest cumulative mortality rate (2006) was recorded in the AMT while in the CON and SRF it was more than twice as much (Table 1). As contrasted to the AMT, in the CON and SRF the annual mortality rates were elevated during the initial years after planting and indicated a post-planting shock. During the second part of the referred period, the annual mortality rates were low if any in all compared treatments.

Height growth

As for height growth (Table 2), the post-planting shock was detectable the second year after planting of the young trees to the air-polluted site. In 1995, the height increment values were, regardless of the treatment, ca by a half lower as compared to the first vegetation period. The spruces from the AMT began to recover from the growth depression already in 1996; the growth adaptation of the CON and SRF treatment lasted one year longer. It should be remembered at this point that the trees in the SRF were fertilised later, in the spring of 1997. Therefore, up to 1996 their growth was similar to that of control trees.

The growth stimulus induced by amphibolite, which had been applied at planting in 1994, found a significant expression in height increment values for the first time in 1996. The slow-release fertiliser significantly increased the height increment values in relation to the control first in 1998, i.e. the second year after application of the tab-

Table 1. Development of mortality rates (%) in treatments

Treatment	Rate	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
CON	CMR	5.6^{a}	7.7^{ab}	13.3^{b}	19.6^{b}	19.6^{b}	19.6^{b}	19.6^{b}	19.6^{b}	21.7^{b}	21.7^{b}	21.7^{b}	21.7^{b}	21.7^{b}
	AMR	5.6	2.1	5.6	6.3	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0
SRF	CMR	4.2^{a}	11.3^{b}	15.5^{b}	20.4^{b}	21.8^{b}	23.9^{b}	24.6^{b}	24.6^{b}	24.6^{b}	24.6^{b}	24.6^{b}	24.6^{b}	24.6^{b}
	AMR	4.2	7.0	4.2	4.9	1.4	2.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0
AMT	CMR	2.1^{a}	3.5^{a}	3.5^{a}	5.6^{a}	6.3^{a}	7.7^{a}	7.7^{a}	7.7^{a}	8.5^{a}	8.5^{a}	8.5^{a}	8.5^{a}	9.9^{a}
	AMR	2.1	1.4	0.0	2.1	0.7	1.4	0.0	0.0	0.7	0.0	0.0	0.0	1.4

CON – control, SRF – slow-release fertiliser, AMT – amphibolite, CMR – cumulative mortality rates, AMR – annual mortality rates, different letters – significant at $\alpha = 0.05$

Table 2. Annual height increment (cm) in the course of the referred period from the spring of 1994 to the autumn of 2006 in treatments

Treatment	Statistics	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
CON	mean	6.3^{a}	2.4^{a}	3.9^{a}	5.9^{a}	10.0^{a}	11.4^{a}	10.2^{a}	18.6^{a}	30.1^{a}	27.7^{a}	21.5^{a}	22.3^{a}	7.0^{a}
	SD	4.38	2.81	3.10	6.46	6.99	7.16	7.76	10.86	14.02	14.81	13.95	13.10	33.74
SRF	mean	5.3^{a}	2.4^{a}	3.9^{a}	7.4^{a}	14.3^{b}	12.3^{a}	13.7^{b}	20.3^{a}	34.4^{a}	33.4^{b}	26.4^{b}	27.5^{a}	8.1^{a}
	SD	3.47	3.06	2.96	6.60	8.36	7.00	10.03	12.21	16.20	17.45	15.64	17.41	35.17
AMT	mean	5.7^{a}	2.9^{a}	5.7^{b}	8.3^{a}	12.5^{ab}	11.7^{a}	12.4^{b}	20.9^{a}	31.9^{a}	30.5^{ab}	22.5^{ab}	23.4^{a}	12.7^{a}
	SD	3.39	3.23	4.61	7.95	8.31	7.34	12.66	14.71	17.38	18.82	13.79	13.25	25.18

CON – control, SRF – slow-release fertiliser, AMT – amphibolite, SD – standard deviation, mean values – results of post-hoc multiple comparison, significant at $\alpha = 0.05$

lets. Since 1997, the mean values of annual height increment recorded in both the fertilised treatments went steadily ahead of the CON, although the difference was significant in four cases only. No significant difference was found between the fertilised treatments.

Markedly lower values of annual increment recorded in 2006 in all three treatments were a result of mechanical damage to trees (top breakages) inflicted by snow and ice coating during the 2005/2006 winter that was extraordinarily rich in snow (Balcar et al. 2012).

Although the stimulation effect seems to be vanishing prior to the end of the evaluated period, the overall effect of fertilisation on height growth is demonstrable on mean periodic annual increment (1994–2006) with the values of 13.6 cm, 16.1 cm and 15.5 cm in the CON, SRF and AMT, respectively. The SRF significantly exceeded the CON in this characteristic whereas the AMT did not differ significantly either from the SRF or from the CON.

Basal stem diameter

The trees of both fertilised treatments showed a significantly larger basal stem diameter than the CON up to 2004 (Table 3). Since 2005 the difference between the CON and AMT ceased to be significant while the SRF was keeping significantly higher values of mean stem basal diameter (as compared to CON) until the end of the evaluated period.

Crown diameter

As for the years in which the mean value of the crown diameter (width of crown) was measured, the difference between AMT and CON was significant only in 2002 (Table 3). The mean crown diameter in the SRF treatment had become significantly larger than in the CON first in 2004; since that year the significant difference lasted till the end of the evaluated period.

Nutritional status of plantations

The foliar N concentrations widely fluctuated in time with a similar pattern for all three treatments (Fig. 1). As far as the development of foliar N concentrations is concerned, no significantly decreasing or increasing trend in time was found in any of the treatments. In the CON and SRF, the N concentrations dropped below the deficiency limit (1.2%) in 2003 and 2005, as for the AMT the deficient level in N supply was recorded in 2003 only.

In all treatments, a significant downward trend in P concentrations was revealed (*P*-values related to the trend significance in the CON, SRF and

Table 3. Basal stem and crown diameters – mean values and results of statistics in treatments

Treatment	Statistics	1999	2002	2004	2005	2006
Basal stem diameter						
CON	mean	1.6^{a}	4.0^{a}	4.9^{a}	5.6^{a}	5.9^{a}
	SD	0.56	1.22	1.54	1.76	1.80
SRF	mean	1.8^{b}	4.5^{b}	5.6^{b}	6.3^{b}	6.8^{b}
	SD	0.63	1.46	1.82	2.05	2.24
AMT	mean	1.9^{b}	4.6^{b}	5.5^{b}	6.0^{ab}	6.4^{ab}
	SD	0.64	3.30	1.89	2.00	2.11
Crown diameter						
CON	mean	48^{a}	104^{a}	134^{a}	139^{a}	150^{a}
	SD	18.3	31.9	36.2	39.4	41.0
SRF	mean	51^{a}	113^{ab}	144^{b}	153^{b}	161^{b}
	SD	17.8	32.7	37.5	40.9	43.3
AMT	mean	53^{a}	120^{b}	141^{ab}	148^{ab}	158^{ab}
	SD	19.1	40.2	38.9	44.1	45.9

CON – control, SRF – slow-release fertiliser, AMT – amphibolite, SD – sample standard deviation, mean values – results of post-hoc multiple comparison, significant at α = 0.05

AMT were 0.04; 0.01 and 0.01, respectively). The downward trend was successively getting the foliar P concentrations to the deficiency threshold (0.10%).

The foliar concentrations of K, Ca and Mg also showed a wide interannual variability and relatively small differences among treatments.

Neither a significant downward nor upward trend in time was registered. As contrasted to foliar N and P, the concentrations of K, Ca and Mg did not get onto the deficiency threshold (equalling to 0.35%, 0.15% and 0.06% for K, Ca and Mg, respectively) or below it, although the K concentrations in 2003 were close to it.

Neither increasing nor decreasing trend in foliar S concentrations was revealed. The S concentrations fluctuated highly above the deficiency threshold (0.06%) and also considerably above the lower threshold of optimal S supply (0.08%).

The N/P ratio reflected the downward trend in foliar P and significantly rose irrespectively of treatment during the evaluated period (Fig. 2). The *P*-values related to the significance of the upward trend in the CON, SRF and AMT were 0.005; 0.002 and 0.010, respectively.

Despite the increasing trend, the N/P ratio in all three treatments remained inside the interval between 6 and 17, which is considered normal or adequate.

Similarly, the N/K, N/Ca and N/Mg ratios registered in all the compared treatments did not get out of the intervals regarded as adequate, which is 1.3–4.9; 2.0–11.3 and 8.0–28.3 for N/K, N/Ca and N/Mg, respectively (de Vries et al. 1998).

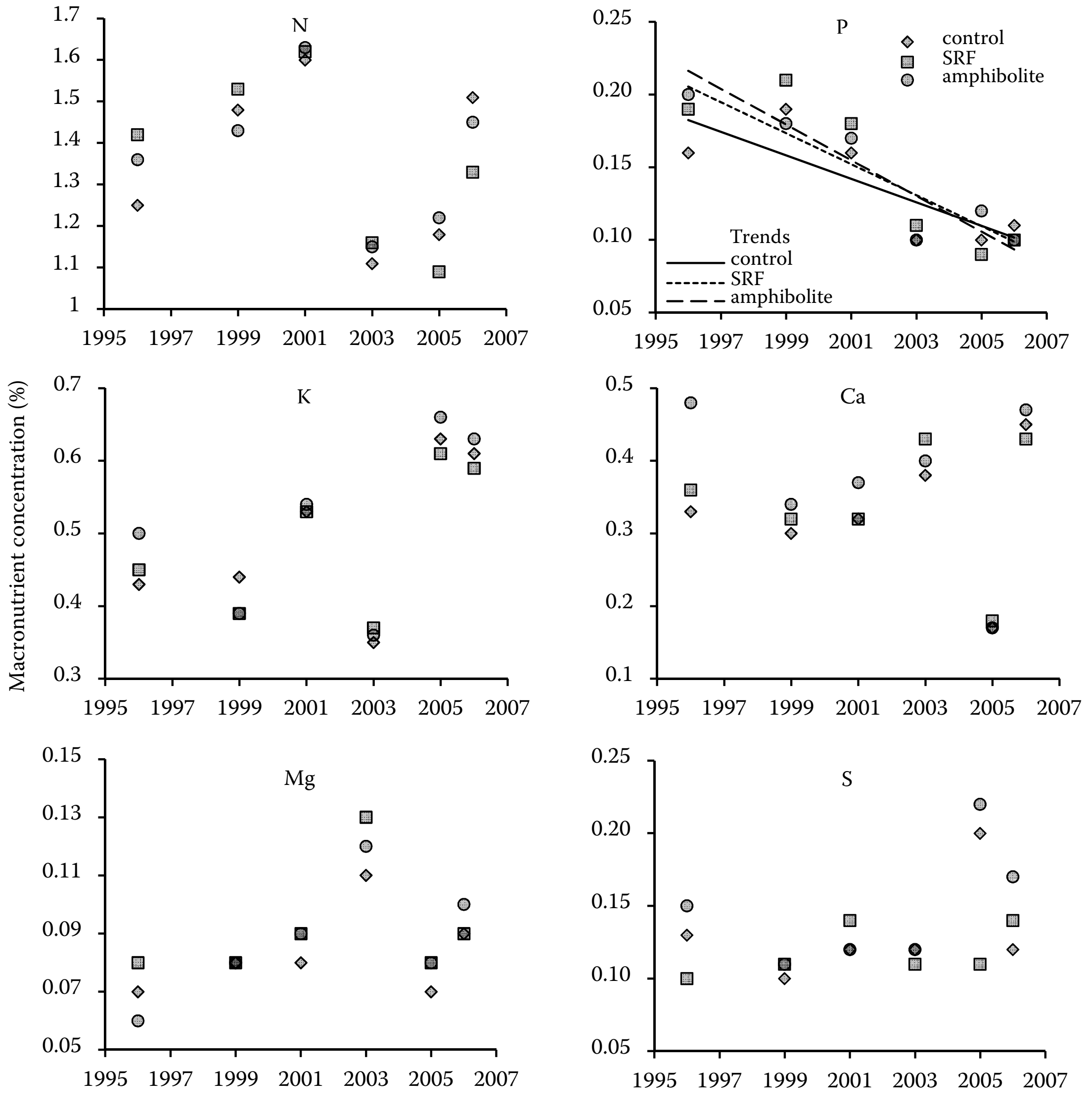

Fig. 1. Macronutrient concentrations in dry mass of current-year needles in the control, slow-release fertiliser (SRF) and amphibolite treatments

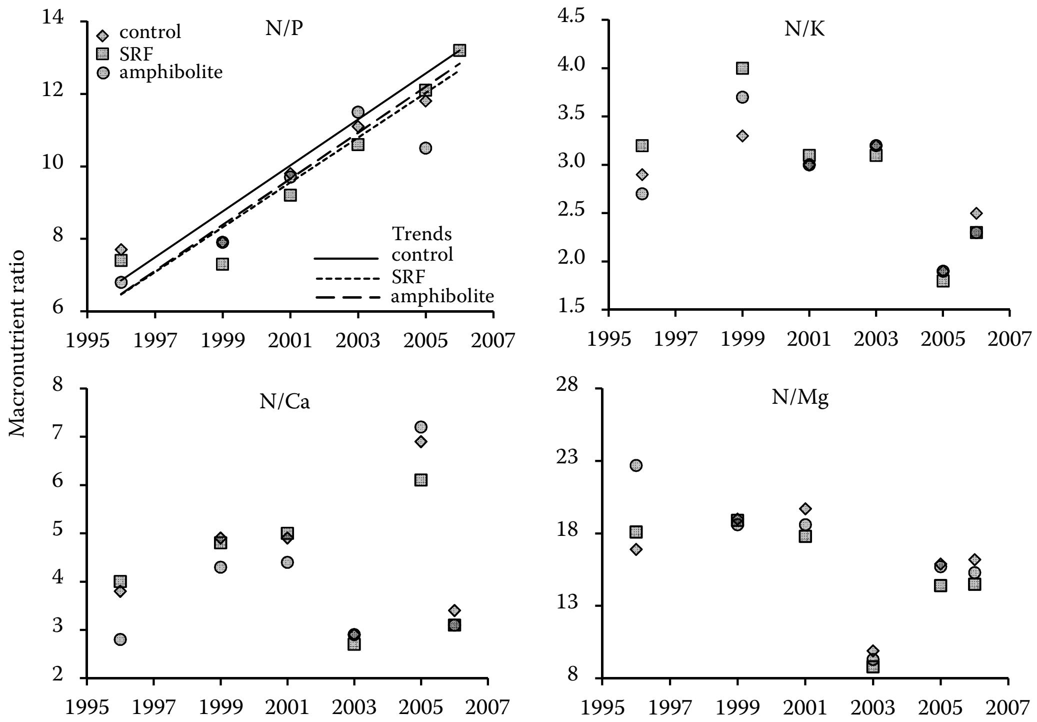

Fig. 2. Macronutrient ratios in the control, slow-release fertiliser (SRF) and amphibolite treatments in the course of evaluated period

As for these ratios, no significantly increasing or decreasing trend was found during the evaluated period.

No significant divergence of regression lines smoothing the macroelement concentration values and their ratios in the compared treatments was found, i.e. the developments of macroelement concentrations and their ratios did not differ significantly among treatments.

DISCUSSION

Importance of new forest stands for sheltering the site

The clear-cutting of damaged stands and subsequent long-lasting absence of forest canopy mean an increased risk of surface humus decay and losses in soil organic matter. Ussiry and Johnson (2007) suggested that clear-cutting resulted in the loss of humic substances from the forest floor and upper mineral horizons.

These substances should be replaced by less decomposed organic matter in the post-clear-cut soils under the regrowing forest. The problem is that on the air-polluted mountainous sites the regrowing forest was missing for a relatively long period of time and the clear-cut sites remained exposed to the factors promoting organic matter mineralisation.

Fertilising as initial support to trees

The slow growth in the initial stage of forest plantation is a serious problem in forestry management because the slow-growing seedlings are vulnerable to wildlife damage, overtopping and matting by competing vegetation for a longer period of time (Austin, Strand 1960). Under mountain conditions the slow-growing plantations are also exposed to snow and ground frost for a longer time.

On poor sites under acidifying conditions the improved nutrient supply may act as a stimulus promoting growth and biomass accumulation (van den Driessche et al. 2005; Podrázský, Remeš 2007; Heiskanen et al. 2009) and also as a factor influencing the vitality and survival of young trees (van den Driessche et al. 2005; Óskarsson et al. 2006).

Areal application of amendments is not suitable for large clear-cut tracts

One of the methods of additional amendment distribution is the areal application. The areal application of basic (deacidifying) amendments is, however, highly risky on the air-polluted clear-cut tracts (Podrázský, Ulbrichová 2003) since this application might further increase the hazard of excessive reduction in soil organic matter and raise N leaching (Kreutzer 1995; Podrázský, Ulbrichová 2003). Moreover, the desirable positive effects of areally applied amendments such as acidity reduction and temporarily improved nutrient supply need to be efficiently utilised by a viable forest stand with adequately developed roots.

For young newly planted cultures this is not really the case (Miller 1981), especially when they are stressed by the harsh environment. It is therefore probable that competing vegetation would take a greater advantage of the areal fertilising than the target tree plantations. However, it is the early stage of forest development, during which the judicious fertiliser application can have the best influence on the subsequent development of the stand (Miller 1981).

Chosen way of amendment application

The method of applying a slow-release amendment in the planting hole or using the tablets placed in the immediate proximity of the planting stock seems to be an effective way (Austin, Strand 1960). This "spot" application, i.e. the application of amendments localised to small patches of soil, is also more "eco-friendly" because the changes in soil chemistry are confined to a relatively small part of soil in reach of planting stock roots (Kuneš et al. 2006). For these reasons the spot application of slow-release amendments was chosen in our experiment.

In the case of tablets applied in the proximity of planting holes (not directly in them), the roots may be motivated to grow actively in the direction of an additional nutrient source. The ability of localised nutrient sources to influence the growth and symmetry of roots was reported e.g. by Krasowski et al. (1999). Although Robinson (1994) stated that this mechanism did not always work, the presumption of root growth oriented to a nutrient source seems legitimate for Norway spruce growing on the site in question. Kuneš et al. (2007) referred that the roots of spruces limed into planting holes (at planting) actively grew to the planting holes of neighbouring limed trees.

Choice of amendments

The pulverised silicate rocks may seem outdated at present because the dosage needed is high and so the application is laborious and expensive. In Central Europe, there was, however, a long tradition of using these materials (Němec 1956; Materna 1963; Lhotský et al. 1987) that were considered to be an environment-friendly alternative to artificial (synthetic) fertilisers. Therefore the inclusion of amphibolite in the experiment design was reasonable for comparison with a slow-release fertiliser. A long-lasting amending effect is, moreover, in favour of the silicate material (Balcar, Kacálek 2008). Positive experiences with the use of noncarbonate basic rock materials as amendments were reported e.g. by Aarnio et al. (2003).

A question may be raised why the N-containing fertiliser (SRF) was used in the experiment on an N-polluted site when the undesirable effects of an airborne N load on forest ecosystems such as acidification, nutrient leaching, imbalances in nutrition, susceptibility to parasite attacks were documented (Hallbäcken, Zhang 1998; Dise et al. 1998; Flückiger, Braun 1999; Bobbink, Lamers 2002).

An explanation is as follows: firstly, foliar N nutrition of the spruce stands is deficient on the site (Kuneš 2003; Kuneš et al. 2007); secondly, there was a need to promote the growth of plantations and get trees ahead of competing weeds and their terminal buds above the zone of ground frost. In this regard, the slow-release N-containing amendments often act as an efficient growth promoting stimulus.

Aarnio and Martikainen (1996) reported that the slow-release N fertiliser based on Ureaform increases the availability of mineral N in acid forest soils without increasing nitrification and hence the risk of NO_3^- leaching is not amplified. Similarly, Jahns et al. (1999) suggested that fertilisers based on methylene ureas solve problems such as nitrogen loss by leaching of nitrate, denitrification and volatilization after fertilising.

Effects of initial fertilising on growth and survival

Positive influence of artificial (synthetic) slow-release or controlled-release fertilisers on the survival or growth of newly planted trees was documented under various conditions (Austin, Strand 1960; Jacobs et al. 2005; Óskarsson et al. 2006).

A substantial improvement in the growth of grand fir cultivated on an acidic site was reported after application of a slow-release N-P-K-Mg fertiliser of the same type as we tested (Podrázský, Remeš 2007). The height increment of the fertilised treatments was significantly higher than in the control (by 5–15 cm annually) in the course of the whole study period (1997–2006) and the effect was achieved by the same dosage as we applied.

There were also some negative experiences with the use of slow-release fertilisers at planting (Jacobs et al. 2004b). These experiences were however related to drought-prone sites. Moreover, the polymer coated fertilisers tested by Jacobs et al. (2004b) have a different mechanism of nutrient release from that of the Ureaform-based fertiliser applied in our experiment.

As for amendments produced from basic rocks, the favourable effects of amphibolite powder on the growth and survival of silver fir (*Abies alba* Mill.) under harsh mountain conditions were reported by Balcar and Kacálek (2008). These authors also mentioned the long duration of supportive effects of amphibolite powder as compared to applied limestone.

In our experiment, the amphibolite powder applied to trees at planting efficiently reduced the mortality rate. The survival of trees treated with amphibolite (90.1% in 2006) was significantly higher than that recorded in the SRF (75.4%) and CON (78.3% in 2006). It is to note that results of mortality rates in this paper are slightly refined and more precise than the earlier presented data (Kuneš et al. 2004) since some corrections in mortality database were done.

It is important to remind that the SRF tablets were applied later, in the spring of 1997. The postponement of fertiliser application to the second or third year after planting was often recommended to avoid fertilising of trees which were not able to survive after transplanting on forest site. In 1997 the plantation already began to recover from the post-planting shock that is often accompanied by an increased mortality rate (Kuneš 2003; Jacobs et al. 2004a). Thereafter, annual mortality rates of all treatments were minimal, which explains why the SRF tablets had no positive effect on the survival of plantation.

Hence, to achieve a desirable fertilisation effect on the plantation survival in a harsh environment, the slow-release fertiliser must be applied at planting, though it means that a certain amount of the fertiliser will be applied in vain. The assumption of a need to create as favourable conditions as possible in the initial stage of forest seems to hold true regardless of the way of regeneration. Madsen (1997) similarly stressed the importance of favourable growth conditions during the early phase of seedling establishment for natural regeneration.

In relation to the control, the fertilising induced an increase in periodic annual increment (1994–2006) by 14% and 16% in the AMT and SRF, respectively. In the study presented by Podrázský and Remeš (2007) on grand fir the differences between the control and fertilised treatments were considerably more profound in favour of the SRF than in our case. A different species was treated, which naturally played a role. We can, however, assume that the more profound effect of fertilising reported by Podrázský and Remeš (2007) might be explained also by a less climatically exposed site on which the trees might respond to the nutritional stimulus without being restricted by climate.

The crown diameter values (2006) in the AMT and SRF were higher than that in the CON by 5% and 7%, respectively. Although the difference is not great, with regard to the initial plantation spacing the fertilising could expedite the formation of the closed canopy approximately by one season. Similarly, the values of basal stem diameter (BSD 2006) in the AMT and SRF were higher than that in the CON by 8% a 15%, respectively. Hence, the ratio between the height and basal stem diameter (BSD) remained on a comparable level in all three treatments, which is important from the viewpoint of mechanical resistance and stability of the plantations.

The data on height growth, basal stem and crown diameter in this paper slightly differ from those presented in the earlier study on the plantation (Kuneš et al. 2004). It is a result of the retrospective exclusion of data belonging to trees that died after 2002 from the processed data files (Material and Methods section).

Nutritional status

The interannual variability in nutrient concentrations plays a much more important role than the difference among the treatments. The climatic conditions in the respective growth periods probably played a role. The late spring and summer of 2003, for example, were extremely dry (Balcar, Kacálek 2008), which was reflected in availability and subsequently in foliar concentrations of several elements (Fig.1).

The principal information elicited from the chemical analyses is that there is a decreasing trend of foliar P concentrations in all three treatments, which is documented also by the rising N/P ratio. The demand for nutrients is highest in young stands, in which the nutrient-rich foliage is being built up (Miller 1981). The demand for nutrients decreases when the canopy starts to close and the crown expansion ceases.

The absence of a marked rise in macroelement concentrations in needles of fertilised trees can be explained by a "dilution effect". The amendments stimulated the growth of trees and a limited amount of added nutrients had to be distributed into a higher amount of biomass that was accumulated in the fertilised trees as compared to the control. The dilution effect was described under various circumstances also by other authors (Timmer, Stone 1978; Stockfors et al. 1997; Óskarsson et al. 2006).

The high foliar S concentrations indicate persisting S load in the mountain environment of northern Bohemia and are in accordance with conclusions of older studies (Fottová, Skořepová 1998).

Because our experimental plantation is situated on a climatically exposed site, the issue of N nutrition and frost sensitivity should also be discussed. Some works suggest that an additional (luxurious) nitrogen supply may really predispose some woody species to a greater risk of frost damage (Benzian et al. 1974; Jönsson et al. 2004; Villar-Salvador et al. 2005). Though, the luxurious N is often viewed rather as a secondary factor than the decisive one. For instance Thomas and Ahlers (2007) admitted that N excess might play a role in the increased frost sensitivity of oaks, but these authors considered the water supply prior to frost stress onset and the course of winter temperature much more important than N excess.

On the other hand, there are studies implying that sufficient or luxurious N supply enhances frost hardiness. Sheppard (1994) and Sheppard et al. (1998) pointed out that a low to deficient N status in red and Norway spruce nutrition increases the likelihood of injury by winter acid mist because carbon acquisition is restricted. de Hayes et al. (1989) concluded that N fertilisation enhanced the cold tolerance of red spruce seedlings. Analogously, Rikala and Repo (1997) found that the frost hardiness of Scots pine seedlings increased with an increase in foliar N concentration. Luoranen et al. (2008) recommend a combination of "short-day" treatment and subsequent luxurious nutrient supply (rising the foliar N content to 15–25 g per kg of dry mass) in order to accelerate the autumn frost hardening of Norway spruce seedlings. In general, the issue seems to be more complex depending on the species and the environmental factors.

In our case, no marked visual differences in frost damage among treatments were observed. Similarly, as far as the frequency of serious mechanical damage caused by snow and ice coating is in concern, no significant differences among treatments were found (data not shown).

CONCLUSIONS

The application of SRF tablets resulted in a significant growth stimulation of the spruce plantation in terms of mean height, basal stem diameter and crown diameter. The growth stimulation by amphibolite incorporated into soil inside the planting holes was perceptible but not significant; this amendment, however, significantly reduced mortality. To achieve a desirable effect on the plantation survival in a harsh environment, fertilisation must be applied at planting.

The interannual variability in nutrient concentrations played a much more important role than the difference among the treatments. No marked changes in the chemical composition of foliage as a result of fertilising were observed. This can be ascribed to a "dilution effect".

The significantly decreasing trend of foliar P concentrations and also significantly rising values of the N/P ratio in all three treatments indicate that phosphorus is the most deprived macroelement in spruce nutrition on this site.

As far as the growth stimulation in a short- to medium-term horizon is concerned, the SRF seems to be a more efficient amendment than AMT because the macroelements are more concentrated and a substantially lower amount of material is needed to achieve the growth stimulation (less laborious application). The presence of slow-release nitrogen in SRF tablets, which is absent in amphibolite, seems to be beneficial. On the other hand, a longer lasting effect of amphibolite on the growth of spruce culture as compared to SRF can be expected.

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References

Aarnio T., Martikainen P.J. (1996): Mineralization of carbon and nitrogen, and nitrification in Scots pine forest soil treated with fast- and slow-release nitrogen fertilizers. Biology and Fertility of Soils, ***22***: 214–220.

Aarnio T., Räty M., Märtikainen P.J. (2003): Long-term availability of nutients in forest soil derived from fast- and slow-release fertilizers. Plant and Soil, ***252***: 227–239.

Alexander A., Helm H.U. (1990): Ureaform as a slow release fertilizer: a review. Journal of Plant Nutrition and Soil Science, ***154***: 249–255.

Anděl J. (1998): Statistické metody. [Statistical Methods.] Praha, Matfyzpress: 274.

Austin R.C., Strand R.F. (1960): The use of slowly soluble fertilizers in forest planting in the pacific Northwest. Journal of Forestry, ***58***: 619–627.

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., Dušek D. (2011): Effect of soil liming on European beech (*Fagus sylvatica* L.) and sycamore maple (*Acer pseudoplatanus* L.) plantations. Folia Forestalia Polonica, ***53***: 85–92.

Balcar V., Špulák O., Kacálek D., Kuneš I. (2012): Klimatické podmínky na výzkumné ploše Jizerka – I. srážky a půdní vlhkost. [Climatic conditions in the Jizerka experimental plot - I. Precipitation and soil moisture.] Zprávy lesnického výzkumu, ***57***: 74–81.

Benzian B., Brown R.M., Freeman S.C.R. (1974): Effect of late-season top-dressings of n (and k) applied to conifer transplants in the nursery on their survival and growth on british forest sites. Forestry, ***47***: 153–184.

Bobbink R., Lamers L.P.M. (2002): Effect of increased nitrogen deposition. In: Bell J.N.B., Treshow M. (eds): Air Pollution and Plant Life. Chichester, John Wiley & Sons: 201–235.

Boháčová L., Buriánek V., Damašková J., Fabiánek P., Fadrhonsová V., Hejdová J., Lomský B., Novotný R., Neumann L., Šrámek V., Uhlířová H. (2003): Monitoring zdravotního stavu lesa v České republice. Ročenka programu ICP Forests – Data 2003. [Forest Condition Monitoring in the Czech Republic. Annual Report ICP Forests – Data 2003.] Jíloviště-Strnady, VÚLHM: 92.

de Hayes D.H., Ingle M.A., Waite C.E. (1989): Nitrogen fertilization enhances cold tolerance of red spruce seedlings. Canadian Journal of Forest Research, ***19***: 1037–1043.

de Vries W., Reinds G.J., Deelstra H.D., Klap J.M., Vel E.M. (1998): Intensive Monitoring of Forest Ecosystems in Europe. Brussel, Geneva, United Nations Economic Commission for Europe, European Commission: 161.

Dise N.B., Matzner E., Gundersen P. (1998): Synthesis of nitrogen pools and fluxes from European forest ecosystems. Water, Air, and Soil Pollution, ***105***: 143–154.

Filipiak M., Ufnalski K. (2004): Growth reaction of European Silver fir [*Abies alba* Mill.] associated with air quality improvement in the Sudeten Mountains. Polish Journal of Environmental Studies, ***13***: 267–273.

Flückiger W., Braun S. (1999): Nitrogen and its effects on growth and nutrient status and parasite attacks in beech and Norway spruce. Water, Air, and Soil Pollution, ***116***: 99–110

Fottová D., Skořepová I. (1998): Changes in mass element fluxes and their importance for critical loads: Geomon network, Czech Republic. Water, Air, and Soil Pollution, ***105***: 365–376.

Granhus A., Brække F.H. (2001): Nutrient status of Norway spruce stands subjected to different levels of overstorey removal. Trees, ***15***: 393–402.

Hallbäcken L., Zhang L.Q. (1998): Effects of experimental acidification, nitrogen addition and liming on ground vegetation in a mature stand of Norway spruce (*Picea abies* [L.] Karst.) in SE Sweden. Forest Ecology and Management, ***108***: 201–213.

Heiskanen J., Lahti M., Luoranen J., Rikala R. (2009): Nutrient loading has a transitory effect on the nitrogen status and growth of outplanted Norway spruce seedlings. Silva Fennica, ***43***: 249–260.

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

Hrkal Z. (2004): Changes in acid atmospheric deposition in Krušné Mts. and Šumava (Czech Republic) and their impact on groundwater quality. Water, Air, and Soil Pollution, ***157***: 163–178.

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.

Jacobs D.F., Rose R., Haase D.L., Alzugaray P.O. (2004a): Fertilization at planting impairs root system development and drought avoidance of Douglas-fir (*Pseudotsuga menziesii*) seedlings. Annals of Forest Science, ***61***: 643–651.

Jacobs D.F., Ross-Davis A.L., Davis A.S. (2004b): Establishment success of conservation tree plantations in relation to silvicultural practices in Indiana, USA. New Forests, ***28***: 23–36

Jacobs D.F., Salifu K.F., Seifert J.R. (2005): Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting. Forest Ecology and Management, ***214***: 28–39.

Jahns T., Schepp R., Siersdorfer C., Kaltwasser H. (1999): Biodegradation of slow-release fertilizers (methyleneureas) in soil. Journal of Environmental Polymer Degradation, ***7***: 75–82.

Jezierski P., Szynkiewitz A., Jedrysek M.O. (2006): Natural and anthropogenic origin sulphate in an mountainous groundwater system: S and O isotope evidences. Water, Air, and Soil Pollution, ***173***: 81–101.

Jönsson A.M., Rosengren U., Nihlgård B. (2004): Excess nitrogen affects the frost sensitivity of the inner bark of Norway spruce. Annals of Forest Science, ***61***: 293–298

Kandler O., Innes J.L. (1995): Air pollution and forest decline in Central Europe. Environmental pollution, ***90***: 171–180.

Koňasová T., Kuneš I., Baláš M., Millerová K., Balcar V., Špulák O., Drury M. (2012): Influence of limestone and amphibolite application on growth of Norway spruce plantation under harsh mountain conditions. Journal of Forest Science, ***58***: 492–502.

Krasowski M.J., Owens J.N., Tackaberry L.E., Massicotte H.B. (1999): Above- and below-ground growth of white spruce seedlings with roots divided into different substrates with or without controlled-release fertilizer. Plant and Soil, ***217***: 131–143.

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. (2003): Prosperity of spruce plantation after application of dolomitic limestone powder. Journal of Forest Science, ***49***: 220–228.

Kuneš I., Balcar V., Čížek M. (2004): Influence of amphibolite powder and Silvamix fertiliser on Norway spruce plantation in conditions of air-polluted mountains. Journal of Forest Science, ***50***: 366–373.

Kuneš I., Balcar V., Vykypělová E., Zadina J. (2006): Vliv jamkové aplikace moučky dolomitického vápence na půdní prostředí uvnitř sadebních jamek a mimo jamkový prostor v rámci podmínek kyselého horského stanoviště v Jizerských horách. [Effects of planting hole application of dolomitic limestone powder on soil in planting holes and out of them in conditions of an acidic mountain site in the Jizerske hory Mts.] Zprávy lesnického výzkumu, ***51***: 84–91.

Kuneš I., Balcar V., Vykypělová E., Zadina J., Šedlbauerová J., Zahradník D. (2007): Vliv jamkové a pomístné povrchové aplikace dolomitického vápence na množství a chemické složení biomasy smrku ztepilého v Jizerských horách. [Effects of planting hole application or spot surface application of finely ground dolomitic limestone on amount and chemical composition of biomass of Norway spruce in the Jizerské hory Mts.] Zprávy lesnického výzkumu, ***52***: 316–327.

Kuneš I., Koňasová T., Balcar V., Baláš M., Zahradník D., Kacálek D., Vítámvás J., Jakl M., Dytrtová J. (2011): Growth response of *Alnus viridis* to application of crushed limestone and amphibolite and forestry potential of the species in harsh acidic mountain sites. Journal of Forest Science, ***57***: 200–209.

Kuneš I., Baláš M., Koňasová T., Zahradník D., Balcar V., Špulák O., Kacálek D., Jakl M., Jaklová Dytrtová J. (2012): Cultivation of speckled alder under harsh mountain conditions. Journal of Forest Science, ***58***: 234–244.

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

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

Luoranen J., Lahti M., Rikala R. (2008): Frost hardiness of nutrient-loaded two-year-old *Picea abies* seedlings in autumn and at the end of freezer storage. New Forests, ***35***: 207–220

Madsen P., Larsen J.B. (1997): Natural regeneration of beech (*Fagus sylvatica* L.) with respect to canopy density, soil moisture and soil carbon content. Forest Ecology and Management, ***97***: 95–105.

Materna J. (1963): Výživa a hnojení lesních porostů. [Nutrition and Fertilising of Forest Stands.] Praha, SZN: 228.

Miller H.G. (1981): Forest fertilization: some guiding concepts. Forestry, ***54***: 157–167

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

Óskarsson H., Sigurgeirsson A., Raulund-Rasmussen K. (2006): Survival, growth, and nutrition of tree seedlings fertilized at planting on andisol soils in Iceland: six-year results. Forest Ecology and Management, ***229***: 88–97.

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.

Podrázský V., Remeš J. (2007): Fertilization effect on the grand fir plantations. Scientia Agriculturae Bohemica, ***38***: 198–201.

Rikala R., Repo T. (1997): The effect of late summer fertilization on the frost hardening of second-year Scots pine seedlings. New Forests, ***14***: 33–44.

Robinson D. (1994): Tansley review No. 73: the responses of plants to non-uniform supplies of nutrients. New Phytologist, ***127***: 635–674.

Sheppard L.J. (1994): Causal mechanisms by which sulphate, nitrate and acidity influence frost hardiness in red spruce; review and hypothesis. New Phytologist, ***127***: 69–82.

Sheppard L.J., Leith I.D., Murray M.B., Cape J.N., Kennedy V.H. (1998): The response of Norway spruce seedlings to simulated acid mist. New Phytologist, ***138***: 709–723.

Stockfors J., Linder S., Aronsson A. (1997): Effects of long-term fertilisation and growth on micronutrient status in Norway spruce trees. Studia Forestalia Suecica, ***202***: 1–15.

Thomas F.M., Ahlers U. (2007): Effects of excess nitrogen on frost hardiness and freezing injury of above-ground tissue in young oaks (*Quercus petraea* and *Q. robur*). New Phytologist, ***144***: 73–83.

Timmer V.R., Stone E.L. (1978): Comparative foliar analysis of young Balsam fir fertilized with nitrogen, phosphorus, potassium, and lime. Soil Science Society of America Journal, ***42***: 125–130.

Ussiry D.A.N., Johnson C.E. (2007): Organic matter composition and dynamics in a northern hardwood forest ecosystem 15 years after clear-cutting. Forest Ecology and Management, ***240***: 131–142.

Vacek S. (2003): Mountain Forests of the Czech Republic. Prague, Ministry of Agriculture of the Czech Republic: 308.

van den Driessche R., Niemi F., Charleson L. (2005): Fourth year response of aspen seedlings to lime, nitrogen and phosphorus applied at planting and 1 year after planting. Forest Ecology and Management, ***219***: 216–228.

Villar-Salvador P., Puértolas J., Peñuelas J.L., Planelles R. (2005): Effect of nitrogen fertilization in the nursery on the drought and frost resistance of Mediterranean forest species. Investigación Agraria: Sistemas y Recurso Forestales, ***14***: 408–418.

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