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Aboveground biomass and nutrients in an 18-years-old stand of blue spruce (*Picea pungens* Engelm.) as a substitute tree species

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ABSTRACT: Sample trees were taken for analyses from an 18-years-old blue spruce stand growing in the summit part of the Jizerské hory Mts. (Czech Republic). The sample trees were measured and dry matter and nutrient contents were analysed in needles, branches, bark and stem wood. Based on the actual stand structure, correlations were calculated between the diameter, dry weight of components and nutrient reserves. Dry matter of the stand constituted 46% of the stand fresh weight. The highest amount of nutrients was accumulated in needles (from 42% in magnesium to 82% in phosphorus) and the lowest in the stem wood (from 2% in phosphorus to 15% in potassium). Regarding the character of the locality, the complete removal of aboveground biomass during tending operations represents a considerable loss of nutrients. If only the merchantable timber volume is processed, the loss of the elements from the ecosystem could be reduced to 8% (phosphorus) to 22% (calcium and potassium) of the total content of these elements in the aboveground biomass of removals.

Keywords: aboveground biomass; nutrients; blue spruce; substitute tree species stands

Stands of substitute tree species emerged in Central Europe in the 1970–1980's in areas severely affected by air pollution, mainly in the mountains, in localities where the disintegrating stands could not be replaced by appropriate target species. The aim of establishing substitute tree species stands was to maintain the continuity of forest stands so that they could fulfil at least the most important ecological functions in the given areas – soil protection and hydrological functions (Tesař 1982; Hering, Irgang 2005; Slodičák et al. 2005). At the same time, these substitute tree species stands were to create conditions for later conversions with the use of biologically more demanding and economically more valuable tree species (Šindelář 1982).

Blue spruce (*Picea pungens* Engelm. – BLS) originating from the western part of northern America has become the most common introduced species of substitute tree species stands in the Czech Republic. To a lesser extent, it was used as a substitute tree species also in the neighbouring East Germany (Ranft 1982; Küssner, Mosandl 2002; Zerbe 2007). In its home country, the blue spruce often behaves as a long-aged species of the succession stages of forest stands, being very resistant to browsing. Great importance is attached to the species and its stands for its capacity to provide ecological shelter for wildlife and recreational function for visitors (Pavek 1993).

The species was introduced into substitute tree species stands for its high resistance to climate extremes and air pollution stress (Šika 1976), and also for its resistance against damage by hoofed game (Kubelka et al. 1992) as well as for its relatively simple cultivation in forest nurseries (Remeš et al. 2002). It used to be planted particularly at

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higher mountain elevations, often on sites not corresponding properly to natural requirements of the species (Podrázský, Souček 1996). In its home country, its timber production value is considered very low because the wood is fragile, often knotty and hardly finds any important application (Pavek 1993). It is unfit even for the chemical processing (Remeš et al. 2002) although some considerations about its use in the production of cellulose were recorded (Šika 1976).

Growth curves of blue spruce are very similar to those of Norway spruce (Jirgle 1982); however, the growth of BLS is demonstrably slower and its total wood mass production is lower (Šika 1976). Closed stands of blue spruce are instable and usually vulnerable to climatic effects – snow or windbreaks, top breakages and windfalls (Slodičák 2001).

From the production aspect, blue spruce is considered a non-economically important species in its homeland (Pavek 1993). Similarly, its plantations in the Czech Republic and in the former East Germany were to provide primarily for temporary soil cover as substitute tree species stands with ecological functions. Despite the low biomass accumulation and vitality, under certain conditions the blue spruce has recently created a forest environment in the stands of substitute species that is favourable for subsequent regeneration with target species (Balcar, Kacálek 2008).

At present, the stands with blue spruce are intended for gradual reconstruction (El Kateb et al. 2004). Within the reconstruction of stands in the northern mountain ranges of the Czech Republic, the biomass accumulated in the stands of blue spruce at small pole stage started to be used for fuel chips with the intention of growing target species in the released localities. Apart from adverse microclimatic impacts at these higher mountain elevations (Balcar, Kacálek 2008), the decision may also have a negative impact on the balance of nutrients in the sites concerned.

Studies dealing with the biomass of blue spruce are scarce. The methodology for tending the stands of substitute tree species (Slodičák, Novák 2008b) allows for the production of fuel chips only from the material removed outside the plots on which upper humus horizons were scraped by the dozer before planting (Podrázský et al. 2010). In spite of this, it also warns against the danger of depleting the site of calcium and magnesium. The methodology was based on results from previous sporadic partial surveys in the Krušné hory Mts. (small stand groups – Šika 1976, BLS stand aged 22 years – Slodičák, Novák 2008a) or in the Krkonoše Mts. foothills (BLS stand aged 18–23 years near a source of heavy air pollution – Moravčík, Podrázský 1993).

The objective of the study was to determine the aboveground biomass and nutrient content of trees of an 18-years-old blue spruce stand growing in the spruce forest altitudinal zone in the Jizerské hory Mts. on the border with Poland, in which the area of blue spruce stands amounts to 1,640 ha (Slodičák et al. 2005). Specifically, the study aims (1) to analyse the balance of nutrients, (2) to analyse aboveground biomass accumulation and nutrient content within the blue spruce stand, and (3) to assess limitations for a possible use of the biomass.

MATERIAL AND METHODS

Biomass accumulation in a small pole stage stand of blue spruce was studied in 2007 in the Plochý locality (880 m a.s.l., 5% W slope gradient, 8K Acidic Spruce – according to the Czech typological system, see Viewegh et al. 2003) in the Jizerské hory Mts. The analysed stand of blue spruce on the research plot of 0.12 ha in size was ca 18 years old (the stand had been improved). Complete measurements of tree characteristics from 2007 were already published (Špulák 2009a) and fundamental parameters are presented in the Results section.

Seven sample trees were selected for biomass and nutrient analysis in October 2007 (Table 1). Tree selection was carried out by selecting trees that represented diameter classes around the mean stem with emphasis on dominant trees (from –10 to +40% in diameter at breast height – DBH) representing the bulk of the forest stand biomass for a complex destructive analysis into production and chemical parameters. The first analysis of sample tree data was published in the Czech language (Špulák 2009b). Selected trees were cut at the ground level, and stem height and diameter at each whorl and the length of all branches were measured. From four of these sample trees, all annual shoots were taken by individual whorls and dry matter (DM) was determined. Chemical analysis of needles and wood from the annual shoots (from the terminal and even shoots) was conducted to determine contents of macronutrients (nitrogen – N, phosphorus – P, potassium – K, calcium – Ca, magnesium – Mg, sulphur – S) and silicon (Si). The samples were mineralized. Total N concentration was analysed according to Kjeldahl, P was established calorimetrically, K by atomic absorption spectrophotometer, Ca and Mg

Table 1. Parameters of the sample blue spruce trees

Sample tree	Diameter	Height	Crown base height	Dry matter				Total stem volume	Volume of merchantable timber*
				stem wood	stem bark	branches	needles		
	(cm)			(kg)				(dm³)	
1	12.0	533	86	10.4	3.9	9.4	8.6	34.5	30.4
2	9.1	420	56	6.3	1.9	9.9	7.7	19.4	16.5
3	11.5	522	90	9.6	2.4	7.4	7.2	29.6	26.0
4	9.6	444	90	7.5	1.9	6.3	5.7	22.6	19.3
5	13.2	544	63	14.1	2.8	12.9	10.9	45.1	42.4
6	8.3	451	75	5.3	1.4	5.4	4.2	16.2	12.4
7	9.5	447	86	5.8	1.6	7.1	4.9	17.3	13.6

*timber to the top of 7 cm over bark

by atomic absorption after the addition of lanthanum, S and Si using the Balks method.

Branches were taken from the individual sample trees by five whorls (whorl 1–5, whorl 6–10 etc. counted from above, each whorl represented one growth season). Their fresh and dry weight was determined and the content of elements was analysed in the needles (mixture of samples of all year-classes) and in branch wood inside bark (samples of wood chips). Branches from intermediate whorls of individual sample trees were processed separately.

Each stem was measured for its fresh weight. Four samples (discs) were taken from each stem: from the butt end, from the mid-length and at heights at which the stems reached diameters of 7 cm over bark (o.b.; commonly used limit of merchantable timber) and 5 cm. The volume of wood and bark was measured in the samples with dry matter being analysed in both and chemical analysis being made using the above-mentioned methods. Stem volume, bark volume and their dry matter were calculated by the formula for the calculation of the volume of truncated right circular cone:

$$V = \frac{\pi v}{3} (r_i^2 + r_1 r_2 + r_2^2)$$

where:
v – cone height
r_1, r_2 – radii

A non-linear regression model was created for the correlation of diameter at breast height (as x, in cm) and tree weight parameters (fresh weight, dry weight of stem wood, stem bark, wood of branches inside bark, needles as y, in kg) according to the relation $y = b_0 \times x^{b_1}$.

The close correlation between the two variables was demonstrated in a number of studies (e.g. Černý 1990; Hochbichler et al. 2006; Pokorný, Tomášková 2007; Slodičák, Novák 2008a) with the power function having a tradition of being used to balance the relations. One sample tree was excluded from the calculations with respect to the outlying ratio of stem volume to the volume of branches and needles and due to the outlying value of fresh weight. Actual tree diameters on the research plots were incorporated into the obtained equations and the model values of fresh and dry weight were calculated. Based on mean nutrient concentrations, the aboveground nutrient content of each tree was calculated, and the total accumulation of nutrients in the stand was obtained after summarization and using the plot size as expanding factor.

Mean values (pivot halfsum – P_L) and dispersions (pivot range – R_L) were calculated using Horn's quantile-based procedure for small samples ($4 \leq n \leq 20$) based on order statistics (Meloun et al. 2001). The statistical comparison of data was made in Unistat 5.6.01 (Unistat Ltd., London, UK) and R 2.11.1 (The R Foundation for Statistical Computing) programmes. The comparison of two samples was made using the F-test and t-test; multiple samples were compared by the multilevel hierarchically designed ANOVA with Tukey's test for multiple comparisons. The Kruskal-Wallis non-parametrical test was used in the case of abnormal and/or non-homogeneous means. The calculations were made at a significance level α = 0.05.

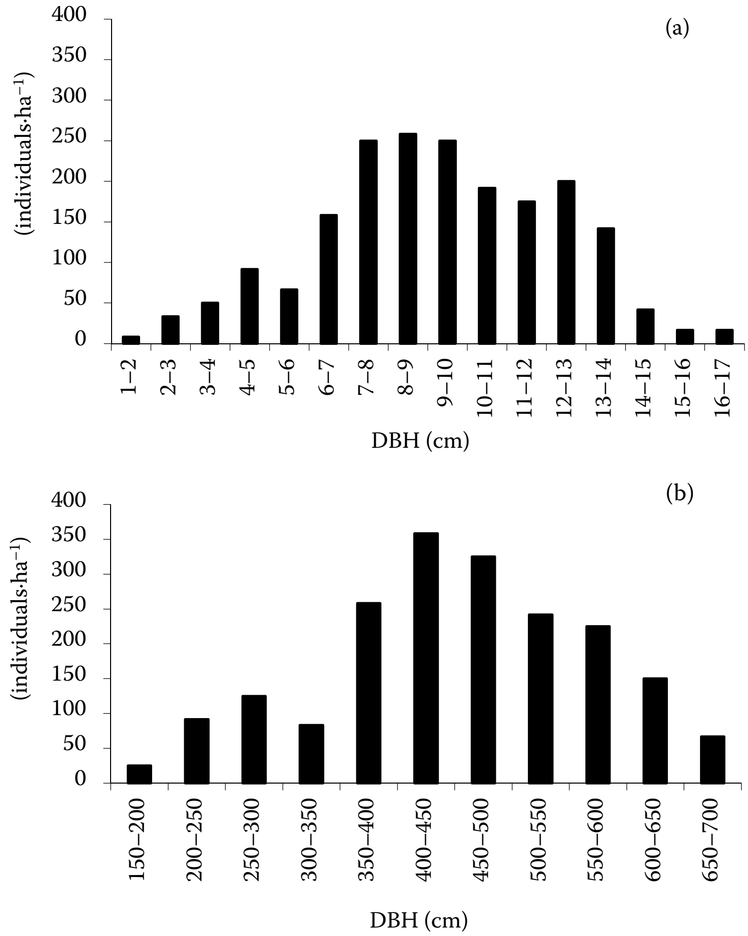

Fig. 1. Diameter – DBH (a) and tree height (b) structure of blue spruce stand in the Plochý research locality in 2005

RESULTS

Stand

In 2006, the stand density in the Plochý locality was 2,340 individuals per hectare, i.e. an average distance of 2.07 m between the trees. After the elimination (also for the further calculation) of sporadically occurring Norway spruce individuals (25 trees·ha^{-1}), a relatively considerable amount of dwarfing BLS individuals up to 1.5 m and distinctly malformed BLS individuals, the stand density was 1,950 trees.ha^{-1}.

Table 2. Contents of basic nutrients and silicon in annual needles by whorls – terminal and even whorls (%)

	N		P		K		Ca		Mg		S		Si	
	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L
Terminal	1.125	0.488	0.097	0.061	0.655[a]	0.170	0.230	0.260	0.066	0.049	0.142	0.107	0.243	0.112
2	1.289	0.134	0.104	0.020	0.405[ab]	0.250	0.280	0.300	0.104	0.076	0.142	0.067	0.224	0.028
4	1.247	0.043	0.127	0.087	0.400[b]	0.200	0.290	0.240	0.095	0.038	0.164	0.140	0.180	0.079
6	1.274	0.087	0.093	0.035	0.395[b]	0.190	0.345	0.330	0.098	0.055	0.141	0.081	0.180	0.079
8	1.290	0.150	0.094	0.022	0.410[ab]	0.160	0.380	0.460	0.093	0.034	0.164	0.131	0.241	0.164
10	1.328	0.242	0.097	0.028	0.405[ab]	0.150	0.535	0.750	0.127	0.085	0.153	0.111	0.243	0.234
12*	1.207	0.116	0.098	0.063	0.420[ab]	0.160	0.695	0.990	0.132	0.076	0.109	0.038	0.143	0.117
Weighted mean (Horn)	1.249	0.083	0.099	0.010	0.410	0.020	0.408	0.255	0.110	0.034	0.153	0.023	0.212	0.063

*indicates only 3 samples

Mean values (pivot halfsum – P_L) and dispersions (pivot range – R_L) were calculated by Horn's quantile-based procedure. Different letters for the whorls in particular elements denote significant differences at a level of significance α = 0.05 (ANOVA or Kruskal-Wallis analysis of variance and Tukey's test), no letters denote the absence of significant differences

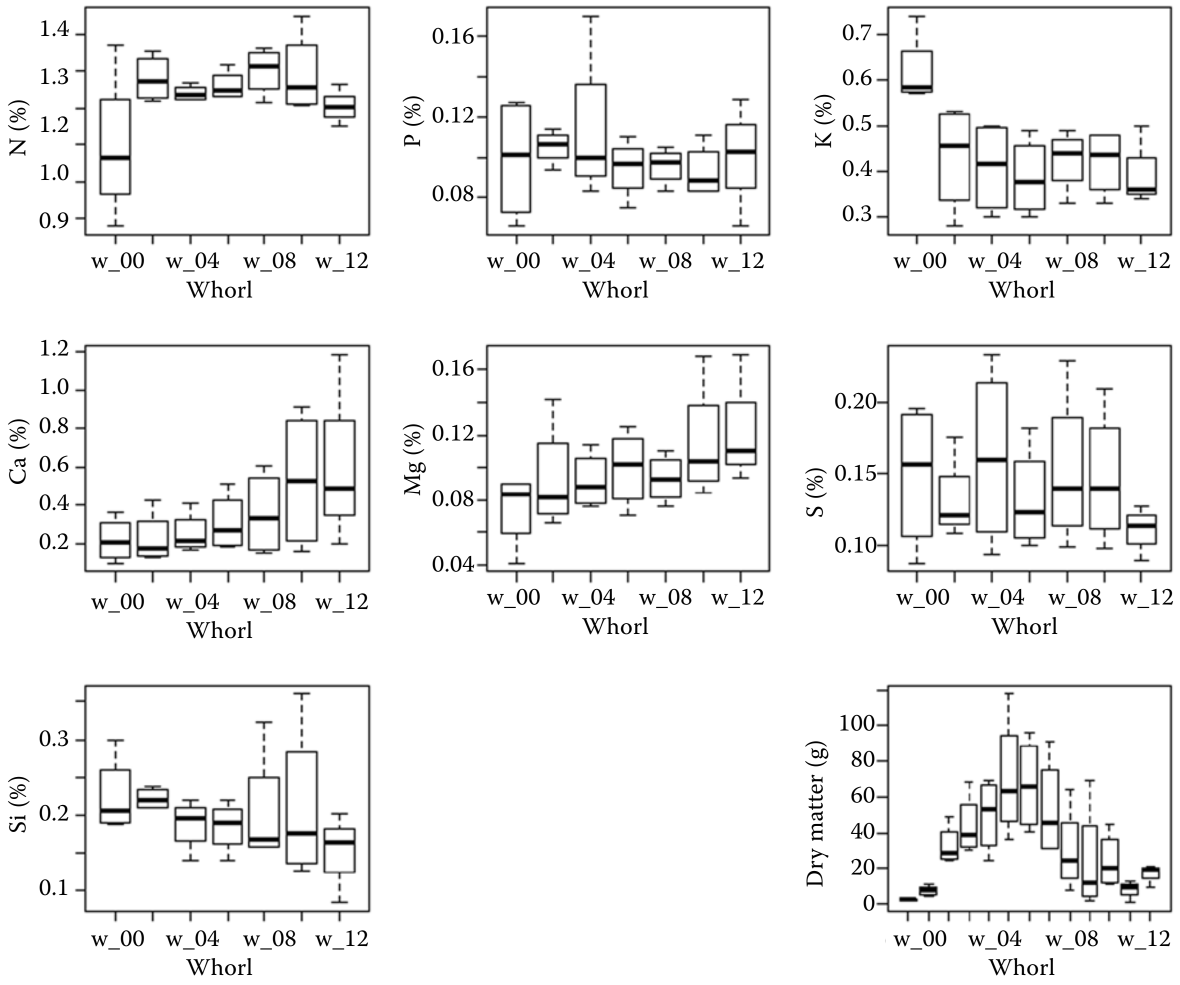

Fig. 2. Plots of annual needle nutrient contents (N, P, K, Ca, Mg, S and Si) and dry matter per relative crown height (expressed by whorls). W_00 – terminal shoot, w_01 – first, w_02 – second whorl from above etc.

In 2005, the mean height of the stand (excluding dwarfing and malformed trees) was 453 cm [standard deviation (Sx) 116 cm], mean diameter 9.2 cm (Sx 3.0 cm; Fig. 1) and basal area 14.3 $m^2 \cdot ha^{-1}$.

Biomass of sample trees

The analysed sample trees had a mean diameter (P_L) of 10.55 cm (R_L 2.90), height of 488.5 cm (R_L 89.0) and crown setting height 76.5 cm (R_L 29.0). Stem volume over bark was 16–45 dm^3 and merchantable timber (timber to the top of 7 cm over bark) accounted for 76.6–94.0% of the stem volume. Total fresh weight of the analysed sample trees ranged from 40.8 to 94.1 kg, of which 49–56% was allocated in branches with needles (mean value 52%). In terms of dry matter, this represented 16.4–40.7 kg of tree biomass, which indicates that 43–49% of the tree weight fell to dry matter. A relatively higher amount of dry matter was contained in branches with needles (49–56%) than in the stem over bark (36–42%).

Mean dry weight of the stem wood was comparable with the dry weight of branches, representing about 33% of aboveground tree biomass. In general, the weight proportions of individual tree components were quite equable among the sample trees. Needles had the lowest proportion in total dry weight (25–30%, P_L 26.5%, R_L 1.2). Stem bark represented about 8% of aboveground tree biomass. As to the ratio of the dry matter of the respective components, sample tree No. 2 was considered as outlier in its stem biomass (minimum value) and the ratio of the biomass of branches to needles (maximum value).

Annual needles

Dry weight of new shoots in the analysed sample trees ranged from 595 to 1,032 g (P_L 783 g) in 2007,

Table 3. Contents of nutrients and silicon in needles and branch wood by whorl groups (in %)

Part	Group of whorls	N		P		K		Ca		Mg		S		Si	
		P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L
Wood	1–5	0.933[a]	0.773	0.027[a]	0.023	0.380[a]	0.140	0.310	0.200	0.065	0.033	0.067	0.032	0.077	0.061
	6–10	0.500[ab]	0.199	0.012[ab]	0.008	0.215[b]	0.070	0.315	0.110	0.052	0.014	0.073	0.038	0.086	0.051
	11–15	0.324[b]	0.082	0.002[*b]	0.001	0.120[c]	0.040	0.425	0.110	0.045	0.019	0.068	0.029	0.084	0.075
	weighted mean (Horn)**	0.358[b]	0.048	0.004[b]	0.003	0.139[b]	0.048	0.344[b]	0.045	0.042[b]	0.016	0.071[b]	0.024	0.080[b]	0.028
Needles	1–5	1.299	0.267	0.078	0.036	0.388[a]	0.136	0.319[b]	0.278	0.072	0.018	0.184	0.107	0.419	0.106
	6–10	1.250	0.346	0.047	0.021	0.340[ab]	0.120	0.548[ab]	0.336	0.080	0.029	0.147	0.066	0.528	0.081
	11–15	1.226	0.243	0.040	0.032	0.393[b]	0.113	0.696[a]	0.313	0.099	0.044	0.159	0.078	0.670	0.195
	weighted mean (Horn)**	1.160[a]	0.124	0.045[a]	0.020	0.338[a]	0.078	0.545[a]	0.252	0.075[a]	0.006	0.156[a]	0.010	0.550[a]	0.031

*limit of method accuracy, **including intermediate whorls
Mean values (pivot halfsum – P_L) and dispersions (pivot range – R_L) were calculated by Horn's quantile-based procedure. Different letters between the groups of whorls and between the parts in the particular elements denote significant differences at a level of significance $\alpha = 0.05$ (ANOVA or Kruskal-Wallis analysis of variance and Tukey's test), no letters denote the absence of significant differences

Table 4. Basic nutrients and silicon in bark and stem wood (in %) in particular stem parts (at a diameter of 5 cm, small end, stem middle and butt end)

	Part	N		P		K		Ca		Mg		S		Si	
		P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L	P_L	R_L
Bark	5 cm	0.575[a]	0.115	0.026[a]	0.022	0.310[a]	0.040	0.575	0.150	0.081[a]	0.015	0.054	0.033	0.072[a]	0.079
	small end	0.520[a]	0.143	0.027[ab]	0.021	0.300[a]	0.060	0.705	0.350	0.081[a]	0.024	0.048	0.008	0.091[ab]	0.033
	stem middle	0.472[ab]	0.087	0.013[ab]	0.023	0.235[ab]	0.050	0.845	0.190	0.070[ab]	0.014	0.055	0.033	0.077[ab]	0.023
	butt end	0.378[b]	0.052	0.008[b]	0.014	0.220[b]	0.060	0.695	0.150	0.053[b]	0.017	0.048	0.022	0.042[b]	0.028
	weighted mean (Horn)	0.434[a]	0.061	0.012	0.014	0.245[a]	0.066	0.739[a]	0.042	0.065[a]	0.014	0.051[a]	0.026	0.062[a]	0.014
Stem wood	5 cm	0.090	0.016	–*	–	0.060[b]	0.020	0.085	0.010	0.015[a]	0.003	0.025	0.021	0.021	0.014
	small end	0.097	0.015	–	–	0.070[ab]	0.020	0.090	0.020	0.014[ab]	0.004	0.026	0.014	0.033	0.028
	stem middle	0.087	0.014	–	–	0.075[ab]	0.010	0.085	0.010	0.012[bc]	0.003	0.047	0.047	0.028	0.019
	butt end	0.094	0.020	–	–	0.085[a]	0.010	0.070	0.020	0.010[c]	0.005	0.062	0.074	0.026	0.014
	weighted mean (Horn)	0.091[b]	0.010	–	–	0.079[b]	0.009	0.076[b]	0.017	0.011[b]	0.004	0.053[a]	0.059	0.026[b]	0.014

*under the limit of method accuracy
Mean values (pivot halfsum – P_L) and dispersions (pivot range – R_L) were calculated by Horn's quantile-based procedure. Different letters between logs and their parts in the particular elements denote significant differences at a level of significance $\alpha = 0.05$ (ANOVA or Kruskal-Wallis analysis of variance and Tukey's test), no letters denote the absence of significant differences

which represented 1.5–5.3% of the total dry matter of the sample trees. Of this, 27.9–31.4% was the mass of needles and the rest were twigs. The highest DM of new shoots was detected between the 5th and 7th whorl from above (Fig. 2). The proportion of needles in the total weight of shoots (incl. twigs) in the respective whorls was increasing from the upper to the lower part of the crown; while the proportion of needles on the terminal ranged from 15–20%, it amounted to 74–80% on the 10th whorl.

The chemical analysis showed no significant differences in nutrient content in annual needles according to the whorl position with the exception of K, whose content in annual needles of the terminal shoot was significantly higher than in needles from the 4th and 6th whorl (P = 0.023, Table 2). Relatively high dispersion parameters (R_L), especially in the case of Ca, are caused by inter-sampling variability on a small number of samples. Profiles of nutrient contents of annual needles are plotted in Figure 2.

Following the criteria for nutrient contents cited for Norway spruce (Bergmann 1988), the annual needles exhibit deficient N, P, K concentrations and limiting Ca and Mg values.

Branches with needles

As expected, the dry weight of branch wood (with bark) increased with the increasing age of the group of whorls. An opposite trend was observed in the smallest tree (sample 2), where the weight of its lower whorls was lower. By contrast, lower dry weight of needles was (with the exception of sample tree 7) detected in the group of whorls 11–15 than in the group of whorls 6–10.

Concentrations of some elements in branch wood from the upper and lower part of the crown differed. The concentrations of N and P differed significantly (P = 0.026 and 0.003); in the group of whorls 11–15, the concentration of P ranged around the limit of accuracy of the method. A decrease in the content of K between whorl groups was highly significant (P < 0.001), while the indicated decrease in the concentration of Mg was non-significant (P = 0.091, Table 3).

A correlation between the contents of elements and the location of needles within the crown was observed also in the composite sample of all needle years. Similarly like in annual shoots, a negative correlation was shown between the height and the Ca concentration (P = 0.010). At the same time, all mean values of Si content in branch wood and needles suggested an increasing trend. As compared with the branch wood, the percentage of all analysed nutrients in the needles was significantly higher (Table 3).

Stem wood and bark

Nutrient concentrations in stem bark with the exception of S (P = 0.671) were many times higher than in stem wood (P < 0.001, Table 3). It was noticeable that P concentration in stem wood did not reach the minimum traceable level by the used analytical method. Concentrations of N, P, K, Mg and Si in the bark were higher at the top of the stem (P ≤ 0.048, Table 4). Magnesium in wood exhibited a similar ratio (P < 0.001) while the content of K was lowest in the upper part of the tree (P < 0.006). Other elements contained in wood did not exhibit any trends related to stem height.

Nutrient reserve in the stand

Parameter estimates of the allometric model used to correlate DBH and tree component biomass are shown in Table 5. Changes in tree diameter explained more than 95% of variation of the dry mass of stem wood, needles and total fresh weight. Relations between the diameter and dry matter of branches and needles were looser (R^2 0.86 and 0.66).

Table 5. Regression coefficients (b_0 and b_1), their standard errors (SE), coefficient of determination (R^2), significance level of regression model (P-value) and Durbin-Watson Statistic (D–W)

	Compartment	b_0	SE(b_0)	b_1	SE(b_1)	R^2	P-value	D–W
Dry matter	stem wood	0.0492	0.0232	2.1778	0.1932	0.9646	< 0.001	1.7697
	stem bark	0.0357	0.0517	1.7585	0.5972	0.6575	0.027	0.9847
	branches	0.0934	0.0899	1.8754	0.3936	0.8586	0.008	0.8877
	needles	0.0422	0.0201	2.1401	0.1943	0.9722	< 0.001	1.6849
Fresh weight		0,2863	0.1876	2.2264	0.2665	0.9523	0.001	1.3950

Table 6. Total reserve of nutrients and silicon in the aboveground biomass of small pole stand of blue spruce (kg·ha^{-1} and %) for the actual stand density of 2,300 trees per hectare, calculated from relation trends (Table 5), dry matter and fresh weight of average tree (kg)

	Dry matter										Fresh weight
	Stem wood	(%)	Stem bark	(%)	Branches	(%)	Needles	(%)	total	(%)	total
Weight	13,624.0	33.5	3,686.0	9.1	12,678.0	31.2	10,680.0	26.3	40,668.0	100	88,959.0
N	12.4	6.3	16.0	8.1	45.4	23.0	123.9	62.7	197.7	100	
P	0.1*	2.3	0.4	7.5	0.5	8.6	4.8	81.6	5.9	100	
K	10.8	14.6	9.0	12.3	17.6	24.0	36.1	49.1	73.5	100	
Ca	10.4	7.4	27.2	19.5	43.6	31.3	58.2	41.8	139.4	100	
Mg	1.5	8.7	2.4	13.9	5.3	30.9	8.0	46.5	17.2	100	
S	7.2	20.8	1.9	5.4	9.0	25.9	16.7	47.9	34.8	100	
Si	3.5	4.7	2.3	3.1	10.1	13.6	58.7	78.6	74.7	100	
Average tree	7.0	33.5	1.9	9.1	6.5	31.2	5.5	26.3	20.9	100	45.6

*content below the accuracy limit of the method of chemical analysis

Total DM contents of stem wood and branch wood biomass in the stand were very similar (13.6 and 12.7 t·ha^{-1}, respectively). However, the contents of nutrients accumulated in them showed large differences (Table 6). The lowest biomass weight in the stand of blue spruce was found in the bark (3.7 t·ha^{-1}, i.e. 9% of total DM); however as compared with the wood, the accumulation of N, P, Ca and Mg in bark was higher. The difference was particularly significant in Ca (29.2 kg·ha^{-1} in stem bark as compared with 10.4 kg·ha^{-1} in stem wood).

Even though the foliage proportion amounted to about 26.3% of dry matter in the aboveground biomass, it accumulated most of the nutrients stored in the stand, accounting for about 63, 82, 49, 42, 47, 48 and 79% of N, P, K, Ca, Mg, S and Si, respectively (Table 6).

DISCUSSION

The analyses revealed a loss of relative biomass weight both in new needles and in all needle years occurring in the lower part of sample tree crowns. The reason may be seen in the competition of neighbouring trees by shading, demonstrated in the suppressed development of new shoots on the one hand and in the reduction of inefficient photosynthetic tissues (casting of older needle years) on the other hand. The life-span of needles was up to 6 years.

The reason for the observed relation between the BLS needle content of elements and the height within the crown may be the average level of insolation (shading) of the branch layer and the translocation of nutrients associated with the potential of photosynthetic activity of needles within the crown (Givnish 1988; Helmisaari 1992). The relation to crown shading can be derived also from a comparison with results of a study focused among other things on the monitoring of differences in the chemistry of foliage on the insolated and shaded crown parts in balsam fir and red spruce (Richardson 2004). Shaded needles contained more P and K. Nevertheless, unlike our study Richardson (2004) observed a lower content of Ca in shaded needles of the balsam fir while the Ca concentration in the red spruce did not differ.

On the other hand, the chemical analysis of branch wood inside bark showed decreased contents of some elements from the top to the crown base. In the case of K, the trend was opposite to that in the needles. The difference in nutrient concentration may have to do with the variable proportion of bark in branches occurring within the crown and a redistribution of elements can be considered within the tree, associated with the nutrient supply to photosynthetically active locations.

The representation and reserve of Si in needles markedly exceeded the contents of the element in the other parts of the tree. This corresponds with the results of the analysis of assimilatory apparatus of many coniferous and deciduous trees (Cornelis et al. 2010) as Si is an important (supportive) element for plants helping them to cope with abiotic stress (Liang et al. 2007).

At the same time, an indirect correlation was suggested between the height within the crown and the mean value of Si content in annual needles ($P < 0.001$) and to a lesser extent in bark ($P = 0.061$). Godde et al. (1991) recorded increased Si content in a spruce tree with impaired health condition as compared with a healthy-looking spruce tree. However, they compared only two trees growing in slightly different soil conditions. Nonetheless, should the finding be of general validity, the stress caused by the heavy shading of older needle years could have conditioned the higher Si accumulation in our study.

Available criteria for the contents of nutrients in new needles cited for Norway spruce (Bergmann 1988) pointed to generally deficient nutrition. Of course, actual limit values may differ among the species; however, the worsening health condition of the stand (Špulák 2009a) would correspond to the non-optimal nutrition status. In spite of the health condition that was far from optimal, the ratio of the dry matter of needles to the dry matter of branches was 84%, which is more than recorded in the young blue spruce stands in the study from the Krušné hory Mts. (63%, Slodičák, Novák 2008a) and from the Krkonoše Mts. foothills (69%, Moravčík, Podrázský 1993).

As compared to our results, Slodičák and Novák (2008a) recorded by more than a third higher dry matter of total aboveground biomass (38%) in a 22-years-old stand in the Krušné hory Mts. (800 m a.s.l., 2,022 trees·ha^{-1}). The greatest weight difference between the stands was found in the biomass of branches (by 80% and more), DM of needles was by 35% and of stem wood by 16% higher. On the other hand, the stand in the Krušné hory Mts. had by 15% lower weight of bark as compared with our stand. Analysing a forest stand of substantially higher density (2,950 trees·ha^{-1}) aged 25 years in the Krkonoše Mts. foothills Moravčík and Podrázský (1993) also observed different proportions of stand dry matter as compared with our research plot. Dry matter of stem wood, branches and bark in their study was by 56%, 34% and 18% higher, respectively, the least difference was found in the mass of needles (by 10% and more). The total weight of aboveground biomass was higher by 43%.

Apart from the uncertainty stemming from the methods of sampling in the particular studies, the disproportions can be attributed to local site differences reflecting in the health status and growth response of the trees. Taking into consideration different age and stand density, the stand in the Plochý locality is closer to the stand of blue spruce in the Krkonoše Mts. foothills notwithstanding the fact that the latter occurs by three forest altitudinal zones lower (5K – Acidic Fir-Beech). However, the growth period of that stand showed a greater overlap with the period of increased air pollution stress (Vacek et al. 1999).

Within the biomass of the whole stand, the main reserve of nutrients was accumulated in the needles and fewest elements were accumulated in the stem wood. The aboveground biomass overall exhibited the low reserve of P (only 5.9 kg·ha^{-1}). Comparing our results with the 22-years-old stand in the Krušné hory Mts. (Slodičák, Novák 2008a), the deficit of P and the generally low nutrient reserve of our experiment can be stated. The authors reported higher reserves in all elements, the difference ranged from 14% (Ca – deficient) to 88% (K) and the content of P was more than 4.5-times higher (474%) than our values.

Pedological surveys in the locality revealed the accumulation of 153 tons of dry matter in organic horizons (L, F, H) under the blue spruce (Špulák, Dušek 2009). Reserves of N, P, K, Ca and Mg established by the Mehlich III method were 2.28 t, 3.8 kg, 71.7 kg, 140.0 kg and 41.16 kg per ha, respectively. Similarly like in the aboveground biomass, P was a limiting element for the site. Even if considering a different method of the chemical analysis, the hypothesis is further supported by a comparison with the study of organic horizons from the BLS stand in the Krušné hory Mts. (Ulbrichová et al. 2005).

According to the current methodology for the conversion of substitute tree species stands in the Czech Republic (Slodičák, Novák 2008b) for less favourable ecological conditions with air pollution stress, the recommended intensity of the first silvicultural measure (tending) in the BLS stand considers the number of trees reduced by ca 30% and the basal area reduced by max. 15%. In full-tree harvesting (e.g. for fuel chips), the measure would entail the removal of 0.9 kg of P, 29.7 kg N, 11.0 kg K, 20.9 kg Ca and 2.6 kg Mg per hectare, contained in more than 13 tons of fresh biomass. With respect to the generally low fertility of the site, the contents are not negligible and as to nutrient cycling, it would be more beneficial to leave the felled material on the site.

As to stand components, the highest reserve of P was found in needles that were followed by branches and bark. The bark exhibited higher concentrations of elements in the upper part of the stem. Forest managers also have to consider economic aspects. Using a technology by which only the merchantable timber volume would be processed, the loss of nutrients from the ecosystem would be reduced. Considering the fact that the merchantable timber volume contains 80% of the total content of elements in the stem, the content of nutrients in the biomass of the merchantable timber volume would range from 8% in P to 22% in Ca and K from the total content of elements in the secondary crop. This would be an appreciable benefit for the site as compared with the method of full-tree logging.

Long-term investigations of the Norway spruce nutrition and soil chemistry in the Jizerské hory Mts. indicated decreasing availability not only of P but also of Mg, which in combination with soil acidification may be limiting factors for the forest nutrition in the future (Lomský et al. 2012). On poor sites under former acidification stress the improved nutrient supply may act as a stimulus promoting growth and influencing the vitality and survival of especially young trees (Nilsen, Abrahamsen 2003; Podrázský et al. 2003; Kupka 2005; Óskarsson et al. 2006). Liming increasing the Ca and Mg supply can partly improve the accessibility of P (Formánek, Vránová 2002). It was found that P content in spruce needles (Kulhavý et al. 2009) as well as its content in forest litter (Šrámek et al. 2006) increased as a consequence of liming. However, if the mineral weathering of soil is the main source of this nutrient, liming consequently leads to a reduction of P content in lower soil layers. Potential nutrient removals by BLS tending and the site specific nutritional deficiencies could be counteracted by P and Mg fertilization. Considering the ecological and economic effects of nutrient amendment, the point application of an appropriate slow-release fertiliser (SRF; Jahns, Kaltwasser 2000) to support the growth of target trees – especially nutrient demanding species of subsequent regeneration during conversions of the substitute species stands – could be an adequate option.

CONCLUSION

It follows from our study that the dry matter of trees constituting the young stand of blue spruce in the spruce forest altitudinal zone of the Jizerské hory Mts. accounted for 43–49% of the tree fresh weight. Therein, the highest percentage volume of nutrients is accumulated in the mass of annual needles (mean values 1.25% N, 0.10% P, 0.41% K, 0.41% Ca, 0.11% Mg and 0.15% S) and the lowest concentration of nutrients is accumulated in the stem wood (0.09% N, $<$ 0.001% P, 0.08% K, 0.09% Ca, 0.01% Mg and 0,05% S). As to the total biomass volume of the 20-years-old stand with 1,950 trees per hectare, the highest amount of nutrients was contained in needles (from 42% in Mg to 82% in P), followed by the mass of branches inside bark and stem bark while the least amount of nutrients was found in the stem wood (from 2% in P to 21% in S). Phosphorus was a limiting element for the site. Regarding the generally low content of nutrients in the locality, possible complete removal and processing of the aboveground biomass from tending operations would result in severe impoverishment of the ecosystem in terms of nutrient loss. A reasonable compromise between the total removal of nutrients and the partial fulfilment of wood-producing functions may be the processing of merchantable timber volume only. With the use of this method, the loss of elements from the ecosystem would range from 8% (P) to 22% (Ca and Mg) of the total content of elements in the felled aboveground biomass. Taking into account the character of geological basement and historically grounded air-pollution stress at higher mountain elevations of the northern part of the Czech Republic, leaving branches and small wood on the site would be beneficial for most localities on which the blue spruce has been used as a substitute tree species.

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