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Effects of fertilisation on biomass of Norway spruce on a harsh mountain site

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ABSTRACT: The organic matter produced and accumulated by plants is a crucial component in the ecosystems on environmentally disturbed sites. The aim of our study was to evaluate the influence of initial fertilising on the aboveground and belowground tree biomass of Norway spruce. The biomass amount, distribution and chemical composition were studied in a young spruce stand growing on an acidified mountain clear-cut tract. The fertilised trees accumulated a higher amount of tree biomass. They nonetheless showed lower concentrations of P, N, and K in some root compartments than control trees, which could be ascribed to a dilution effect. As for the aboveground compartments, no significant differences in element concentrations were proved.

Keywords: *Picea abies*; fertilization; nutrient pools; nutrient concentrations; biomass model

The mountain ecosystems in the northern and north-western parts of the Czech Republic experienced a serious forest decline during the 1970s and 1980s (Vacek 2003). Coal-burning power plants situated in the eastern part of former East Germany, northern Bohemia, and southern Poland emitted an excessive quantity of pollutants, mainly S and N compounds. The above-mentioned area in Central Europe was therefore called Black Triangle (Křeček, Hořická 2006). The forests in the Black Triangle weakened by pollution, degraded soil and climatic stresses often succumbed to pest attacks. Extensive areas of mountain forest were disturbed in this way and then usually clear-felled (Vacek 2003). In the Jizerské hory Mts. the proportion of damaged or clear-felled forests reached 43% of the overall forest area (Balcar et al. 1994).

Since the beginning of the 1990s, the situation of industrial air-pollution stress has markedly improved because desulphurisation technologies and dust collectors have been implemented in the local power plants (Hrkal 2004) and some of the most outdated thermal power plants or their sections were closed. The above-mentioned development resulted in a marked reduction in S emissions and in a decrease in the regional S and particulate load (Filipiak, Ufnalski 2004).

A prompt replanting of clear-felled tracts in the mountains was crucial in order to prevent accelerated mineralisation of surface humus, nutrient losses (Podrázský 2006) and also intraskeletal erosion (on the stony subsoil) (Šach et al. 2008). The replanting was, however, extremely difficult. A harsh environment of the mountain sites located on acidic and poor soils was deepened by a microclimate of exposed clear-felled tracts.

Therefore several experiments were installed in the Black Triangle region that were focused on ap-

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plications of fertilisers and pulverised basic rocks as a means of providing the initial support to young plantations as well as a means counteracting the soil acidity (Podrázský 1995; Balcar 2001; Kateb et al. 2004).

The paper focuses on an experimental Norway spruce plantation in the Jizerské hory Mts. in the northern part of the Czech Republic. The aim of the study is to evaluate and compare the effects of a slow-release fertiliser (based on methylene urea) and applied finely ground amphibolite powder on the quantity and chemical composition of the aboveground and belowground biomass of a young Norway spruce plantation in a harsh environment of an air-polluted mountain site.

The hypotheses tested are as follows:

(1) The application of the amendments directly to trees is able to promote biomass production and nutrient storage in the spruce plantation growing on a site prone to losses of soil organic matter.

(2) In a short-term horizon (ca 10 years), the small dose of an artificial slow-release fertiliser can result in comparable or even better growth stimulation and biomass production than pulverised amphibolite applied in a substantially larger amount.

MATERIAL AND METHODS

Site description

The planting experiment was installed on a clear-felled area in the Jizerské hory Mts. (northern part of the Czech Republic) at an altitude of 960 m on a 10% southwest-facing slope (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). The bedrock was biotitic granite. The well-drained soil was determined as a mountain humus podzol (Umbri Placic Podzol according to the FAO terminology). 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 basic pedochemical characteristics were summarised by Kuneš (2003). The average current air pollution measured by a passive sampler method was as follows: SO_2 = 4 μg·m^{-3} (investigation period 2005–2008), NO_2 = 5 μg·m^{-3} (2006–2008), O_3 = 102 μg·m^{-3} (2003–2008), Balcar and Kacálek (2008). However, the air-pollution load was considerably higher in the 1990s (Balcar, Vacek 1994), when the field experiment was installed.

Experimental plantation and biometric measurements

The experiment consisted of 9 plots (10 × 10 m) arranged in a Latin square design with three treatments and three replications (the plots represent 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. (north-eastern Moravia, Czech Republic). The treatments consisted of (1) control (CON), (2) slow-release fertiliser (SRF) as a representative of modern amendments, and (3) amphibolite treatment (AMT). Amphibolite was one of the strongly recommended natural fertilisers in the Czech Republic for use in the forestry practice (Němec 1956, Materna 1963) during the air-pollution period, but serious research was missing.

In the SRF, four tablets of the Silvamix Forte (Ecolab Znojmo, Ltd., Czech Republic) slow-release fertiliser (40 g altogether) were applied to each tree in the spring of 1997 (i.e. three years after planting). The fertiliser contained 17.5% N compounds (60% of total nitrogen derived from methylene urea), 7.7% P, 8.7% K and 5.4% Mg (contents of P, K and Mg expressed in elementary forms). Phosphorus and K were present in the fertiliser in potassium-magnesium phosphates. The SRF tablets were regularly placed in circles around the trees, approximately 30 cm from the stem and 5–10 cm under the soil surface.

In the AMT, two kg of finely ground amphibolite powder was incorporated into the soil in a planting hole (35 × 35 × 25 cm) of each tree as the spruces were planted. Amphibolite from a quarry near the village of Markovice (Central Bohemia) was used and contained 0.13% P, 0.82% K, 7.9% Ca and 4.82% Mg. The particle size distribution of the amphibolite powder was as follows: 5% of particles with a diameter over 0.25 mm, 53% of particles 0.25–0.05 mm in size and 42% particles below 0.05 mm in size.

Mortality rates were recorded annually. Tree heights were measured with a telescopic measuring staff to the nearest 1 cm and maximal crown diameter to the nearest 10 cm. A calliper was used to measure the stem base diameter with an accuracy of ± 1 mm.

Selection of sample trees

Six sample trees per each treatment (aboveground biomass and root systems) were harvested

in July of 2006. As the harvesting of more than sixteen-year-old trees and excavating their complete root systems is extremely laborious and random sampling of small numbers would bring higher errors of models, mean height, stem-base and crown diameters were used as standards for the selection of sample trees as treatment representatives. Differences of sample trees from their respective treatment mean were within 10% for stem base diameter and height, and within 15% for crown diameter (Table 1).

Characteristics of sample trees

The characteristics recorded in the autumn of 2005 were relevant for the selection of sample trees, because the whole plantation is measured annually when the seasonal growth is finished. However, it would have been imprecise to use those characteristics for biomass calculations, because the sample trees were harvested in the summer of 2006 (when the root excavation was possible). Therefore, prior to the processing of selected sample trees, their up-to-date stem base diameter, height and crown diameter were recorded again and used to determine their relationships to tree biomass and in designing and testing the biomass equations.

Processing of aboveground parts

The aboveground part of each sample tree was divided into the following compartments: (1) needles, (2) branches and twigs, (3) stem wood and (4) stem bark. All branches, twigs, stem wood and bark were chipped separately for each sample tree and compartment.

Processing of root systems

When the aboveground parts had been felled, the root systems were carefully excavated so that it was possible to separate roots as thin as 2 mm in diameter. As the fine roots (less than 2 mm) were integrated in the greensward and some of them were lost during excavation, they were excluded from the present study.

The excavated root system of each sample tree was thoroughly rinsed and dismembered into the following root size classes: (1) less than 0.5 cm in diameter, (2) 0.5–1.0 cm in diameter, (3) 1.0–1.5 cm in diameter, (4) 1.5–2.0 cm in diameter, (5) 2.0–3.0 cm in diameter and (6) more than 3.0 cm in diameter. The roots were chipped.

Determination of dry mass and macroelement concentrations

The whole compartments for each tree were oven-dried at 70°C to a constant weight, which was then determined. From all aboveground and belowground compartments of each tree a random sample was taken to be analysed for N, P, K, Ca, Mg and S concentrations. As for taking the tissue samples for chemical analysis, only the stem wood was sampled differently since it was not completely homogenised. The wood chippings for chemical analysis were obtained with an auger: all wood chippings released by one drilling across the basal, central and apical part of one clean-barked stem were pooled in one stem-wood sample.

The applied analytic chemical methods were shortly summarised by Kuneš et al. (2012).

Table 1. Mean values of stem base diameter (SBD), height (H) and crown diameter (CD) characterising groups of sample trees and their respective treatments including differences (whole variant = 100%) in the autumn of 2005

Treatment	Mean	SBD (cm)	Difference (%)	H (cm)	Difference (%)	CD (cm)	Difference (%)
CON	sample trees	5.5	–2.2	191.3	–5.9	140	0.7
	whole treatment	5.6[a]		203.3[a]		139[a]	
SRF	sample trees	5.9	–6.0	235.2	–0.6	155	1.3
	whole treatment	6.3[b]		236.6[b]		153[a]	
AMT	sample trees	6.2	3.2	229.7	3.4	145	–2.0
	whole treatment	6.0[ab]		222.1[ab]		148[a]	

CON – control, SRF – slow-release fertiliser, AMT – amphibolite treatment, mean values of dendrometric characteristics of whole treatments that are followed by different letters are significantly different from each other at $\alpha = 0.05$ (results of post-hoc multiple comparisons by Nemeny's method)

Statistical analysis of macroelement concentrations

The Kruskal-Wallis procedure and Nemeny's multiple comparisons were used to compare dendrometric parameters and concentrations of N, P, K, Ca, Mg and S in compartments of sample trees belonging to the tested treatments. STATISTICA 8.0 (StatSoft, Inc., Tulsa, USA) software was used for the statistical analysis. The procedures implemented in the software are described by Hill and Lewicki (2006). The critical value of α for all tests was 0.05. The dry mass and the total amounts of nutrients in compartments, which are dependent on dry mass weight, were not statistically tested because the data derived from biomass amount are of non-random character.

Biomass functions

The relationship between the stem base diameter, tree height and total below- and aboveground dry biomass (total dry mass for further reference) was modelled by the following functions:

Table 2. Mean concentrations of macronutrients and S in aboveground compartments of harvested trees (in %)

Compartment	Treatment		N	P	K	Ca	Mg	S
Needles	K-W test		0.0710	0.0618	0.8671	0.0766	0.9599	0.1827
	CON	mean	1.15[a]	0.064[a]	0.46[a]	0.72[a]	0.116[a]	0.131[a]
		SD	0.053	0.0066	0.063	0.133	0.0316	0.0250
	SRF	mean	1.04[a]	0.051[a]	0.48[a]	0.86[a]	0.113[a]	0.160[a]
		SD	0.129	0.0092	0.091	0.094	0.0421	0.0306
	AMT	mean	1.03[a]	0.054[a]	0.48[a]	0.72[a]	0.106[a]	0.133[a]
		SD	0.097	0.0156	0.051	0.134	0.0204	0.0186
Branches and twigs	K-W test		0.3156	0.3587	0.8539	0.6676	0.8942	0.4878
	CON	mean	0.35[a]	0.011[a]	0.22[a]	0.48[a]	0.055[a]	0.052[a]
		SD	0.046	0.0109	0.0321	0.069	0.0060	0.0158
	SRF	mean	0.31[a]	0.005[a]	0.22[a]	0.45[a]	0.057[a]	0.055[a]
		SD	0.042	0.0045	0.0331	0.017	0.0133	0.0121
	AMT	mean	0.32[a]	0.006[a]	0.21[a]	0.46[a]	0.055[a]	0.061[a]
		SD	0.055	0.0055	0.010	0.046	0.0061	0.0104
Bark	K-W test		0.7454	0.1474	0.4968	0.3836	0.8231	0.0836
	CON	mean	0.61[a]	0.054[a]	0.43[a]	0.80[a]	0.104[a]	0.085[a]
		SD	0.0631	0.0132	0.0885	0.0969	0.0294	0.0060
	SRF	mean	0.57[a]	0.047[a]	0.40[a]	0.92[a]	0.106[a]	0.065[a]
		SD	0.0684	0.0109	0.0802	0.1754	0.0378	0.0170
	AMT	mean	0.60[a]	0.042[a]	0.43[a]	0.86[a]	0.113[a]	0.078[a]
		SD	0.0431	0.0065	0.0531	0.0705	0.0267	0.0219
Stem wood	K-W test		0.2774	1.0000	0.2172	0.3943	0.3527	0.0565
	CON	mean	0.10[a]	0.001[a]	0.05[a]	0.14[a]	0.020[a]	0.038[a]
		SD	0.037	0.0000	0.008	0.014	0.0016	0.0161
	SRF	mean	0.09[a]	0.001[a]	0.06[a]	0.15[a]	0.020[a]	0.065[a]
		SD	0.014	0.0000	0.014	0.016	0.0027	0.0224
	AMT	mean	0.08[a]	0.001[a]	0.06[a]	0.15[a]	0.019[a]	0.035[a]
		SD	0.010	0.0000	0.019	0.016	0.0018	0.0126

SD – sample standard deviation, K-W test – results of Kruskal-Wallis analysis (overall difference), CON – control, SRF – slow-release fertiliser and AMT – amphibolite treatment, mean values in table columns followed by different letters are significantly different from each other at α = 0.05 (results of post-hoc multiple comparisons by Nemeny's method)

$$B = e^{(b_0 + b_1 \ln d_0)} \quad (1)$$

$$B = e^{(b_0 + b_1 \ln h)} \quad (2)$$

$$B = e^{(b_0 + b_1 \ln d_0 + b_2 \ln h)} \quad (3)$$

where:
B – dry biomass (g),
b_0, b_1, b_2 – coefficients,
d_0 – stem base diameter (mm),
h – tree height (m).

These general forms of functions are analogous to those listed by Pajtík et al. (2008); however, we did not use the suggested λ correction factor as the coefficients of our functions were fitted with non-linear regression.

RESULTS

Mortality rate, height, stem base diameter and crown diameter in 2005

The cumulative mortality rates (2005) in the CON, SRF and AMT were 21.7%, 24.5% and 8.5%, respectively. The application of the SRF significantly increased the average tree height (236.6 cm) and stem base diameter (6.3 cm) of the Norway spruce plantation compared to the CON (203.3 and 5.6 cm, respectively). The amphibolite powder, despite a positive tendency in favour of this treatment, had no significant effect on the growth of Norway spruce (Table 1). The detailed assessment of the survival and growth characteristics is a subject of another study to be published soon.

Table 3. Total contents (means and standard deviations – SD) of macronutrients and S bound in the aboveground compartments of an average sample tree in the control (CON), slow-release fertiliser (SRF) and amphibolite treatment (AMT) (in g)

Compartment	Treatment		Dry mass	N	P	K	Ca	Mg	S
Needles	CON	mean	1145.79	13.14	0.73	5.32	8.19	1.33	1.49
		SD	87.65	1.020	0.074	0.849	1.246	0.386	0.212
	SRF	mean	1506.46	15.46	0.76	7.17	12.86	1.67	2.35
		SD	273.77	2.363	0.126	1.742	2.586	0.547	0.207
	AMT	mean	1314.45	13.49	0.70	6.28	9.48	1.38	1.73
		SD	193.58	1.968	0.165	1.074	2.292	0.259	0.213
Branches and twigs	CON	mean	870.25	3.01	0.09	1.85	4.16	0.47	0.44
		SD	133.87	0.337	0.083	0.217	0.727	0.067	0.105
	SRF	mean	1051.25	3.28	0.05	2.30	4.71	0.58	0.59
		SD	115.93	0.567	0.047	0.466	0.513	0.080	0.173
	AMT	mean	952.08	2.94	0.05	1.99	4.38	0.52	0.57
		SD	155.68	0.409	0.041	0.363	0.862	0.106	0.111
Bark	CON	mean	199.05	1.22	0.11	0.87	1.59	0.20	0.17
		SD	21.91	0.164	0.027	0.214	0.215	0.055	0.021
	SRF	mean	236.45	1.35	0.11	0.96	2.17	0.25	0.16
		SD	21.10	0.224	0.029	0.238	0.327	0.085	0.048
	AMT	mean	229.52	1.38	0.10	0.97	1.96	0.26	0.18
		SD	23.01	0.135	0.012	0.077	0.157	0.053	0.048
Stem wood	CON	mean	705.50	0.71	0.01	0.33	0.96	0.14	0.26
		SD	101.24	0.265	0.001	0.070	0.159	0.016	0.106
	SRF	mean	978.50	0.85	0.01	0.59	1.44	0.19	0.62
		SD	132.51	0.216	0.001	0.168	0.145	0.042	0.194
	AMT	mean	968.00	0.74	0.01	0.57	1.41	0.18	0.33
		SD	79.66	0.088	0.001	0.166	0.206	0.020	0.091

Aboveground biomass

The statistical analysis did not reveal any significant differences in macroelement concentrations among treatments in any of the aboveground compartments of the sample trees (Table 2). However, the outcomes of chemical analysis indicate that the control sample trees might have a higher concentration of N and P, mainly in the dry mass of needles (1.15% N and 0.064% P in the CON as compared to 1.04% N, 0.051% P in the SRF and 1.03% N, 0.054% P in the AMT, respectively). The *P*-values of Kruskal-Wallis test (0.071 and 0.0618, resp.) lay only closely beyond the limits of statistical significance as far as N and P concentrations in needles are concerned. Similarly, some indications of differences in S concentrations, though not supported statistically, are detected in stem wood and bark.

Table 3 summarises the total amount of dry mass and macroelements bound in the particular aboveground compartments of an average sixteen-year-old tree in the CON, SRF and AMT, respectively, in 2006. The higher biomass production of both the fertilised treatments is well documented in the dry-mass column.

Needles have proved to be the biggest pool of macronutrients and S in the aboveground part of the young Norway spruce plantation: 73–74% of total aboveground N, 79–82% P, 63–65% K, 54–60% Ca, 59–61% Mg and 62–63% S were allocated in needles. The smallest pool of macronutrients was stem wood with 4% of total aboveground N, 1% P, 4–6% K, 7–8% Ca and 7–8% Mg. The smallest aboveground pool of sulphur was bark with 4–7% S (Table 3).

The application of the slow-release fertiliser influenced the biomass production more effectively than amphibolite powder (Table 4). The absolute amount of aboveground dry mass accumulated by an average tree in the SRF was by 29% higher than that in the CON, while the AMT was ahead of the CON only by 18%.

The aboveground part of an average tree from the SRF contained the highest absolute amounts of N, K, Ca, Mg and S. The lowest total content of N, K, Ca, Mg and S was recorded in the CON. The total contents of P bound in the aboveground part in the SRF and CON were comparable. In the AMT, the sum of P in aboveground tissues was lower as compared to the two latter treatments (Table 4).

Root system

The macronutrient and S concentrations in the compartments of the root system are summarised in Table 5.

Regarding roots 0.5 cm and less in diameter, the S concentration was significantly lower in the CON compared to the SRF (0.055% vs. 0.091%). In the 0.5–1.0 cm compartment, the concentration of P in the CON was significantly higher than that in the AMT (0.012% vs. 0.005%), and the S concentration in the AMT was significantly lower than that in the SRF (0.046% vs. 0.079%). Regarding the 1.0–1.5 cm compartment of roots, the P concentrations in the SRF and AMT were significantly lower than those in the CON (0.001% vs. 0.004%). In the 1.5–2.0 cm compartment, K concentration recorded in the CON was significantly higher than in the AMT (0.18% vs. 0.12%). In the 2.0–3.0 cm compartment, N concentration in the CON was significantly higher than that in the AMT (0.21% vs. 0.12%), the P concentration in the CON significantly exceeded those in the SRF and AMT (0.003% vs. 0.001%) and the S concentrations registered in the CON and SRF treatments were significantly higher than the S concentration in the AMT (0.076% and 0.079%, respectively vs. 0.049%).

Table 4. Sum of macronutrients and S bound in the aboveground part of an average sample tree in the control (CON), slow-release fertiliser (SRF) and amphibolite (AMT) treatments 12.5 vegetation seasons after planting four-year-old transplants (in g)

Treatment		Dry mass	N	P	K	Ca	Mg	S
CON	mean	2921	18.08	0.94	8.37	14.91	2.15	2.36
	SD	258.6	1.461	0.132	1.026	1.036	0.405	0.409
SRF	mean	3773	20.94	0.93	11.03	21.18	2.69	3.72
	SD	423.7	3.105	0.179	2.429	3.030	0.658	0.292
AMT	mean	3464	18.55	0.86	9.81	17.23	2.34	2.81
	SD	293.4	2.290	0.208	1.369	3.011	0.338	0.289

SD – standard deviation

Table 5. Macroelement concentrations (in %) in dry mass of root compartments of sample trees in particular treatments

Root compartment DC (cm)	Treatment		N	P	K	Ca	Mg	S
(0.2; 0.5>	K-W test		0.4561	0.1246	0.4587	0.3444	0.2019	**0.0116**
	CON	mean	0.40[a]	0.024[a]	0.35[a]	0.34[a]	0.118[a]	0.055[a]
		SD	0.063	0.0066	0.070	0.034	0.0227	0.0120
	SRF	mean	0.41[a]	0.026[a]	0.35[a]	0.36[a]	0.113[a]	0.091[b]
		SD	0.092	0.0103	0.059	0.079	0.0238	0.0185
	AMT	mean	0.35[a]	0.017[a]	0.30[a]	0.31[a]	0.136[a]	0.073[ab]
		SD	0.039	0.0056	0.031	0.031	0.0193	0.0160
(0.5; 1.0>	K-W test		**0.0477**	**0.0474**	0.1972	0.9804	0.1368	**0.0139**
	CON	mean	0.38[a]	0.012[b]	0.28[a]	0.25[a]	0.058[a]	0.055[ab]
		SD	0.074	0.0041	0.034	0.050	0.0120	0.0094
	SRF	mean	0.30[a]	0.006[ab]	0.25[a]	0.25[a]	0.055[a]	0.079[b]
		SD	0.059	0.0057	0.057	0.045	0.0152	0.0122
	AMT	mean	0.30[a]	0.005[a]	0.24[a]	0.23[a]	0.072[a]	0.046[a]
		SD	0.044	0.0045	0.028	0.026	0.0164	0.0229
(1.0; 1.5>	K-W test		0.1642	**0.0345**	0.4943	0.1506	0.5242	0.2719
	CON	mean	0.27[a]	0.004[b]	0.19[a]	0.16[a]	0.037[a]	0.067[a]
		SD	0.075	0.0033	0.037	0.015	0.0089	0.0219
	SRF	mean	0.21[a]	0.001[a]	0.17[a]	0.19[a]	0.035[a]	0.075[a]
		SD	0.023	0.0000	0.043	0.025	0.0100	0.0118
	AMT	mean	0.22[a]	0.001[a]	0.17[a]	0.19[a]	0.039[a]	0.058[a]
		SD	0.037	0.0000	0.046	0.029	0.0060	0.0151
(1.5; 2.0>	K-W test		0.4626	0.3313	**0.0156**	0.5476	0.9722	0.3883
	CON	mean	0.19[a]	0.003[a]	0.18[b]	0.18[a]	0.032[a]	0.065[a]
		SD	0.060	0.0029	0.046	0.043	0.0066	0.0225
	SRF	mean	0.17[a]	0.002[a]	0.13[ab]	0.18[a]	0.030[a]	0.047[a]
		SD	0.037	0.0016	0.036	0.027	0.0079	0.0187
	AMT	mean	0.16a	0.001a	0.12[a]	0.17[a]	0.032[a]	0.044[a]
		SD	0.023	0.0008	0.018	0.019	0.0035	0.0120
(2.0; 3.0>	K-W test		**0.0250**	**0.0342**	0.1230	0.0730	0.4214	**0.0031**
	CON	mean	0.21[b]	0.003[b]	0.14[a]	0.14[a]	0.026[a]	0.076[b]
		SD	0.056	0.0030	0.034	0.039	0.0088	0.0148
	SRF	mean	0.17[ab]	0.001[a]	0.12[a]	0.14[a]	0.025[a]	0.079[b]
		SD	0.067	0.0000	0.041	0.024	0.0113	0.0141
	AMT	mean	0.12[a]	0.001[a]	0.10[a]	0.11[a]	0.021[a]	0.046[a]
		SD	0.017	0.0000	0.023	0.014	0.0037	0.0038
3+	K-W test		0.1568	1.0000	0.6785	0.0663	0.8897	0.2154
	CON	mean	0.10[a]	0.001[a]	0.07[a]	0.10[a]	0.021[a]	0.064[a]
		SD	0.016	0.0000	0.021	0.012	0.0031	0.0243
	SRF	mean	0.09[a]	0.001[a]	0.08[a]	0.12[a]	0.022[a]	0.050[a]
		SD	0.025	0.0000	0.033	0.014	0.0056	0.0143
	AMT	mean	0.08[a]	0.001[a]	0.08[a]	0.10[a]	0.020[a]	0.065[a]
		SD	0.014	0.0000	0.021	0.012	0.0033	0.0183

DC – diameter class, CON – control, SRF – slow release fertilizer, AMT – amphibolite treatment, SD – sample standard deviation, K-W test – results of Kruskal-Wallis analysis (overall difference), significant overall differences at $\alpha = 0.05$ are marked in bold, results of post-hoc multiple comparison by Nemeny's method are expressed by letter indexing: mean values in table columns followed by different letter indexes are significantly different from each other at $\alpha = 0.05$

In the 3+ cm root compartment, no significant differences were recorded.

It is apparent that the trees in the fertilised treatments produced a distinctly higher amount of root biomass (Tables 6 and 7). The coarse-root biomass accumulated by an average tree in the SRF and AMT exceeded that of an average control tree by 38% and 23%, respectively. Therefore, the total contents of nutrients bound in the fertilised trees were mostly higher although in some cases they showed significantly lower concentrations of nutrients (%) as compared to the CON (see Table 5). As far as the belowground biomass is concerned, the thinnest roots proved to be the greatest pool of macronutri-

Table 6. Total mean amount of dry mass, nutrients and S bound in the coarse roots of sample trees (weight in g per tree and treatment)

Root compartment – DC (cm)	Treatment		Dry mass	N	P	K	Ca	Mg	S
(0.2; 0.5>	CON	mean	158.3	0.63	0.036	0.55	0.54	0.186	0.09
		SD	25.87	0.089	0.0087	0.100	0.137	0.0408	0.022
	SRF	mean	280.6	1.18	0.076	0.90	0.99	0.313	0.25
		SD	73.54	0.550	0.0468	0.353	0.241	0.0898	0.044
	AMT	mean	205.5	0.72	0.034	0.62	0.63	0.273	0.15
		SD	66.15	0.215	0.0143	0.200	0.181	0.0703	0.035
(0.5; 1.0>	CON	mean	85.5	0.32	0.010	0.24	0.22	0.049	0.05
		SD	18.12	0.075	0.0038	0.064	0.081	0.0122	0.012
	SRF	mean	126.3	0.37	0.006	0.31	0.31	0.070	0.10
		SD	35.10	0.111	0.0058	0.097	0.101	0.0248	0.033
	AMT	mean	112.2	0.33	0.004	0.28	0.25	0.078	0.05
		SD	49.51	0.122	0.0031	0.129	0.077	0.0259	0.025
(1.0; 1.5>	CON	mean	49.8	0.13	0.002	0.09	0.08	0.018	0.03
		SD	11.86	0.039	0.0014	0.023	0.021	0.0035	0.016
	SRF	mean	78.8	0.17	0.001	0.13	0.15	0.027	0.06
		SD	18.33	0.050	0.0002	0.033	0.033	0.0047	0.019
	AMT	mean	75.0	0.16	0.001	0.12	0.14	0.029	0.04
		SD	14.98	0.036	0.0001	0.027	0.033	0.0060	0.016
(1.5; 2.0>	CON	mean	61.4	0.11	0.002	0.11	0.10	0.018	0.04
		SD	24.24	0.037	0.0011	0.045	0.030	0.0032	0.029
	SRF	mean	66.4	0.12	0.001	0.08	0.11	0.020	0.03
		SD	21.20	0.056	0.0005	0.038	0.030	0.0079	0.007
	AMT	mean	60.9	0.10	0.001	0.07	0.10	0.019	0.03
		SD	17.27	0.024	0.0002	0.015	0.031	0.0051	0.007
(2.0; 3.0>	CON	mean	77.2	0.15	0.002	0.10	0.10	0.018	0.06
		SD	36.29	0.041	0.0018	0.033	0.033	0.0060	0.032
	SRF	mean	115.7	0.19	0.001	0.13	0.16	0.027	0.09
		SD	48.58	0.100	0.0005	0.060	0.068	0.0109	0.033
	AMT	mean	112.4	0.13	0.001	0.10	0.12	0.023	0.05
		SD	58.62	0.056	0.0006	0.041	0.069	0.0111	0.024
3+	CON	mean	487.3	0.48	0.005	0.36	0.48	0.097	0.32
		SD	148.09	0.193	0.0015	0.183	0.120	0.0238	0.147
	SRF	mean	605.0	0.57	0.006	0.51	0.71	0.130	0.31
		SD	63.10	0.174	0.0006	0.211	0.103	0.0277	0.086
	AMT	mean	563.0	0.43	0.006	0.44	0.56	0.110	0.37
		SD	151.12	0.173	0.0015	0.243	0.195	0.0257	0.156

DC – diameter class, SD – standard deviation, CON – control, SRF – slow-release fertiliser, AMT – amphibolite treatment

Table 7. Sum of macronutrients and S bound in the belowground part of an average tree in the control (CON), slow-release fertiliser (SRF) and amphibolite treatments (AMT) 12.5 vegetation seasons after planting four-year-old transplants (in g)

Treatment		Dry mass	N	P	K	Ca	Mg	S
CON	mean	920	1.82	0.06	1.44	1.53	0.39	0.59
	SD	163.9	0.257	0.010	0.300	0.217	0.044	0.143
SRF	mean	1273	2.58	0.09	2.06	2.42	0.59	0.83
	SD	173.7	0.687	0.046	0.481	0.433	0.110	0.128
AMT	mean	1129	1.87	0.05	1.63	1.81	0.53	0.69
	SD	146.9	0.335	0.015	0.319	0.240	0.065	0.143

SD – standard deviation

ents. However, in terms of biomass accumulation, the thickest roots (3+ cm) were the leaders. The thickest roots bound also the highest amount of S in their biomass.

Table 8 encompasses shoot-to-root ratios of biomass and macroelement contents in the compared treatments. Regarding biomass, both the ameliorated treatments showed slightly lower ratios than the CON. With the exception of S, the SRF showed also lower ratios in terms of macroelements, as compared to the latter two treatments.

Dry mass function

Regression coefficients for the total dry mass functions (1), (2) and (3) that were yielded from our data are summarized in Table 9. The models have proved to be statistically significant in most cases.

DISCUSSION

Effects of amendments on the amount of tree biomass and its chemical composition

The amendments promoted not only the growth of the aboveground parts of trees but also the biomass of root systems, which can be demonstrated on the dry mass ratios (Table 8). Fertilising probably induced a proliferation of root systems in the initial years, which is critical for the future growth of trees (Grossnickle 2005).

Consequently the roots presumably help the ameliorated trees to stay ahead of their control counterparts although the direct amelioration effect of the amendments (improved nutrition of trees) has already diminished, at least according to the macroelement concentrations in the tissues of sample trees (Tables 2 and 5).

It is the absence of improved nutrient concentrations in the tissues of fertilised trees that indicates the diminishment of fertilisation effects at the time of sampling. Similarly, with the passage of ten-year study period, Renou-Wilson and Farrell (2007) described a deterioration of the nutrient status of Norway and Sitka spruce plantations on an extremely poor site that had been fertilised at planting.

The (seemingly paradoxical) significantly lower N, P and K concentrations in some root compartments of fertilised trees can be explained by an effect of dilution. Phosphorus and to some extent also N seem to be the most limiting elements in the nutrition of young spruces on the site (Kuneš et al. 2007). At present, when fertilising effects have

Table 8. Mean (weight) shoot-to-root ratios of dry mass and nutrients in the compared treatments (in $g \cdot g^{-1}$)

Treatment		Dry mass	N	P	K	Ca	Mg	S
CON	mean	3.3	10.1	16.7	6.0	9.9	5.6	4.2
	SD	0.50	1.19	2.92	0.86	1.52	1.03	0.90
SRF	mean	3.0	8.4	12.0	5.5	8.8	4.7	4.6
	SD	0.34	1.25	4.20	1.20	0.85	1.33	0.52
AMT	mean	3.1	10.1	19.8	6.3	9.7	4.5	4.3
	SD	0.46	2.08	7.07	1.71	2.16	0.93	1.16

SD – standard deviation, CON – control, SRF – slow-release fertiliser, AMT – amphibolite treatment

been diminishing, the faster growing spruces in the fertilised treatments have to distribute a limited amount of available P and N to a higher amount of biomass. The hypothesis of limited P supply on the site is supported, besides the low P concentrations in tissues (Tables 2 and 5), also by the calculation of total nutrients bound in the tree biomass (sums of values in Table 4 and 7). While the higher biomass amount in fertilised trees resulted in a higher sum of total N, K, Ca, Mg and S bound in their tissues, the sum of P bound in the fertilised trees remained equal or even slightly depressed (amphibolite treatment) compared to the control. A dilution effect after initial fertilising of tree plantations was described e.g. by Óskarsson et al. (2006).

Macroelement distribution in aboveground parts

From Table 3 it is apparent that wood alone is poor in macroelements while the needles, branches and twigs are their principal pools. It is, therefore, important to leave the branches and needles on the site when forest tending is performed. Recently, chippings from tending residuals and their sale as energetic chips have often been contemplated by forest practitioners in order to compensate the tending costs. After juvenile tending, the chipping of whole trees, including needles and branches, is often in question. The removal of chips produced in this way as marketable material from the stand is undesirable, since it would lead to losses of mineral nutrients. Similarly Slodičák and Novák (2008) reported that the removal of aboveground biomass after tending of young blue spruce in areas previously degraded by acid deposition might result in the deficiency of Ca and Mg.

Root-to-shoot ratios, allocation of roots

As for dry mass of roots, the ratio of root system to biomass of the whole tree is similar in all three treatments. The obtained values ranging from 23.9% (CON) to 25.2% (SRF) are in accordance with results presented by Vinš and Šika (1977). Our values of the root system ratio to the total tree biomass are higher than the values around 16% presented by Kuneš et al. (2007), who assessed biomass distribution in another young spruce stand in a close proximity to the site of our experiment.

Table 9. Regression coefficients (b_0, b_1 and b_2), their standard errors (SE), coefficient of determination (R^2), significance level of regression model (P-value) and mean squared error (MSE)

Equation	Item	b_0	SE (b_0)	b_1	SE (b_1)	b_2	SE (b_2)	R^2	P	MSE
(1)	stem	–2.8687	0.6465	1.4981	0.3489			0.527	**0.0005**	0.1173
	branches	–1.4245	0.7453	0.755	0.4048			0.180	0.0787	0.1486
	needles	–2.0488	0.7762	1.2707	0.4197			0.376	**0.0075**	0.2113
	roots	–1.8888	0.8661	1.0871	0.4690			0.253	**0.0326**	0.1982
	aboveground	–0.9158	0.4969	1.1659	0.2689			0.546	**0.0005**	0.3471
	whole tree	–0.5963	0.5260	1.1460	0.2847			0.506	**0.0009**	0.4878
(2)	stem	–1.2052	0.3678	1.2701	0.4221			0.371	**0.0069**	0.1381
	branches	–0.5286	0.3678	0.5718	0.4272			0.103	0.1948	0.1560
	needles	–0.5721	0.4046	1.0007	0.4665			0.230	**0.0436**	0.2310
	roots	–0.7371	0.4267	0.9861	0.4921			0.205	0.0575	0.2041
	aboveground	0.4286	0.2837	0.9299	0.3275			0.344	**0.0106**	0.4165
	whole tree	0.6993	0.2897	0.9443	0.3343			0.340	**0.0109**	0.5638
(3)	stem	–2.8737	0.5792	1.1382	0.3487	0.7801	0.3681	0.631	**0.0004**	0.1062
	branches	–1.4284	0.7569	0.6230	0.4612	0.2891	0.4696	0.201	0.1862	0.1517
	needles	–2.0328	0.7569	0.9873	0.4584	0.5915	0.4771	0.430	**0.0159**	0.2079
	roots	–1.8530	0.8458	0.7733	0.5099	0.6336	0.5301	0.306	0.0605	0.1956
	aboveground	–0.9136	0.4596	0.9157	0.2787	0.5363	0.2888	0.629	**0.0006**	0.3238
	whole tree	–0.5865	0.4874	0.8807	0.2951	0.5599	0.3061	0.590	**0.0011**	0.4560

in bold – statistically significant

Lower values (15%) were also reported by Svoboda et al. (2006).

Almost the whole biomass of root systems including the main coarse roots was located immediately under the greensward layer or directly in the grass rhizosphere. Though it is common that Norway spruce forms flat-shaped root systems, such an extremely shallow anchoring was surprising (the soil on the site is well drained) and may predispose the trees to drought and other stresses. Like it was described by Jentschke et al. (2001), we hypothesise that the phenomenon of extremely shallow anchoring is related to the acidification of subsoil and mainly to a reduction of the humus layer thickness due to accelerated surface humus mineralisation (Podrázský 2006) induced by the absence of sheltering canopy of older stands.

Models vs. hands on research

Recently, a lot of attention has been paid to biomass estimation of trees or their compartments (Zianis et al. 2005). Regarding indirect methods of forest tree or stand biomass estimation, young stands (like ours) have substantially different biomass proportions compared to older stands (Kantola, Mäkelä 2006).

Pajtík et al. (2008) therefore proposed biomass equations and biomass expansion factors specifically adapted to young Norway spruce.

However, there are other important factors which should be emphasised: it is density of young spruce stands and microenvironmental specificity of the site. Young naturally regenerated spruces usually grow in substantially denser stands than those planted and this difference in growth conditions might find its expression in different shape of young trees from natural and artificial regeneration and thus also in different biomass proportions.

Since Pajtík estimated the biomass in naturally regenerated trees on mountain sites in Central Slovakia, we decided to calculate b_0, b_1 and b_2 coefficients based on our data derived from planted trees growing on the mountain site in Northern Bohemia (i.e. in the same Central European region). The aboveground biomass of a tree (instead of the total tree biomass) was used for comparison, because it was not clear whether Pajtík et al. (2008) included thin roots and rootlets in their study (our lower limit for excavation was 2 mm in diameter).

The comparison of the total aboveground dry mass of the analysed sample trees and outcomes yielded from our and Pajtík's models is depicted in Figs. 1 and 2. The differences are considerable.

At a certain height, our trees accumulated much more aboveground biomass than the trees of the same height analysed by the authors of the compared study (Pajtík et al. 2008). The opposite was proved as far as basal stem diameter was concerned. In relation to trees analysed by Pajtík et al. (2008) our sample trees showed substantially higher stem taper (lower height/stem base diameter ratio).

The large stem taper of our sample trees resulting perhaps mainly from the low stand density (and to some extent also butt deformations caused by snow) will find its expression when a certain diameter at stem base is used as a reference parameter.

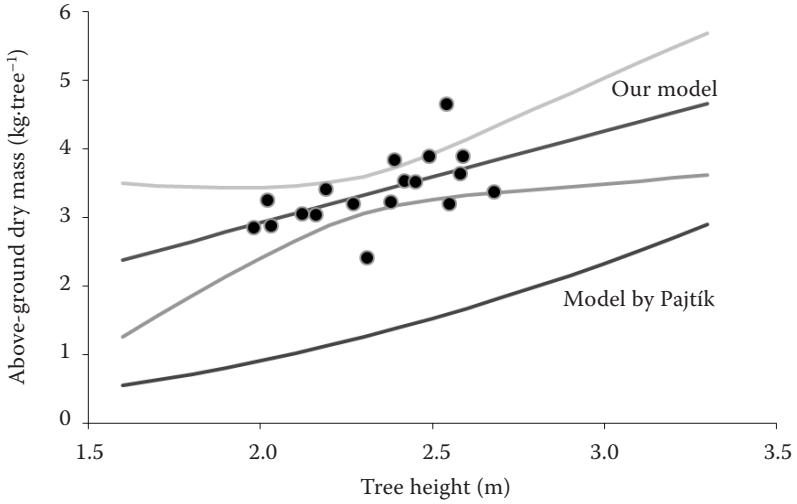

Fig. 1. Total aboveground biomass of a tree in relation to tree height (in summer 2006) according to our model and model by Pajtík et al. (2008). The grey lines depict the 95% confidence interval limits of our model. The small points shown represent the real aboveground biomass of sample trees taken in our experiment

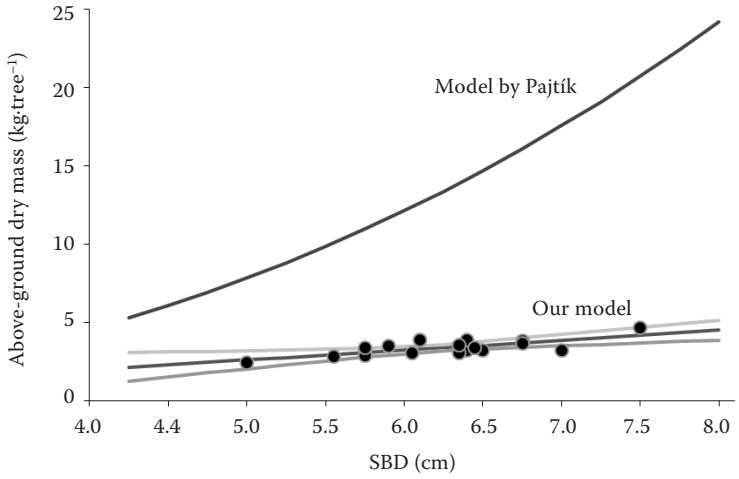

Fig. 2. Total aboveground biomass of a tree in relation to diameter at stem base (SDB in summer 2006) according our model and model by Pajtík et al. (2008). The grey lines depict the 95% confidence interval limits of our model. The circular points shown represent the aboveground dry mass of sample trees harvested in our experiment

Our sample trees accumulated much less biomass compared to the trees of the same stem base diameter processed by Pajtík et al. (2008).

During the initial decade the height growth of trees under environmental conditions of our experiment was naturally very slow and often retarded by frost or snow damage to terminal leaders and lateral shoots. This has an analogous effect on the tree shape as trimming or pruning of shoots: the crown compartment becomes very compact and dense, with a higher amount of biomass than that accumulated by a tree of the same height and certainly lower age growing on a less environmentally exposed site and in a much denser stand.

The importance of the environmental specificity of our experimental site was supported by comparing our data with the function by Kantor et al. (2009), which was designed to express the relationship of spruce needle biomass to tree height (data not shown). The model estimates were lower than our biomass data. Since Kantor et al. (2009) derived their function from a young artificially established stand planted at a comparable spacing (density) and in generally similar conditions to ours (acidic mountain site), we can presume that the density is not the only factor affecting different biomass proportions of our trees.

As for our model (restricted to a spruce plantation growing under highly specific conditions), rather than to design and suggest new altered forms of biomass functions our aim was to demonstrate the dependence of the models on stand density and site microenvironment. It is not to say that the models by Pajtík et al. (2008) or Kantor et al. (2009) are incorrect. The idea was to express the need to be extremely careful to avoid the incorrect application of any models and indirect methods in situations that do not perfectly match their preconditions.

Therefore, the direct field "hands on" research including taking of sample trees and excavating of roots is sometimes inevitable to obtain site-relevant results.

CONCLUSIONS

No significant differences in macroelement concentrations were proved among the compared treatments in any of the aboveground compartment of Norway spruce. However, lower P and N concentrations in needles of the formerly fertilised treatments were indicated. Significant differences were found in root systems showing lower concentrations of P, N, and K in some root compartments in fertilised trees, which might be ascribed to the effect of dilution: the trees in the ameliorated treatments accumulated a higher amount of biomass although the direct fertilising effects of the formerly applied amendments have been diminishing or in the case of the SRF they have probably already ceased. The faster growing fertilised trees thus have to distribute or redistribute available macronutrients to a higher amount of biomass.

Within a short- to medium-term horizon since planting (i.e. ca 10–20 years), the slow-release fertiliser was a more effective amendment than the basic rock powder. The potential of slow-release fertiliser to stimulate the growth and aboveground biomass production of trees was higher and the dose to be applied substantially lower compared

to the basic rock. The presence of slow-soluble N seems to be an important factor resulting in better stimulation efficiency of the SRF. On the other hand, longer lasting effects of amphibolite compared to SRF cannot be excluded (slow solubility of the silicate rock).

Our study showed that the biomass production of young Norway spruces can be highly variable and the models to estimate the spruce biomass indirectly should be used with extreme caution.

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