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Effect of wood ash application on the biomass distribution and physiological state of Norway spruce seedlings on sandy soils

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Abstract

The effect of wood ash applied as a fertiliser (0.25, 0.5 and 1 kg m^{-2}) to nutrient poor sandy soil on 4-year-old Norway spruce (*Picea abies*) growing in small-scale sample plots was studied. Analyses carried out with roots, stems, needles and shoots of different age showed that an increase in the pH level and K and Ca concentrations and a decrease in N and P concentrations in the soil was accompanied by a disbalance of nutrients in tree compartments. Stimulation of pigment synthesis in Norway spruce needles was observed, and no disbalances occurred in the pigment system (Chl*a*/Chl*b*, TChl/Car) guaranteeing normal process of photosynthesis. Biomass responses to wood ash application depended on the age of needles and shoots, being only slightly notable in current year organs. Inhibition of height growth of seedlings, but stimulation of root biomass was established.

Introduction

In recent years sustainable management of forest ecosystems and environmental protection have brought about increasing interest in the use of renewable energy resources. Biofuels are becoming increasingly important worldwide as a present and future alternative to fossil fuels. More than 25% of boilers with capacities over 50 MW have already been transferred to wood and wood chips in Estonia. In Sweden around 200 heating plants with capacities over 5 GWh yr^{-1} use wood fuels (www.novator.se 2002–01–23). About 5% of the total energy consumption in Norway is covered by bioenergy and the main part of this originates from trees. The increased use of wood bioenergy also will lead to an increase in the production of wood ash (Ring et al., 1999). In connection with this, application possibilities and utilisation of wood ash are becoming increasingly more serious problems. Storing wood ash in special waste stores is costly and a deviation from principles of sustainable development. It is known that essential elements are removed from forest ecosystem with timber harvests, which can represent a drain on soil nutrition (Olsson et al., 1993; Kukkola and Mälkonen, 1997; Jacobson et al., 2000). Land application of wood ash from boilers can reduce the bulk of material placed in landfills and partially compensate for cation removals made during forest harvest.

Therefore, possible use of wood ash as a liming material or an additional fertiliser is of great interest from the perspective of maintaining the nutrient balance in managed forest ecosystems in areas from where timber has been removed. Judicious use of wood ash both solves a waste disposal problem and provides an economically attractive alternative to chemical fertilisers. Research on the effects of wood ash on plants has never received the same level of attention as that given to mineral fertilisers. That is why the wood ash reactions with soils and forest responses to wood ash application are not as well understood or quantified (Ohno and Erich, 1990).

Irrespective of the origin of wood ash its water solution is highly alkaline (pH 11–12.5) (Campbell, 1990; Kahl et al., 1996). Therefore, it has been recommended that wood ash should be used for liming acid

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soils (Meiwes, 1995; Kärblane, 1996), for enriching the nutrient poor growth substrate and reducing the toxicity of Al and Mn (Voundi Nkana et al., 1998).

On the other hand, as ash from biomass contains heavy metals that originate from the fuel, it is necessary to stress the possibility of harmful effects of the application of wood ash. Due to the high variability of metal concentrations in ashes, most studies end up with showing tendencies to, but not significant, increased levels in soils (Rosén et al., 1993; Bramryd and Fransman, 1995; Moilanen and Issakainen, 2000). However, in the soils of a pine stand in Northern Germany significantly increased levels of Zn, Cu, Cr, Ni, Co and Cd were found in the upper 4 cm of the litter horizon after application of 2.4 t ha^{-1} wood ash (Rumpf et al., 2001). Also in two pine seedling stands in Southern Finland an increase in the total Cd concentration was observed in the humus layer after wood ash application of 3 t ha^{-1} (Tamminen, 1998, 2000). There are relatively few studies and contradictory results on changes in heavy metal uptake and concentration in the trees after ash application to forest soil. In Sweden in a Norway spruce and Scots pine stand on mineral soil, wood ash in doses 1, 3 and 6 t ha^{-1} increased the concentrations of Cd and Zn in needles and their elevated concentrations could be seen even 4–7 years after ash application (Jacobson, 1998). In Finland elevated needle Zn concentrations were found 18 months after ash application in a Scots pine stand of *E. nigrum – C. vulgaris* site type, but no increases in needle Zn or other heavy metal concentrations were recorded in long-term experiments (Moilanen and Issakainen, 2000). On the contrary, the application of hardened wood ash of 3 t ha^{-1} decreased needle Cd concentrations in Norway spruce stands at 5 sites out of 12 sites within a climate and fertility gradient in Sweden (Arvidsson and Lundkvist, 2002). But the information in the literature shows that the uptake of heavy metals from wood ash treated soils must be influenced by several factors and needs special scientific attention.

However, our basic knowledge on the effect of nutrient imbalance on the conifers physiological status is still inadequate, it was supposed that the vitality of the trees can be greatly improved by ash fertilization. The Finnish researches found the highest volume increment gained by ash fertilization to be more than 4 m^3 per ha per year (Ferm et al., 1992). This result is comparable with other wood ash fertilization studies (Silfverberg and Huikari, 1985; Shepard, 1997). Still, the effect on height growth is much smaller than the effect on stem cross-section growth (Shepard, 1997).

Nevertheless, the mechanisms of wood ash effects on plants are not yet fully understood. So, it is only possible to make assumptions about the physiological-biochemical responses to wood ash relying on our knowledge and research results on the effect of several other substances used widely for liming (e.g. cement dust, oil shale ash, limestone dust etc.) and by drawing parallels to find out relationships between biochemical processes in trees. The chemical composition of wood ash varies depending on the raw material burnt and burning conditions. Available data on the properties of wood ash are very variable and generalisations are therefore difficult to make (Demeyer et al., 2001). It is important to stress that the variability of the properties of wood ash, soil and plant metabolism makes comparison of the results of controlled experiments carried out under natural conditions questionable. Modelled experiments should be carried out before investigations under natural conditions or used as control to find out the mechanisms through which wood ash affects plants and to develop suitable concentrations for different plant species.

This study was undertaken to investigate the influence of wood ash on the mineral composition and biomass formation of Norway spruce. Changes in chlorophyll contents and modifications of pigment composition have been used as biochemical indicators to assess the physiological state of spruces under alkalisation of the growth substrate.

Material and methods

Study area and experiments

Experiments were established on the territory of Raudalu nursery, Harju county, Estonia (59°22′15″ N, 24°45′17″ E) to study the responses of Norway spruce (*Picea abies* (L.) Karst) to wood ash (WA).

The soil in the nursery was characterised as nutrient poor sandy soil. However, as a result of digging, in the nursery the soil has lost its natural characteristics and it can be described as a nutrient poor growth substrate affected by human activity.

The weather in the experimental area during the years of our investigations, according to the nearest weather station, Harku (10 km SW), was relatively dry, warm and sunny. The mean monthly amount of precipitation was 54.7 mm; the average of temperature was 6.5 °C.

Table 1. Chemical composition of wood ash from Türi (Estonia) heating plant used in the experiment ($n = 4$)

Element	mg kg−1
N	250
P	15500
S	10150
Al	3300
Ba	1560
Ca	123000
Cu	197
Fe	10400
K	48000
Mg	19400
Na	17900
Mn	9850
Pb	76
Zn	4340

Investigations of WA effect on Norway spruce began in May 2000. Twelve small-scale experimental plots (25 × 25 m) for WA application were situated in four variants on the territory of a nursery with 4-year-old homogeneous in habitus Norway spruce seedlings grown up from seeds of the same mother tree and cultivated in the same nursery before planting on the sample plots. For treatments and control approximately 100 trees were used on each sample plot. Application of WA to soil was carried out in June, a month after the planting of seedlings. Scoops were used to avoid dropping WA on plants and to guarantee its even distribution.

The characteristics and chemical composition of WA depend on the fuel incineration technique, additives and storage conditions (Kofman, 1987). Raw WA with the pH 12.1–12.6 used in experiments originated from Türi (58°48′22″ N, 25°25′17″, Central Estonia) heating plant using for combustion both deciduous and coniferous wood. Dry WA was collected from ten places of ash storage at the heating plant and mixed carefully to get homogenous material for spreading. The same ash was used in all variants and replications and its chemical composition (Table 1) was analysed in the laboratory of Estonian Environmental Research Centre Ltd., which is competent according to EVS-EN ISO/IEC 17025:2000 to conduct of environmental chemical analyses.

Four treatments of experiment in three replications were carried out with different doses of WA application to soil:

1. 0.25 kg m^{-2}
2. 0.5 kg m^{-2}
3. 1.0 kg m^{-2}
4. Control (C), untreated sample plot.

For interpretation of the physiological state of seedlings in the experiment the chemical composition of the growth substrate in the sample plots after the application of WA was analysed. Soil samples were collected with a steel bore cylinder from depths of 30 cm, taking into account that approximately 80% of feeder roots of trees are located in the layer of 10–30 cm (Orlov and Koshelnikov, 1971). Soil sampling was carried out 7 times in three replications per treatment from August 2000 till October 2001 (10 Aug. 2000, 07 Nov. 2000, 18 June 2001, 10 July 2001, 24 Aug. 2001, 27 Sept. 2001, 17 Oct. 2001). The nutrient status of the soil upper horizon (30 cm) prior to the WA application was determined in the Laboratory of Soil Chemistry of the Estonian Control Centre of Plant Production. Standard methods of soil analysis were used: the content of P and K was determined by the Egner-Riehm double lactate method and that of Ca by the Egner-Riehm-Domingo ammonium acetate-lactate method (ISO/11260, 1995). Total N was determined by the Kjelldahl method (ISO/11261, 1995) and the pH of the soil was measured as the potential acidity in H_2O (ISO/10390, 1994).

Biochemical analyses

Analyses of pigments

The seasonal dynamics of the total content of chlorophylls (TChl, Chl*a*, Chl*b*) and carotenoids (Car) was investigated monthly from the June of 2001 until May 2002. The collection of samples was carried out at 10.00–12.00 a.m. local time on a cloudy day. The needles for analyses (0.2 g) were fixed in liquid nitrogen and homogenised in 80% ice-cold acetone solution for 3–5 min under dim light at a low temperature. The extract was filtered through a fritted-glass filter. The content of pigments was measured with a spectrophotometer Heλios α (Unicam Ltd., U.K.) at a wavelength of 649 for Chl*a*, 665 for Chl*b* and 470 nm for Car and calculated in mg g^{-1} dw according to the formulas of Vernon (1960) and Lichtenthaler and Wellburn (1983).

Analyses of mineral composition

Ten visually of average height 6-year-old trees of each treatment were dug up in August 2002. The roots, stems, shoots (c.yr., 1-yr.) and needles (c.yr., 1-yr.) were separated, carefully cleaned , cut into small pieces and oven-dried at 70 °C to stop metabolic activity (Wilde et al., 1979; Landis, 1985). After drying and grinding (Mixer Mill MM200, Germany) 3 g of grinded compartments of 10 trees was weiged for composite samples of needles, shoots, stems and roots. From composite samples of different organs 1–2 g of dried and mixed plant material was chemically analysed in the Laboratory of Plant and Feed Chemistry of the Estonian Control Centre of Plant Production, which is accredited by the Estonian Accreditation Centre from 1999 and has competence according to EVS-EN ISO/IEC 17025:2001. The methods used for analyses are certified by international ringtests including FATAS 2002, AACC, European Grain Network, Estonian/Baltic etc. Concentrations of metals (Ca, K) were determined using an atom-adsorption analyser AAA-1N (Karl Zeiss, Jena). N was measured by the method of Kjeldahl and P was extracted with vanadium molybdate yellow complex.

Morphological measurements

In August 2001, after growth had stopped, 10 visually of average height 6-year-old trees of each treatment were excavated and the roots, stems, current-year, 1-, 2- and 3-year-old shoots and needles were separated for the assessment of their fresh and dry mass (g), dry matter content (dry mass : fresh mass × 100, %) and height of trees (cm).

Statistical analyses

Regression trendlines and determination coefficient (R^2) were calculated using the Statgraphics and Microsoft Excel 5.0 (Sachs, 1982). For the analysis of differences in the concentrations of pigments between the control trees and trees under treatment the t-test was used (Girden, 1992). Significance (P) of differences was accepted at $P < 0.05$.

Results and discussion

The effect of WA applied to the soil on the physiological status of trees is maintained primarily through the pH and the chemical composition of soil. Irrespective of the origin, the pH of WA is usually alkaline (pH_{H_2O} 11.0–12.5) (Campbell, 1990; Kahl et al., 1996; Kärblane, 1996). WA used in our experiments has an average pH 12.4. As the dose of WA increased, a linear increase in the soil pH from 6.4 to 6.9, 7.1 and 7.3 in different treatments was observed (Table 2). An increase in the concentrations of available K and a decrease in the biogenic elements N and P were established in the nutrient poor sandy soil under Norway spruce seedlings (Table 2). Although there was a relatively high content of Ca in the wood ash used in the experiment, the mean concentration of available Ca showed no change under the treatment with 0.25 kg m^{-2} and a decrease under the treatment with 0.5 and 1.0 kg m^{-2} compared to untreated control. Many researchers have reported increases of Mg, K and Ca after wood ash fertilization (Naylor and Schmidt, 1989; Ulery et al., 1993; Bramryd and Fransman, 1995; Catricala et al., 1996; Kahl, et al., 1996; Eriksson, 1998), but availability of Ca from the soils treated with wood ash depends on the type of forest soils (Saarsalmi et al., 2001) and depth of sampling (Valeur et al., 2000), on the chemical character of ash (Someshwar, 1996) and the time after ash application (Kahl et al., 1996; Saarsalmi et al., 2001), etc. The decrease of the concentration of available Ca estimated by us in sandy soil with pH > 7 may have resulted from the reaction of carbonisation or formation of relatively stable compounds having a very low solubility (Steenari and Lindqvist, 1997; Steenari et al., 1998). But still it is not entirely clear how or by what mechanism a treatment with wood ash may affect the decrease of available Ca in soil.

Table 2. Concentration (mg kg^{-1}) of available mineral elements and pH in the soil of sample plots treated with wood ash ($n = 7$). Characteristics were calculated as average of seven sampling dates, samplings were carried out in three replications of each treatment

Treatment	Ph	N	P	K	Ca
Control	6.4	8.0	152.6	12.5	493.7
0.25 kg m^{-2}	6.9	6.2	105.1	31.3	506.0
0.5 kg m^{-2}	7.1	6.4	80.8	16.5	416.4
1.0 kg m^{-2}	7.3	2.9	43.0	54.5	316.4

Pigments

Spruces growing on the sample plots treated with WA showed an increment in the concentration of Chl and Car in needles (Table 3). A rapid increase in the pigment concentration, which exceeded the control, was proven by t-test, but the control and the treated trees did not differ in the ratios Chl$a$/Chl$b$ and TChl/Car

Table 3. The average content of pigments (mg g^{-1} dw, ±SD, $n = 45$) and their ratios in Norway spruce needles on wood ash treated sample plots in 2001–2002 (P-value of difference according to two-sided t-test)

Parameter	Control	0.25 kg m^{-2}	0.5 kg m^{-2}	1.0 kg m^{-2}
Chl*a*	1.13 ± 0.06	1.38 ± 0.09 $P = 0.0003$	1.42 ± 0.12 $P = 0.0000008$	1.26 ± 0.08 $P = 0.0839$
Chl*b*	0.67 ± 0.05	0.79 ± 0.05 $P = 0.0053$	0.92 ± 0.05 $P = 0.00001$	0.77 ± 0.12 $P = 0.0257$
Car	0.38 ± 0.06	0.46 ± 0.03 $P = 0.0022$	0.46 ± 0.03 $P = 0.0028$	0.42 ± 0.02 $P = 0.0551$
TChl	1.79 ± 0.02	2.18 ± 0.15 $P = 0.0001$	2.33 ± 0.17 $P = 0.0000003$	2.04 ± 0.12 $P = 0.021$
Chl*a*/Chl*b*	1.68 ± 0.14	1.75 ± 0.18 $P = 0.6616$	1.62 ± 0.07 $P = 0.6736$	1.67 ± 0.16 $P = 0.8889$
TChl/Car	4.71 ± 0.10	4.78 ± 0.24 $P = 0.2774$	5.05 ± 0.10 $P = 0.8705$	4.85 ± 0.16 $P = 0.8097$

(Table 3). An essential stimulation of pigment synthesis was shown in the case of WA treatment of 0.5 kg m^{-2}.

It has been shown earlier that the alkalisation of the environment in the vicinity of a cement plant and cement dust deposition on the trees or application of cement dust to soil in an unpolluted territory cause a significant decrease in the Chl content due to the degradation of its molecule or inhibition of Chl synthesis (Manning, 1971; Borka, 1980; Kangur, 1988; Mandre and Tuulmets, 1997; Mandre and Korsjukov, 2002). The most significant decrease has been observed in Chl*a* content, while Chl*b* seems to be less affected. The relative tolerance of Chl*b* to environmental changes may be explained by the fact that Chl*b* is synthesised from Chl*a* molecules in enzymatic dark processes (Shlyk et al., 1975; Goodwin and Mercer, 1983) and the gradual decrease of Chl becomes evident on the level of Chl*a*. However, the effect may be different when cement kiln dust or wood ash (having both pH > 11) are used for treating nutrient poor soils.

It is known that for optimal growth Norway spruce needs fertile soil with pH between 4 and 5 (Schmidt-Vogt, 1987), and alkalisation of soil could be a stress factor for spruce. However, in experiments with WA application to soil stimulation of the synthesis of pigments in needles was found at the increased pH of soil.

WA application to soil under seedlings of Norway spruce resulted in an increase of Chl and Car, but no statistically proved changes in their ratios (Table 3). The pattern of the seasonal dynamics in the treated trees did not vary (Figure 1), but the mean concentrations of Chl*a*, Chl*b* and Car were much higher than in control trees. Although no major differences from control were observed in the concentration of pigments in needles during the intensive growth period of trees (June–September), in late autumn and winter (October–February) a high excess of Chl and Car occurred in the needles of WA treated trees, especially in the case of the treatment of 0.5 kg m^{-2} at an average soil pH 7.41 (Figure 1). The ratios Chl*a*/Chl*b* and TChl/Car did not show statistically proved disbalances in the needles during the whole year (Figure 2). This suggests that the ratio of photosynthetically active pigments (Chl*a*) and auxiliary pigments (Chl*b*, Car) was optimum and it guaranteed an undisturbed course of photosynthetic processes. Our results suggest that the changes in the spruce pigment systems caused by WA depend on the amount of the material applied to the soil.

The fact that changes in different directions occurred in the pigment system in the case different liming materials were applied indicates that it is the amount of nutrients available for plants and their ratio in the organism that are the major factors affecting the pigment system rather than soil parameters. There is little information on this issue, but enough information exists on WA influence on the mineral composition of plants. Although WA is poor in N, S and P, as in the

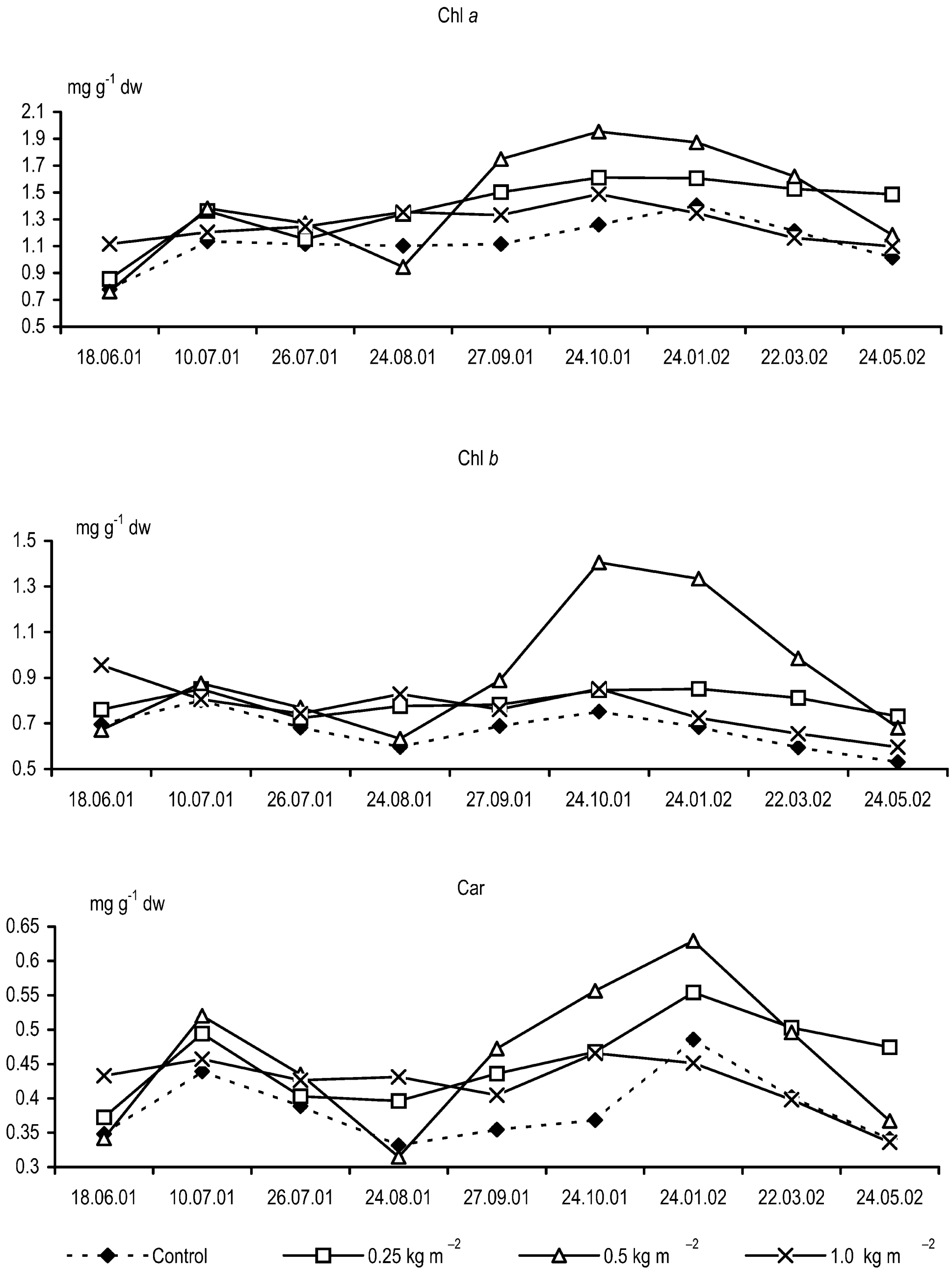

Figure 1. Seasonal dynamics of the content of pigments in current-year needles of Norway spruce growing on the sample plots treated with wood ash in 2001–2002.

course of burning these elements volatilise in compounds (Campbell, 1990; Etiegni et al., 1991; Kahl et al., 1996; Kärblane, 1996), it has long been regarded as a source of K and Mg in suitable ratios for plant growth (Etiegni et al., 1991; Huang et al., 1992). These elements favour pigment synthesis and in WA they occur in ratios characteristic of live trees. Regression analysis showed that relationships between TChl and P in soil ($R^2 = 0.6743$) and K ($R^2 = 0.7904$) and Ca ($R^2 = 0.6158$) in the needles are statistically significant ($P < 0.05$).

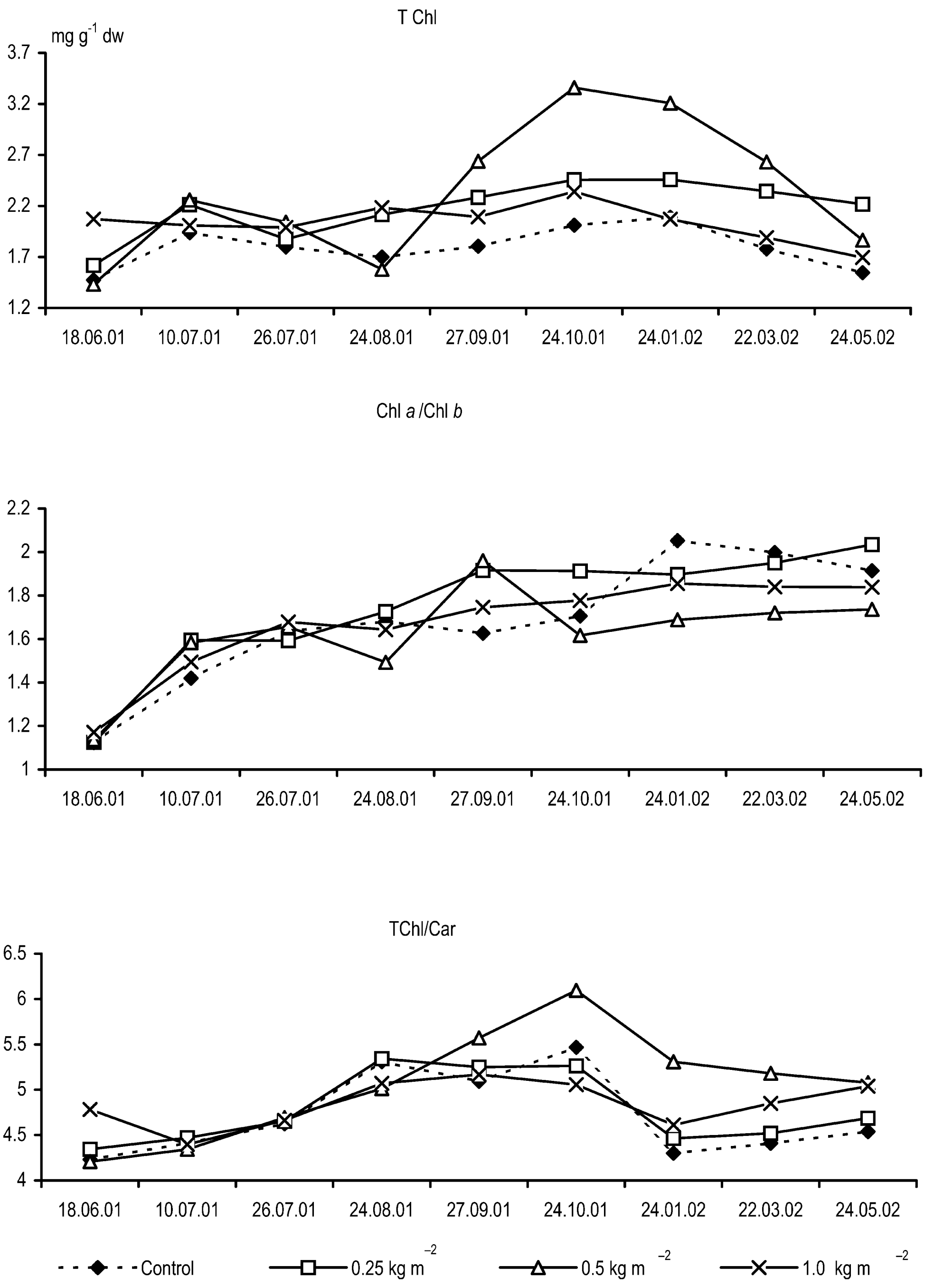

Figure 2. Seasonal dynamics of the total content of chlorophylls and the ratios of pigments in current-year needles of Norway spruce growing on the sample plots treated with wood ash in 2001–2002.

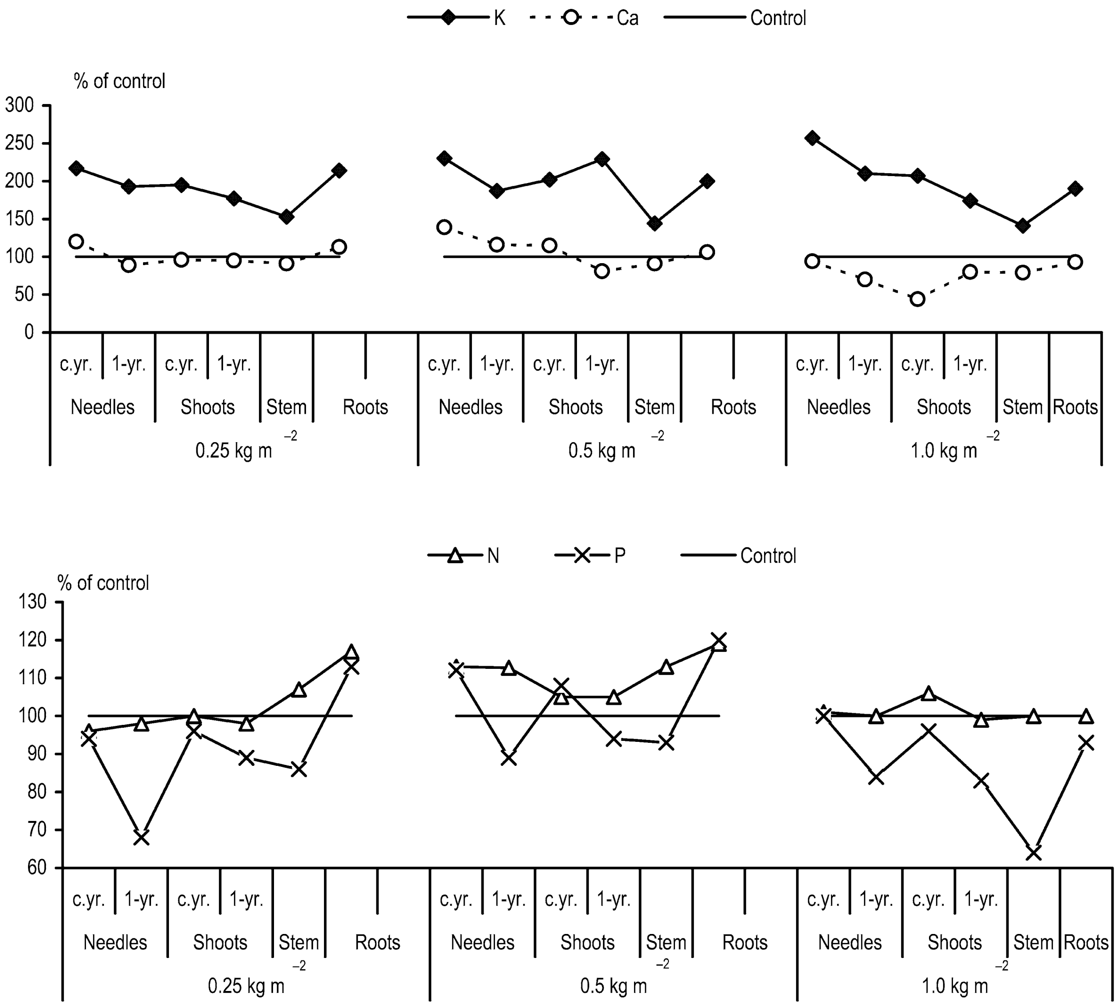

Figure 3. Partitioning of mineral elements in different organs of Norway spruce growing on the sample plots treated with wood ash in August 2002, and their comparison with control (% of control).

Mineral elements

Apart from N and S, WA contains mineral nutrients in almost the same proportions as in the live trees and possible alterations in nutrient composition would be expected for elements added with WA to soil. WA application to soil caused deviations in the mineral composition of Norway spruce seedlings. A substantial increase in the average K contents was found in the investigated seedlings in each variant of treatment (Table 4, Figure 3). However, the average Ca content decreased 18% as compared with control in the trees treated with 1.0 kg m^{-2} and increased by about 9% in trees treated with 0.5 kg m^{-2}. Differences in the dynamics of K and Ca concentrations in changed growth conditions often depend on the physiological antagonism of these elements in mineral nutrition processes of plants. It should be stressed that in alkalised soils and after treatment of soil with WA the antagonism between Ca and K may deepen and the concentration of Ca in the plants will fall (Saarela, 1991; Demeyer et al., 2001). The average level of the ratio Ca/K in Norway spruce seedlings after 2 years of WA application was about 50% lower than that in the control trees, being the lowest in the variant with the highest ash doses (Figure 4).

The main function of the biogenic elements N and P, which serve as constituents of proteins and nucleic acid, is quite evident and readily described. P and N did not change from the control or had a tendency to be elevated in the Norway spruce seedlings in plots treated with 0.5 kg m^{-2} WA doses. The shifts in

Table 4. Content of mineral elements (% dw, ±SD, $n = 3$) in the needles, shoots, stems and roots of Norway spruce growing on the sample plots treated with wood ash and in the control area in August 2002

Treatment	Organ	Age	N	K	Ca	P
Control	Needles	c.yr.	1.28 ± 0.11	0.3 ± 0.01	0.51 ± 0.07	0.17 ± 0.01
		1-yr.	1.18 ± 0.11	0.3 ± 0.01	1.27 ± 0.01	0.19 ± 0.02
	Shoots	c.yr.	1.15 ± 0.17	0.58 ± 0.09	0.54 ± 0.04	0.25 ± 0.09
		1-yr.	0.88 ± 0.07	0.35 ± 0.08	0.59 ± 0.03	0.18 ± 0.02
	Stem		0.61 ± 0.02	0.34 ± 0.06	0.47 ± 0.03	0.14 ± 0.03
	Roots		0.75 ± 0.09	0.21 ± 0.02	0.67 ± 0.01	0.15 ± 0.05
0.25 kg m^{-2}	Needles	c.yr.	1.23 ± 0.09	0.65 ± 0.08	0.61 ± 0.01	0.16 ± 0.01
		1-yr.	1.16 ± 0.04	0.58 ± 0.08	1.13 ± 0.17	0.13 ± 0.04
	Shoots	c.yr.	1.15 ± 0.02	1.13 ± 0.13	0.52 ± 0.08	0.24 ± 0.04
		1-yr.	0.86 ± 0.01	0.62 ± 0.08	0.56 ± 0.01	0.16 ± 0.03
	Stem		0.65 ± 0.03	0.52 ± 0.07	0.43 ± 0.01	0.12 ± 0.01
	Roots		0.88 ± 0.09	0.45 ± 0.06	0.76 ± 0.02	0.17 ± 0.02
0.5 kg m−2	Needles	c.yr.	1.45 ± 0.09	0.69 ± 0.03	0.71 ± 0.06	0.19 ± 0.02
		1-yr.	1.33 ± 0.10	0.56 ± 0.04	1.47 ± 0.08	0.17 ± 0.01
	Shoots	c.yr.	1.21 ± 0.09	1.17 ± 0.02	0.62 ± 0.05	0.27 ± 0.01
		1-yr.	0.92 ± 0.01	0.71 ± 0.06	0.48 ± 0.05	0.17 ± 0.01
	Stem		0.69 ± 0.03	0.49 ± 0.02	0.43 ± 0.01	0.13 ± 0.01
	Roots		0.89 ± 0.02	0.42 ± 0.03	0.71 ± 0.04	0.18 ± 0.01
1.0 kg m^{-2}	Needles	c.yr.	1.29 ± 0.09	0.77 ± 0.05	0.48 ± 0.02	0.17 ± 0.02
		1-yr.	1.18 ± 0.01	0.63 ± 0.03	0.89 ± 0.03	0.16 ± 0.01
	Shoots	c.yr.	1.22 ± 0.10	1.20 ± 0.09	0.55 ± 0.02	0.24 ± 0.01
		1-yr.	0.87 ± 0.03	0.61 ± 0.03	0.47 ± 0.05	0.15 ± 0.01
	Stem		0.61 ± 0.04	0.48 ± 0.02	0.37 ± 0.03	0.09 ± 0.01
	Roots		0.75 ± 0.06	0.40 ± 0.01	0.62 ± 0.02	0.14 ± 0.01

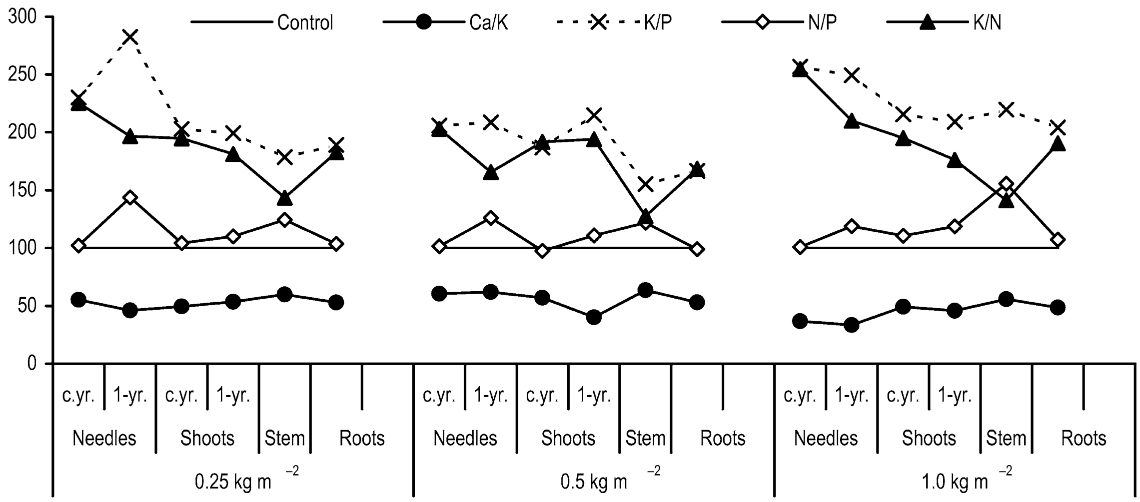

Figure 4. Ratios of mineral elements in different organs of Norway spruce growing on the sample plots treated with wood ash in August 2002, and their comparison with control (% of control).

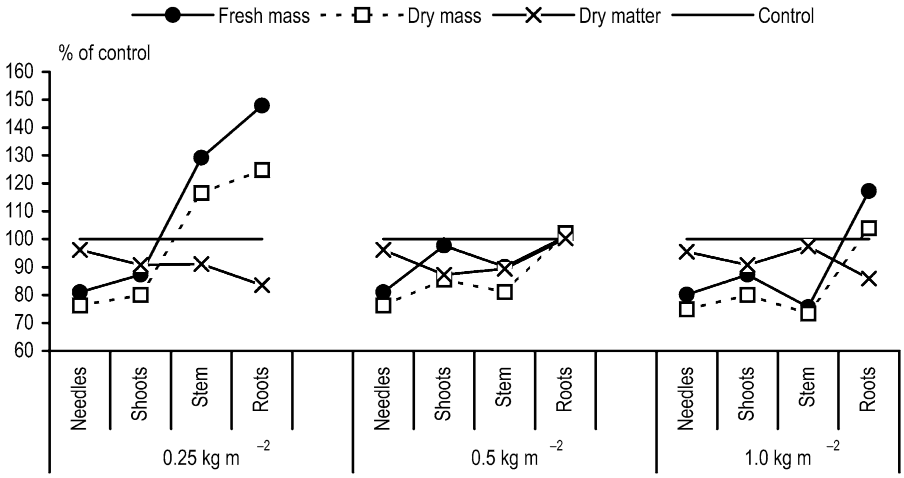

Figure 5. Comparison of growth parameters of different organs of Norway spruce growing on the sample plots treated with wood ash in August 2001, and their comparison with control (% of control).

plant N and P composition may reflect the changes in several metabolic pathways.

Contrary to the Ca/K ratio, the levels of K/P, K/N and N/P were found to increase rapidly in spruce seedlings treated with WA, being on average 208, 180 and 114% of control, respectively it is clear that the increase in soil pH and chemical character of WA cause disbalances in the mineral composition of trees (Figure 4).

In addition, it should be stressed that the responses of plants to affected factors may be different in the different compartments of trees (Kozlowski et al., 1991; Mandre, 1995; Mandre et al., 1999). Liming of soils has its primary effect in roots, with the response being either negative or positive. Roots are responsible for most of the absorption of mineral elements. The results of Mandre and Ots (1999) show that alkalisation of soil (pH > 8) due to cement dust pollution decreases the biomass of the roots of *Picea abies P. mariana* and *P. glauca* more than 60% of control. This complicates mineral nutrition processes and results in changes in the allocation of nutrients in different tree compartments. The direction of translocation of nutrients is primarily regulated by the relative sink strength of organs. Thus source-sink relationships as well as the content of nutrients are not static, and almost all plant organs can act as a sink at some stage of their development. In experiments with WA application it was found that the K content increased in all organs of spruces in all WA treatment variants, Ca content increased in the needles and decreased in shoots and stems, N increased in stems and roots and P in roots in the case of 0.25 and 0.5 kg m^{-2} of treatment (Table 4, Figure 3). Four WA application variants (0, 0.25, 0.5 and 1.0 kg m^{-2}) were introduced also into regression equations computed and statistically significant relationships ($P < 0.05$) were found between the K concentrations in the soil and in the needles ($R^2 = 0.7513$) and shoots ($R^2 = 0.5071$); between the Ca concentration in the soil and in the shoots ($R^2 = 0.7768$), stems ($R^2 = 0.7613$) and roots ($R^2 = 0.5667$); between the P concentration in the soil and in the shoots ($R^2 = 0.7335$) and stems ($R^2 = 0.7462$).

Growth and biomass formation

In the experiments carried out it was possible to identify some morphological differences between the untreated control and the WA treated 4-year-old Norway spruces after some months from the beginning of the treatment. At the end of the vegetation period of 2001 the treated trees were 7–15% shorter than the untreated trees. The dry mass of shoots, needles and stems was estimated to have decreased on average 22% under the influence of WA application (Figure 5 Table 5). But the fresh and dry mass of the roots and stems had increased at the lowest amounts of WA application (0.25 kg m^{-2}) (Figure 5 Table 5). The increasing proportion of root biomass in the total mass of six-year-old Pinus sylvestris, *Picea mariana* and *Pseudotsuga menziesii* in an alkalized area influenced by the cement dust in the vicinity of a cement plant was earlier established (Mandre et al., 1999). Also an increase of soluble sugars and starch in the roots and

Table 5. Growth parameters in different organs of Norway spruce seedlings growing on sample plots treated with wood ash in August 2001 ($n = 5$, ± SD, P-value of difference according to two-sided t-test)

Treatment	Organ	Fresh mass, g	Dry mass, g	Dry matter, %
Control	Needles	129.72 ± 9.13	54.99 ± 3.37	48.68 ± 2.37
	Shoots	32.87 ± 2.79	18.82 ± 1.32	50.68 ± 1.75
	Stem	12.72 ± 2.67	6.05 ± 0.09	47.82 ± 1.85
	Roots	9.22 ± 1.61	4.30 ± 0.62	47.05 ± 6.91
0.25 kg m^{-2}	Needles	105.11 ± 11.48	41.97 ± 4.83	46.83 ± 3.74
		$P = 0.936$	$P = 0.897$	$P = 0.846$
	Shoots	28.71 ± 2.16	12.67 ± 1.73	46.02 ± 2.05
		$P = 0.163$	$P = 0.296$	$P = 0.00002$
	Stem	16.44 ± 2.81	7.05 ± 0.58	43.58 ± 3.59
		$P = 0.251$	$P = 0.417$	$P = 0.046$
	Roots	13.63 ± 1.74	5.36 ± 0.34	39.30 ± 3.91
		$P = 0.094$	$P = 0.240$	$P = 0.998$
0.5 kg m^{-2}	Needles	105.12 ± 15.23	41.97 ± 4.09	46.83 ± 1.62
		$P = 0.561$	$P = 0.403$	$P = 0.079$
	Shoots	32.12 ± 3.46	13.53 ± 1.33	44.26 ± 4.18
		$P = 0.878$	$P = 0.677$	$P = 0.000005$
	Stem	11.47 ± 1.10	4.90 ± 0.48	42.76 ± 0.01
		$P = 0.728$	$P = 0.479$	$P = 0.089$
	Roots	9.30 ± 0.98	4.39 ± 0.44	47.20 ± 0.39
		$P = 0.980$	$P = 0.950$	$P = 0.387$
1.0 kg m^{-2}	Needles	103.99 ± 12.19	41.19 ± 4.48	46.51 ± 3.39
		$P = 0.497$	$P = 0.324$	$P = 0.005$
	Shoots	28.71 ± 2.12	12.67 ± 1.13	46.02 ± 2.59
		$P = 0.453$	$P = 0.283$	$P = 0.00007$
	Stem	9.63 ± 1.10	4.44 ± 0.71	46.60 ± 4.25
		$P = 0.298$	$P = 0.222$	$P = 0.566$
	Roots	10.81 ± 1.90	4.46 ± 0.98	40.43 ± 3.92
		$P = 0.521$	$P = 0.887$	$P = 0.023$

stems of *Picea glauca* and *Pinus sylvestris* was found under the environmental conditions described above (Mandre and Klõšeiko, 1997). Intensive accumulation of sucrose in the needles *Picea abies* and leaves *Salix dasyclados* in the sample plots treated with cement dust was also found by Klõšeiko and Mandre (2001). Taking into account the results of studies on the influence of cement dust and alkalization of growth substrate, it is possible to suppose that the increase in the biomass of roots and stems under the influence of WA (0.25 kg m^{-2}) should result from intensified translocation of carbohydrates into roots and stems or photosynthetic efficiency of the needles. An increase of sucrose in the needles of *Picea abies* seedlings in July to October under the lowest amounts of WA application was shown by Klõšeiko (2003). However, the relationships between biomass formation and carbohydrate metabolism of conifers in alkalised growth conditions are not fully understood and need further studies.

Regression analyses revealed the relationships between the height of seedlings and the concentration of P ($R^2 = 0.7823$) and N ($R^2 = 0.5011$) in soil at the statistical significance $P < 0.05$.

Deviations from the control depended slightly on the age of the organs of trees. Statistically significant differences (t-test) from the control in dry mass were established only for current year needles ($P = 0.0020$) and shoots ($P = 0.0034$) (Figure 6).

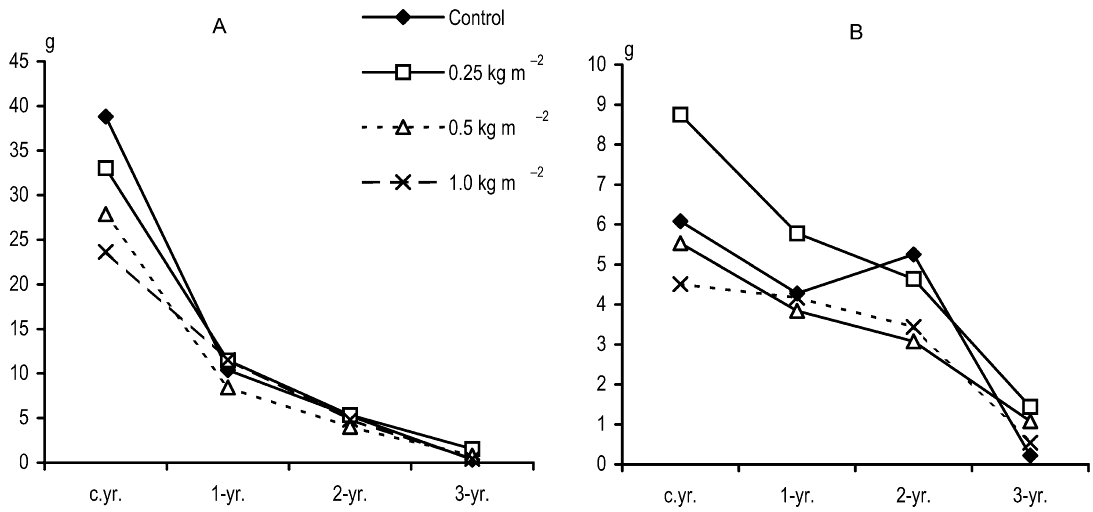

Figure 6. Dry mass (g/per plant) of needles (A) and shoots (B) of Norway spruce in sample plots treated with wood ash in August 2001.

Conclusions

The mechanisms through which wood ash application to soil affects plants are not yet fully understood. Research results published until now are basically limited to the description of tree growth, content of mineral nutrients and biomass dynamics, that is to the description of consequences.

In the literature used no information could be found on changes in the plant physiology. However it is evident that the altered mineral composition of soil may cause changes in metabolism and in physiological activity of trees in general. Although the pattern of the seasonal dynamics in the treated trees did not vary, the mean amount of Chl*a*, Chl*b* and Car was quantitatively higher than in control trees and relationships between disbalances in mineral composition of soil and tree tissues were revealed. Still the stability of the levels of the ratios Chl*a*/Chl*b* and TChl/Car allowed us to conclude that no disturbances occurred in the possibilities for photosynthesis.

The fertilisation of nutrient poor sandy soil with wood ash decreased N and P concentrations in the soil but not the average biomass of trees. The disbalance in mineral composition in tissues of different Norway spruce organs favoured biosynthesis of pigments participating in photosynthesis. It can be stated that application of WA in a dose 0.5 kg m^{-2} to Norway spruce seedlings on sandy soils could have a positive effect on tree physiology and root biomass formation.

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