The Effect of Cement Dust on the Growth, Content of Nutrients and Carbohydrates in Various Organs of Five Conifer Species

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Long-term impact of dust (pH 12.3–12.9, supernatant of dust:water 1:3) from a cement plant on the growth and content of carbohydrates and nutrient composition was studied in Norway spruce, white spruce, black spruce, Scots pine, and Douglas fir in field experiments. A comparative analysis indicated a decrease in the contents of starch and hemicelluloses and the influence on their partitioning between organs of trees. Elevated contents of K and Ca in the environment and in the trees reduced the content of N and its allocation within the organism ($r_{N/Ca} = -0.727$, $p < 0.001$; $r_{N/K} = -0.782$, $p < 0.01$). Alkaline dust retarded the height of trees and the length of shoots and decreased their biomass. On the basis of morphological changes in trees the resistance of the studied species to alkalization of the environment can be ordered as follows: *Pseudotsuga menziesii* > *Picea abies* > *Pinus sylvestris* > *Picea glauca* > *P. mariana*.

Key words: biomass, carbohydrates, cement dust pollution, conifers, growth, nutrients.

Introduction

In order to forecast and estimate the development of forest ecosystems, it is necessary to understand the response reactions of trees to pollutants emitted by different industries. In addition to the atmospheric pollutants O_3, SO_2, NO_x and acidic rain, which have been widely studied, industrial regions are often confronted with the problems of alkalization due to the high content of various industrial alkaline dusts and ash (Farmer 1993).

It is well known that depending on the load, the duration of the effect, chemical composition of pollutants and the tolerance of the plant, pollution may cause negative or positive responses in plant growth and biomass formation. Several studies describe negative changes in the physiology and biochemistry of plants under high levels of alkaline cement dust (Brandt and Rhoades 1973, Sporek 1983, Shukla et al. 1990, Farmer 1993, Mandre et al. 1994, Mandre and Klõšeiko 1997).

Nutrient partitioning is of primary importance with regard to the biomass formation and all life processes in trees. It is an important issue in understanding plant response to air pollution. Research conducted on the effects of technogenic alkaline dust and ash on plants has been relatively modest, though dust pollution formed about 10% of the total pollution in the world before 1990 (Eensaar 1988) and may be increasing due to extension of quarrying and opencast mining (Farmer 1993).

Dust pollution is known to affect several physiological processes linked to carbon metabolism in plants. Studies of the annual carbohydrate dynamics in the needles of *Picea abies* incrusted with cement dust showed that in winter the content of soluble carbohydrates may be 20–30% lower than in unpolluted trees and the starch content is notably lower than the control from April to July (Mandre 1995b). Obviously, light shortage under the dust cover is of great importance in carbon assimilation and photosynthates content in plants. Apparently, the chemical composition and pH of dust are the factors most strongly affecting the metabolism of carbohydrates in plants subjected to dust pollution. Czaja (1961) has shown that the total pH value of *Beta vulgaris* leaves increases up to 10, and that surface plasmolysis of the leaf cells starts one week after the application of cement dust, with an irregular distribution of chloroplasts and halt of starch formation. Iliescu (1981) has reported that alkaline dust from the electric filters of a cement plant, applied to *Begon-*

ia sp., rapidly inhibited the formation of reducing carbohydrates. Steinhübel (1962) has concluded that the critical factor in starch formation is light absorption by the dust layer in common holly leaves, whereas the influence on transpiration or overheating of leaf tissue are of minor significance.

The aim of the present study was to compare the content of nutrients and carbohydrates in different organs and different species of conifers growing in the conditions of dust pollution and in dust-free conditions.

Materials and methods

Study area and plant material

Morphological and biochemical parameters of conifers grown in an area of heavy dust pollution were studied and compared with those of trees grown in an unpolluted control area with similar climatic conditions. Climatically the areas investigated belong to the mixed-forest subregion of the Atlantic-continental region, where the influence of the Baltic Sea is strongly felt, the average annual temperature is 4.9 °C, annual amount of precipitation 550–575 mm and dominating winds blow from the south-west at a mean velocity of 5.2 m s^{-1} (Raukas 1993, Annuka 1994). The soils in the areas investigated are Gleyic Podzols, which show essential chemical changes in the vicinity of the cement plant (Mandre et al. 1994).

Two-years-old seedlings of Norway spruce (*Picea abies* (L.) Karst.), white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.), Scots pine (*Pinus sylvestris* L.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (n = 25–40) were planted on sample plots under a high air pollution load at a distance of 0.5 km from the cement plant in Kunda, Northeast Estonia (26°30' E, 59°20' N). Norway spruce and Scots pine were native species. The control trees were planted on the relatively unpolluted area of Lahemaa National Park, located about 30–38 km west from the cement plant, opposite to the prevailing winds (26°00' E, 59°31' N). In all cases the spacing of trees was 50×50 cm.

Air pollution and characteristics of sample plots

The dust from electric filters contains many components, among which the following are predominant: 40–50% CaO; 12–17% SiO_2; 6–9% K_2O; 4–8% SO_3; 3–5% Al_2O_3; 2–4% MgO; 2.8–3.2% Fe_2O_3, but also Mn, Zn, Cu, and B occur. The pH of water solution (supernatant dust:water 1:3) was 12.3–12.6 (Raukas 1993). The total dust emission from the cement plant was extremely high in 1990–1992 being 80–100 kt $year^{-1}$ (Keskkond '90, 1991, Estonian Environment 1991, 1991, Estonian Environment 1995, 1996). In 1993–1996, the emission of cement dust from the plant decreased notably after the installation of efficient filters and amounted to 15–70 kt $year^{-1}$.

In order to characterize technogenic changes in the geocomplexes we used a number of parameters that show qualitative alterations. The most important feature was alkalization and changes in the chemical properties of soil, subsoil water and precipitation. High concentrations of technogenic dust in the air due to emissions from the cement plant have brought about significant alkalization of the soil (pH of humus horizon is 7.2–8.1), precipitation (rain pH 7.1–7.9), snow melt (pH 9.1–11.8) and subsoil water (pH 7.1–7.9) and have changed the chemical composition of the growth conditions of trees (Fig. 1). In the control sample plot the pH of rainwater measured during the investigation period was 6.1–6.6, that of snow melt 6.7–7.0 and the humic horizon of soil had pH 3.6–4.2.

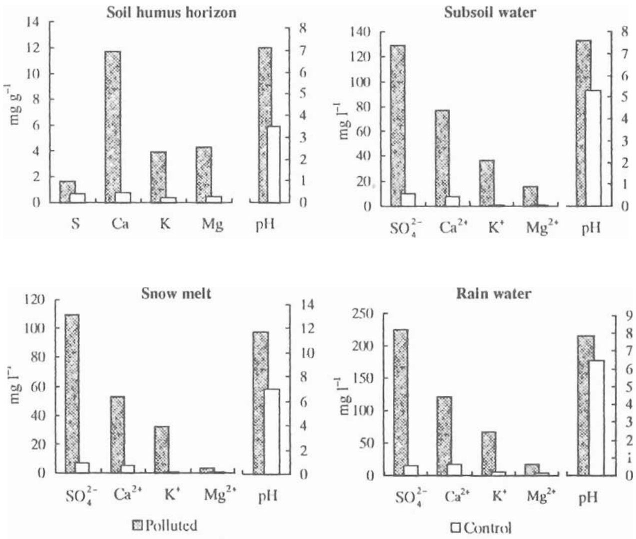

Figure 1. Parameters of the soil and precipitation on the sampling plots in 1993 from January to December.

Morphological measurements

In early May 1994 before bud break, 6–10 six-year-old trees of each species were dug up and the roots, stems, shoots (two last age classes) and needles were separated for the assessment of their fresh and dry (dried at 70 °C to a constant weight) weights (g), dry matter content ([dry weight : fresh weight] × 100, %), length (cm) and for the biochemical analyses of different organs. The height (cm) of trees was measured every autumn beginning with the autumn after planting in 1990.

Chemical analysis

Plant material harvested in May 1994 was used for analyses. The collection of samples was carried out at 10.00–11.00 a.m. local time on a cloudy day at air temperature 5 °C. All the organs separated were carefully cleaned, cut into small pieces and oven-dried at 70 °C for 3 days (Wilde et al. 1979, Landis 1985). Only one-year-old needles and shoots were used for analyses, because they are the most important source of photosynthate and mineral nutrients retranslocation for the new needles and shoots (Ziemer 1971, Ericsson 1978, Marschner 1986). After grinding, the dried plant material (1–2 g) of different organs was subjected to chemical analyses. Concentrations of elements (Ca, K, Mg, Fe, Mn) were determined by atom adsorption spectroscopy (AAA-1N, Karl Zeiss, Jena), N was analysed by the method of Kjeldahl and P by the ammonium molybdate-vanadate method using spectrophotometer SPEKOL 11 (Carl Zeiss, Jena) at 460 nm in the Estonian Control Centre of Plant Production in Saku.

Total soluble carbohydrate and starch concentrations were estimated using the methods recommended by Ferenbaugh (1976), Marshall (1985), Arasimovich and Ermakov (1987). The organs separated from 6–10 trees were immediately fixed in boiling 96% ethanol for 3 min and air dried. 1–5 g of dried and homogenized plant material from lumped and mixed sample was used for repeated extraction of soluble carbohydrates with 80% ethanol. The extracts were centrifuged and the supernatants were collected. All the residue that remained after the removal of soluble carbohydrates was dried, followed by gelatinization in distilled water and digestion with 35% perchloric acid for complete extraction of all starch (Ferenbaugh 1976, Marshall 1985). The extraction of hemicelluloses was carried out with acid hydrolysis (2% H_2SO_4) as recommended by Arasimovich and Ermakov (1987) and Sofronova and Chinenova (1987). The extracts of soluble carbohydrates, starch and hemicelluloses were individually reacted with an anthrone reagent (0.1% anthrone in 72% sulphuric acid) to produce a blue-green colour and their absorbancies were measured at 620 nm with a spectrophotometer (SPEKOL 11, Karl Zeiss, Jena). The concentrations were calculated using glucose curves as a standard.

Statistical analyses

To test the differences, regression analysis, correlation analysis and *t*-tests were used with the help of package Statgraphics 5.0 (Manugistics Inc.). Assuming possible correlation between organs, repeated measures analysis was conducted to test nutrients and carbohydrates for additive dust effect and for organ x dust interaction in all organs and species at once. Site (2 levels) and species (5 levels) were independent variables and organs were dependent variables (5 variables). The dust effect on carbohydrates was further tested using all analysed compounds of carbohydrates (15 dependent variables) at once. General Linear Model procedure in SYSTAT 7.0 (SPPS Inc.) was used for the repeated measures analysis.

Results

Nutrients

Alkaline dust deposited on trees and alkalized growth substrate caused serious deviation in the mineral composition of young conifers. An increase in the average Ca, K, Mg and Fe concentrations was found in the investigated trees. Compared with the trees growing in the control area, the concentrations of these elements were about 155, 82 and 38% higher, respectively. The highest concentrations of Ca and K were observed in the needles of polluted trees (Table 1).

As a consequence of cement dust exposure the contents of several elements (P, Mg, Fe, K) were higher than in the control trees in the above-ground organs, while in the roots they were close to (K, Mg) or significantly lower (Fe, P) than in the control trees (except in *Picea mariana)* (Table 1). The average concentrations of P and Fe in the needles of polluted trees had increased by 89 and 423%, respectively, but in the roots their concentrations were less, being 55 and 47% of the control.

The changes in the chemical composition of trees under stress showed a high variability between species. For example, in *Picea abies* an essential decrease in N concentration was found, which was as the average of different organs by 30–50% lower than that in the control trees. At the same time in *Pinus sylvestris* the differences in the content of N in the needles from the control did not exceed 12% and no essential changes were observed in the roots, stems and shoots.

A drastic decrease in the content of Mn was found in all species and in both organs of the young conifers investigated. An essential Mn deficiency was established in the polluted trees: the Mn concentration in the roots of *Pseudotsuga menziesii* was only 25.0 mg g^{-1} d.w. and in the shoot needles 8.8–22.3 μg g^{-1} d.w. (Table 1).

Carbohydrates

Total concentration of carbohydrates in needles was less in polluted trees, while the degree of differences varied with species (Table 2). The most consist-

Element	Organ	Site	*Pinus sylvestris*	*Picea abies*	*Picea mariana*	*Picea glauca*	*Pseudo-tsuga menziesii*	*p-value*
N	Needles	Control	14,0	12,8	12,5	12,1	10,8	
mg g-1		Polluted	13,0	8,0	10,7	11,6	9,6	0,072
	Roots	Control	5,4	6,0	6,6	6,6	12,2	
		Polluted	5,4	4,0	5,2	4,7	6,4	0,083
P	Needles	Control	1,3	1,7	1,6	1,5	1,9	
mg g-1		Polluted	1,6	4,3	3,9	1,8	3,5	0,043
	Roots	Control	1,8	1,6	1,4	2,0	3,2	
		Polluted	1,3	1,0	1,3	1,2	1,7	0,038
K	Needles	Control	8,4	8,4	8,8	7,4	7,6	
mg g-1		Polluted	12,4	13,6	12,9	9,1	13,2	0,004
	Roots	Control	6,0	6,1	6,8	5,5	8,1	
		Polluted	8,2	6,0	7,4	6,4	7,9	0,191
Ca	Needles	Control	4,1	6,5	5,7	7,6	5,2	
mg g-1		Polluted	10,9	18,6	15,4	19,2	14,4	0,000
	Roots	Control	5,6	5,0	5,0	10,0	8,7	
		Polluted	11,9	9,6	15,2	14,2	10,6	0,017
Mg	Needles	Control	2,2	1,5	1,3	1,5	1,6	
mg g-1		Polluted	3,2	2,8	3,4	3,9	3,3	0,003
	Roots	Control	1,6	1,4	2,5	2,7	2,1	
		Polluted	4,7	1,8	3,3	3,1	2,5	0,121
Mn	Needles	Control	48,5	44,8	37,3	50,5	27,3	
µ g g −1		Polluted	8,8	20,5	14,5	22,3	18,0	0,007
	Roots	Control	144,0	84,3	57,0	120,0	173,0	
		Polluted	32,8	28,3	37,8	34,5	25,0	0,019
Fe	Needles	Control	44,0	69,8	69,1	90,5	133,0	
µ g g−1		Polluted	204,0	530,0	380,0	562,0	452,0	0,004
	Roots	Control	2375,0	1705,0	768,0	2680,0	1755,0	
		Polluted	802,0	713,0	920,0	1281,0	673,0	0,032

Table 1. The content (d.w.) of mineral elements in 1-year-old needles and roots of different 6-year-old coniferous species grown on the control site and near the cement factory (polluted) in May 1994; significance of pollution effect (p-value) according to two-sided paired t-test

ent changes were recorded for hemicellulose which was lower in both roots and needles of all species. Less starch was in needles. Lower content in soluble carbohydrates was most usual across species. Statistical significance of dust effect on soluble carbohydrates for all organs (Table 3) was slightly higher ($p = 0.057$) than for needles or roots singly. If different carbohydrates were tested at once, the p-value of additive dust effect

Parameter	Organ	Site	*Pinus sylvestris*	*Picea abies*	*Picea mariana*	*Picea glauca*	*Pseudo-tsuga menziesii*	*p-value*
Total	Needles	Control	77,0	112,0	107,0	102,0	84,0	
soluble		Polluted	76,0	118,0	91,0	90,0	65,0	0,150
	Roots	Control	34,0	62,0	45,0	37,0	30,0	
		Polluted	43,0	15,0	12,0	40,0	18,0	0,206
Starch	Needles	Control	83,7	141,3	117,9	108,9	126,0	
		Polluted	77,0	111,6	94,5	95,4	109,8	0,011
	Roots	Control	82,8	88,2	72,0	43,2	92,7	
		Polluted	91,8	81,9	71,1	58,5	87,3	0,609
Hemi-	Needles	Control	119,3	175,5	146,3	128,3	171,0	
cellulose		Polluted	114,2	117,0	124,9	106,9	122,7	0,034
	Roots	Control	123,8	124,9	114,8	97,0	129,4	
		Polluted	99,0	102,4	99,0	96,8	114,8	0,022
Total	Needles	Control	280,0	428,8	371,2	339,2	381,0	
		Polluted	267,2	346,6	310,4	292,3	297,5	0,012
	Roots	Control	240,6	275,1	231,8	177,2	252,1	
		Polluted	233,8	199,3	182,1	195,3	220,1	0,148
Soluble/	Needles	Control	0,92	0,79	0,91	0,94	0,67	
Starch		Polluted	0,99	1,06	0,96	0,94	0,59	0,318
	Roots	Control	0,41	0,70	0,63	0,86	0,32	
		Polluted	0,47	0,18	0,17	0,68	0,21	0,089

Table 2. The content of carbohydrates (mg g-1, d.w.) in 1-year-old needles and roots of different 6-year-old coniferous species grown on the control site and near the cement factory (polluted) in May 1994; significance of pollution effect (p-value) according to two-sided paired t-test

Table 3. Significances (p-values) of cement dust effect on the mineral elements and carbohydrates according to repeated measures analysis organs and species tested at once

Parameter	Source of variation	
	dust	Organ × dust
	p-value	
N	0,038	0,331
P	0,220	0,000
K	0,000	0,001
Ca	0,000	0,001
Mg	0,002	0,114
Mn	0,002	0,002
Fe	0,986	0,000
Total mineral elements	0,114	0,000
Soluble carbohydrates	0,057	0,168
Starch	0,148	0,176
Hemicellulose	0,077	0,053
Total carbohydrates	0,057	0,234
Soluble carbohydrates/Starch	0,189	0,068

was also 0.057 and the only significant pollution related result was compound×organ×dust interaction (p = 0.046). Total content of carbohydrates was significantly lower in needles of polluted trees. Some indication of lower soluble carbohydrates to starch ratio was found for roots.

Regression analysis showed the correlation between the starch content and that of the soluble carbohydrates ($R^2 = 0.58, p < 0.001$), and interdependence of starch and hemicelluloses ($R^2 = 0.85$, $p < 0.001$) in trees.

Growth and biomass of trees

In the polluted area the height growth of young conifers became inhibited already from the first year of growth (Fig. 2). In 1996 the total dry weight of *P. sylvestris* control trees was 2234 g (n = 10), but near the factory only 240 g. Respective figures for *P. abies* were 914 and 453 g. Differences from the control trees at the end of experiments were significant at the $p \leq 0.001$ level for all spruce species and for *P. sylvestris*. The height of the *P. abies* measured in 1993, on average was 55% of the control and for *P. sylvestris* 47% of the control. The deviation from the control in height of trees increased in the following years. In comparision with the control, the height of *P. mariana* was most strongly reduced in 1992 and 1993 being 31% and 25% of the control, respectively. This large difference may be attributed to climatic factors because in these two years the amount of precipitation was only 1/3 to 1/8 of the long-term mean and *P. mariana* seemed to be the most sensitive species. Abundant rainfall may reduce the concentration of pollutant in the soil. Surprisingly, the *P. menziesii* that had grown under dust pollution did not differ considerably from the control. Under stress the length of spruce shoots was by 15–76% and 65–87% smaller than the control in 1992 and 1993, respectively (Fig. 3). The large amounts of cement dust had a strong negative effect also on the formation of the weight of the conifers. This was especially evident in the case of the fresh and dry weight of roots, stems and shoots, less in the case of needles (Fig. 3). The weight of various organs of *Picea mariana* in particular was notably affected by large amounts of dust.

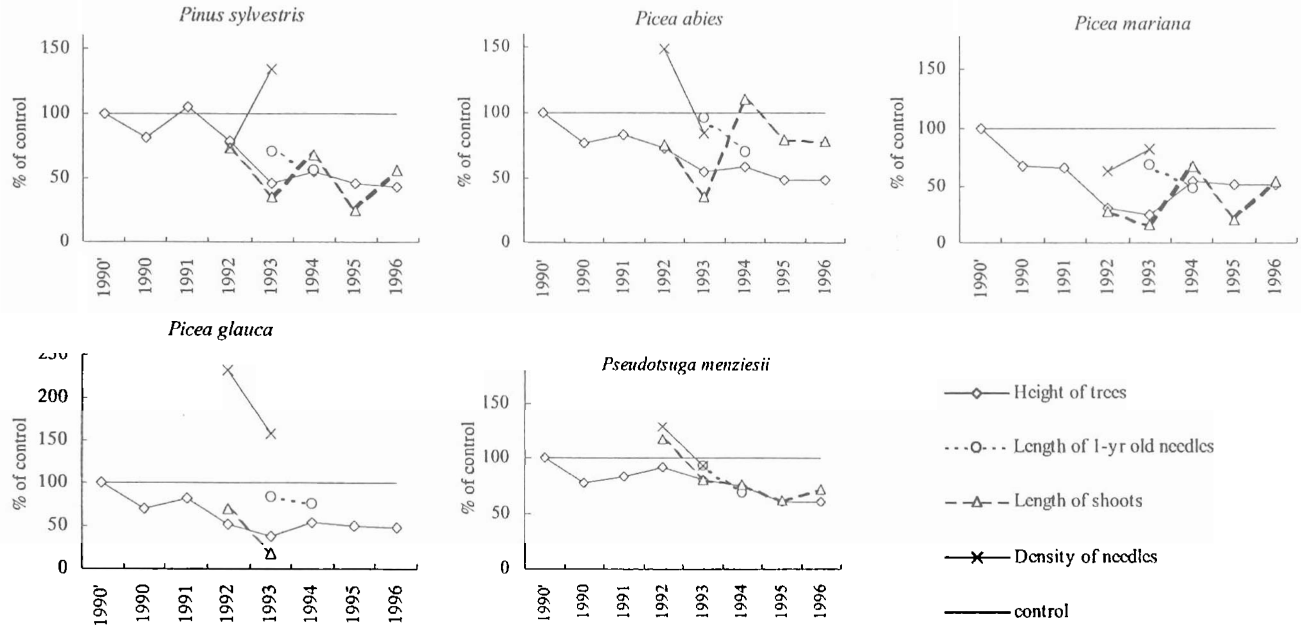

Figure 2. Annual dynamics of morphological differences from the control (% of control) of young coniferous trees in dust pollution conditions in 1990–1996. 1990', planted in May 1990.

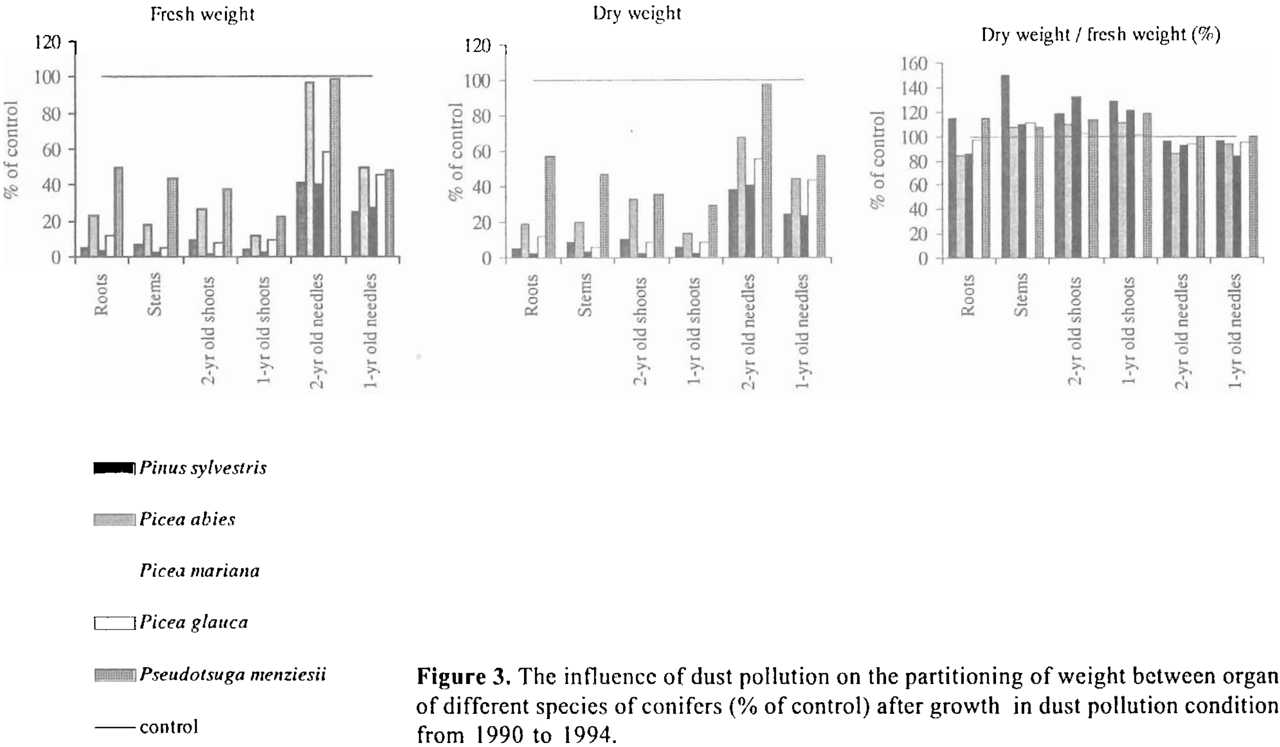

Figure 3. The influence of dust pollution on the partitioning of weight between organs of different species of conifers (% of control) after growth in dust pollution conditions from 1990 to 1994.

Discussion and conclusions

High alkalinity of the environment – soil, subsoil water and precipitation – caused by high levels of alkaline dust pollution, induces essential changes in the plant physiology and morphology. Somewhat lower content of mineral elements and the reduced concentration of N, P, Fe and Mn in the roots points to lower availability of those nutrients from the alkalized growth substrate or to an intensive translocation from the roots to the above-ground organs. The increased content of nutrients in the needles suggests the incorporation of nutrients from the dust layer on needles through the needle surface.

Our earlier investigations with 60–80-year old *Picea abies* and *Pinus sylvestris* show that prolonged cement dust impact and alkalization of the environment cause changes in the availability of several plant nutrients, their content and ratio in needles, and alter the pattern of the seasonal dynamics of nutrients (Mandre, 1995a). For example, while under dust-free conditions the maximum content of N in one-year-old *Picea abies* needles occurs in March–April, then under stress due to the influence of cement dust pollution the maximum N values of needles are observed in the period from September to February. It was found that cement dust raises the Ca, K and S content in needles, but decreases that of Mn and N (Mandre, 1995a). Elevated S content could be caused by elevated S emissions. Similar results were obtained for foliar nutrient composition by Lal and Ambasht (1982).

Trees were analysed for carbohydrates in early May when their buds did not yet show any important morphological changes, but metabolic processes in them had already been activated. Comparing five coniferous species, we found that the content of starch, which is practically absent in both buds and needles in winter (Sofronova, 1985, Mandre, 1995b), very likely, was near the peak associated with bud break, as was the content of hemicellulose. Before bud break evergreen conifers accumulate in needles starch gained from net photosynthetic activity (Mattsson and Troeng, 1986, Sofronova, 1985, Ericsson, 1980) and a relatively large quantity of foliar carbohydrates may be accumulated in conifers (Amundson et al., 1993, 1995, Mandre, 1995b, Wallin et al., 1996). It is known that amount of soluble carbohydrates tends to decrease in needles at the pre-bud-break period (Sofronova, 1985, Mandre, 1995b, Wallin et al., 1996). Still, their content in young conifers, as studied by us, was highest in needles but low in roots, stems and shoots. A low content of N, P and Mn in the tissues may be one of the factors causing reduced contents of soluble carbohydrates (SS) ($r_{SS/N} = 0.68, p < 0.001$; $r_{SS/P} = 0.72$, $p < 0.001$; $r_{SS/Mn} = 0.61$, $p < 0.05$).

It was established that in the pre-bud-break period young conifers contained 23–30% of total carbohydrates, most of this amount being starch and hemicellulose. The distribution of carbohydrates in the organism is determined by the functional properties and activity of the organs. Thus, in needles, serving as photosynthetic organs, the content of carbohydrates is much higher than in non-photosynthesizing roots and stem. Roots and stems are composed mainly of cellulose and lignin and carbohydrates are located mostly in vascular tissues and ray cells. Different proportions of living and dead tissues in stems and roots may cause some differences in carbohydrates between polluted and control trees. Soluble carbohydrates have also the osmotic function. The requirements of osmotic pressure might be different for the polluted and unpolluted trees or in the polluted trees part of osmotically active carbohydrates might be replaced by compatible substances. In general, air pollution reduces allocation to roots, which is positively correlated with the changes of carbohydrates in needles.

The alkaline dust emitted from the cement plant and the concomitant alkalization of the growth substrate retard the height growth of trees and decrease total plant weight. The height growth of conifers in the polluted area was found to be restrained and it differed considerably from that in the control area. In contrast to fresh and dry weight of organs, the dry weight/fresh weight ratio (%) in various organs may be higher under air pollution except in needles where the dry weight/fresh weight ratio did not differ from the control (*Pseudotsuga menziesii, Picea glauca, Pinus sylvestris*) or showed a tendency to decrease (*Picea abies* and *Picea mariana*).

Moreover, for all conifers investigated the partitioning of dry mass in different organs depends significantly on the N and K content at the level of significance $p < 0.01$. In a polluted area the dry weight of trees largely depends also on the dominant elements of the pollution complex, Ca ($r_{d.w./Ca} = -0.58; p < 0.01$) and Mg ($r_{d.w./Mg} = -0.44; p < 0.01$) .We failed to find such dependence in the control trees.

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ВЛИЯНИЕ ЦЕМЕНТНОЙ ПЫЛИ НА РОСТ, СОДЕРЖАНИЕ ПИТАТЕЛНЫХ ВЕЩЕСТВ И УГЛЕВОДОВ В ПЯТИ ВИДАХ ХВОЙНЫХ

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Резюме

Исследовали влияние цементной пыли на рост, содержание питательных веществ и углеводов в пяти видах хвойных. Содержание гемицеллюлоз и крахмала уменьшилось в загрязненных деревьях. Повышенные уровни K и Ca в среде уменьшили содержание N в деревьях. На основе морфологических изменений виды по толерантности к загрязнению чередовались: *Pseudotsuga menziesii* > *Picea abies* > *Pinus sylvestris* > *Picea glauca* > *P. mariana*.

Ключевые слова: рост, цементная пыль, питательные вещества, углеводы, хвойные