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Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust

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Abstract Long-term influence of alkaline dust (pH 12.3–12.7) pollution emitted over 40 years from a cement plant in Estonia was the reason of alkalisation (pH 6.7–7.9) and high concentrations of K, Ca and Mg in the soil of affected territories. Although dust emission has diminished during the last 10 years, the disbalances in nutrition substrate and their influence on the growth of trees are notable up to now. The study of morphological and physical properties of 70–80-year-old Scots pine (*Pinus sylvestris* L.) crown, stems and stemwood from three different air pollution zones showed serious deviations in comparison with a relatively healthy forest in an unpolluted area. The specimens from polluted trees, if compared to reference site, showed significantly smaller height growth, radial increment and width of annual rings of sapwood. In heartwood wider annual rings were found in polluted areas. In the period of heartwood formation the dust pollution level emitted from the plant was relatively modest and cement dust, which contains elements necessary for mineral nutrition of trees, may have acted as fertiliser. The moisture content in sapwood and heartwood, especially in the upper layers of stems, was lower in the polluted area than in reference site trees. Regression analysis revealed a strong dependence between latewood percentage and sapwood or heartwood in stems of Scots pine in all sample plots.

Keywords Dust pollution · Growth · Scots pine · Soil · Stemwood

Introduction

The growth of trees and wood formation are not only constitutive, developmentally controlled processes, but represent also a flexible metabolic response to external conditions such as nutrient and water availability, climatic factors and air pollution emitted from different industrial enterprises (Chapin 1991; Kozlowski 1991; Nerg et al. 1994).

Numerous investigations describe the damage of large forest areas in many industrial countries in Europe and America by acidic air pollution at the end of the twentieth century (Smith 1990; Staaf and Tyler 1995; Härtling and Schulz 1998). Problems of forest damages caused by alkaline types of pollution,

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however, are not completely understood and interpreted although these are not new. Research into the impact of different alkaline types of air pollution on forests has never drawn so much attention as that of acid rain, SO_2, NO_x or O_3. The production of building materials, open-cast mining and quarrying, metallurgical engineering and chemical industry are among the important emitters of solid pollutants in the form of dusts and ashes. As many authors have found serious deviations in plant metabolism and physiology (Auclair 1977; Manning and Feder 1980; Lal and Ambasht 1982; Mandre 1995a,b; Manning 2001; Klõšeiko 2003; Skuodene 2005) and deviations in growth and bioproduction (Gluch 1980; Jäger 1980; Rauk 1995; Ots 2002) caused by alkaline dust pollution and alkalisation of the environment, the problem of the impact of alkaline air pollution needs greater attention as a topic of investigation. So far the research into the effects of alkaline types of pollutants on plants has been insufficient.

One of the major producers of industrial alkaline dust pollution in Estonia is the cement plant in Kunda established in 1871. Several ecophysiological and botanical deviations from the optimal were established under the influence of dust emission from this plant (Annuka 1994; Kannukene 1995; Nilson 1995). However, very little information is available on the effects of dusts on the wood quality, heartwood and sapwood formation and lignification. Earlier studies by Mandre (2002, p. 369) showed that in 6-year-old Norway spruces an up to 16–20% increase in the lignin content in the needles occurs under alkaline dust pollution. It brought about a decrease in growth (Ots 2002), especially in the biomass of roots, and a decrease in the level of soluble sugars in stems and roots of 6-year-old *Picea abies, P. glauca* and *P. mariana* (Mandre 1995b). Long-term impact of dust pollution from the cement plant has resulted in a deterioration of the morphological status of middle-aged and mature conifer stands as compared with the trees from unpolluted areas (Ots 2000). Using the measured trunk volume, height of trees and breast height diameter and the formula given by Krigul and Vaus (1980) was calculated the percentage of the current volume increment of stands by Rauk (1995, p. 121) and showed that in the peak years of emissions from the Kunda cement plant in the early 1990s each year 1,500 m^3 of stemwood was less in area polluted by cement dust if compared to unpolluted forest sites. Relationships between changes in growth conditions and lignification processes of Norway spruce in the vicinity of the cement plant were established and intensive lignification processes in needles and by about 30–40% more intensive lignification than in the control were found (Tohver and Mandre 1995). There is no information on the influence of alkalisation of the environment and alkaline dust pollution on the structure, mechanical and physical properties of stemwood, although it is known that the structure and properties of wood are very much affected by growth conditions (Nekrasova 1994; Lindeberg 2001; Wodzicki 2001). Differences in sapwood and heartwood ratios might be attributed to ecological factors such as altitude, lime and organic material content of the soil and soil type (Bektas et al. 2003).

As 67–84% of the biomass of adult coniferous trees is in the stems and branches (Knight 1991; Thornley 1991), the quality of stemwood and its dependence on growth conditions and nutrient balance are of great importance for forestry. The aim of the present work was to find out whether long-term alkaline air pollution from a cement plant and alkalisation of soil have an effect on the growth of trees and on some physical properties of pinewood.

Materials and methods

Study area

Investigations were carried out on a territory affected over 40 years by a cement plant in the town of Kunda (59°30′ N, 26°32′ E), Northeast Estonia, established in 1871. The sample plots were situated at distances of 2.5 and 5 km E and 3 km W from the emission centre and the reference sample plot was located in similar climatic conditions on a relatively unpolluted area in Lahemaa National Park (59°31′ N, 26°00′ E) at a distance of about 38 km W, opposite to prevailing winds.

The main damaging factor to trees in the investigation area was apparently a high level of dust emission from the electric filters. The dust 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; but also Fe, Mn, Zn, Cu, B, etc. occur. The water solution of dust from electric filters had pH values from 12.3 to 12.7 (Mandre 2002).

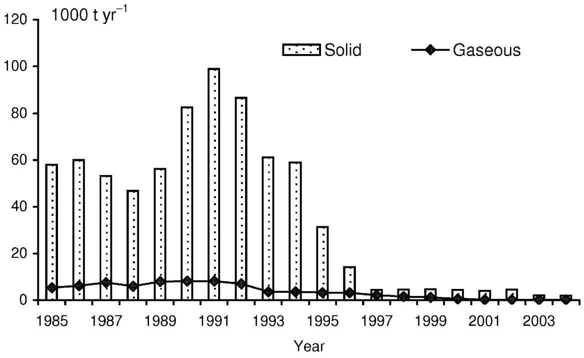


Fig. 1 Emission of dust and gaseous pollutants into the atmosphere from the cement plant in Kunda, Northeast Estonia

The dust emission from the cement plant was extremely high in 1990–1992 being 80–100 kt per year (Environment '90 1991; Estonian Environment 1991 1991; Estonian Environment 1995 1996; Environmental Review No. 13 2004) (Fig. 1). The emission from the cement plant contained 87–91% technological dust and 9–13% gaseous pollutants (SO_2, NO_x, CO etc.; Mandre et al. 1994). In 1993–1996 the emission of cement dust from the plant decreased notably thanks to the installation of efficient filters and at the present time it is lower than the permitted quantity (421 t year^{-1}; Environmental Review No. 13 2004). However, the long-term impact of the high level of dust pollution has brought about alkalisation and serious changes in the chemical composition of the soil, groundwater and precipitation in this area. At a distance of 0.5 km from the cement plant, the pH of the soil ranged from 7.6 to 8.1, the pH of rainwater was between 7.6 and 8.2 and that of snow melt 10.1–11.0 in many years (Mandre 2002). In the vicinity of the cement plant the concentrations of Ca, K, Mg, S and other elements predominating in the dust are extremely high in the upper layers of soil and in precipitation.

In the reference sites the pH value of the soil humus horizon was from 2.9 to 3.3, that of rainwater 5.6–6.6 and snow water 6.3–6.6 (Mandre 2002).

Plant material

The investigation was performed on a 70–80-year-old mixed stand of *Oxalis-Myrtillus* site type with the II site class (height on fixed age).

In September 2005 three dominant trees with a similar habitus of canopy from each sample plot were selected for analysis so that they would represent evenly the diameter classes (25–27 cm at breast height) of the stand in the sample plots and the average trees within each sample plot. Trees were felled and the stem of each tree was divided into three equal horizontal layers (Fig. 2). Altogether, 12 sample trees were selected and felled, from which sample blocks (1.2 m in length) for preparing test bodies were obtained at a level of 1.3 m ($h_{1.3}$), 1/2 of tree height ($h_{1/2}$) and 3/4 of tree height ($h_{3/4}$).

Analysis of physical properties of stemwood

In fresh cut trees the distribution of moisture was measured at the above-mentioned three levels of stems at 20°C with an electronic moisture meter (Hydromette HT85T, Germany).

In measuring the absolute (oven-dry) density of pine stemwood 508 sample bodies were made (20×20×30 cm) from different heights of stems and ISO 3130 (1975) and ISO 3131 (1975) were followed. The absolute density was determined at 102°C so that a constant oven-dry weight had been reached.

Morphological analysis of trees

The annual height increment of the last 10 years and the length of lateral shoots (cm, n=30) were measured. The crowns of pines were divided into three horizons and the length of the current-year shoots (Fig. 2) was measured. Ten branches from each

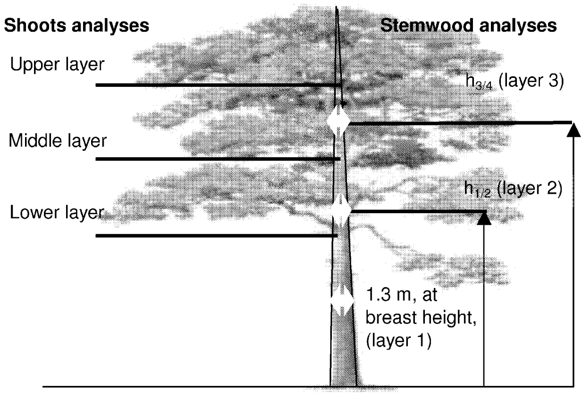


Fig. 2 Sampling of the material for Scots pine stem analyses

horizon of every tree were collected from each (north, south, east and west) sides to get objective information about shoot characteristics.

The annual radial increment was measured to the nearest 0.01 mm on dried cross-section disks. The program WinDENDRO TM (Ver. 2002a, Regent Instruments Inc.) was used for measuring the width of annual rings. The number of annual rings was counted. Also the latewood percentage in the annual ring and heart- and sapwood percentage on cross-sections were determined.

Soil analysis

For characterising the present status of the growth environment, soil samples were collected in five replications per sample plot in September 2005. The soil samples were collected with a steel bore cylinder from depths of 30 cm, taking into account that approximately 80% of the feeder roots of trees are located in the layer of 10–30 cm (Orlov and Koshel'nikov 1971). The nutrient status of the soil upper horizon (30 cm) was determined in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences. 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 and Mg by Egner-Riehm-Domingo ammonium acetate—lactate method (ISO 11260 1995). Total N was determined by the Kjeldahl method (ISO 11261 1995) and the pH of the soil was measured as the potential acidity in H_2O (ISO 10390 1994). Organic matter (OM) in the soil was determined after incinerating at 360°C (Schulte 1995).

Statistical analyses

Regression trendlines and determination coefficient (R^2) were calculated to test relationships between stem parameters and chemical components of soil. Differences in the mean parameters of stems between trees from the polluted area and reference area were estimated by the t test. Statistical calculations were performed with Excel 2003 (Microsoft Corp., USA).

Results

Soil character

Although the soils of the experimental areas had initially been of the same type, the long-term impact of dust pollution from the cement plant had caused a significant rise in the contents of the predominant elements of dust in the Gleyic Podzols on sands of the region surrounding the cement plant.

Significant variation between pH, N, P, OM, Ca, K and Mg in the soils of sample plots was established also in 2005 (Table 1). Since 1996, after the installation of effective electrofilters, a notable reduction of alkaline dust emission from the cement plant in Kunda has occurred (Fig. 1). However, significant differences between the soil layers up to 30 cm depth in the vicinity of the cement plant and in the reference area can still be observed. The results show that neutralisation of strongly alkalised soil is a long-term process. The concentrations of K, Ca and Mg, which affect the soil pH, were respectively 9–16, 7–11 and 3–7 times higher than reference site (Table 1). As compared to

Table 1 Chemical composition of soil on sample plots at different distances from the emission centre in 2005 (±SD, $n=5$)

Distance and direction from the emission centre	pH	N %	OM	P mg kg^{-1}	K	Ca	Mg
38 km W	3.84 ±0.02	0.428 ±0.081	21.35 ±1.90	71.52 ±6.88	54.0 ±2.8	850 ±51	101.6 ±9.8
3 km W	6.69 ±0.25*	1.003 ±0.125**	43.34 ±0.97**	94.24 ±4.24*	485.8 ±19.6***	7559 ±167***	341.7 ±19.7***
2.5 km E	7.86 ±0.15**	0.403 ±0.024*	15.13 ±1.42*	153.11 ±14.44**	890.9 ±45.4***	6382 ±217***	344.8 ±17.4***
5 km E	7.76 ±0.07**	1.460 ±0.105***	29.02 ±0.16	27.41 ±2.54**	506.1 ±19.4***	9436 ±128***	682.5 ±66.6***

Significance of differences between soil parameters in polluted and reference site area, mean determined by two-sided t test: $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

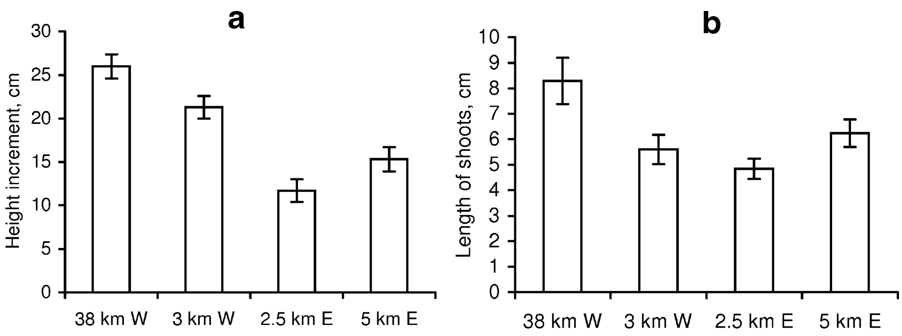


Fig. 3 Height increment of Scots pine in the last 10 years (**a**) and length growth of lateral shoots (**b**) (mean±SE) in the vicinity of Kunda cement plant and in the reference site area

earlier results, the concentrations had not changed much (Kokk 1988; Annuka 1994), which indicates that the conditions for tree growth are still extreme.

Morphological properties of trees

The high level of air pollution and serious disbalances in growth conditions have resulted in different physiological and metabolic changes in trees. Changes in carbohydrate metabolism (Mandre 1995b; Klõšeiko 2003), photosynthetic availability (Mandre and Tuulmets 1997; Mandre and Korsjukov 2002) and disbalances in the mineral composition (Mandre 1995a; Ots 2003) have influenced the growth and biomass formation of trees.

Although air pollution has diminished during the last 10 years, the 10-year average height increment of pines (Fig. 3) was inhibited in the stands in the influence zone of the cement plant with the greatest stress observed in the stand located closest to the pollution source (2.5 km E). As compared to reference site, the average length of the top shoots of pines growing in the vicinity of the cement plant was shorter: by 18% 3 km W, 55% 2.5 km E and 41% 5 km E. The current-year lateral shoots in sample plots 2.5 km E and 5 km E from the cement plant were in the lower layer of the crown 35% and in the middle part of the crown 21–55% longer than in the reference sample plot. However, in the upper layer a serious inhibition of the length of the lateral shoots was observed (about 40–53%).

It was found that analogously to the difference of the lengths of the lateral and top shoots from reference site, also important parameters of the stem were different. The proportion of sapwood in the stem was smaller than reference site in all polluted sites in

Table 2 Mean characteristics of stemwood of model trees on sample plots (±SE)

Parameter	Distance and direction from the emission centre			
	38 km W	3 km W	2.5 km E	5 km E
Diameter, cm (h 1.3 m)	25.5±0.5	25.3±0.4	27.1±0.1	25.3±0.7
Sapwood, %	75.2±5.9	65.8±4.6	50.3±7.9**	68.2±4.3
No of annual rings	33.7±0.3	42.0±2.1	46.3±3.5	43.3±0.3
Width of annual rings, mm	1.64±0.22	1.10±0.06**	0.82±0.09**	1.16±0.09**
Latewood, %	38.2±1.1	48.3±1.4**	45.0±1.3**	48.5±1.4**
Absolute density, kg m^{-3}	546±7	587±7**	539±7	581±8**
Moisture content, %	54.9±0.4	51.7±0.9	52.9±0.7	51.8±0.5
Heartwood, %	24.8±2.3	34.2±2.6	49.7±3.9	31.8±2.6
No of annual rings	28.0±2.5	26.3±1.9	32.3±2.6	31.0±2.6
Width of annual rings, mm	1.96±0.11	2.31±0.18*	2.60±0.22*	2.20±0.19*
Latewood, %	29.4±1.4	31.0±2.0	28.6±1.9	34.1±2.6*
Absolute density, kg m^{-3}	505±13	498±21	467±16	495±26
Moisture content, %	37.7±0.9	35.6±1.9	34.1±0.3	33.4±0.8

Significance of differences between stem parameters in polluted and reference site area, mean determined by two-sided *t* test: $^{*}p<0.05$, $^{**}p<0.01$

Table 3 Results of regression analysis for radial increment versus soil chemical composition in September 2005

Distance and direction from the emission centre	Soil characteristics						
	pH	N	P	OM	K	Ca	Mg
38 km W	0.400	0.773**	0.399	0.828**	0.358	0.827**	0.851**
3 km W	0.586*	0.654*	0.611*	0.857**	0.113	0.688*	0.857**
2.5 km E	0.866**	0.964**	0.003	0.996***	0.815**	0.987***	0.005
5 km E	0.624**	0.492	0.612*	0.798**	0.963***	0.505*	0.411

Significance of determination: $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

the influence zone of the cement plant. In the stand closest to the plant (2.5 km E) the width of the annual ring made up 43% of the width of the annual ring of the reference site stand, at a distance of 3 km W the proportion was 65% and 5 km E, 85% of the reference site. However, the number of annual rings in sapwood at breast height was 3 km W by 24%, 2.5 km E by 37% and 5 km E by 28% greater than reference site (Table 2). The average width of annual rings of heartwood was significantly greater than that of reference site, respectively by 34, 19 and 13%.

Although some researchers (Mäkinen 1998) argue that the relationship between the length of the top shoot and the width of the annual rings is weak, our analysis of the width of annual rings at three different heights and the growth of the top during the last 10 years revealed a very strong relationship: in the reference variant $R^2=0.95$ and in the polluted stands $R^2=0.87–0.93$).

A statistically significant increase of the latewood percentage in the polluted stands at breast height was recorded (Table 2). The sapwood of the reference site pines contained on average 38.2% latewood and in the other stands on average 45.0–48.3%; the heartwood at breast height contained 29.4% latewood in the reference site stand and 28.6–34.1% in the polluted stands.

Measurements of width of annual sapwood rings showed that as an average for the last 10 years the stand closest to the pollution source had a substantially significant differences than the reference site stand (Table 2). Regression analysis showed that the soil pH and Ca and K concentrations might have affected significantly the radial increment in the strongly polluted areas (Table 3).

In general, it should be stressed that the formation of sapwood in the stands investigated depends statistically significantly on the concentrations of N, OM, K and pH of the soil. The formation of heartwood seems to be more independent of the soil pH and the concentrations of K, Ca and N. Both the sapwood and heartwood in the stem are strongly related with P in the soil (Table 4). As a rule, lignification affects both sapwood and heartwood formation, because lignin incorporation renders plant cells mechanically rigid and water repellent (Ziegler 1997; Miidla 1989; Magel et al. 1997; Monties 1989), stop the extension of cell walls (Polle et al. 1997) and cause cessation of growth (Miidla 1984). Extremely high pH and concentrations of Ca and K in soil in the vicinity of the cement plant brought about serious changes in partitioning of mineral nutrients, carbohydrates and lignin in trees (Mandre et al. 1999; Mandre 2002). The rapid increase of K, Ca and decrease of N

Table 4 Results of regression analysis and coefficients of determination between means of parameters of stemwood and soil characteristics in September 2005

Parameter	Soil characteristics						
	pH	N	P	OM	K	Ca	Mg
Sapwood	0.512*	0.787**	0.663**	0.801**	0.647*	0.304	0.172
No of annual rings in sapwood	0.229	0.033	0.801**	0.080	0.956***	0.229	0.069
Heartwood	0.695**	0.899**	0.566*	0.162	0.945***	0.695*	0.504
Annual radial increment	0.001	0.578*	0.986***	0.222	0.051	0.007	0.104

Significance of determination: $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

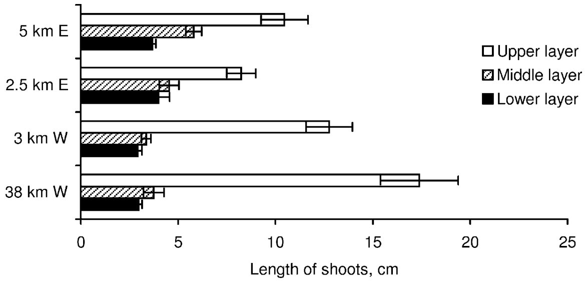


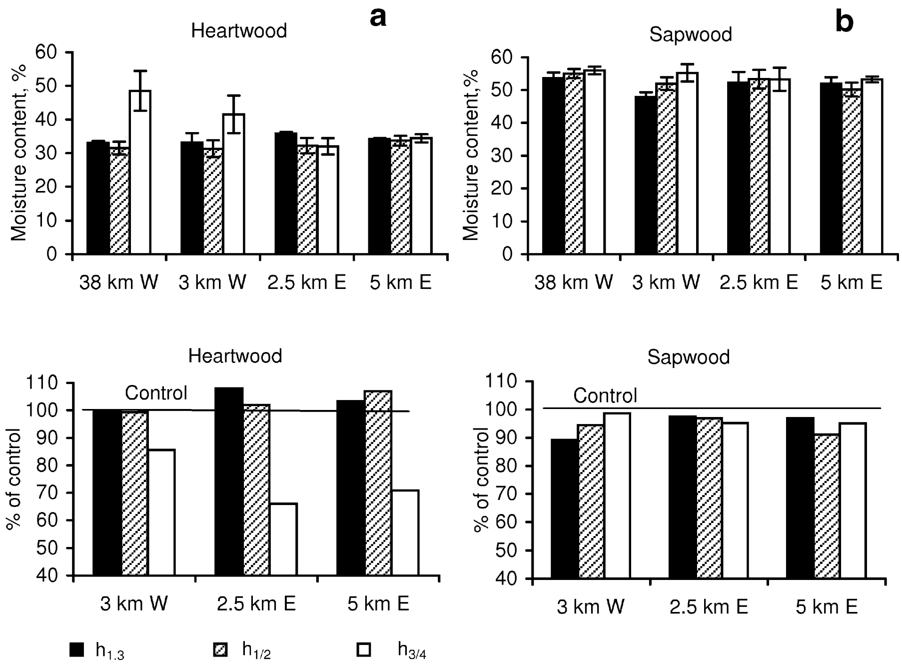
Fig. 4 Length growth of current-year shoots (mean±SE) in different layers of Scots pine crowns at different distances (km) and directions from the cement plant and in the reference site area in 2005

in trees had been showed also (Mandre 2002; Ots 2002). It has previously been reported that increase in the high K concentration stimulates the lignification processes (Miidla 1989). Hojatti and Maleki (1972, p.47) reported that K increased the methionine content in wheat and L-methionine may be a precursor of $-OCH_3$ groups by the process of methylation in lignin formation. Also, it is fairly clear, that in case of N deficiency high lignin contents may occur in plants (Matsuyama 1975; Flanagan and van Cleve 1983; Padu et al. 1989). Ca has been classified as an apoplastic element and a rise in the content of Ca in plant cell wall compartment was found to increase the activity of peroxydase (Penel 1986), favour the lignification (Heath and Castillo 1987).

Physical characteristics of stemwood

The average moisture content of sapwood measured in the stems of pines that had grown under similar climatic conditions was 52.8±0.7% and that of heartwood 35.1±0.5% in the middle of September. The moisture content of sapwood in the polluted stands was on average by 3.6 to 6.2% lower than in the reference site stand. No statistically significant differences in the heartwood moisture content were found. Some increase of moisture content in sapwood and heartwood toward the top of pines was observed in optimal growth conditions and on the sample plot with the lowest pollution level, but the differences are not statistically significant. However, the content of moisture in the heartwood of stems in the upper layer ($h_{3/4}$) from the heavily polluted sample plots (2.5 km E, 5 km E) may be about 21–29% lower than that in the upper layer of reference site trees (Fig. 4). It is understood, that long-distance water flow occurs in the sapwood. The cell walls of tracheary elements are impregnated with lignin, which impedes lateral water flow and makes the cell wall rigid (Pallardy et al. 1995; Magel et al. 1997). Increase of lignin content in needles and shoots of Norway spruce in strongly alkalised substrate was estimated (Tohver and Mandre 1995; Mandre 2002, 2005) and it is possible, that the intensive lignification in *Pinus sylvestris* might be one

Fig. 5 Dynamics of the moisture content in Scots pine stem heartwood and sapwood (mean±SD) at different heights and different distances from the emission source in September 2005



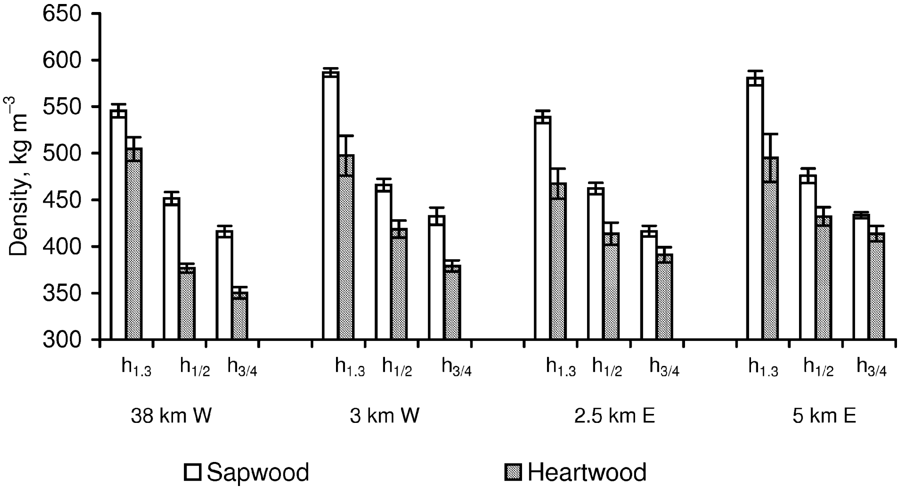


Fig. 6 Density of sapwood and heartwood of model trees on sample plots (±SE) on the different height and on the different distances from the emission source in September 2005

of the reason of shortage of moisture storage in upper layer of stems. Also the wide of sapwood areas of conifer stems are significant both for water storage and water transport (Lassoie et al. 1977). The essential decrease of width of sapwood annual rings in alkalised growth conditions if compared to unpolluted trees (Table 2) was found in present study. So the decreasing tendency of the sapwood moisture in the upper layer of stems may indicate deviations in the water regime and transport under alkaline stress conditions.

The results show that the wood density varies in different areas of the stem and depending on the growth conditions in the stands (Fig. 5). As a rule, the wood density decreases towards the top of trees. The trees growing in the areas of the highest pollution loads (2.5 and 5 km E) are characterised by the lowest absolute density of sapwood and relatively high density of heartwood in the highest part of the stem. Mostly the maximum value of sapwood density occurs at breast height for all trees (Table 2, Fig. 6). The sapwood density at the breast height level of the reference site variant was 546 kg m^{-3} and of the polluted stands 539–587 kg m^{-3}. The heartwood density at the same levels was respectively 505 kg m^{-3} and 467–498 kg m^{-3}.

Regression analysis indicated significant linear dependence (R^2) between the density of sapwood or heartwood and latewood percentage in annual rings. It can be expressed by the following regression coefficients ($p<0.05$): for sapwood: 38 km W $R^2=0.72$; 3 km W $R^2=0.85$; 2.5 km E $R^2=0.73$; 5 km E $R^2=0.67$; for heartwood: 38 km W $R^2=0.78$; 3 km W $R^2=0.82$; 2.5 km E $R^2=0.43$; 5 km E $R^2=0.80$.

Discussion

Although the soils of the experimental areas had originally been of the same type, the long-term impact of dust pollution from the cement plant had caused a significant rise in the contents of the predominant elements of dust in the Gleyic Podzols on sands of the region surrounding the cement plant. An especially high accumulation of dust components characterises the litter horizon of forests. When in a natural, unpolluted geocomplex in the reference site area the upper, 0–2 cm layer of the litter horizon contains 11% and the deeper, 3–7 cm layer about 30% of the elements contained in dust, then at a distance of 2 km to the east of the plant the respective figures are 74 and 61% (Annuka 1994).

An increase in the concentration of elements occurring in dust in the deeper layers (3–7 cm) was found even at a distance of 10 km in the direction of dominating winds. It was shown by Teras (1984, p. 15) that soils in the region affected by Kunda cement plant (1.25 km E, 3.5 km NE, 5 km E, etc.) are characterised by a high saturation degree that in some excavations reaches 100%. The increase of base saturation under dust pollution was indicated also by Farmer (1993, p. 66). The most noteworthy phenomenon is the enrichment of soil with Ca, K and Mg, which causes changes in the balance of the absorbed cations in the absorbing complex of the soil. Compared to the unpolluted reference sites territory, the amount of absorbed alkali has increased, and hydrolytic acidity of the soil has decreased (Kokk 1988). Long-term dust deposition on the surface has caused a significant increase in the soil pH value, reaching 7.6 in the humus horizon of forest soils and 8.1–8.4 in the upper horizons of the soils in the studied areas around the cement plant in 1995 (Annuka 1994). Results on the character of soil in the studied areas in 2005 did not differ from data of previous investigations.

In addition to natural environmental factors (temperature, precipitation etc.), the growth of the trees and the characteristics of the wood of the trees growing under the extreme conditions described above might be affected by disbalanced availability of nutrients and a relatively high pH of soil. The results indicated that the height growth of trees and the length of lateral shoots might be inhibited in the areas of the largest pollution loads. However, in the area where the pollution load is relatively low, the growth of lateral shoots may be stimulated, which was observed at distances over 6 km west from Kunda cement plant (Mandre 1989). Still, the average length of the top shoot during the last 10 years studied in the present work was shorter than reference site in all polluted sites studied by us. Several studies have shown that the changes in the parameters of lateral shoots are often one of the best indicators in studying the impact of industrial emissions on conifers (Huttunen et al. 1983; Mandre et al. 1994). In 1992 the lateral shoots of Scots pines in the vicinity of the cement plant on the sample plot under the prevailing winds were 2.5 times shorter than reference site (Ots and Pöör 1994; Mandre et al. 1995). It has been suggested that deviations in the moisture regime of plants due to dust pollution may even result in drought stress of plants (Flückiger et al. 1982; Farmer 1993). The inhibition of the length growth of the main and lateral shoots in the upper layers of the crown is most probably due to the disturbed moisture regime of trees in the alkalised environment, as data presented in the present work also indicate deviations in the moisture regime of the sapwood of polluted trees.

The internal content of moisture in trees is not important only for growth, but it is one of the characteristics showing wood quality, depending on season, precipitation amount and forest type (Uzunovic and Dickinson 1998; Hannrup et al. 2000; Seeling 2000; Kask et al. 2002). The prevailing opinion is that an optimal water content in a growing tree guarantees the optimal physiological activity (Miidla 1984). Alkalisation of soil is known to change the water regime in plants and does not favour several physiological processes of plants linked to photosynthesis (Lal and Ambasht 1982), carbohydrate metabolism (Iliescu 1981; Klõšeiko 2003), pigment system (Manning 1971; Mandre and Tuulmets 1997), mineral nutrition (Ludwig et al. 2002; Saarsalmi et al. 2004) etc. Changes in the biochemical processes in plant leaves have an effect also on the growth and development of other organs, including shoots growth and the formation of the stem biomass.

The radial increment as well as widths of annual rings in sapwood and heartwood may vary in trees growing in the same study area. There are very important the concentration of nutrients in soil and possibilities for mineral nutrition processes. The formation of sapwood and heartwood was found to depend on the concentration of K and P in the soil and their accumulation into the tree. As these elements are important in the lignin synthesis, changes in sapwood and heartwood formation can be related with lignification processes in the stem. These relationships are not completely understood and need further research. Generally, the mean width of an annual ring of sapwood is smaller in the polluted stands than in the reference site stand, in the most heavily polluted stand (2.5 km E) it was as much as two times smaller. The mean width of an annual ring of heartwood, on the contrary, is by 13–34% greater in the polluted stands. As heartwood formed during the period when the production of the cement plant was small and the amount of air pollutants emitted was relatively insignificant as compared to the later period, the modest amounts of cement dust rich in numerous macro- and microelements fostered tree growth. Besides the accumulation of Ca, water loss is argued to be closely correlated with heartwood formation (Hillis 1987). Later, with increasing pollution load, a decrease of moisture in stems was observed in the present study and intensive accumulation of Ca and K into different compartments of young Scots pines in the vicinity of the cement plant shown by Mandre et al. (1999, p. 212, 213) may stimulate lignification processes and heartwood formation. Although the mechanisms of Ca and K in the lignification of trees are not completely understood, both K and Ca/K were significantly correlated to lignin in shoots of trees grown at different distances from the cement plant (Mandre 2002). Also sapwood and heartwood percentages in the stem had a strong relationship with K.

Based on the level of the regression coefficient, K seems to be more important than Ca in wood formation in Scots pines growing in alkaline conditions. Ots and Rauk (1999, p. 529) observed in time of high air pollution loads a strong negative correlation of increment of Scots pine with high concentrations of K and Ca in the environment (air, soil, subsoil water).

It is noted that the sapwood/heartwood proportions are related to the following technological properties: moisture content, density, shrinkage and water vapour diffusivity (Allegretti et al. 1999). The proportion of heartwood differed at breast height and half tree height in the experimental plots. The higher the pollution load under which the tree has grown, the larger the proportion of heartwood in the cross-section. Although for the evaluation of the maturity of a forest tree the heartwood content is far better than age or size, it appears to be independent of growth rate and tree size (Kärenlampi and Riekkinen 2002). Under the conditions of pollution the maturation period of stands may start earlier. Whether this is accompanied by shortened life of trees remained unclear in the present study.

The width of annual rings is one of the criteria for wood density in young stands (Mattsson 2002). In older pines the ring width is only of limited value in assessing wood properties, whereas latewood percentage is an important criterion (Wimmer 1991; Seco and Barra 1996). Latewood fibres exhibit greater strength and stiffness than earlywood fibres irrespective of tree height or juvenility (Mott et al. 2002).

The amount of latewood depends on growth conditions and forest type (Nekrasova 1994). However, wood of similar density may contain different percentages of latewood (Zvirbul’ et al. 1976). With the ageing of trees the proportion of latewood in the annual ring usually increases. A relatively high percentage of latewood in sapwood and heartwood was characteristic of trees from the polluted stands.

Mechanical properties of wood are most strongly affected by density and amount of latewood (Wilhelmsson et al. 2002). However, the density has a weaker relationship with the width of the annual ring (Seco and Barra 1996), but it depends on the growth rate (Sipi and Rikala 2000). In a rapidly growing stem the percentage of latewood in the annual ring and wood density are smaller, fibres are shorter and have thinner walls than in a slowly growing stem (Hannrup et al. 2000; Mattsson 2002). Very often fertilisation has a negative effect on the wood density of pines (Saikku 1975; Verbyla and Šleinys 1981). Standpoints described above are valid especially for sapwood properties of pines in alkalised areas. Regression analyses showed a strong relationship between latewood and the density of sapwood or heartwood in stems of pines in sample plots.

Our results showed that alkalised growth environment and long-term dust pollution have affected the absolute density of stemwood although not significantly. The largest differences in stem density were observed between different zones of the stem both in sapwood and heartwood, being smaller in upper part of stems. Also Mattsson (2002, p. 19) noted that the variation from pith to bark is great in all wood parameters. Differences are great also in the density of middle and top logs, and in the juvenile wood and heartwood (Duchesne et al. 1997). This means that the density of wood is not constant, it depends on many external and internal factors.

Conclusions

The alkalisation of the environment and long-term emission of alkaline dust from the cement plant might have decreased the growth of top and lateral shoots and radial increment, but may stimulate the proportion of heartwood, precocious maturation and ageing of the stand, accompanied by decreasing wood moisture in the growing tree. To verify these conclusions it is necessary to identify the chemical composition of stemwood and to elucidate lignification intensity. Earlier research showed increasing lignin content in conifer needles in an alkaline growth environment, which suggests that the respective processes may intensify also in the stem. Various contradicting standpoints about the relationships of soil chemical composition and wood quality can be found in the literature. Still we can state that nutrient disbalance in the alkaline soil, shown by our studies, has a major direct impact on the growth of trees and stemwood quality. Changes in wood quality in extreme growth conditions require special attention as the problem is of great significance from the standpoint of forestry and in relation to pulping technology.

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