Ca/Al ratio in Norway spruce fine roots on monitoring plots in the Czech Republic

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ABSTRACT: This article is focused on the evaluation of the Al/Ca ratio in fine roots of Norway spruce on the plots belonging to the ICP Forests monitoring programme in the Czech Republic. In total 122 fine root samples were collected from twenty plots from two soil layers of 0–10 and 10–20 cm and then analysed. The mean Ca/Al molar ratio in the fine roots from the 0–10 cm topsoil layer is higher than in the lower 10–20 cm soil layer, which corresponds to the distribution of fine roots – on average 80% of fine roots were found in the topsoil. 6% of the samples in the lower soil layer strongly indicate aluminium stress (Ca/Al < 0.1) and 30% of the samples may demonstrate the adverse effects of aluminium (< 0.2). On the other hand, no relationship was found between the Ca/Al ratio in the fine roots and the fine root biomass and vitality or crown condition. These results suggest that the potential aluminium toxicity is not the driving factor of the crown condition in Norway spruce and the Ca/Al ratio itself does not pose a risk to forest health in the region.

Keywords: aluminium toxicity; forest health; soil acidification

Central European forests were significantly influenced by the impact of air pollution during the second half of the 20th Century. Apart from regions in which extreme concentrations of sulphur dioxide had caused a mass dieback of forest stands like in the Krušné hory Mts. and Jizerské hory Mts. (Kubelka 1993; Lomský et al. 2002, 2012), the acidic atmospheric deposition played the role of the main anthropogenic stressor. The measured mean deposition of sulphates was more than 40 $kg\cdot ha^{-1}\cdot yr^{-1}$ in open field (bulk) deposition and more than 100 $kg\cdot ha^{-1}\cdot yr^{-1}$ in throughfall deposition to Norway spruce stands at the turn of the 1980's and the 1990's in the Czech Republic (Lochman et al. 2008). During the 1990's the acid deposition load in the Central European countries decreased significantly with the increasing importance of nitrate deposition as compared to strongly reduced sulphates (Hůnová et al. 2004; Lochman et al. 2008; Vícha et al. 2012, 2013). On the one hand, critical loads of sulphur and nitrogen deposition are still exceeded in some regions of Central Europe (Šrámek et al. 2008a; Reinds et al. 2008), on the other hand the long-term acid deposition led to adverse changes in forest soils including the leaching of base cations, which contributes to nutrient deficiency in forest stands (Vanoehe 1992; Hüttl, Schaaf 1997; Novotný et al. 2008). While on the European scale the deciduous trees exhibit a higher level of damage than do conifers (ICP Forests 2012), Scots pine and Norway spruce are the most defoliated species in the Czech Republic (Fabiánek et al. 2012). The shallowly rooted Norway spruce in particular could be negatively influenced by a lack of base nutrients both on heavily acidified mountain sites and also at lower altitudes where the input of nutrients is limited during periods of drought (Ewald 2005; Musio et al. 2007; Šrámek et al. 2008b; Lomský et al. 2012).

The adverse effect of forest soil acidification does not consist solely in the depletion of base cations but also in the increased concentrations of ionic aluminium which is potentially toxic to plants (Balsberg Påhlsson 1990; Boudot et al. 1994; Persson, Majdi 1995; Kinrade 2003). The Ca/Al molar ratio as an indicator of aluminium toxicity

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was first applied by Lund (1970) in his study of soybean root elongation. Hutterman and Ulrich (1984) suggested the Ca/Al molar ratio as the most significant indicator of the aluminium toxicity being associated with forest decline. The reliability of the Ca/Al molar ratio as a stress indicator in soil solution, fine roots and tree biomass was thoroughly discussed in reviews by Cronan and Grigal (1995), Álvarez et al. (2005) and Vanguelova et al. (2005).

According to the results of the Second European Forest Soil Survey (BioSoil) (de Vos, Cools 2011) the forest soils in the Czech Republic exhibit deficiencies in exchangeable calcium and magnesium and the base saturation in the upper layers of mineral soil (0–20 cm) is critical (< 10%) at more than 40% of the plots studied (Šrámek et al. 2011). The potential toxicity of aluminium in forest soils in the Czech Republic has also been mentioned, e.g. by Borůvka et al. (2009) and Tejnecký et al. (2010).

This article is focused on the evaluation of the Ca/Al ratio in fine roots on the ICP Forests monitoring plots in the Czech Republic with dominance of Norway spruce (*Picea abies* [L.] Karst), in relation to soil chemistry and defoliation data.

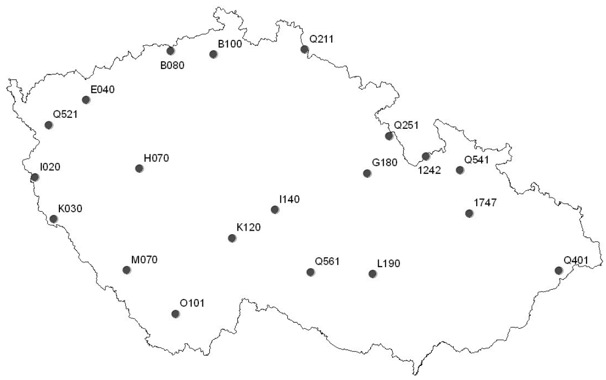

Fig 1. Distribution of sampling plots within the Czech Republic

MATERIAL AND METHODS

Plot selection. The plots for root sampling were selected from the network of 146 ICP Forests monitoring plots in the Czech Republic where the soil survey was carried out in the framework of BioSoil survey (de Vos, Cools 2011). The defined selection parameters were: (*i*) Norway spruce as a dominant species, (*ii*) forest stands of more than 50 years of age and (*iii*) the soil type not being influenced by water (e.g. Cambisols or Podzols). The plot distribution and its basic characteristics are shown in Table 1 and Fig. 1. Defoliation (crown transparency)

Table 1. Basic characteristics of sampling plots

Plot No.	Plot name	Altitude (m a.s.l)	Norway spruce representation (%)	Age of stand	Soil type
I020	Kateřina	521	89	101	cambisol
K030	Babylon	581	100	104	podzol
Q521	Lazy	875	100	123	cambisol
E040	Kyselka	441	98	91	cambisol
H070	Lhota pod Radčem	509	100	112	cambisol
M070	Branišov	795	100	102	cambisol
B080	Krupka	557	95	98	cambisol
O101	Český Krumlov	806	99	100	cambisol
B100	Valkeřice	433	97	79	cambisol
K120	Velmovice	536	94	115	cambisol
Q211	Jizerka	910	100	62	podzol
I140	Želivka	440	100	108	cambisol
Q561	Nová Brtnice	640	100	108	cambisol
G180	Choceň	337	88	87	cambisol
Q251	Luisino údolí	940	100	97	podzol
L190	Braniškov	442	73	99	cambisol
1242	Dolní Morava	925	100	55	cambisol
Q541	Švýcárna	1,300	98	119	podzol
1747	Dalov	637	99	57	cambisol
Q401	Klepačka	650	79	85	cambisol

assessment of the plots in 5% steps, in accordance with the methodology of the ICP Forests monitoring programme (UNECE 2006a), is carried out on a yearly basis. For the evaluation we use the mean defoliation of the individual plots (Table 2) dating from the year 2009, when root samples were collected for chemical analyses. Information about soil chemistry on the plots was adopted from the results of the BioSoil survey. We used data on the mineral soil from two depth-intervals – 0–10 cm and 10–20 cm. The pH levels and the exchangeable contents of Al, Ca, K and Mg are shown in Table 2. The detailed methods that were employed for the sampling and soil sample analyses were published

Table 2. Mean defoliation and soil chemistry on sampling plots (exchangeable contents of elements)

Plot No.	Plot name	Spruce defoliation (%)	Soil properties						
			soil layer (cm)	pH_{H_2O}	Al (mg·kg^{-1})	Ca (mg·kg^{-1})	K (mg·kg^{-1})	Mg (mg·kg^{-1})	BS (%)
I020	Kateřina	35.9	0–10 10–20	4.11 4.56	419.9 301.6	43.8 15.8	33.5 26.0	23.4 11.9	8.9 6.5
K030	Babylon	32.6	0–10 10–20	3.51 3.67	561.7 762.3	91.8 53.1	61.0 47.4	22.7 15.6	9.8 5.4
Q521	Lazy	35.5	0–10 10–20	3.83 4.03	474.3 552.1	70.0 22.7	35.3 25.1	19.1 8.6	9.5 3.9
E040	Kyselka	27.5	0–10 10–20	4.68 5.28	605.5 206.2	1269.6 2476.8	78.0 83.0	390.3 739.2	57.1 86.7
H070	Lhota pod Radčem	34.4	0–10 10–20	4.02 4.48	540.3 333.3	83.3 20.1	69.2 46.4	11.4 4.1	9.1 5.7
M070	Branišov	39.9	0–10 10–20	4.09 4.39	496.7 351.3	88.8 25.4	32.5 14.2	31.1 11.3	11.2 5.9
B080	Krupka	28.2	0–10 10–20	4.24 4.30	475.5 490.2	42.3 30.6	33.8 36.0	15.0 10.6	7.0 5.8
O101	Český Krumlov	40.1	0–10 10–20	3.95 4.31	491.4 388.1	18.8 9.4	31.5 20.2	9.3 3.6	4.3 3.0
B100	Valkeřice	32.7	0–10 10–20	4.37 4.97	817.5 415.2	822.3 1,653.4	69.3 47.6	223.3 367.2	39.6 70.3
K120	Velmovice	30.5	0–10 10–20	4.31 4.51	556.9 321.8	55.3 26.6	25.1 23.7	15.5 8.3	6.7 6.3
Q211	Jizerka	25.2	0–10 10–20	4.16 4.27	642.6 507.6	102.8 34.6	67.8 29.1	54.2 17.2	12.9 6.4
I140	Želivka	34.9	0–10 10–20	4.02 4.28	583.7 409.4	149.9 45.0	57.5 32.3	31.5 7.8	14.1 7.0
Q561	Nová Brtnice	34.7	0–10 10–20	4.03 4.25	499.6 387.0	122.7 46.3	50.5 32.9	29.1 16.5	13.4 8.6
G180	Choceň	32.4	0–10 10–20	3.71 3.79	238.1 250.9	94.1 35.6	36.0 26.3	16.1 7.2	16.6 8.4
Q251	Luisino údolí	31.1	0–10 10–20	4.06 3.98	658.5 538.9	186.8 74.4	55.0 23.2	60.5 17.4	16.7 8.7
L190	Braniškov	37.6	0–10 10–20	4.15 4.15	506.4 475.3	290.2 148.8	32.5 26.3	23.2 13.9	21.8 14.5
1242	Dolní Morava	12.8	0–10 10–20	4.17 4.32	803.4 615.9	15.3 8.3	35.3 26.1	15.2 10.8	3.1 2.8
Q541	Švýcárna	36.3	0–10 10–20	3.82 4.06	504.2 550.2	37.2 22.7	28.8 11.7	18.4 11.6	6.2 3.5
1747	Dalov	26.8	0–10 10–20	4.21 4.46	482.4 352.5	96.0 85.8	38.4 27.0	15.5 11.5	10.8 12.3
Q401	Klepačka	39.3	0–10 10–20	3.71 4.04	895.4 832.6	51.3 37.2	62.9 33.6	19.1 9.7	5.0 3.6

BS – base saturation

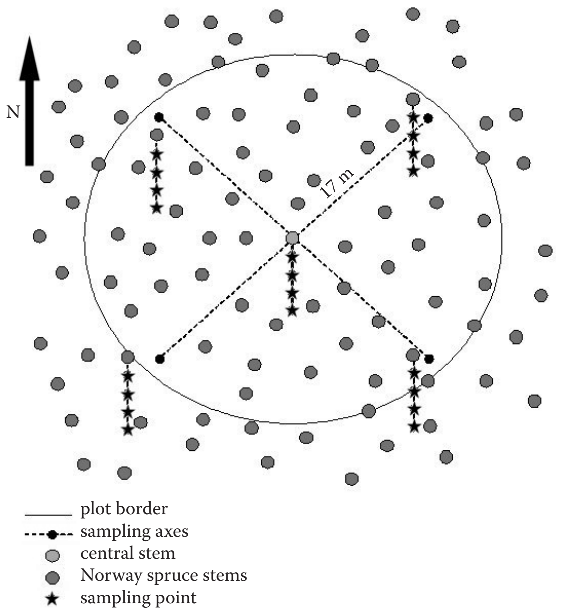

Fig. 2. Sampling design

by UNECE (2006b), de Vos and Cools (2011) and Šrámek et al (2012).

Root sampling and chemical analyses. The Norway spruce roots were sampled following the main growing season during the period between September 21st and December 4th, 2009. On each plot five sample trees were selected – the "central" tree and four trees closest to the midpoints of four geographically oriented quadrants – ca 17 m from the central tree. Root samples were taken from two soil depth-intervals 0–10 cm and 10–20 cm using the Eijkelkamp drilling-crown root auger. From each sample tree the four sampling points were located in a line, oriented in accordance with the slope of the plot or, in the flat terrain, to the south. The sampling points were at distances of 1 m, 3 m, 5 m and 7 m from the stem of the sample tree. In this manner 20 root samples of each soil layer were taken from each plot (Fig 2). After they had been transported to the laboratory, the roots were carefully washed with tap water to remove the mineral soil and separated into two groups – fine roots of up to 2 mm in diameter and coarse roots - and dried at 60°C and then weighed. The results in regard to root vitality and biomass were published by Šrámek and Fadrhonsová (2011).

Prior to their analysis the roots were pooled to a smaller number of samples in accordance with the plot and the depth of sampling to obtain an appropriate quantity of samples (minimal amount of the sample for chemical analysis was 5 g of dry weight). As a rule, for the particular soil layer on each plot, 3–5 composite samples were analysed. In total 122 samples were analysed. After mineralisation in a microwave oven in accordance with the COST method (Luster, Finlay 2006) the contents of Al, Ca, K and Mg were analysed using an inductively conducted plasma/optical emission spectrometer (ICP OES).

Statistical evaluation. Statistical analysis of the data was carried out using the Unistat 5.1 (Unistat Ltd., London, UK). The basic description of the variables was performed by EDA (exploratory data analysis), differences between variables were described by multiple comparisons for *t* distribution as a part of the Kruskal-Wallis non-parametric ANOVA, regression analysis was done using the Pearson correlation (Meloun, Militký 2006).

RESULTS AND DISCUSSION

Chemical composition of fine roots

The median of the aluminium content in the fine roots of Norway spruce differs distinctly between the individual plots; from 1,954 mg·kg^{-1} on the H070 Lhota pod Radčem plot to 9,327 mg·kg^{-1} on the I020

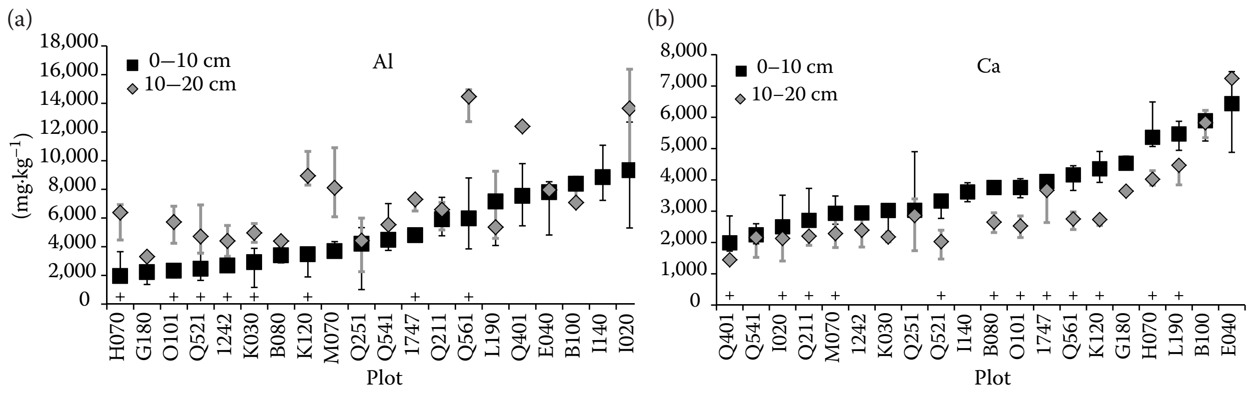

Fig. 3. Aluminium and calcium contents in fine roots on monitoring plots in two soil layers 0–10 cm and 10–20 cm. Abscissae represent maximal and minimal values obtained in individual samples. Dagger at the bottom axes marks a significant difference between contents in the two soil layers (95% *t* interval)

Sv. Kateřina plot in the topsoil layer of 0–10 cm (Fig. 3, Table 3). An interesting view is provided by comparing the topsoil layer, which is richer in soil organic matter and on average amounts to 85% of Norway spruce fine roots (Šrámek, Fadrhonsová 2011), with the deeper soil layer (10–20 cm). The Al concentrations in roots from deeper soil layers are generally higher – they reach even as high as 14,474 mg·kg^{-1} on the Q561 Nová Brtnice plot. A significant difference was confirmed on eight plots. The comparison of the Al concentrations at two soil depths in individual soil cores is significantly correlated at $P < 0.001$ (Fig. 4). The median calcium content in the upper soil layer (0–10 cm) varied for individual plots

Table 3. Fine root chemistry on monitoring plots

Plot No.	Plot name	Soil layer (cm)	Fine root amount (kg·ha^{-1})		Fine root chemistry (kg·ha^{-1})							
					Al		Ca		K		Mg	
			median	SD	median	SD	median	SD	median	SD	median	SD
I020	Kateřina	0–10 10–20	4,499 1,553	2,551 1,171	9,327 13,646	3,019 2,982	2,504 2,128	509 398	2,992 3,217	63 693	1,180 1,476	283 430
K030	Babylon	0–10 10–20	2,846 697	1,145 825	2,918 4,961	1,130 655	3,025 2,179	445 158	1,653 1,344	192 147	517 600	95 190
Q521	Lazy	0–10 10–20	1,791 338	687 411	2,467 4,717	719 1,394	3,327 2,027	254 379	1,831 2,299	188 533	623 487	63 81
E040	Kyselka	0–10 10–20	627 199	653 154	7,798 7,958	1,608 –	6,435 7,241	1,061 –	3,082 2,147	248 –	1,728 1,904	179 –
H070	Lhota pod Radčem	0–10 10–20	3,473 906	1,303 595	1,954 6,379	854 1,056	5,362 4,019	614 191	2,808 2,327	160 293	634 572	87 85
M070	Branišov	0–10 10–20	3,991 916	1,804 1,159	3,696 8,113	334 1,977	2,935 2,284	333 433	1,829 1,804	135 241	786 938	109 76
B080	Krupka	0–10 10–20	1,811 159	851 243	3,395 4,389	428 501	3,757 2,649	64 258	1,790 1,426	862 538	689 520	183 162
O101	Český Krumlov	0–10 10–20	2,538 1,373	1,417 1,561	2,325 5,728	324 1,059	3,758 2,531	248 282	1,304 1,351	274 110	686 605	26 139
B100	Valkeřice	0–10 10–20	1,981 796	1,021 651	8,389 7,082	682 473	5,891 5,826	308 357	3,603 2,675	1,170 1,109	2,143 1,895	428 472
K120	Velmovice	0–10 10–20	2,677 607	684 461	3,467 8,948	747 991	4,356 2,733	404 108	2,132 2,473	129 205	758 898	52 33
Q211	Jizerka	0–10 10–20	4,359 727	1,158 596	5,914 6,575	887 810	2,708 2,203	520 142	1,621 1,653	156 79	792 635	132 66
I140	Želivka	0–10 10–20	4,260 –	2,479 –	8,849 –	1,533 –	3,615 –	244 –	3,245 –	204 –	1167 –	151 –
Q561	Nová Brtnice	0–10 10–20	2,379 627	906 356	5,968 14,474	1,889 958	4,161 2,752	312 231	2,903 3,529	253 712	910 1,287	145 728
G180	Choceň	0–10 10–20	1,941 269	611 220	2,225 3,315	439 –	4,531 3,639	114 –	1,703 1,153	170 –	705 463	43 –
Q251	Luisino údolí	0–10 10–20	3,205 458	1,382 1,491	4,210 4,427	1,451 1,532	3,031 2,864	768 691	2,233 2,039	305 166	916 1,010	109 217
L190	Braniškov	0–10 10–20	2,827 458	1,228 387	7,148 5,363	1,493 2,049	5,467 4,466	380 331	3,624 2,310	406 215	1,026 1,030	117 49
1242	Dolní Morava	0–10 10–20	1,324 478	913 450	2,687 4,408	109 1,077	2,946 2,394	171 539	1,389 1,399	112 263	495 556	55 23
Q541	Švýcárna	0–10 10–20	2,478 488	1,793 561	4,478 5,536	1,228 119	2,246 2,158	207 340	1,939 1,485	282 303	569 900	63 99
1747	Dalov	0–10 10–20	1,483 289	766 308	4,799 7,304	79 406	3,950 3,667	109 508	2,758 2,487	198 242	923 1,068	130 251
Q401	Klepačka	0–10 10–20	1,702 149	1,843 301	7,534 12,389	1,407 203	1,991 1,447	400 3	2,206 2,718	250 206	701 871	74 25

SD – standard deviation

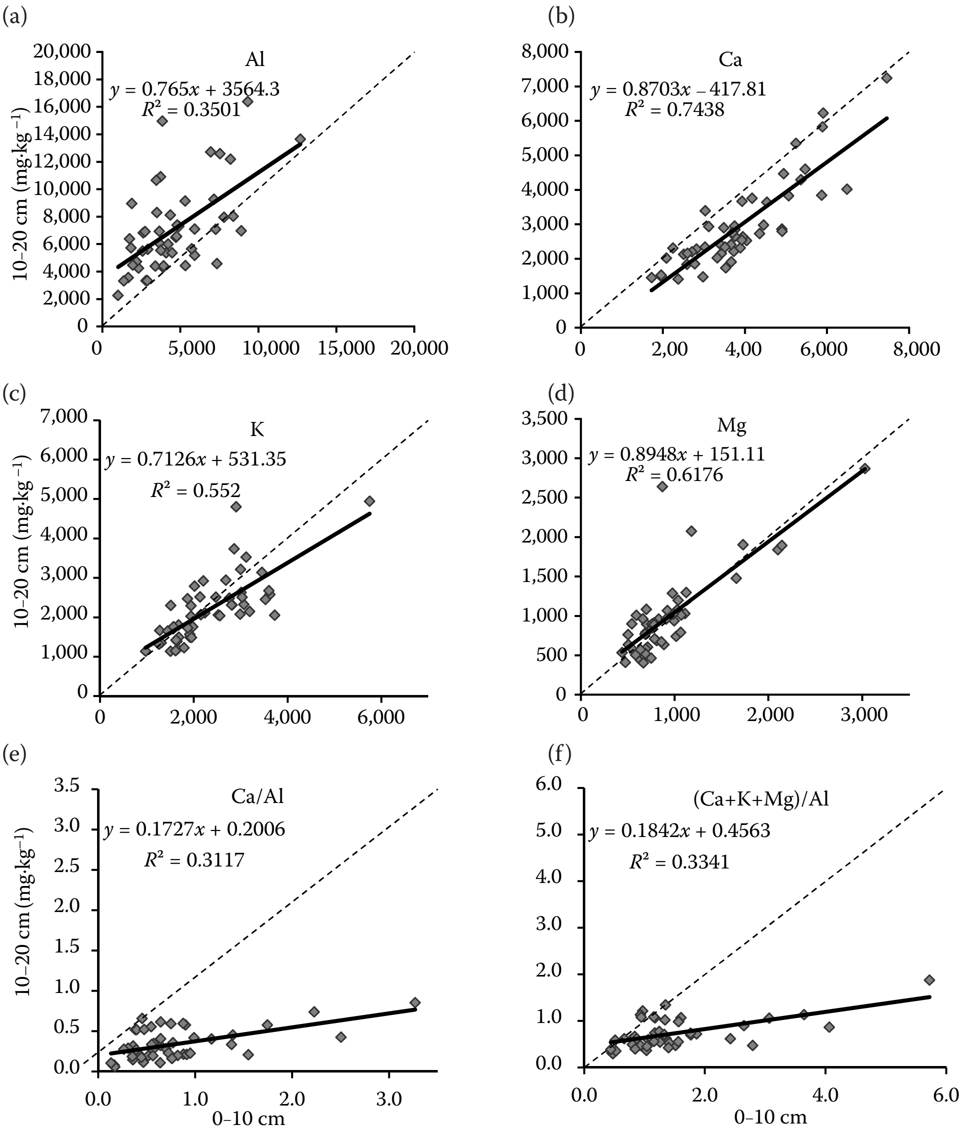

Fig. 4. Chemical properties of Norway spruce fine roots – comparison of results from two soil layers (0–10 cm and 10–20 cm) for individual sampling points

R^2 – confidence coefficient

from 1,991 mg·kg^{-1} on the Q401 Klepačka plot to 6,435 mg·kg^{-1} on the E140 Kyselka plot. There was an opposite relationship between the upper and the deeper soil layers than that of aluminium; in deeper soil (10 to 20 cm) the amount of fine root Ca was significantly lower on the majority of the plots (Fig. 3). The relationship between the two soil layers is closer than that of aluminium with a correlation coefficient of R = 0.862 (Fig. 3). The content of aluminium and calcium in fine roots corresponds to the data published for Bavarian study sites on acidic soils (pH 2.9–4.3; BS 2–10% in mineral horizons) by Borken et al. (2007) as well as to the values reported from Norwegian acid soils (pH 4.0–4.9; base saturation 4.2–7.7% in mineral horizons) by Nygaard and de Witt (2004) or Eldhuset et al. (2006). Nygaard and de Witt (2004) found even very high calcium contents on their sites (at 3,300 mg·kg^{-1}); on the other hand, Persson and Majdi (1995) reported the calcium content of fine roots as low as 1,500 mg·kg^{-1} in the Norway spruce forests in Sweden. The increase of aluminium and the decrease of calcium in accordance with the soil depth coincide with the exchangeable aluminium and calcium content in the forest soil profile (Table 2). In the upper organic horizon aluminium is bound to stable organic complexes (Cloutier-Hurteau et al. 2010) while the level of exchangeable calcium is usually much higher than it is in mineral soil. The content of potassium and magnesium in the fine roots does not exhibit any consistent differences between the two soil layers evaluated (0–10 cm; 10–20 cm) – on most of the plots they are relatively similar (Fig. 4). The correlation between the two soil layers is significant for both K (R = 0.743) and Mg (R = 0.786). The mean values on individual plots range between 1,304 mg·kg^{-1} and 3,624 mg·kg^{-1} for potassium and between 463 mg·kg^{-1} and 2,143 mg·kg^{-1} for magnesium. These values for both base cations are higher than those reported by Persson and Majdi (1995) for Norway spruce in

Sweden and the Mg content is also higher when comparing this data with the results obtained by Borken et al. (2007) on four plots in southeastern Germany.

The mean Ca/Al molar ratio in the fine roots of the 0–10 cm upper soil layer is 0.74 and varies between 0.2 and 1.75 on the particular plots. In the deeper soil horizon of 0–20 cm the Ca/Al values are significantly lower (Fig. 4). The mean value of all the plots is only 0.35. According to Cronan and Grigal (1995) the fine root Ca/Al molar ratio ≤ 0.2 represents a 50% risk rate, while according to a review by Vanguelova et al. (2000) this limit represents even as high as 90% risk of a negative impact on root and aboveground growth. In the upper soil such low values were detected only on the Q401 Klepačka plot where the individual samples exhibit the Ca/Al ratio between 0.14 and 0.35. Individual samples with the fine root Ca/Al ratio below 0.2 were also recorded on the I020 Kateřina plot. In the deeper soil layer (10–20 cm) aluminium stress was strongly indicated on the Q401 Klepačka plot by the mean Ca/Al ratio of 0.08 and high risk is also probable for plots I020 Kateřina (0.11), Q561 Nová Brtnice (0.13) and K120 Velmovice (0.20). Looking at the distribution of the Ca/Al ratio in the individual samples we can evaluate 6% of the samples as showing strong indications of aluminium stress (< 0.1) and 30% of the samples indicating negative effects (< 0.2) in the deeper 0–20 cm soil layer (Fig. 5). In the upper soil, on the other hand, only 8% of the samples of fine roots exhibit the Ca/Al ratio of 0.2 or less. This is consistent with the significantly higher content of biomass of the fine roots in the upper soil layer that was found on our plots (Table 3) – on average 80% of the total fine root biomass from the soil depth of up to 20 cm was found in the upper (0–10 cm) soil layer. The decrease in the fine root Ca/Al ratio with the soil depth has been reported by many authors – e.g. Persson and Majdi (1995), Vanguelova et al. (2007) and Borken et al. (2007); the absolute values on the previously mentioned plots, however, are quite low in comparison with other European surveys. Persson and Majdi (1995) found a low Ca/Al ratio in acidified soils in Sweden ranging between 0.05 and 0.38; Nygaard and de Witt (2004) found ratios from 0.16 to 2.67 in Nordmoen in Norway, Borken et al. (2007) reported values from 0.5 to 8.5 in the Norway spruce in Bavaria (Germany), while Brunner et al. (2002) identified values ranging between 0.8 and 19.43 on four plots in Switzerland. Konôpka and Lukac (2009) identified a significant drop in the Ca/Al ratio between the healthy and damaged Norway spruce in the Kysucké Beskydy Mountains (Slovakia) with absolute values between ca 2 and 3.

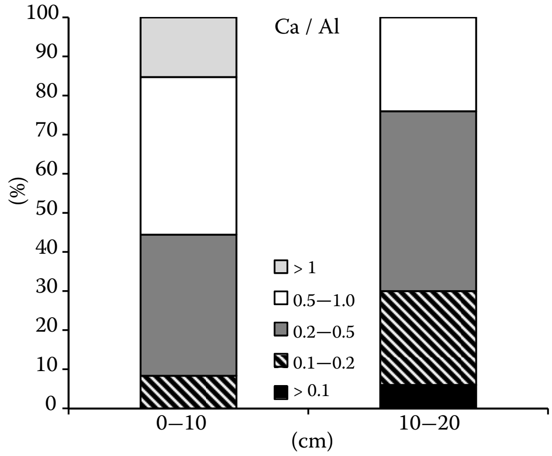

Fig 5. Relative number of individual fine root samples within the different classes of Ca/Al ratio for two collected soil layers

The molar ratio of base cations to aluminium [(Ca+K+Mg)/Al or BC/Al] could represent a more precise tool for risk assessment at sites where potassium has a more noticeable impact on the sorption complex of forest soils. The (Ca+K+Mg)/Al soil solution ratio was suggested by Sverdrup (1995) as a basis for calculating the critical load of soil acidification and it was also mentioned as a risk indicator of forest health by Cronan and Grigal (1995). In our study we found the mean values of the (Ca+K+Mg)/Al ratio between 0.34 and 3.29 for the individual plots. The significantly lower values were recorded in the deeper 10–20 cm soil layer (Fig. 4).

Table 4. Correlation coefficients between concentrations of individual fine root elements

	(Ca+K+Mg)/Al	Al	Ca	K	Mg
Ca/Al	0.997****	–0.738***	0.409*	–0.251^{ns}	–0.323^{ns}
(Ca+K+Mg)/Al	–	–0.725***	0.428*	–0.217^{ns}	–0.285^{ns}
Al		–	0.110^{ns}	0.738***	0.720***
Ca			–	0.579**	0.606**
K				–	0.745****

^{ns}not significant, *P < 0.05, **P < 0.01, ***P < 0.001, ****P < 0.0001

Correlation analysis

The results of the comparison of the mean element contents of fine roots on the individual plots are presented in Table 4. A strong significant correlation has been found between Ca/Al and (Ca+K+Mg)/Al, suggesting that the Ca/Al ratio is quite sufficient for the assessment of fine root chemistry on our plots. Both these ratios exhibit a highly significant negative correlation with the aluminium content in fine roots; the positive dependence on the calcium content is also significant, but weaker. There is no significant relationship between the (Ca+K+Mg)/Al ratio and the other base cations (K, Mg), which supports the conclusion that the fine roots Ca/Al ratio in itself is fully sufficient for evaluating the aluminium risk under our conditions. A significant positive correlation was found between all the elements analysed, with the exception of Ca and Al and this could be associated with the competition for the root uptake between these elements (Sverdrup, Warfinge 1992). The positive correlation between the content of Al and Mg or K in fine roots is harder to explain. de Witt et al. (2010) found increased calcium and magnesium concentrations in the soil solution of Norway spruce stands following the long-term addition of $AlCl_3$ which were ascribed to the elevated H^+ concentration and the increased cation exchange as the consequence. In general, however, the increased availability of aluminium should reduce the uptake particularly of magnesium and calcium base cations at least at sites where the stock of base cations is limited (Gobran et al. 1993, van Scholl et al. 2004, de Witt et al. 2010).

Table 5 presents the correlation between the chemistry of fine roots and the topsoil (0–10 cm) layer. The Ca/Al and (Ca+K+Mg)/Al indexes show a slightly negative correlation with total sulphur and nitrogen. This relation is in line with significant negative correlation between the fine root Ca content and soil nitrogen and sulphur content which illustrates the sulphur and nitrogen deposition role in the soil acidification and leaching of base cations. Unlike in the findings of Brunner et al. (2002) there was no significant correlation between Ca/Al and the pH of the soil which could be explained by the generally lower pH on our set of plots. In terms of the base cations the strongest correlations were found for the fine root magnesium content with the mineral soil base saturation, exchangeable calcium and exchangeable magnesium. These soil parameters also have a strong and significant relationship to the fine root calcium content and a weaker but still significant relationship to the fine root potassium content. All the fine root base cations also bear a significant relationship to the pH of the soil, which corresponds with the findings of Brunner et al. (2002). The aluminium concentration is slightly but significantly correlated to the soil's exchangeable calcium and exchangeable magnesium and its base saturation. This is in part consistent with the statement mentioned above by de Witt et al. (2010) concerning the soil solution. Brunner et al. (2002) found a significant positive correlation between the fine root aluminium content and the pH of an organic soil layer and a negative correlation with the pH of mineral soil.

A comparison of the chemical composition of fine roots with the parameters of fine root biomass and vitality or Norway spruce defoliation (Table 6) did not reveal any significant relationship. A previous study of our plots (Šrámek, Fadrhonsová 2011) reported a slight but significant negative correlation between the plot defoliation and pH of the soil. The absence of any effect from an elevated level of aluminium on the properties of fine roots was also reported by Nygaard and de Witt (2004) and Elduset et al. (2006). Borken et al. (2007) suggested that the variation in the deposition of N between

Table 5. Correlation coefficients between the fine root chemistry and chemical properties of forest soil

Fine root chemistry	Forest mineral top soil (0–10 cm) chemistry							
	pH_{H_2O}	N_{tot}	S_{tot}	Al_{exch}	Ca_{exch}	K_{exch}	Mg_{exch}	BS
Ca/Al	-0.144^{ns}	-0.431^{*}	-0.464^{*}	-0.380^{ns}	-0.137^{ns}	-0.061^{ns}	-0.167^{ns}	-0.126^{ns}
(Ca+K+Mg)/Al	-0.123^{ns}	-0.433^{*}	-0.458^{*}	-0.373^{ns}	-0.110^{ns}	-0.043^{ns}	-0.143^{ns}	-0.098^{ns}
Ca	0.573^{**}	-0.534^{**}	-0.395^{*}	-0.100^{ns}	0.709^{***}	0.314^{ns}	0.607^{**}	0.733^{***}
K	0.444^{*}	-0.341^{ns}	-0.179^{ns}	0.106^{ns}	0.536^{**}	0.349^{ns}	0.421^{*}	0.574^{**}
Mg	0.643^{**}	-0.126^{ns}	0.045^{ns}	0.254^{ns}	0.838^{****}	0.469^{*}	0.796^{****}	0.845^{****}
Al	0.364^{ns}	0.050^{ns}	0.132^{ns}	0.321^{ns}	0.469^{*}	0.369^{ns}	0.441^{*}	0.478^{*}

N_{tot}, S_{tot} – total content of nitrogen and sulphur, Al_{excht}, Ca_{excht}, K_{excht}, Mg_{excht} – exchangeable contents of aluminium, calcium, potassium and magnesium, BS – base saturation, ^{ns}not significant, $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, $^{****}P < 0.0001$

Table 6. Correlation coefficients between the fine root chemistry, root biomass and vitality and plot defoliation

Fine root chemistry	Root		Plot defoliation
	biomass	vitality	
Ca/Al	–0.167	–0.016	–0.028
(Ca+K+Mg)/Al	–0.161	–0.028	–0.013
Ca	–0.395	–0.131	–0.054
K	0.027	–0.292	0.210
Mg	–0.113	–0.194	0.036
Al	0.186	–0.242	0.160

all values are not significant

17 and 26 kg·ha^{-1}·yr^{-1} had no effect on the fine root biomass nor on their vitality. Brunner et al. (2002) did not find any effect of the low Ca/Al ratio on the crown condition on plots in Switzerland, nor did de Witt et al. (2010) in the course of an aluminium addition experiment undertaken in Sweden. It can be concluded that the crown condition of Norway spruce forests at acidified sites is more significantly influenced by the insufficient supply of base cations – primarily magnesium – than by the actual aluminium toxicity. The influence of magnesium deficiency on spruce defoliation – amongst other stress factors – was supported, for example, in studies by Musio et al. (2007), de Witt et al. (2010) and Lomsky et al. (2012).

CONCLUSIONS

Data on the chemistry of fine roots from twenty monitoring plots in the Czech Republic show values corresponding to sites that have been affected by long-term acidification. The Ca/Al ratio in the fine roots is significantly lower in the deeper soil layer (10–20 cm) than in the topsoil (0–10 cm), which corresponds to the lower fine root biomass. Looking at the Ca/Al ratio in the deeper soil layer, 76% of the collected samples could be evaluated as potentially being affected by aluminium toxicity (Ca/Al < 0.5), with 30% at a risk of aluminium toxicity (Ca/Al < 0.2) and 6% at a high risk of aluminium toxicity (Ca/Al < 0.1). The ratio of the base cations to aluminium (Ca+K+Mg)/Al is strongly correlated with Ca/Al. No significant influence of other base cations was found, which means that the Ca/Al ratio is fully sufficient for the evaluation of the aluminium toxicity risk at our sites. The variation in the fine root Ca/Al ratio is influenced more by Al than by Ca content in the root tissue. It is negatively correlated with the total nitrogen and sulphur content in forest soils, which is probably connected with the long-term acidic deposition of these compounds.

In contrast with the relatively low Ca/Al ratio in the fine root samples no relation of this indicator to fine root biomass, vitality or crown condition was revealed. Our data suggest that based on the condition of the Central European Norway spruce forests potential aluminium toxicity is not a driving factor in regard to forest health and the Ca/Al ratio in itself does not constitute a risk to the forest health of the region.

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