Eesti Maaülikool
Estonian University of Life Sciences

THE INFLUENCE OF GROWTH CONDITIONS ON PHYSICO-MECHANICAL PROPERTIES OF SCOTS PINE (*Pinus sylvestris* L.) WOOD IN ESTONIA

KASVUTINGIMUSTE MÕJU HARILIKU MÄNNI (*Pinus sylvestris* L.) PUIDU FÜÜSIKALIS-MEHAANILISTELE OMADUSTELE EESTIS

REGINO KASK

A Thesis
for applying for the degree of Doctor of Philosophy in Forestry

Väitekiri
filosoofiadoktori kraadi taotlemiseks metsanduse erialal

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According to verdict No 1 of April 16, 2015, the Doctoral Committee of the Forestry of the Estonian University of Life Sciences has accepted the thesis for the defence of the degree of Doctor of Philosophy in Forestry.

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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following papers, references to which in the text are given by Roman numerals. The papers are reproduced with the kind permission of the publishers.

I **Kask**, **R**., Pikk, J. 2009. Second thinning Scots pine wood properties in different forest site types in Estonia. – *Baltic Forestry*, 15(1): 97–104.

II **Kask**, **R**., Ots, K., Mandre, M., Pikk, J. 2008. Scots pine (*Pinus sylvestris* L.) wood properties in an alkaline air pollution environment. – *Trees – Structure and Function*, 22(6): 815–823.

III Mandre, M., **Kask**, **R**., Pikk, J., Ots, K. 2008. Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust. – *Environmental Monitoring and Assessment*, 138(1–3): 51–63.

IV Pikk, J., **Kask**, **R**., Peterson, P. 2006. The wood quality of fertilized Scots pine *(Pinus sylvestris* L.*)* stands on *Vaccinium vitis-idaea* and *Cladonia* site type. – *Forestry Studies*, 44: 9–19.

V Pikk, J., **Kask**, **R**. 2004. Mechanical properties of juvenile wood of Scots pine *(Pinus sylvestris* L.*)* on *Myrtillus* forest site type. – *Baltic Forestry*, 10(1): 72–78.

VI **Kask**, **R**., Pikk, J., Kuusepuu, T. 2002. Hariliku männi (*P. sylvestris* L.) puiduniiskus ja maltspuidu osatähtsus erinevates kasvukohatüüpides. [Scots pine (*P. sylvestris* L.) wood moisture and sapwood ratio on different forest site types]. – *Forestry Studies*, 37: 129–141. [In Estonian with English summary]

The contributions of the authors to the papers were as follows:

	Paper					
	I	II	III	IV	V	VI
Original idea	**RK**	**RK**	MM	JP	**RK**	**RK**
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Data collection	**RK**, JP	**RK**, KO, JP	**RK**, KO, JP	**RK**, JP	**RK**, JP	All
Data analysis	**RK**, JP	All	All	JP, **RK**	**RK**, JP	**RK**
Preparation of manuscript	**RK**, JP	**RK**, JP	All	All	**RK**, JP	All

JP – Jaak Pikk, KO – Katri Ots, MM – Malle Mandre, **RK – Regino Kask**, All – all authors of the paper

ABBREVIATIONS

Arw	Annual ring width
Bs	Bending strength
C	Control stands
Cs	Compression strength
Egh	End-grain hardness
F	Fertilized stands
h	Tree height
HW	Heartwood
Jm	*Oxalis-Myrtillus* site type
Kmds	Drained birch fen
Kn	*Calluna* site type
Krb	Drained raised bog
Ks	Drained swamp
Kss	Drained transitional bog
LW	Latewood
Ms	*Myrtillus* site type
NPK	Nitrogen (N), phosphorus oxide (P_2O_5), potassium oxide (K_2O)
Odd	Oven-dry density
Ph	*Rhodococcum* site type
Rb	Raised bog
Sm	*Cladonia* site type
SW	Sapwood
Tsh	Tangential surface hardness

1. INTRODUCTION

Scots pine (*Pinus sylvestris* L.) is the most widespread conifer species in the northern hemisphere with a European range stretching from the Atlantic to the Urals and from the Mediterranean to the Barents Sea (Nikolov and Helmisaari, 1992; Mason *et al.*, 2007). This species is found in all member states of the European Union, where it covers approximately 20% of the commercial forest area, and it is of considerable importance as a timber producing species particularly in the Nordic countries (Mason and Alia, 2000; Macdonald *et al.*, 2010). The primary users of coniferous roundwood are enterprises of the mechanical wood processing industry (Rikala, 2003).

The specific wood properties of Scots pine applicable for further processed end-use products, as well as their variation and the affecting factors, are neither well known and demonstrated or fully utilized in the marketing argumentation (Riekkinen *et al.*, 2005). The main problems of wood as a raw material for several end-uses are associated with large variations in a variety of properties, as well as with the hygroscopicity and anisotropy of wood material (Grekin, 2006). Pine wood tends to have large variations in quality and material properties related to silviculture and growth region (Riekkinen *et al.*, 2005).

Wood quality can be generally defined as a measure of the characteristics of wood that influence properties of products made from it (Bowyer *et al.*, 2003). As quality is described mainly through the properties of wood, the necessity for research into these properties is evident. The most important wood properties are annual ring width, wood density, proportion of latewood, heartwood and compression wood, moisture content and presence of juvenile wood, but the diameter of possible juvenile wood and internal defects (checks, pitch pockets, decay) are important as well. Wood properties affect weight, hardness, toughness and strength of wood products, among others (Rikala, 2003). In general, it has been found that wood properties depend on genetics, growing conditions and the age of a tree (Некрасова, 1994; Ojansuu and Maltamo, 1995; Wodzicki, 2001; Lindeberg, 2001; Bektas *et al.*, 2003). The quality of growing stands cannot be changed through their genotype. However, the growing conditions (thinning, fertilization and drainage) of stands can be changed and this is the main way in silviculture to improve the growth and quality of stands.

Air pollution with dust and gases had a significant impact on growing conditions in the past decades. Numerous investigations describe the damage done by acidic air pollution in forest areas in many industrial countries towards the end of the 20th century (Smith, 1990; Staaf and Tyler, 1995; Härtling and Schulz, 1998). At the same time, research into the impact of different types of alkaline air pollution on forests has failed to attract as much attention as that of acid pollution. No information is available on the effect of alkalization of the environment and of alkaline dust pollution on the structure and mechanical and physical properties of stemwood.

Forest fertilization considerably stimulates the growth of branches and needles, which is a precondition for stem wood growth. The rank growth may influence wood properties. Therefore fertilization of young stands is not advisable as it increases the diameter of branches and reduces the stem quality (Nikkola, 1985; Mäkinen and Uusvaara, 1992; Saarsalmi and Mälkonen, 2001). In addition to bigger branchiness, mechanical wood properties deteriorate and also stem rot tends to spread (Pape, 1999).

In the context of wood transformation, the concept of juvenile wood is also presented (Rikala, 2003). The indefiniteness of juvenile wood is due to the continuum of different wood properties. Juvenile wood transforms gradually into heartwood, except in the top of the tree. Because of the low density and strength of juvenile wood its presence is not acceptable in mechanical wood processing (Saranpää, 1994; Kärkkäinen, 2003; Rikala, 2003).

The rapidly changing economy, ever-modernizing wood processing technology (heat treatment, impregnation, green wood gluing, etc.), warming climate, environmental pollution, etc. create a need for constant regional research at stand, tree, macro- and micro-levels. For these reasons intensive research work in Finland (Saranpää *et al.*, 2000a; Sipi and Rikala, 2000), Latvia (Pushinskis *et al.*, 1998; Zālītis, 1999) and Sweden (Lindstrom, 1996) has been started again.

In order to evaluate the same physico-mechanical wood properties of Scots pine in Estonian forest site types and to investigate the influence of silvicultural methods and air pollution, a long-term research programme has been initiated. The current thesis primarily concentrates on the results of research on pine wood properties and summarizes the variation in the properties of wood obtained from Estonian pine forests.

2. REVIEW OF LITERATURE

2.1. Physical and mechanical properties of pine wood

Differences between the properties of Scots pine wood depending on growth site conditions have been observed for more than a century. The higher the nutrient content in the soil, the better the wood technical properties, other conditions being equal (Hartig, 1901). According to Яхонтов (1913), deterioration in soil conditions leads to decreased wood density and compression strength. Since the late 19th century, researchers have correlated wood properties with growth site index (Omeis, 1895; Schwappach, 1897; Werberg, 1930; Kõresaar, 1938). In Europe, research has focused on delving deeper into the wood properties of trees and exploring the physiological processes in wood formation (Wilhelmsson *et al.*, 2001; Aleinikovas and Grigaliūnas, 2006; Jelonek *et al.*, 2006; Mandre *et al.*, 2008).

Generally, the structure and properties of wood are affected by genetic, environmental and anthropogenic factors acting during the formation of wood cells and tissue (Larson, 1969; Olesen, 1982; Megraw, 1985; Lindström, 1997; Lindeberg, 2001; Wodzicki, 2001; Bektas *et al.,* 2003; Savidge, 2003) and differences between the levels of nutrients and other elements found in stemwood, depending on the growth site (Andrews *et al.*, 1999; Finér and Kaunisto, 2000). Wood properties derive from the relative amounts of different cell types, as well as their properties (Chaffey, 2000; Pereira *et al.*, 2003; Jyske, 2008). However, it has been ascertained that pine wood properties vary from one geographical region to another (Полубояринов и др., 2000; Mencuccini and Bonosi, 2001; Verkasalo and Leban, 2002).

The physical and mechanical properties, resistance to biological deterioration and dimensional stability of any wood-based product are all affected by the amount of wood moisture content (Veibri, 1982; Bowyer *et al.*, 2003). Moreover, the tracheids of latewood show a high sensitivity to changes in climate factors; among the climate factors, the relationship between soil water availability in the first and second half of the vegetation period is of special importance (Кузьмин и др., 2008).

The best measure of the growth conditions is annual ring width (Mäkinen, 1998). Annual ring width varies a lot within a single tree and among trees, depending on the tree age, seasonal growing conditions and site fertility as well as on available nutrient resources (Seppälä, 1976; Henttonen, 1984; Malinen *et al.*, 2005). Annual ring width is one of the criteria of wood density, modulus of rupture and modulus of elasticity in young stands (Mattsson, 2002). In older pines, annual ring width is only of limited value in predicting wood properties, whereas latewood percentage is an important criterion (Wimmer, 1991; Seco and Barra, 1996). The amount of latewood depends on growth conditions and forest type (Некрасова, 1994). Latewood tracheids exhibit greater strength and stiffness than earlywood tracheids irrespective of tree height or juvenile age (Mott *et al.*, 2002). However, wood of similar density may contain different percentages of latewood (Звирбуль и др., 1976).

In solid wood products, the proportion of heartwood is important. A high heartwood proportion is usually an advantage for the use of wood, since, for example, heartwood has good dimension stability and it is relatively resistant to decay. Heartwood proportion of pine correlates negatively with its high growth rate, high crown ratio and dominance of trees (Kärkkäinen, 1972). The possibilities of forecasting the proportions of heartwood and latewood have been checked by means of external tree characteristics. It is noted that sapwood/heartwood proportions are related to the following technological properties: moisture content, density, shrinkage and water vapour diffusivity (Allegretti *et al.*, 1999). Pine heartwood formation is regarded as a sign of maturation in silviculture. The rate of heartwood is a much better indicator to determine maturation of the tree than age and size, because heartwood appears to be independent of growth rate and size (Kärenlampi and Riekkinen, 2002). It is known that pine has more heartwood in dense stands and it decreases remarkably according to relative tree growth (Ojansuu and Maltamo, 1995). The results by Uusitalo (2004) show that heartwood starts to form when the cambium age is roughly 20 years and after that it increases by two-thirds of the year ring annually. Heartwood formation is a regulatory process serving to keep the amount of sapwood at an optimum level (Bamber, 1976). The differences between sapwood and heartwood proportion might be attributed to ecological factors such as altitude, lime and organic material content in the soil and soil type (Bektas *et al.*, 2003). Advanced tree age, slow growth rate and suppressed position have been found to correlate with high heartwood proportion (Lappi-Seppälä, 1952; Tamminen, 1962, 1964; Sellin, 1994). Environmental factors and genotype have a considerable influence on the formation of heartwood (the latter appears in critical growth conditions) (Lindeberg, 2001).

Density of wood is a prime determinant of strength, and the strength/density relationship is direct (Bowyer *et al.*, 2003). The mechanical properties of wood are most strongly affected by density and the amount of latewood (Wilhelmsson *et al.*, 2002). Although density has a weaker correlation with annual ring width (Seco and Barra, 1996; Wimmer, 1991), it is dependent on growth rate (Sipi and Rikala, 2000). In a rapidly growing stem the percentage of latewood in annual rings and the density of wood are lower and the fibres are shorter and have thinner walls than in a slowly growing stem (Матюшкина и др., 1974; Paavilainen, 1990; Hannrup *et al.*, 2000; Mattsson, 2002). The basic density of pine decreases from butt to top and increases slightly from pith to bark (Sipi and Rikala, 2000). Density variation within Nordic Scots pine stems (between inner heartwood and outer sapwood) is over two times larger in the south than in the north, and the density difference between different heights increases from the north to the south (Verkasalo *et al.*, 2005). Scientific literature (Werberg, 1930; Звирбуль и др., 1976; Kairiūkštis and Malinauskas, 2001; Mäkinen *et al.*, 2002) has verified a strong relationship between latewood percentage and wood density, a precondition for getting wood with good strength properties (Kask, 2003).

There are several silvicultural methods for intensifying wood increment in stands, the most widely used of which include expansion of tree space by stand thinning, facilitation of nutrient availability by drainage of excessively wet forestland, provision of additional nutrients by using mineral fertilizers, etc.

The best technical properties of pine wood are obtained when a stand has a density of 0.8–0.9 as thinning results in deteriorated physical and mechanical properties of wood, increased branchiness and diameter decrease (Перелыгин и Уголев, 1971). In the case of moderate and light thinning, the compressive and the bending strength of wood increase (Литаш и Рябоконь, 1984), whereas in the case of heavy thinning, the bending strength may decrease by up to 47% (Рябоконь и Литаш, 1981). According to Минин и Москалева (1986), the thinning of a 42-year-old artificial pine stand by 15–25% does not result in decreased density; on the contrary, density is even increased in tall trees. However, as thinning intensity is increased, the mean wood density falls by up to 17%.

About half a million hectares of forest land has been drained in Estonia (Estonian forests…, 1995). For this reason we now have a remarkable amount of drained swamp pine forests. An increase in growth due to drainage means a decrease in basic density and latewood proportion (Rikala, 2003). Within 20 years after drainage, other wood properties also deteriorate as a result of a sharp increase in radial increment. As increment later slowly declines, mechanical properties improve and even achieve a higher level than before drainage (Перелыгин и Уголев, 1971).

The inherent structural dynamics of drained peatland forests may result in a great variation in various wood and fibre properties. The wood formed prior to drainage has a higher density, shorter fibres, slightly slower delignification by cooking, and its yield is slightly lower than that of post-drainage wood. The properties, except high density, are typical of juvenile wood (Varhimo *et al.*, 2003).

To improve the nutritional conditions of trees fertilization of forests was started in Estonia in 1967. The effects of fertilization can be seen most clearly in bog forests, where fertilizers significantly increase the growth of trees; however, this influence is of short duration (Pikk *et al.*, 1999; Pikk *et al.*, 2001).

Studies on wood properties after fertilization have given different results. Nitrogen fertilization increases the width of the annual rings (Mäkinen and Uusvaara, 1992). The greatest influence has been spotted during the third or fourth year following fertilization; however, to a certain extent the basic density depends on the site type (Saikku, 1975; Вярбила и Шлейнис, 1981). In the Novgorod region the wood density of pine wood decreased during five years after fertilization while the annual ring width and the latewood width increased (Звирбуль и др., 1976). Fertilization of drained bog pine stands increases the latewood proportion a few percentage points (Пикк, 1988; Pikk *et al.,* 2004). Very often, fertilization has a negative effect on pine wood density (Saikku, 1975; Вярбила и Шлейнис, 1981). After fertilization, wood density may remain unchanged if the width of annual rings in a mature stand does not exceed 1.0–1.5 mm; it is only after surpassing the limit that the volume of earlywood increases, resulting in the reduction of total density (Van Lear *et al.*, 1973).

The possibility of affecting the amount of heartwood in individual trees by thinning and fertilization is limited (Mörling and Valinger, 1999; Mörling, 2002). Trees remaining when surrounding trees are removed by thinning or partial cutting respond to the more open environment by stimulated crown development and formation of a wider growth ring along the bole.

Many authors have found serious deviations in plant metabolism and physiology (Auclair, 1977; Lal and Ambasht, 1982; Mandre, 1995a,b; Klõšeiko, 2003; Skuodene, 2005) as well as in growth and productivity (Gluch, 1980; Jäger and Mörchen, 1980; Rauk, 1995; Ots, 2002) caused by alkaline dust pollution and alkalization of the environment. The effect of alkalization of the environment and of alkaline dust pollution on the structure and mechanical and physical properties of stemwood is notable.

Juvenile wood forms a little less than 10 annual rings around the spruce pith (Saranpää, 2002), but data on the pine tree are very different. Conifers usually have 5–25 annual rings of juvenile wood (Hakkila, 1979; Lindström, 2002). According to some authors, the transition period of pine juvenile wood to mature wood at cambial age takes approximately 22 years with a standard deviation of 5–7 years (Sauter *et al.*, 1999). By Saarman (1998) juvenile wood forms 10–20 annual rings nearest to the pith. In recent years problems due to the properties of juvenile wood and its superfluity in the stem have become evident (Arlinger and Wilhelmsson, 1999; Larson *et al.*, 2001; Jayawickrama, 2001).

In juvenile wood, tracheids are generally shorter with thinner cell walls, higher microfibril angle, smaller lumen diameters, lower strength, increased longitudinal shrinkage and a lower cellulose to lignin ratio than in mature wood (Olesen, 1977; Romberger *et al.*, 1993; Saranpää *et al.*, 2000b; Burdon *et al.*, 2004; Jyske, 2008). A very large part of juvenile wood is not suitable as a building material (Saarman, 1998). Juvenile wood may cause some difficulties in using Scots pine wood, but these are not that severe compared to some other species (Grekin, 2006).

2.2. Research needs

The main objective of the current study was to develop a better understanding of some of the physical and mechanical properties of pine wood in different growing conditions. Understanding the effects of growth conditions on pine wood properties is greatly needed. Additionally, material with different properties can be obtained from the same stem, and the same wood can be of different value for different users.

Information on the large radial and longitudinal variation in the properties of wood as a raw material in tree trunk and between trees and stands is essential for foresters and wood industries. Year by year, both wood supply and demand, primarily for high-quality pine timber, are increasing. Yet recorded data concerning the quality and properties of tree species in Estonia are extremely scarce and at times controversial.

On the other hand, the increasing and changing anthropogenic impact is reflected in wood formation and quality. Active forest management influences the growth conditions of stands. The effect of the conditions on the physico-mechanical properties of wood and its duration are not clear and research results often vary on a large scale. Scientific papers present different positions on the formation of wood properties after stand thinning, drainage and fertilization. Regarding environmental pollution, the influence of alkaline dust pollution on forests and wood growth is visible around plants and pits.

The use of pine wood in the construction and woodworking industries is complicated due to the physico-mechanical characteristics of juvenile wood. There are relatively little data on the raw material made of pole timber, but as the number of consumers has increased, there is a growing interest in it.

3. AIMS OF THE STUDY

The objective of this thesis is to concentrate the results of pine wood research in Estonia and to analyse pine wood properties in relation to growth conditions in different natural forest site types and in human-made growth conditions. Wood moisture content, density, annual ring width, latewood percentage, heartwood percentage, sapwood age, bending strength, compression strength and hardness were studied.

In this doctoral thesis, the studies dealing with pine wood properties are a continuation of the MSc thesis completed in 2003 (Kask, 2003).

The main hypotheses of the studies were:

– technical properties of Scots pine wood are the best in fertile forest site types;
– the influence of silvicultural treatments on the technical properties of Scots pine is variable;
– alkaline dust pollution affects negatively the physical and mechanical properties of Scots pine wood.

The specific aims of the studies were:

– to determine the variations in some physical and mechanical properties of the wood of Scots pine growing on pine-dominated forest site types (**I**, **IV**, **V**, **VI**);
– to study the radial and longitudinal variation in some wood properties in pine stems (**I**, **V**, **VI**);
– to evaluate the differences between the properties of juvenile wood of pine stem (**V**);
– to find out the influence of some silvicultural treatments (drainage, fertilization) on the formation of pine wood properties (**I**, **IV**);
– to determine the influence of long-term alkaline dust pollution on wood properties (**II**, **III**).

4. MATERIALS AND METHODS

4.1. Study areas

The study comprises 41 pine stands on the most widespread types of pine sites in Estonia (Fig. 1). These stands represent 73.1% of the sites suitable for pine. Among these *Rhodococcum* and *Myrtillus* site types are the most widespread in Estonia, comprising 40.9% (Yearbook Forest, 2010) of the pine-dominated forest land. The existing classification of Estonian forests includes a total of 22 forest site types (Lõhmus, 1984). According to this classification, each site type has as many subtypes as it has neighbouring site types (Lõhmus, 1995).

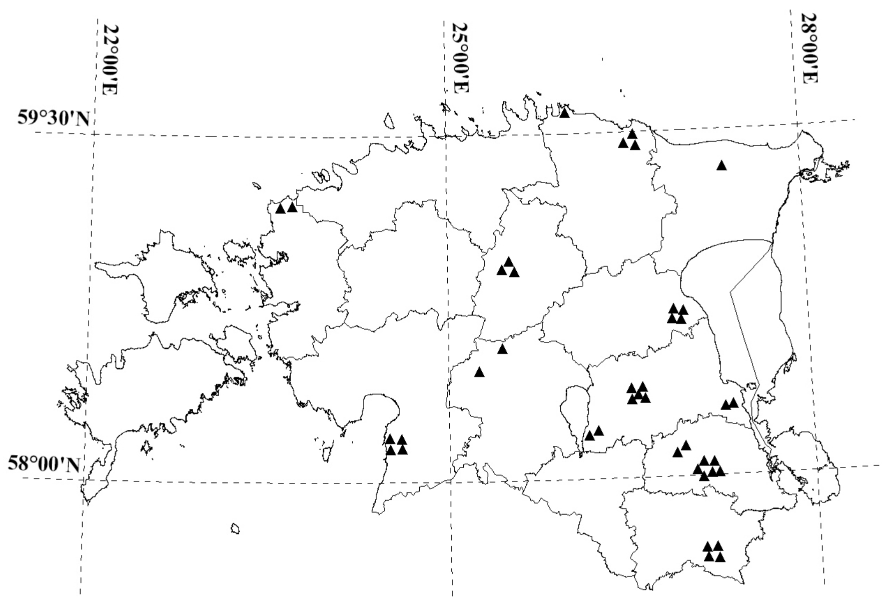

Figure 1. Location of the studied stands.

In each of the 41 stands (Table 1) selected, 6–10 sample trees were felled. More trees were felled in less thinned stands. According to Saladis and Aleinikovas (2004), no less than six trees must be examined in a single forest stand in order to obtain wood properties with 10% accuracy. Eight stands had been fertilized once with NPK and twice with N about 25–30 years ago.

Table 1. Location and characteristics of the studied stands and analysed stand types. Jm – *Oxalis-Myrtillus* site type; Kmds – drained birch fen; Kn – *Calluna* site type; Krb – drained raised bog; Ks – drained swamp; Kss – drained transitional bog; Ms – *Myrtillus* site type; Ph – *Rhodococcum* site type; Rb – raised bog; Sm – *Cladonia* site type; 1 – site type; 2 – fertilized stands; 3 – fertilized control stands; 4 – drained stands; 5 – drained control stands; 6 – polluted stands; 7 – polluted control stands.

Stand	Site type	Site index	Sample trees	Analysed stand types						
				1	2	3	4	5	6	7
Ahtme	Ms	1	6	*						
Järvselja I	Ms	1	6	*		*				
Järvselja II	Ms	1	6		*					
Kaansoo	Kss	4	6	*						
Kabala	Ks	3	6	*						
Konguta I	Ms	1	10	*						
Konguta II	Ms	1	6	*						
Kubja	Ms	1	8	*						
Kubja	Sm	3	6	*						
Kubja II	Sm	3	Cores		*					
Kubja II	Sm	3	Cores			*				
Kubja III	Ph	2	Cores		*					
Kubja III	Ph	2	Cores			*				
Lontova	Jm	2	3						*	
Malla	Jm	2	3						*	
Misso I	Ph	1	6	*						
Misso II	Ph	2	6	*						
Nõva	Sm	4	6	*						
Nõva	Kn	4	6	*						
Revoja	Jm	2	3							*
Saare I	Ms	2	6	*		*				
Saare II	Ms	2	6		*					
Saare III	Sm	5	Cores		*					
Saare III	Sm	5	Cores			*				
Sõmerpalu I	Ph	2	10	*						
Sõmerpalu II	Ph	1	6	*						
Surju I	Ph	3	6	*						
Surju I	Rb	5	10	*						
Surju II	Ph	2	6	*						
Surju II	Kss	4	6	*						
Tähtvere I	Krb	5	6	*		*	*			
Tähtvere I	Krb	5	6		*					
Tähtvere II	Krb	5.3	6	*		*	*			
Tähtvere II	Krb	5.3	6		*					
Tähtvere III	Rb	5.5	6	*		*		*		
Toolse	Jm	2	3						*	
Väätsa	Ms	2	6	*						
Väätsa I	Kss	3	6	*						
Väätsa II	Kmds	4	8	*						
Vastseliina IV	Ph	0.5	Cores			*				
Vastseliina IV	Ph	0.5	Cores		*					

To assess the influence of air pollution on wood properties, a study was performed in a territory affected for over 135 years by a cement plant in Kunda, NE Estonia. Three sample trees were felled in four stands (3 km west, 2.5 and 5 km east of the cement plant and as control, 38 km west of the emission source).

4.2. Field and laboratory measurements

For sampling the selected trees the methods suggested in ISO 4471 (1982) were used. Sample blocks for determining wood properties were cut at a height of 1.3 m ($h_{1.3}$ – breast height), at half tree height ($h_{1/2}$) and at three-quarters of tree height ($h_{3/4}$); these stem sections roughly represent the butt log, the second log and the pulpwood, respectively. The length of the stem, crown size, diameter at $h_{1.3}$, at quarter of tree height ($h_{1/4}$), $h_{1/2}$ and $h_{3/4}$ and the annual height increment of the last 10 years were measured.

The following properties were subjected to study: annual ring width, latewood proportion, heartwood proportion, oven-dry density, bending strength, modulus of elasticity, compression strength and end-grain hardness.

The image analysis system WinDENDRO™ (Ver. 2002a, Regent Instruments Inc., Quebec, Canada) was used to measure annual ring widths and latewood proportions. Annual ring widths were measured with an accuracy of 0.01 mm. Heartwood percentage was determined as a proportion of the cross-sectional area at various heights in a tree and as a proportion of its volume in stem.

To measure the moisture content and the oven-dry density of pine stemwood, 7360 specimens (cross-section 20 mm × 20 mm and height 30 mm) from different stem heights were prepared in compliance with the requirements of ISO 3130 (1975) and ISO 3131 (1975). This method yielded 41 to 45 sample specimens per tree with respect to the heartwood cross-section area at tree height $h_{3/4}$. The oven-dry density for each specimen was determined after a constant weight was achieved at 103 °C. A total of 7360 specimens were prepared for determining the static tangential bending strength test and the modulus of elasticity test perpendicular to grain and 7360 specimens for the compression parallel to grain. The specimens from sapwood did not include wood from the five latest annual rings and heartwood specimens did not include two rings nearest to the pith. Every set of specimens used for testing density, bending and compression strength was obtained from the same preliminary material with a cross-section of 20 mm × 20 mm. Additionally, annual ring widths were measured and latewood percentage was calculated for every specimen used to determine density, compression strength and bending strength. To determine the surface hardness, 606 tests were conducted in three directions (radial, tangential and longitudinal).

Experiments for determining mechanical properties were prepared and performed in conformity with ISO standards 3129 (1975), 3133 (1975), 3349 (1975), 3350 (1975) and 3787 (1976). All mechanical tests were conducted using the electromechanical testing systems INSTRON 3369 (Instron Corp., Norwood, MA, USA).

The bending test was made using four points for pressure. The sample size for testing surface hardness was restricted to include a test point of rings situated on the edge of the sample. In testing at the INSTRON load cell capacity of 50 kN and testing speed of 1350±150 N/min (bending strength), 3–6 mm/min (static hardness) and 25000±5000 N/min (compression strength) were used according to ISO standards.

A total of 4416 experiments were performed to establish the end-grain hardness. The mechanical testing took place at the wood moisture content of 8±0.5%. All the mechanical properties in the present thesis were adjusted to a 12% wood moisture level τ_{12} using the following equation (Михайличенко и Садовничий, 1983):

$$\tau_{12} = \tau_w[1 + \alpha(W - 12)],$$

where W is the moisture content of the specimen, τ_w is the specimen's modulus of rupture on the test machine and α is the coefficient for 1% moisture difference ($\alpha = 0.04$ for bending and compression strength and $\alpha = 0.03$ for end-grain hardness).

Weighted average strength indicators for each stand at three different heights and thereafter strength indicators were found for all the stemwood. For each site type, the vertical reduction of tree trunk strength properties was calculated in percentages.

4.3. Statistical analyses

A two-way analysis of variance (ANOVA) was computed with the PROC GLM method (Cody and Smith, 2006) with the statistical analysis software SAS (Ver. 9.1, SAS Institute Inc., Cary, NC, USA). Differences in average wood properties between the site types were estimated using one-way ANOVA. The critical p-value was 0.05. Statistical calculations were performed in Excel (Microsoft Corp., USA). Regression trendlines and determination coefficients (R^2) were calculated to test relationships between wood density and site index.

The significance of differences between stem parameters in the polluted areas and the control area were determined by the two-sided t-test: * $p < 0.05$, ** $p < 0.01$.

5. RESULTS

5.1. Wood moisture content (VI)

Within the same stand, mean model trees exhibited a greater variation in wood moisture content in the higher part of the stem compared to breast height. Wood moisture content varied in the crown area rather than by site. The moisture content was considerably lower in freshly felled wood in *Rhodococcum* and *Myrtillus* site types than in the wood cut at the same time in peatland forests.

In *Rhodococcum* and *Myrtillus* site types, heartwood moisture content at breast height and half tree height was 35%, whereas at $h_{3/4}$ the moisture content was significantly higher, reaching 48%. On peatlands, heartwood moisture content was higher by 9% already at $h_{1/2}$ compared to breast height and it continued to rise toward the tree top.

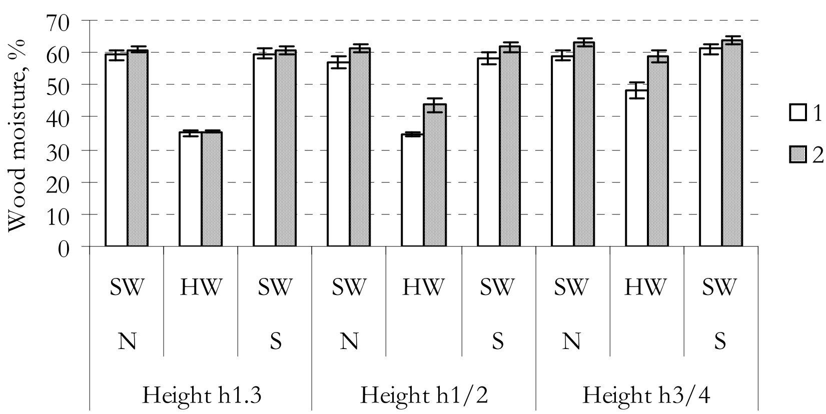

Figure 2. Moisture content (mean ± standard error) of pine wood in different parts of the tree growing on *Rhodococcum* and *Myrtillus* site types (1) and on peatlands (2). h1.3 – samples from a height of 1.3 m (breast height), h1/2 – samples from half tree height, h3/4 – samples from 3/4 of tree height, SW – sapwood, HW – heartwood, N – north, S – south.

Sapwood moisture content increased slightly from breast height toward $h_{1/2}$, not exceeding 58–62%, but rose considerably toward the top. Variation in the mean moisture content was unnoticeable on the north and south sides of the stem up to $h_{1/2}$. At $h_{3/4}$ the sapwood from the south side of trees in

Rhodococcum and *Myrtillus* site types contained 3.3% and on peatlands 1.4% more moisture than the sapwood from the north side (Fig. 2).

5.2. Sapwood and heartwood proportion (VI)

Depending on the site type and site index, the sapwood proportion in the stem cross-section varied toward the top in pine forests (Fig. 3). In many cases, especially in drained stands, trees lacked heartwood at the height of $h_{3/4}$. Results from all the experimental objects showed that the sapwood proportion was higher in younger stands; the correlation with age was moderate to medium (r = –0.4 to –0.53). In these stands, the best results were gained from model trees growing in *Rhodococcum* and *Myrtillus* site types.

A strong positive correlation between stand site index and the sapwood proportion was determined at breast height and $h_{1/2}$ with r = 0.80 and r = 0.83, respectively. At $h_{3/4}$, the correlation was noticeable (r = 0.65).

By site types, the weighted average volume of heartwood constituted 7.1–25.2% (Table 2).

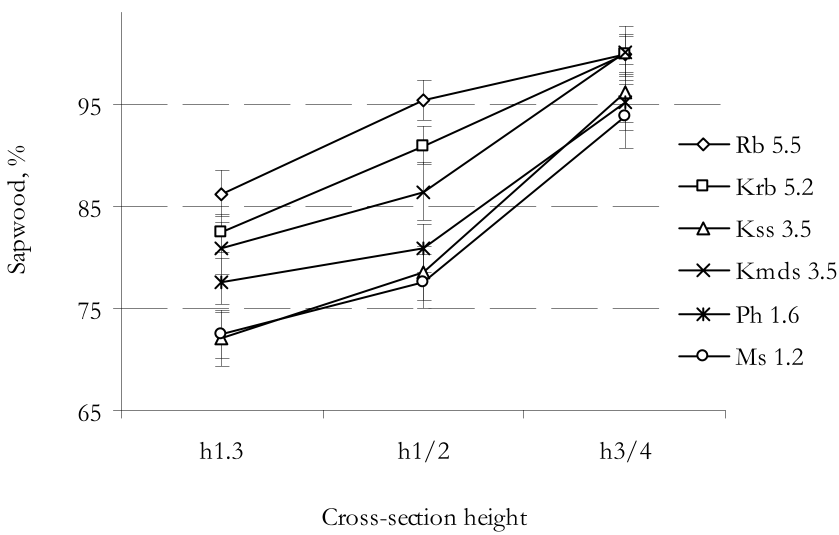

Figure 3. Sapwood proportion of pine stands at different cross-section heights depending on the site type and site index. Bars indicate standard error. Rb – raised bog, Krb – drained raised bog, Kss – drained transitional bog, Kmds – drained birch fen, Ph – *Rhodococcum* site type, Ms – *Myrtillus* site type, h1.3 – samples from the height of 1.3 m, h1/2 – samples from half tree height, h3/4 – samples from ¾ of tree height.

Table 2. Pine stem average strength properties and heartwood proportion (mean ± standard error) by different forest site types. Ms – *Myrtillus* site type, Krb – drained raised bog, Ph – *Rhodococcum* site type*,* Sm – *Cladonia* site type, Rb – raised bog, Kmds – drained birch fen, Kn – *Calluna* site type, Ks – drained swamp, Kss – drained transitional bog, Arw – annual ring width, Bs – bending strength, Cs – compression strength, Egh – end-grain hardness, HW – heartwood, LW – latewood, Odd – oven-dry density.

Site type	Site index	Stem average						
		Odd, kg/m^3	Bs, MPa	Cs, MPa	Egh, MPa	Arw, mm	LW, %	HW, %
Sm	3.5	513 ±10	100.2 ±2.3	54.7 ±0.9	37.2 ±1.5	1.15 ±0.05	33.9 ±1.2	17.2 ±3.8
Kn	4.0	545 ±12	97.1 ±4.1	55.7 ±1.7	36.9 ±1.7	1.42 ±0.06	35.8 ±1.1	14.3 ±2.1
Ph	1.6	479 ±14	86.9 ±4.3	56.4 ±2.8	27.1 ±1.0	1.71 ±0.08	31.9 ±1.4	17.3 ±3.2
Ms	1.4	482 ±15	89.1 ±4.4	54.8 ±3.0	29.7 ±0.9	1.92 ±0.08	32.8 ±1.5	25.2 ±4.3
Ks	3.3	464 ±12	80.2 ±3.0	49.8 ±1.5	31.9 ±1.1	1.70 ±0.05	35.5 ±1.0	21.5 ±1.7
Kmds	3.7	446 ±15	79.3 ±4.5	48.7 ±2.3	34.2 ±1.5	1.65 ±0.09	35.9 ±2.0	13.2 ±2.1
Kss	3.6	447 ±11	83.2 ±3.7	44.5 ±1.2	35.2 ±1.1	1.54 ±0.12	34.5 ±1.1	17.4 ±1.9
Krb	5.2	450 ±8	77.7 ±2.0	52.1 ±1.1	34.7 ±1.4	1.62 ±0.06	31.3 ±0.9	10.7 ±1.7
Rb	5.3	414 ±13	71.6 ±3.4	41.4 ±1.8	33.7 ±1.6	1.54 ±0.06	27.0 ±1.1	7.1 ±1.6
Variation, %		8.4	10.9	10.3	9.9	13.5	8.6	34.1
ANOVA *p*-value		<0.0001	<0.0001	<0.0001	0.0025	<0.0001	<0.0001	<0.0001

In bog sites, the cross-sectional sapwood area correlated relatively weakly with crown volume (r = 0.37 at breast height, r = 0.51 at $h_{1/2}$). The correlation proved moderate in *Rhodococcum* and *Myrtillus* site types.

5.3. Strength indicators (I)

The weighted average stem strength indicators of the pine stands researched at three different heights were widely divergent (Table 3). On tree level the annual ring width increased but all the strength indicators decreased towards the crown. The decrease was significantly more intensive from breast height to half tree height than to ¾ of tree height. The correlation between the strength indicators was very strong (r = 0.85–1.00). A significant correlation between oven-dry density of wood at breast height and site index was found (Fig. 4).

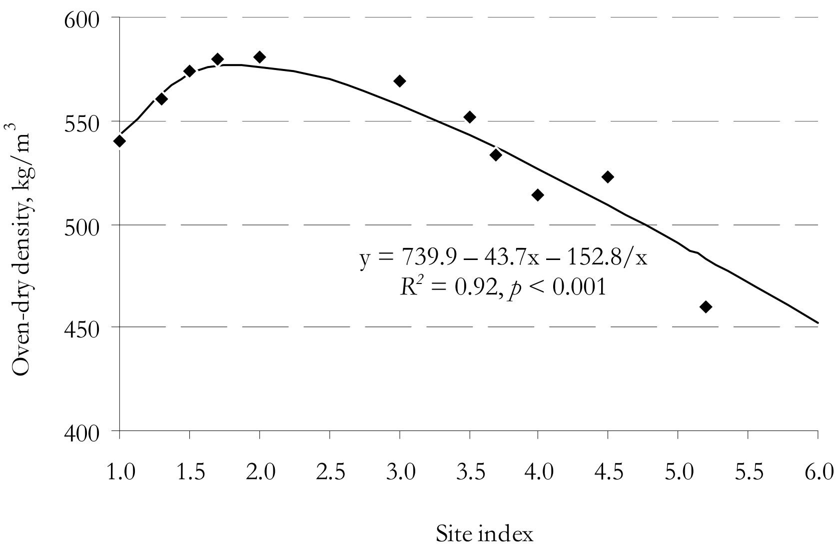

Figure 4. Oven-dry density of pine wood at breast height in different site index classes.

The pine latewood proportion at breast height was 30–43%. At half tree stem height the proportion of latewood was significantly smaller, 22–33%, and at three-quarters of tree stem height there was even less latewood, 18–32%. The weighted average values are given in Table 3.

Table 3. Average wood properties at three stem heights and their alteration towards the top (%). Arw – annual ring width, Bs – bending strength, Cs – compression strength, Egh – end-grain hardness, HW – heartwood, LW – latewood, Odd – oven-dry density, $h_{1.3}$ – samples from a height of 1.3 m, $h_{1/2}$ – samples from half tree height, $h_{3/4}$ – samples from ¾ of tree height.

Relative height	Arw, mm	LW, %	HW, %	Odd, kg/m^3	Bs, MPa	Cs, MPa	Egh, MPa
$h_{1.3}$	1.3	40.5	46.4	540.8	104.1	60.2	40.9
$h_{1/2}$	1.9	31.8	19.7	458.2	82.0	50.1	35.9
$h_{3/4}$	2.4	27.7	4.4	434.6	71.8	45.0	34.5
Alteration, %							
$h_{1.3} – h_{1/2}$	44.1	–21.5	–25.4	–15.3	–21.2	–16.7	–12.3
$h_{1/2} – h_{3/4}$	22.3	–12.8	–77.8	–5.2	–12.5	–10.1	–3.7

Stands growing on fresh and dry soils showed good averages for stem strength indicators. The same indicators, however, were poor for trees growing in swamps and bogs (Table 2).

Variations in strength indicators between the site types were notable. As could be expected, they were greater in annual ring width and heartwood proportion. As for the other properties, the variations remained within the range of 8.4–10.9%.

In our research Scots pine wood was the strongest growing on heath and the weakest on raised bogs, its average density being 513–545 kg/m^3 and 414–464 kg/m^3, bending strength 97–100 MPa and 71–83 MPa and compression strength 55–56 MPa and 41–52 MPa, respectively.

The relation between the longitudinal decrease of bending and compression strength and site index is quite variable. The relation is weak between the decrease of hardness and site index (Fig. 5).

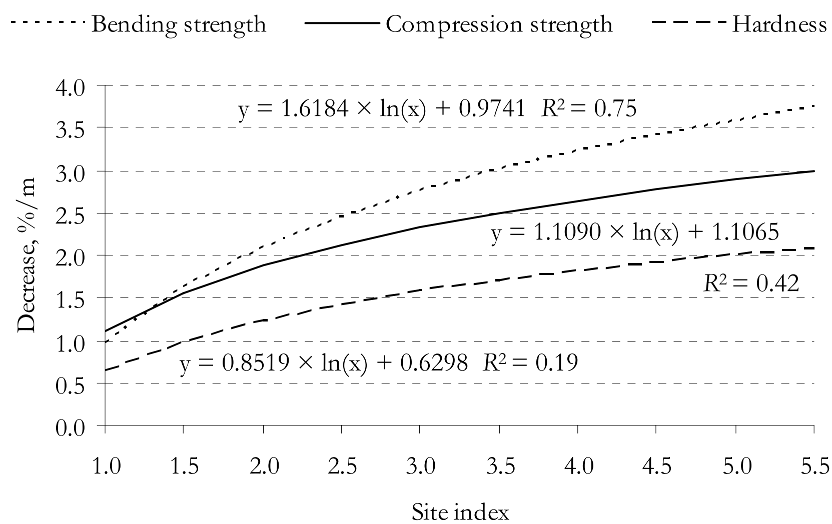

Figure 5. Longitudinal percent-per-metre decrease of strength properties in different site index classes.

5.4. Influence of silvicultural treatments (IV)

The effect of fertilization on stand parameters, i.e. tree diameter and height, stand productivity etc., and on their variability during the stand growth is obvious. Thinning intensity on experimental plots has been limited to felling dead trees and light thinning (10–16%) only. So the stands have generally had a high stand density (0.65–0.95), which was also observed during the last measurement. There is an exceptional pine stand on *Cladonia* site type with low soil fertility where the thinning of the control stand was 30% and of the fertilized stand 43.6%.

During the experimental period the productivity of the fertilized stands of the three experimental areas was higher compared to the control stands. The length of live crowns in fertilized experimental areas was higher than in unfertilized areas, but this difference is not statistically significant.

Table 4. Internal characteristics of pine wood at breast height (mean ± standard error) in control (C) and fertilized (F) stands. Ms – *Myrtillus* site type, Krb – drained raised bog, Ph – *Rhodococcum* site type, Sm – *Cladonia* site type.

Stand and site type	Variant	Number of annual rings in sapwood	Annual ring width in sapwood, mm	Heartwood, %	Latewood of experiment period, %
Vastseliina 4 Ph	C	49.8±0.8	0.95±0.04	53.7±0.9	40.5±0.6
	F	48.0±1.0	1.03±0.05	49.1±0.9*	38.1±0.5*
Kubja 3 Sm	C	40.0±1.9	1.30±0.05	53.1±2.1	40.1±0.8
	F	39.5±1.4	1.36±0.11	55.9±3.8	39.3±0.9
Kubja 2 Ph	C	41.8±1.3	1.08±0.06	52.9±1.9	37.2±0.5
	F	43.4±1.2	1.17±0.07	46.4±2.5*	38.2±0.6
Saare 3 Sm	C	28.9±0.4	1.69±0.06	22.0±0.5	37.1±0.6
	F	29.6±0.4	1.77±0.05	22.5±0.5	39.5±0.5*
Tähtvere 1 Krb	C	39.0±2.6	1.10±0.05	19.6±2.9	37.1±0.9
	F	37.3±4.1	1.22±0.06	24.0±6.5	34.5±1.0
Tähtvere 2 Krb	C	33.7±1.8	1.26±0.04	12.7±2.0	37.0±0.8
	F	32.7±2.0	1.25±0.05	14.3±2.2	38.6±1.0
Järvselja 1 Ms	C	42.8±4.1	1.14±0.05	36.9±2.9	45.0±1.0
	F	42.7±1.2	1.15±0.06	37.8±2.2	46.6±0.9
Saare 2 Ms	C	49.5±3.8	0.98±0.06	35.2±3.4	41.7±0.8
	F	45.3±3.0	0.96±0.08	38.3±3.0	42.7±0.7

*difference from control ($p<0.05$)

Trees from younger stands had fewer annual rings in their sapwood at breast height (28.9–49.8) than older stands (Table 4). A moderate correlation was registered ($r = 0.45–0.55$). Higher-quality sites evidenced more annual rings in sapwood.

The study of the width of annual rings after fertilization showed a small decrease in latewood at breast height (Table 4), and thus, a decrease in wood density can be inferred during those years. As the following periods showed the opposite tendencies in growth, this phenomenon is of little importance. The consideration is based on the fact that wood grown after the beginning of the experiment (>30 years) has a lower latewood percentage after fertilization only in two experimental areas.

The heartwood proportion of repeatedly fertilized stands decreased in the breast height cross-section of the stems only in two cases. The difference remained within the limits of relative error in other experimental areas. Fertilization significantly increased wood density in two cases (Table 5).

Table 5. Sapwood density, kg/m^3 (mean ± standard error) at different heights of control (C) and fertilized (F) stands. $h_{1.3}$ – samples from a height of 1.3 m, $h_{1/2}$ – samples from half tree height, $h_{3/4}$ – samples from 3/4 of tree height, Ms – *Myrtillus* site type, Krb – drained raised bog, Rb – raised bog.

Stand	Site type	Height $h_{1.3}$		Height $h_{1/2}$		Height $h_{3/4}$	
		C	F	C	F	C	F
Järvselja 1	Ms	601 ±7	610 ±7	484 ±5	467 ±7	433 ±4	422 ±6
Saare 2	Ms	585 ±5	603 ±7*	476 ±4	488 ±7	432 ±5	423 ±4
Tähtvere 1	Krb	495 ±5	490 ±13	438 ±4	460 ±10*	411 ±5	415 ±8
Tähtvere 2	Krb	581 ±11	576 ±8	459 ±5	475 ±10	420 ±7	415 ±9
Tähtvere 3	Rb	489 ±12		438 ±6		399 ±4	

*difference from control ($p<0.05$)

Table 6. Wood bending strength and hardness (mean ± standard error) in different parts of the stem depending on fertilization in a natural, drained and intensively drained bog site (Pikk and Kask, 2004). $h_{1.3}$ – samples from a height of 1.3 m, $h_{1/2}$ – samples from half tree height, $h_{3/4}$ – samples from 3/4 of tree height, C – control stand, F – fertilized stand, HW – heartwood, SW – sapwood.

Stand and drainage	Variant	Height $h_{1.3}$		Height $h_{1/2}$		Height $h_{3/4}$	
		SW	HW	SW	HW	SW	HW
Bending strength (MPa)							
Tähtvere 1 Intensive	C	88.6 ±5.9	74.4 ±3.6	76.9 ±1.8	57.4 ±2.1	58.0 ±3.2	52.9 ±0.0
	F	83.8 ±5.8	70.4 ±3.4	71.2 ±3.8	62.0 ±2.3	53.7 ±4.5	
Tähtvere 2 Normal	C	96.8 ±4.9	77.6 ±5.4	75.5 ±5.3	54.7 ±2.2	53.7 ±3.8	
	F	94.2 ±3.2	73.3 ±2.5	72.4 ±5.2	52.1 ±2.6	55.6 ±4.6	
Tähtvere 3 Undrained	C	87.5 ±4.8	74.5 ±3.9	70.0 ±4.4	55.9 ±3.4	53.2 ±4.6	
End-grain hardness (MPa)							
Tähtvere 1 Intensive	C	34.2 ±0.7	33.3 ±0.7	34.0 ±0.9	33.2 ±0.7	33.9 ±1.0	28.8 ±0.7
	F	36.7 ±1.7	34.5 ±1.1	37.0 ±1.3	31.8 ±1.4	36.9 ±2.0	28.6 ±0.7
Tähtvere 2 Normal	C	39.5 ±1.0	34.4 ±1.2	33.9 ±0.8	27.4 ±0.9	30.9 ±1.6	27.5 ±1.2
	F	37.6 ±1.2	37.2 ±1.7	33.9 ±1.2	27.6 ±1.3	33.2 ±1.3	28.9 ±1.5
Tähtvere 3 Undrained	C	34.2 ±1.5	33.6 ±1.1	32.2 ±1.1	30.4 ±0.7	32.9 ±0.9	32.0 ±1.0

Fertilization did not significantly affect bending strength and end-grain hardness (Table 6).

Fertilization may result in an up to 6% decrease in compression strength. According to earlier research, a very strong correlation can be found between wood density and compression strength in *Rhodococcum* and *Myrtillus* site types (r = 0.95) (Kask, 2003), whereas only a strong correlation was detected in drained bog site types (R^2 = 0.77) (Pikk *et al.*, 2004) (Fig. 6).

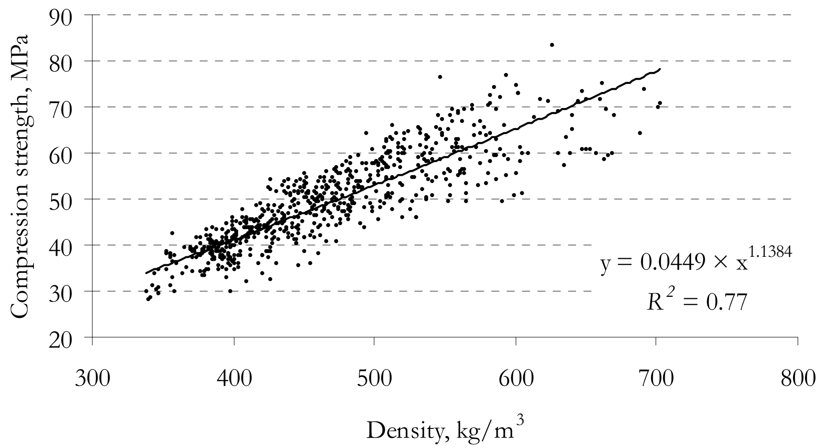

Figure 6. Relationship between density and compression strength in pine stands on drained bogs.

There are notable differences in the relation of bending strength with the intensity of forest drainage at three-quarters of tree height. However, pine wood hardness showed little difference (Fig. 7).

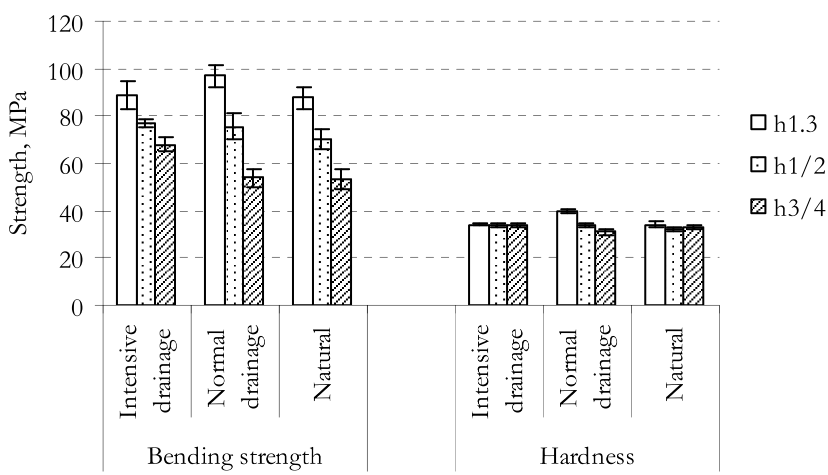

Figure 7. Bending strength and end-grain hardness (mean ± standard error) at different heights of the tree stem in drained and in natural (virginal) bog pine stands. h1.3 – samples from a height of 1.3 m, h1/2 – samples from half tree height, h3/4 – samples from 3/4 of tree height.

5.5. Influence of dust pollution (II, III)

The important parameters of the stemwood of polluted stands were found to be different. Some increase in the moisture content of 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 ($h_{3/4}$) of pines in the heavily polluted sample plots (2.5 and 5 km E of the main pollution source, the cement plant at Kunda) may be about 21–29% lower than that in the upper layer of control trees (38 km W, in the territory of Lahemaa National Park).

The dynamics of the mean annual ring width of different stands are variable (Fig. 8). In the stand closest to the cement plant (2.5 km) the annual ring width in sapwood at breast height ($h_{1.3}$) was 50% of that for the control stand, 68% in the stand 3 km to the west of the plant and 70% in the stand 5 km to the east (Table 7). In contrast, the means for heartwood annual ring widths in the polluted stands proved to be considerably greater than the corresponding mean for the control stand (by 26%, 12% and 4%, respectively).

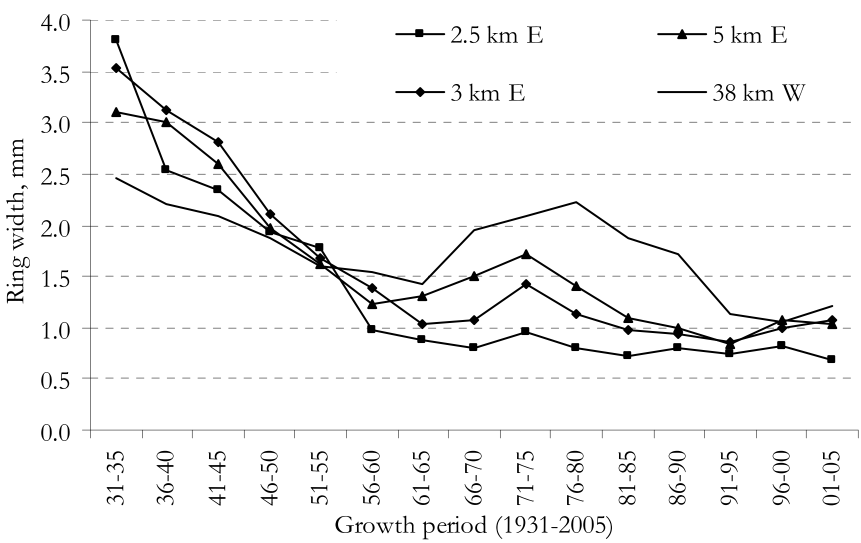

Figure 8. Dynamics of the mean annual ring width in different stands at different distances (km) and directions from the cement plant.

Table 7. Physical properties and hardness (mean ± standard error) of wood in different stands at breast height and at different distances from the emission source. Arw – annual ring width, Egh – end-grain hardness, LW – latewood, SW – sapwood, Odd – oven-dry density, Tsh – tangential surface hardness.

Characteristic	38 km W	3 km W	2.5 km E	5 km E	*p*-value
Sapwood					
SW, %	75.4 ±5.8	66.1 ±4.3	50.5 ±7.7**	67.9 ±4.5	<0.0001
Arw, mm	1.69 ±0.06	1.14 ±0.06**	0.84 ±0.05**	1.19 ±0.06**	<0.0001
LW,%	38.0 ±0.7	47.9 ±0.7**	44.7 ±0.6**	48.1 ±0.6**	<0.0001
Odd, kg/m^3	545±5	586 ±6**	536 ±5	583 ±5**	<0.0001
Egh, MPa	33.1 ±0.6	36.2 ±0.7**	32.9 ±0.7	36.5 ±0.7**	<0.0001
Tsh, MPa	30.2 ±1.1	28.5 ±1.9	30.6 ±1.2	33.2 ±2.1	0.2865
Heartwood					
Arw, mm	1.98 ±0.15	2.21 ±0.13**	2.49 ±0.13*	2.06 ±0.14*	<0.0001
LW, %	30.5 ±1.4	32.3 ±1.3	30.2 ±1.2	33.2 ±1.2*	0.0493

*difference from control, $p < 0.05$
**difference from control, $p < 0.01$

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 control (Table 2 in III).

The sapwood of the control pines contained on average 38.2% latewood; the average in the other stands was 45.0–48.3%. The heartwood at breast height contained 29.4% latewood in the control stand and 28.6–34.1% in the polluted stands.

Sapwood density at breast height was 545 kg/m^3 in the control stand and from 536 to 586 kg/m^3 in the polluted stands. The figures for heartwood density were 503 kg/m^3 and 466 to 495 kg/m^3, respectively (Fig. 9).

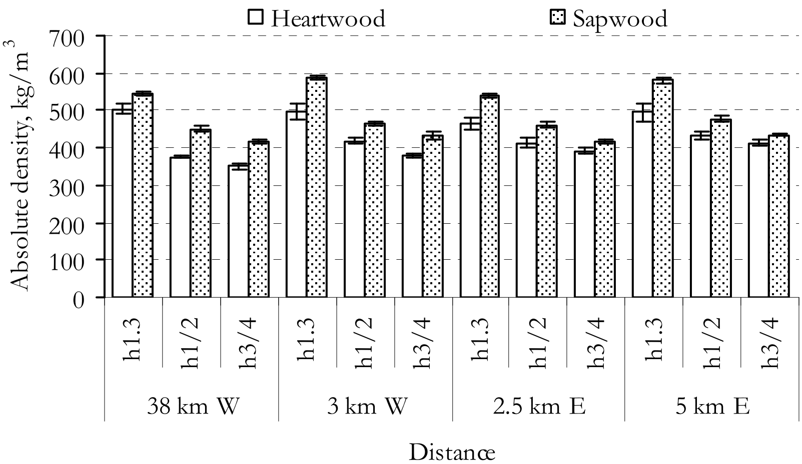

Figure 9. Wood density (mean ± standard error) of sapwood and heartwood at different heights and different distances from the emission source. h1.3 – samples from the height of 1.3 m, h1/2 – samples from half tree height, h3/4 – samples from 3/4 of tree height.

The trends in the variability of the mechanical properties in the tree stems on the experimental plots largely coincide with the trends in the variability of wood densities.

Air pollution had increased sapwood bending strength the most at breast height (by up to 16.3%); at greater heights the difference from the control trees decreased. No difference was found in the very heavily polluted stand compared to the control stand. Heartwood bending strength in the heavily polluted stand proved to be insignificantly smaller than the control value at breast height; towards the top, however, the bending strength of the polluted trees exceeded that of the control trees by up to 25% (Table 8).

Table 8. Bending strength perpendicular to grain (MPa) and modulus of elasticity (MPa) (mean ± standard error) at different heights of tree stem and different distances from the emission source. $h_{1.3}$ – samples from the height of 1.3 m, $h_{1/2}$ – samples from half tree height, $h_{3/4}$ – samples from 3/4 of tree height.

Property and sampling height	38 km W control	3 km W	2.5 km E	5 km E	*p*-value
Bending strength (MPa) of sapwood					
$h_{1.3}$	104.7 ±1.6	120.7 ±1.7**	99.3 ±1.5*	119.3 ±1.5**	<0.0001
$h_{1/2}$	88.1 ±2.1	91.8 ±2.3	87.9 ±2.5	93.1 ±2.2	<0.0001
$h_{3/4}$	78.3 ±2.6	78.20 ±2.23	77.3 ±2.1	81.2 ±2.1	<0.0001
Modulus of elasticity (MPa) of sapwood					
$h_{1.3}$	9587 ±242	14246 ±350	10116 ±216	10935 ±230	<0.0001
$h_{1/2}$	8096 ±337	10986 ±477**	8477 ±399*	8677 ±326*	<0.0001
$h_{3/4}$	7506 ±399	8057 ±420	7638 ±297	7415 ±306	<0.0001
Bending strength (MPa) of heartwood					
$h_{1.3}$	89.6 ±3.3	89.8 ±3.3	77.5 ±3.2	98.7 ±3.2	0.2640
$h_{1/2}$	64.5 ±4.9	72.2 ±5.4*	68.3 ±4.5	79.2 ±4.3**	0.2640
$h_{3/4}$	55.8 ±11.5	64.6 ±11.4*	69.5 ±7.2*	71.2 ±8.1*	0.2640
Modulus of elasticity (MPa) of heartwood					
$h_{1.3}$	8444 ±491	8500 ±413	6484 ±506	8916 ±477	0.1089
$h_{1/2}$	6828 ±716	7029 ±827	7101 ±716	7377 ±640	0.1089
$h_{3/4}$	4768 ±432	5172 ±1068	7014 ±906*	6017 ±514*	0.1089

*difference from control, $p < 0.05$
**difference from control, $p < 0.01$

Values for sapwood compression strength parallel to grain considerably exceeded that of the control stand at breast height and half tree height (by 8–13%) in pines situated at distances of 3 and 5 km from the cement plant. No difference was observed in the crown area. No significant difference was found between the wood from the control stand and from the heavily polluted stand (2.5 km from the plant) (Fig. 10). The trends in the results obtained are largely similar to the variation in bending strength.

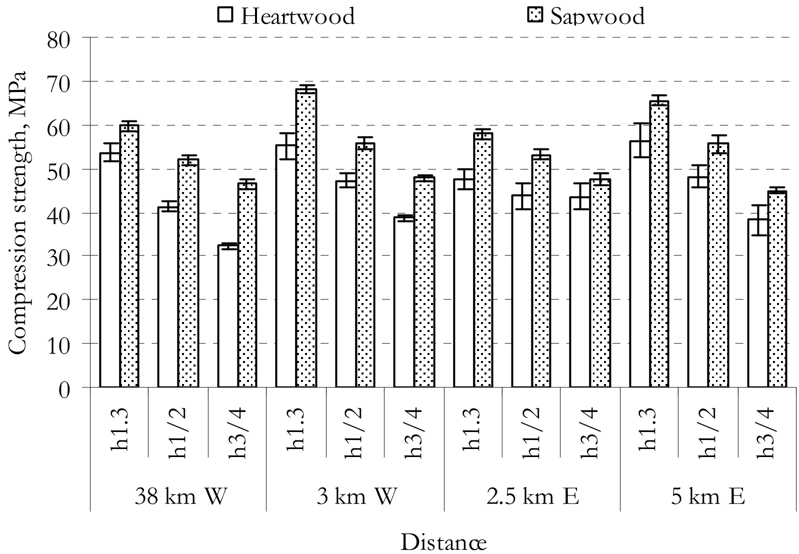

Figure 10. Compression strength (mean ± standard error) of sapwood and heartwood parallel to grain at different heights at different distances from the emission source. h1.3 – samples from the height of 1.3 m, h1/2 – samples from half tree height, h3/4 – samples from 3/4 of tree height.

Heartwood compression strength parallel to grain at breast height, however, proved to be smaller than the control in the heavily polluted stand (12.3%) and greater than the control in the less polluted stand (1.1–2.4%). At half tree height wood compression strength was significantly greater than the control value in the area of lower pollution (8–17%). Furthermore, heartwood compression strength was greater than the control value at $h_{3/4}$ in all the polluted stands.

Greater differences between the trial variants appeared in sapwood hardness along the grain at breast height. Sapwood end-grain hardness is strongly correlated with the hardness of the radial plane and the tangential plane.

With regard to heartwood end-grain hardness at the same height, no statistically significant differences between the experimental plots were observed. The end-grain hardness ranged between 32.2 and 33.4 MPa (p = 0.833) at breast height and between 24.7 and 27.4 MPa (p = 0.609) at half tree height. Tangential plane hardness fell within the ranges of 18.5–23.9 MPa (p = 0.335) and 18.3–21.1 MPa (p = 0.757), respectively.

5.6. Juvenile wood properties (V)

The width of the annual ring, excluding 2–3 annual rings around the pith, was decreasing linearly with the increase in cambial age. This means that the greater the cambial age, the narrower was the annual ring in the cross-section of the stem.

The situation was different with the percentage of latewood. In it the annual rings near the pith were small but from the fifth year onward the percentage of latewood started increasing linearly with cambial age (Fig. 11). In the stand of site index 2 the latewood distribution was more equal.

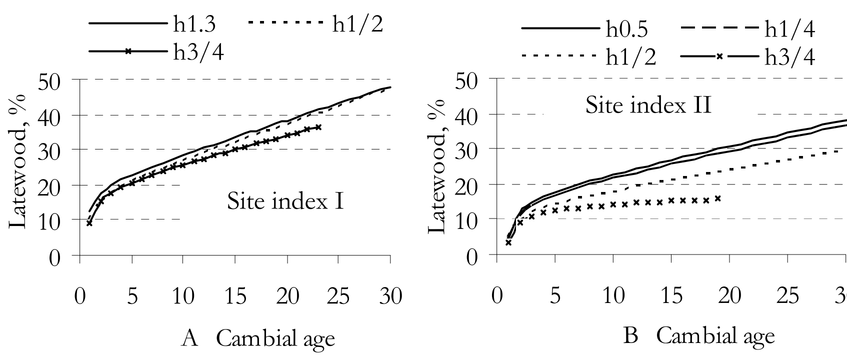

Figure 11. Distribution dynamics of latewood in different cross-sections of pine stem in south (A) and north-east (B) Estonia on *Myrtillus* site type. h0.5 – samples from the height of 0.5 m, h1.3 – samples from the height of 1.3 m, h1/2 – samples from half tree height, h3/4 – samples from 3/4 of tree height.

In the stand with the higher site index, the proportion of latewood was increasing equally with the increase in the cambial age and in this case R^2 = 0.81–0.86.

The highest oven-dry density of sapwood was detected under the bark from the butt log (535.2 kg/m^3). Juvenile wood density at the same level was 448.6 kg/m^3. The density of the juvenile wood in the stem decreased towards the top to the height $h_{3/4}$, where it was 318.3 kg/m^3. So the density of juvenile wood varies in the stem by up to 29%.

The variation range of the static bending strength along the stem of juvenile wood was 61.0–43.7 MPa and in the outer layer of sapwood 101.5–59.4 MPa (Table 1 in V).

The average compression strength parallel to the grain was 30.7±2.4 MPa of juvenile wood and 46.5±1.7 MPa in the outer layer of sapwood, i.e. 1.5 times greater. Variations ranged from 16.9 to 46.1 MPa and from 27.8 to 69.6 MPa, respectively. Compression strength of sapwood varied 2.5 times and of juvenile wood 2.7 times along the stem.

6. DISCUSSION

6.1. Moisture content of tree stem (III, V, VI)

The moisture content is one of the most important factors affecting the properties of wood and one of the main characteristics of wood quality (Veibri, 1982; Kollman and Côté, 1984; Kretschmann and Green, 1996; Tiitta, 2006). The moisture content of the trees was measured immediately after felling. Our results demonstrated that the moisture content of felled trees was partly related to the growth site soil moisture: a considerably lower wood moisture content was evident on dryer mineral soils than on peatlands (Fig. 2). The influence of abundant precipitation before felling cannot be neglected.

In pine stands growing on dryer site types, the moisture content of heartwood was identical at breast height and half tree height but considerably higher at ¾ of tree height. In bog site type stands, where the crown length is relatively large, the heartwood moisture content was higher at half tree height than at breast height and kept rising towards the top. Apparently, heartwood in the crown region participates to some extent in organic life, which is in accordance with other studies (Перелыгин и Уголев, 1971; Veibri and Kokk, 1980).

Similarly, sapwood moisture increased towards the top. The change was slight from breast height to half tree height yet considerable higher up. The difference in the mean wood moisture content was slight between the south and the north side of the stem. It increased towards the top; at ¾ of tree height the sapwood moisture on the south side was higher by just 3.3% on *Rhodococcum* and *Myrtillus* site type and 1.4% on bog site types. On the south side there is more warmth in crowns and thus active metabolism takes place.

Active organic life occurs after fertilization, too. It may increase moisture content in wood, but as many decades had passed since fertilization and its effect was gone (Pikk *et al.*, 2004), no statistically significant difference between fertilized and unfertilized pines was found.

6.2. Sapwood and heartwood proportions on different site types (VI)

In Scots pine, heartwood differs from sapwood in a number of properties and in chemical composition. The percentage of sapwood and heartwood has an effect on technological properties: moisture content, density, shrinkage and water-vapour diffusivity (Ojansuu and Maltamo, 1995; Allegretti *et al.*, 1999).

Among the indicators discussed in this thesis, the heartwood proportion manifested the greatest variations between the site types (Table 2) as well as between different stem heights within a concrete site type (Table 3). Kärenlampi and Riekkinen (2002) claim that the heartwood percentage is the best indicator of tree maturity. However, if the heartwood content varies under similar conditions as widely as our findings show, it cannot be a good property to evaluate maturity. According to Rikala (2003), there is no clear evidence that the heartwood proportions of peatland trees are higher than those of trees grown on mineral soil sites. In our study the heartwood percentage was the lowest in bog pine forests, where the soil moisture is high, stand density low and the tree crown is relatively bulky.

According to Ojansuu and Maltamo (1995), the pine has more heartwood in dense stands and its proportion decreases remarkably in concordance with relative tree growth; moreover, the height of the live crown correlates significantly with the heartwood percentage. Our results do no confirm this position but are consistent with the research of Björklund (1999) where the heartwood percentage varied greatly both between individual trees and between stands and correlated poorly to site, stands and tree variables. This implies that it seems unfeasible to identify heartwood-rich stands or stems, e.g., for the production of heartwood products, by using inventory data.

Younger stands had fewer annual rings in their sapwood than older stands; a moderate correlation was registered between tree age and the number of annual rings in sapwood (r = 0.45–0.55). A medium correlation was registered between the site index and the number of annual rings in sapwood (r = –0.14 to –0.33): a higher quality site evidenced more annual rings in sapwood. A positive correlation between the sapwood percentage and site index was observed at breast height and half tree height (r = 0.40 and r = 0.56, respectively) (Fig. 3). This agrees with other studies (Grier and Waring, 1974; Berninger and Nikinmaa, 1994; Livonen *et al.*, 2001).

6.3. Annual ring width, latewood content, wood density and mechanical properties (I, IV, V)

The mechanical properties of wood are strongly correlated with its physical properties, the most important of which are the wood density, latewood proportion in annual rings and annual ring width. However, the great variations in our research results demonstrate that these are insufficient for estimating the mechanical properties of wood where growth rates are the same but growth conditions are different (Table 2).

The ring width variation between site types was found to be larger than in the case of other characteristics. This indicates that ring width has a weak relationship with other studied characteristics. A moderate relation may exist between ring width and latewood proportion. From this we may deduce that the correlation between growth site and latewood content is weak, which agrees with other studies (Björklund, 1999). Here, consideration must be given to the effect of growing conditions, primarily the nutritional environment and the accumulation of chemical elements; this effect has been addressed in a number of studies (Ogner and Bjor, 1988; Helmisaari and Siltala, 1989; Cave and Walker, 1994; Andrews *et al.*, 2004; Saarela *et al.*, 2005).

Most of the literature reports negative, although weak, relationships between ring width and wood density, while others find no significant relationships at all (Seco and Barra, 1996; Wimmer and Downes, 2003). Some authors (Werberg, 1930; Звирбуль и др., 1976; Kairiūkštis and Malinauskas, 2001; Mäkinen *et al.*, 2002) and our previous studies (Kask, 2003) verified a strong relationship between latewood content and wood density (r = 0.91), a precondition for getting wood with good strength properties.

However, wood density is often different in case of one and the same latewood percentage. For instance, comparison of the densities of the pine wood from a heath of site index 4 and from a swamp of the same site index showed that the latter was significantly lower (Table 2).

Consideration must also be given to fibre length, cell wall thickness, growth tensions, the levels of various elements and compounds, etc.

Noteworthy is the dependence of breast-height wood density on site index in some types of growth sites (Fig. 4). It can be seen that due to intensive growth on very fertile sites, wood density there remains lower than on fresh sites with lower fertility. In a stand growing on mineral soil of a high site index (1a) lower strength indicators can be observed, which is confirmed by data from the literature (Ericson, 1960; Björklund and Walfridsson, 1993). Hence, the site index is not a good wood oven-dry density predictor. According to our data, the strength of the relationship between average stand density and site index is characterized by the determination coefficient $R^2 = 0.60$.

Major differences in stem density were observed between different stem zones in both sapwood and heartwood; the differences were smaller in the upper part of the stems. Mattsson (2002) also noted that variations from pith to bark are extensive in all wood parameters. Large differences in density are also found between middle and upper bole and between juvenile wood and heartwood (Duchesne *et al.*, 1997). This means that wood density is not constant but depends on many external and internal factors.

The wood density in Scots pine decreased from $h_{1.3}$ to $h_{3/4}$, and the difference in wood density in pine stems was over 106 kg/m^3. This result is in agreement with earlier findings (Hakkila, 1966; Björklund, 1984; Repola, 2006).

In stands of site indexes 1 and 2 the wood density and strength properties decreased towards the top by 1–2% per metre, whereas in stands of site index 5 the wood density and bending strength decreased on average by 3.5% per metre. On poorer sites, the reduction in compression strength and end-grain hardness towards the top was less intensive (3%). This indicates that the relation between the bending strength and wood density of pine is very strong ($r = 0.91$) (Kask, 2003).

The longitudinal percent-per-metre reduction in bending strength, compression strength and end-grain hardness in tree stem was smaller on more fertile sites. The tree height, in turn, determined the variation in strength properties in the lower half of the stem. The longer the stem, the less variance in strength properties of timber per metre was registered.

Our results by site types (Table 2) revealed a dependence of mechanical properties (bending and compression strength and hardness) on wood density. The latter was in turn largely influenced by the proportion of latewood in the wood.

The strength properties of pine wood were clearly poorer on our low-fertility wet sites than reported from Finland (Rikala, 2003). Site type is a highly generalized predictor of strength properties, so site index must also be taken into account. Site index may serve as a good predictor of wood relative strength indicators but only to a limited extent, within the range of adjoining types in the chart of ordinated forest site types.

Of mechanical properties, variations were the greatest in end-grain hardness. Hardness is highly dependent on grain direction. In this research, greater variations in end-grain hardness were observed in wood grown on more fertile sites, where, due to the greater width of annual rings, the test press ball might hit only early- or latewood. Accordingly, a smaller or greater result was obtained. The hardness of a wood end-grain surface with narrower annual rings therefore showed less variation and was often greater than the average. With particularly wide annual rings, the probability of the ball hitting early wood was greater and the test result was therefore smaller.

6.4. Influence of silvicultural treatments (IV)

The formation of wood properties is affected by a number of silvicultural treatments. The influence of forest fertilization on tree growth is relatively short. The influence of thinning is prolonged and forest drainage has an effect on tree growth during decades. The influence of fertilization is stronger on the upper part of the tree where faster growth produces more branches, needle mass and height increment, and the ring width compared to the $h_{1.3}$ level is greater. An increased radial growth results in a reduced fibre length, fibre diameter, cell wall thickness, wood density, modulus of rupture and modulus of elasticity but an increased microfibril angle and longitudinal shrinkage (Saranpää *et al.*, 2000b; Mattsson, 2002).

Additional radial growth that followed the fertilization of the investigated stands was already described earlier (Сээмен, 1987; Пикк, 1988; Pikk *et al*., 1999; Pikk *et al*., 2001). It has been observed that the re-fertilizing of pine stands often destroys the nutrient balance and after fertilization a radial increment period will be followed by a period when the radial increment of fertilized stands is lower than in control stands. This will eventually nullify the fertilization effect. Therefore during a longer period an average annual ring in fertilized stands was not much wider than in control stands in most cases (Table 4).

No significant differences in sapwood ring width were observed between the stands examined within this research, although at 3/4 of tree height wider rings (4.0–11.0%) were measured in fertilized trees. In fertilized stands, a notably higher sapwood proportion at breast height was found in only two pine forests in *Rhodococcum* site type (Table 4). As fertilization causes an increase in crown and needle mass, this in turn should improve sapwood proportion, because according to the literature (Albrektson, 1984), sapwood proportion in the cross-sectional area at breast height correlates with pine needle mass. Our results did not confirm this position.

Little variation was found in the number of annual rings in sapwood at breast height of fertilized and unfertilized trees in the sample plots. This coincides with literature data (Mörling and Valinger, 1999). Higher up, the number of annual rings in the sapwood of trees in fertilized stands was greater in our research, which was due to improved growing conditions following fertilization.

Fertilization does not significantly change latewood proportion, as after fertilization annual rings are not expanded by an increase in the size of tracheids but rather in their number, as stated by Вярбила и Шлейнис (1981). In our earlier study we did not discover any significant variation in latewood proportion between fertilized and unfertilized trees either (Pikk *et al*., 2004). However, the fertilization of drained bog pine stands has been observed to increase the latewood proportion by a couple of per cent (Пикк, 1988).

Although fertilization has not resulted in considerably reduced wood density in Estonia, a downward trend was detected in fertilized pine trees in *Myrtillus* site types at $h_{3/4}$ (Pikk *et al*., 2004). In Lithuania, variation in the physical and mechanical properties of pine wood in fertilized stands has proved insignificant; wood density varied the most, decreasing by 5% (Вярбила и Шлейнис, 1981). The same result was obtained in Karelia (Матюшкина и др., 1974), whereas in Finland the decrease was found to be smaller, remaining within 1–4% (Saikku, 1975).

We found that fertilization in *Myrtillus* site types had increased bending strength by 7–8% at breast height, whereas at other heights and in bog sites, fertilization had no effect on bending strength. In general, our research did not reveal a significant effect of fertilization on bending strength as research results were relatively varied.

The reduced compression strength of sapwood in fertilized trees and its greater variation in bog sites is, on the one hand, caused by the specific structure of wood in relation to the transition of juvenile wood into wood with increased density in the relatively slender crown part at $h_{3/4}$ and, on the other hand, by random deviations in the growing process, which often occur in bog sites.

How much fertilization affects the percentage of self-pruning and thinning by cutting in different stands is not clear. On experimental plots cutting intensity has been limited to the elimination of dead trees and light thinning (10–16%). So the stands have grown having a generally high stand density. An exception is a pine stand on *Cladonia* site type with low soil fertility where the thinning in the control stand was 30% and in the fertilized stand 43.6%. It should be mentioned here that in certain cases a temporary increase in foliage mass and a higher degree of canopy cover after fertilization may create an illusion of a higher need for stronger thinning. Pine wood is considered to have the most proper physical and mechanical properties when the stand stocking level is 0.8–0.9 (Aleinikovas, 2007).

As suggested in the literature, fertilization after the first thinning has no influence on the branchiness of butt log (Saramäki and Silander, 1982; Nikkola, 1985). On stands repeatedly fertilized with N the self-pruned stem length is significantly shorter than in control stands (Table 2 in IV). One-time fertilization did not influence self-pruning (Kubja 2).

Forest drainage reduces wood density and latewood proportion (Rikala, 2003). In Estonia, such an effect is observable only in post-draining years, when draining results in reduced density and latewood proportion. Later, the effect is the opposite: the latewood proportion and density increase and ultimately a good result is achieved, as was documented in Russia (Перелыгин и Уголев, 1971). The greater bending strength in moderately drained bog sites only at breast height and in intensively drained bogs also in the crown area is in proportion to the increased wood density in these sites (Fig. 7).

6.5. Impact of alkaline dust pollution (II)

The mean ring width in the sapwood of pines in the heavily polluted stand (2.5 E of the emission source) was half of that of the control stand and also smaller for the other polluted stands. The study of heartwood ring width yielded the opposite result: in the stands of the polluted area annual rings were wider than in the control stand by 13–34%. Annual rings in heartwood have developed during a period when pollution was not particularly heavy. We may assume that on *Myrtillus* site type, where the soil is acidic, moderate amounts of cement dust may have enhanced radial increment. In general, it should be stressed that the formation of sapwood in the stands investigated depends statistically significantly on the concentrations of organic matter, N and K and the 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 to P in the soil (Table 4 in III). The higher the pollution load under which the tree has grown, the larger the proportion of heartwood in the cross-section. Moreover, the intensive accumulation of Ca and K into different compartments of young Scots pines in the vicinity of the cement plant (Mandre *et al.*, 1999) may stimulate lignification processes and heartwood formation.

The number of annual rings in sapwood at breast height pointed to the tendency that heartwood formation had decelerated in the more polluted stands. However, as the ring width in sapwood was significantly smaller in the polluted stands compared to the unpolluted one, the proportion of heartwood in the cross-sections of these trees was nevertheless greater. According to Kärenlämpi and Riekkinen (2002), for evaluating the maturity of a forest tree the heartwood content is far better than age or size. So the stand maturation period may start earlier under the conditions of pollution. Nevertheless, the increased latewood levels in the polluted stands suggest accelerated tree ageing.

On the control plot the heartwood density was equal to or lower than that on the other plots while sapwood density was in all cases lower in the control plot than on the other plots. This indicates a trend analogous to that of the latewood percentage, and at the same time characterizes tree growth conditions during different periods.

In the control stand the sapwood bending strength was greater than the heartwood bending strength, whereas the trend was opposite in the polluted stands (Table 8). In the bottom part of the stem the difference between sapwood and heartwood bending strengths was greater and in the crown area it was smaller, consistent with the variations in wood density. In general, the bending strength of heartwood varied on a greater scale than that of sapwood. The reason is that annual rings are wider in heartwood, and therefore specimens comprise varying numbers of latewood rings, the density of which is higher. Apart from that, heartwood contains a significant share of juvenile wood, whose strength properties are inferior.

Compression strength parallel to the grain in the sapwood of trees situated in areas of moderate pollution may, according to our data, be greater at breast height and significantly greater at $h_{1/2}$. Growing under a greater pollution load, however, increases pine wood compression strength parallel to grain.

Sapwood end-grain hardness at breast height on the polluted plots exceeded the corresponding figure for the control stand by up to 10.4% (Fig. 5 in II) and heartwood hardness by 0.5–3.7%. This is in accordance with wood density.

6.6. Effect of juvenile wood (V)

Pines on different site types have a different wood structure. Annual rings near the pith at breast height are relatively wide and do not differ remarkably among the pines on different site types. However, the difference between their latewood percentages is remarkable (Fig. 3 in IV). Comparison with the results obtained at breast height in pine stands on *Myrtillus* site types (8–12%) suggests that the stand site type cannot be considered as the only causal factor. The abundance or deficiency of some nutrient elements, genetics, length of the growing period, periodical climate conditions and other factors can also be of influence (Henttonen, 1984; Lindeberg, 2001; Bektas *et al.*, 2003). It is noteworthy that the dynamics of the latewood increase varies starting from the pith. The period of juvenile wood formation is not distinguishable in the width of annual rings, but the percentage of latewood increases from the pith until the 5th year smoothly and after that increases proportionally to the age (Fig. 11). Starting from the pith in the frame of five annual rings the mean width and content of latewood from the stub to the top does not change much.

Wider annual rings do not decrease mechanical characteristics, but latewood percentage is of importance, which is in accordance with other studies (Veermets, 1963; Aleinikovas and Grigaliūnas, 2006). Here we cannot exclude that during faster growth the building and resistance of wood cells change as has been suggested by Saranpää *et al.* (2000a) and Mörling (2002).

The bending strength of juvenile wood comprises only 62% of the bending strength of the wood near the bark. So the bending strength factor in juvenile wood has a 1.2 times greater relative standard error of the middle value, which can be explained by the existence of stronger latewood in experimental pieces because of wider rings in juvenile wood. The bending strength of mature pine stands in Lithuania is generally 87.7 MPa, in Belarus 87.3 MPa and in the North-West of Russia 84.5 MPa (Боровиков и Уголев, 1989). Considering these data, the bending strength of the examined pine wood is already similar to that of trees at the age of 60 years (Kask, 2003).

7. CONCLUSIONS

Growing conditions in different forest site types have a significant effect on wood properties. Great variation in pine wood properties can be detected in the stem, in the stand as well as between stands.

Wood moisture content is directly dependent on site conditions. Growing trees contain more wood moisture in peatland forests than in *Rhodococcum* and *Myrtillus* site types. Moreover, the moisture content of heartwood in peatland pines is higher at half tree height and upwards than at breast height. Sapwood contains more moisture on the south side of the stem compared to the north side, which is clearly distinguishable in the crown area.

Scots pine wood is the strongest if growing on heath and the weakest on raised bogs, its average density being 513–545 kg/m^3 and 414–464 kg/m^3, bending strength 97–100 MPa and 71–83 MPa and compression strength 55–56 MPa and 41–52 MPa, respectively. The tree height determines the variation of strength properties in the lower half of the stem. The longer the stem, the less variance occurs in the strength properties of its pole timber.

Use of mineral fertilizers to change growing conditions affects the width of annual rings over a relatively short period following fertilization and may, in some cases, bring about changes in wood density by a few percentages. Variation in wood bending strength is so great that changes in density and latewood proportion as a result of fertilization fail to considerably alter it. However, bending strength may in certain cases decline by up to 6% as a result of fertilization. Fertilization can increase the productivity of pine stands but the possibility of improving timber quality is questionable. Enhanced growth increases production and intensifies the growth of branches and needles in site types with poor fertility, thus creating a higher need for thinning in the stand. On repeatedly fertilized middle-aged stands self-pruning decreases and therefore first log quality remains low. Stronger radial growth after fertilization increases the proportion of sapwood in raw timber where less latewood may exist. Fertilization results in lower wood density and weaker wood properties and has practically no influence upon accelerating heartwood formation. Estimating the stem heartwood–sapwood proportion by the external characteristics of trees is questionable.

Forest drainage reduces the wood density and the latewood proportion; however, such an effect is observable only in post-draining years. Later, the effect is the opposite: the latewood proportion and the density increase and ultimately good results are achieved. The greater bending strength in moderately drained bog sites only at breast height and in intensively drained bogs also in the crown area is in proportion with the increased wood density in these sites.

The alkalization of the environment and long-term emission of alkaline dust from the cement plant at Kunda 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. 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. Alkaline air pollution of trees may stimulate higher heartwood proportions and early stand maturation. Moderate alkaline pollution of a pine stand growing on acidic soil stimulates radial increment, but does not result in lower latewood percentages or wood density. In polluted stands, wood bending strength perpendicular to grain, compression strength parallel to grain and, in some cases, the end-grain hardness increase. A drastic rise in alkaline dust pollution results in slower wood increment formation, narrower annual rings compared to the control variant and higher latewood percentages and wood density; in areas of very high pollution, however, weighted mean strength properties in the stem cross-section are lower than those in unpolluted stands.

Juvenile wood is less favoured in most areas of wood use because of its weaker strength characteristics. The density of juvenile wood makes up 83.8%, bending strength 62% and end-grain hardness 81.2% of the relevant indicators of the sapwood near the bark. Compression strength parallel to grain in juvenile wood decreases faster towards the top log than in sapwood. In comparison with the southern neighbour states, Estonia has good possibilities for growing pine wood with a low content of juvenile wood and good properties because the tested model trees had relatively few annual rings. It is not possible to avoid juvenile wood in pine stems but definitely its relative volume can be reduced by silvicultural treatments.

REFERENCES

Albrektson, A. 1984. Sapwood basal area and needle mass of Scots pine (*Pinus sylvestris* L.) trees in central Sweden. – *Forestry*, 57(1): 35–43.

Aleinikovas, M. 2007. Effect of the mean diameter increment on the pine wood mechanical-physical properties in Lithuania. – *Baltic Forestry*, 13(1): 103–108.

Aleinikovas, M., Grigaliūnas, J. 2006. Differences of pine (*Pinus sylvestris* L.) wood physical and mechanical properties from different forest site types in Lithuania. – *Baltic Forestry*, 12(1): 9–13.

Allegretti, O., Bernabei, M., Negri, M., Piutti, E. 1999. Sapwood – heartwood proportion related to some technological properties in *Picea abies* (L.) Karst. in Trentino (Italy). In: *Proceedings of the Fourth International Conference on the Development of Wood Science, Wood Technology and Forestry*. Forest Products Research Centre, pp 475–485.

Andrews, J.A., Siccama, T.G., Vogt, K.A. 1999. The effect of soil nutrient availability on retranslocation of Ca, Mg and K from senescing sapwood in Atlantic white cedar. – *Plant and Soil*, 208(1): 117–123.

Andrews, S.S., Karlen, D.L., Cambardella, C.A. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Science Society of America Journal*, 68(6): 1945–1962.

Arlinger, J., Wilhelmsson, L. 1999. Wood analysis – an aid to meeting the needs of the mills. SkogForsk, *Results*, 1: 1–4.

Auclair, D. 1977. Effects of dust on photosynthesis II. Effects of particulate matter on photosynthesis of Scots pine and poplar. [Effets des poussières sur la photosynthèse. II. – Influence des polluants particulaires sur la photosynthèse du Pin sylvestre et du Peuplier]. – *Annals of Forest Science*, 34(1): 47–57 [in French with an English summary].

Bamber, R.K. 1976. Heartwood, its function and formation. *Wood Science and Technology*, 10(1): 1–8.

Bektas, I., Alma, M.H., Goker, Y., Yuksel, A., Gundogan, R. 2003. Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. – *Forest Products Journal*, 53(4): 48–50.

Berninger, F., Nikinmaa, E. 1994. Foliage area-sapwood area relationships of Scots pine (*Pinus sylvestris*) trees in different climates. – *Canadian Journal of Forest Research*, 24(11): 2263–2268.

Björklund, L. 1984. Pulpwood basic density and its dependence on different factors. Swedish University of Agricultural Sciences, Department of Forest Products, *Report* 155. 29 p [in Swedish with an English summary].

Björklund, L. 1999. Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. – *Silva Fennica*, 33(2): 119–129.

Björklund, L., Walfridsson, E. 1993. Tallvedens egenskaper i Sverige – Torr-rådensitet, kärnvedhalt, fuktighet och barkhalt. [Properties of Scots pine wood in Sweden – Basic density, heartwood, moisture and bark content]. Swedish University of Agricultural Sciences, Department of Forest Products, *Report* 234. 75 p [in Swedish with an English summary].

Bowyer, J.L., Shmulsky, R., Haygreen, J.G. 2003. *Forest Products and Wood Science – An Introduction*, 4th Edition. Iowa State Press. 554 p.

Burdon, R.D., Kibblewhite, R.P., Walker, J.C.F., Megraw, R.A., Evans, R., Cown, D.J. 2004. Juvenile versus mature wood: a new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *P. taeda*. – *Forest Science*, 50(4): 399–415.

Cave, I.D., Walker, J.C.F. 1994. Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. – *Forest Products Journal*, 44(5): 43–48.

Chaffey, N. 2000. Cytoskeleton, cell walls and cambium: new insights into secondary xylem differentiation. In: Savidge, R., Barnett, J., Napier, R. (eds.). *Cell and Molecular Biology of Wood Formation*, BlOS Scientific Publishers, Oxford, pp 31–42.

Cody, R.P., Smith, J.K. 2006. *Applied Statistics and the SAS Programming language*, 5th Edition. Pearson Education Inc., Upper Saddle River, New Jersey, USA. 459 p.

Duchesne, I., Wilhelmsson, L., Spangberg, K. 1997. Effects of in-forest sorting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) on wood and fibre properties. – *Canadian Journal of Forest Research*, 27(5): 790–795.

Grier, C.C., Waring, R.H. 1974. Conifer foliage mass related to sapwood area. – *Forest Science*, 20(3): 205–206.

Ericson, B. 1960. Studies of the genetical wood density variation in Scots pine and Norway spruce. Statens Skogsforskningsinstitut (Sweden). Avdelningen för skogsproduktion. Forest Research Institute of Sweden, Department of Forest Yield Research. *Report* 4. 52 p.

Estonian Forests and Forestry. 1995. Karoles, K. (ed.). Estonian Forest Department, Tallinn. 128 p.

Finér, L., Kaunisto, S. 2000. Variation in stemwood nutrient concentrations in Scots pine growing on peatland. – *Scandinavian Journal of Forest Research*, 15(4): 424–432.

Gluch, W. 1980. Bioindikation mit produktionsbiologischen und morphometrischen Verfahren. – *Archiv für Naturschutz und Landschaftsforschung*, 20(2): 99–116.

Grekin, M. 2006. *Nordic Scots Pine vs. Selected Competing Species and Non-wood Substitute Materials in Mechanical Wood Products. Literature Survey*. Working Papers of the Finnish Forest Research Institute 36. 66 p.

Hakkila, P. 1966. Investigations on the basic density of Finnish pine, spruce and birch wood. – *Communicationes Instituti Forestalis Fenniae*, 61(5): 1–98.

Hakkila, P. 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. – *Communicationes Instituti Forestalis Fenniae*, 96(3): 1–59.

Hannrup, B., Ekberg, I., Persson, A. 2000. Genetic correlations among wood, growth capacity and stem traits in *Pinus sylvestris*. – *Scandinavian Journal of Forest Research*, 15(2): 161–170.

Hartig, R. 1901. *Holzuntersuchungen. Altes und Neues*. Verlag von Julius Springer, Berlin. 99 p.

Härtling, S., Schulz, H. 1998. Biochemical parameters as biomarkers for the early recognition of environmental pollution in Scots pine trees. I. Phenolic compounds. – *Zeitschrift für Naturforschung*, 53(5–6): 331–340.

Helmisaari, H-S., Siltala, T. 1989. Variation in nutrient concentrations of *Pinus sylvestris* stems. – *Scandinavian Journal of Forest Research*, 4(1–4): 443–451.

Henttonen, H. 1984. The dependence of annual ring indices on some climatic factors. – *Acta Forestalia Fennica*, 186: 1–39.

ISO 3129:1975. 1975. Wood – Sampling methods and general requirements for physical and mechanical tests. International Organization for Standardization, Switzerland. 4 p.

ISO 3130:1975. 1975. Wood – Determination of moisture content for physical and mechanical tests. International Organization for Standardization, Switzerland. 2 p.

ISO 3131:1975. 1975. Wood – Determination of density for physical and mechanical tests. International Organization for Standardization, Switzerland. 2 p.

ISO 3133:1975. 1975. Wood – Determination of ultimate strength in static bending. International Organization for Standardization, Switzerland. 2 p.

ISO 3349:1975. 1975. Wood – Determination of modulus of elasticity in static bending. International Organization for Standardization, Switzerland. 3 p.

ISO 3350:1975. 1975. Wood – Determination of static hardness. International Organization for Standardization, Switzerland. 2 p.

ISO 3787:1976. 1976. Wood test methods – Determination of ultimate stress in compression parallel to grain. International Organization for Standardization, Switzerland. 2 p.

ISO 4471:1982. 1982. Wood – Sampling sample trees and logs for determination of physical and mechanical properties of wood in homogeneous stands. International Organization for Standardization, Switzerland. 7 p.

Jäger, E.J., Mörchen, G. 1980. Indikation von Luftverunreinigungen durch morphometrische Untersuchungen an Höheren Pflanzen. In: Schubert, R., Schuh, J. (eds.). *Bioindikation. Teil 3. Kongreß- und Tagungsberichte der Martin-Luther-Universität.* Halle-Wittenberg, Wiss. Beiträge, 26(10): 43–52.

Jayawickrama, K.J.S. 2001. Breeding radiata pine for wood stiffness: review and analysis. – *Australian Forestry*, 64(1): 51–56.

Jelonek, T., Pazdrowski, W., Tomczak, A., Stypuła, I. 2006. Radial and axial variability of the proportion of sapwood and heartwood in stems of Scots pine trees (*Pinus sylvestris* L.) developed in conditions of former farmlands and typical forest sites. *Electronic Journal of Polish Agricultural Universities*, *Forestry*, 9(3).

Jyske, T. 2008. The effects of thinning and fertilisation on wood and tracheid properties of Norway spruce (*Picea abies*) – the results of long-term experiments. Academic dissertation. University of Helsinki. 59 p.

Kairiūkštis, L., Malinauskas, A. 2001. The influence of the initial density on spruce (*Picea abies* Karsten.) wood quality. – *Baltic Forestry*, 7(2): 8–17.

Kärenlampi, P.P., Riekkinen, M. 2002. Pine heartwood formation as a maturation phenomenon. – *Jourrnal of Wood Science*, 48(6): 467–472.

Kärkkäinen, M. 1972. On the proportion of heartwood in Norway spruce (*Picea abies*) and Scots pine (*Pinus silvestris* L.). – *Silva Fennica*, 6(3): 193–208 [in Finnish with an English summary].

Kärkkäinen, M. 2003. *Puutieteen perusteet*. Metsälehti kustannus, Hämeenlinna. 451 p [in Finnish].

Kask, R. 2003. Hariliku männi (*Pinus sylvestris* L.) puidu mehaanilised ja füüsikalised omadused pohla ja mustika metsakasvukohatüübis. [Mechanical and physical properties of Scots pine (*Pinus sylvestris* L.) wood on *Vaccinium vitis-idaea* and *Myrtillus* site type]. M.Sc. Thesis. Estonian Agricultural University, Tartu. 142 p [in Estonian with an English abstract].

Klõšeiko, J. 2003. Carbohydrate metabolism of conifers in alkalised growth conditions. Doctoral thesis. Estonian Agricultural University, Tartu. 183 p.

Kollman, F.F.P., Côté, W.A. 1984. *Principles of Wood Science and Technology. Volume I: Solid Wood*. Springer-Verlag, Berlin-Heidelberg. 502 p.

Kõresaar, J. 1938. *Uurimusi tugipuude eriomadustest Alutaguse männikutes*. [Untersuchungen über die spezifischen Eigenschaften des Grunbenholzes aus den Kiefärnwäldern von Alutaguse]. Tartu Ülikooli metsaosakonna toimetused No. 30. Tartu Ülikooli Õppe- ja Katsemetskonna kirjastus, Tartu. 161 p [in Estonian with a German summary].

Kretschmann, D.E., Green, D.W. 1996. Modeling moisture content-mechanical property relationships for clear southern pine. – *Wood and Fiber Science*, 28(3): 320–337.

Lal, B., Ambasht, R.S. 1982. Impact of cement dust on the mineral and energy concentration of *Psidium guayava*. – *Environmental Pollution. Series A: Ecological and Biological*, 29(4): 241–247.

Lappi-Seppälä, M. 1952. Männyn sydänpuusta ja runkomuodosta. Referat: Über Verkernung und Stammform der Kiefer. *Communicationes Instituti Forestalis Fenniae*, 40(25): 1–26.

Larson, P.R. 1969. *Wood Formation and the Concept of Wood Quality*. Yale University, School of Forestry and Environmental Studies, Bulletin No. 74: 3–17.

Larson, P.R., Kretschmann, D. E, Clark, A., Isebrands, J. G. 2001. Formation and properties of juvenile wood in southern pines. A synopsis. United States Department of Agriculture, Forest Service, Forest Products Laboratory, *General Technical Report* 129. 42 p.

Lindeberg, J. 2001. X-ray based dendro-analyses of wood properties. Rapporter - *Sveriges lantbruksuniversitet, Institutionen för skogsskötsel.* Volume 50, Swedish University of Agricultural Sciences. 18 p.

Lindstrom, H. 1996. Basic density in Norway spruce. Part III. Development from pith outwards. – *Wood and Fiber Science*, 28(4): 391–405.

Lindström, H. 1997. Fibre length, tracheid diameter, and latewood percentage in Norway spruce: development from pith outwards. – *Wood and Fiber Science*, 29(1):21–34.

Lindström, H. 2002. Intra-tree models of juvenile wood in Norway spruce as an input to simulation software. – *Silva Fennica*, 36(2): 521–534.

Livonen, S., Rikala, R., Vapaavuori, E. 2001. Seasonal root growth of Scots pine seedlings in relation to shoot phenology, carbohydrate status and nutrient supply. – *Canadian Journal of Forest Research*, 31(9): 1569–1578.

Lõhmus, E. 1984. *Eesti metsakasvukohatüübid.* [The Estonian forest site types]. Tallinn. 88 p [in Estonian].

Lõhmus, E. 1995. Conditions of forest growth. In: Karoles. K. (ed.). *Estonian Forests and Forestry*. Tallinn, pp 6–20.

Macdonald, E., Moore, J., Connolly, T., Gardiner, B. 2010. Assessing Timber Quality of Scots Pine (*Pinus sylvestris* L.). The Final Conference of COST Action E53. *The Future of Quality Control for Wood & Wood Products*. 4.–7.05.10, Edinburgh. 11 p.

Mäkinen, H. 1998. The suitability of height and radial increment variation in *Pinus sylvestris* (L.) for expressing environmental signals. – *Forest Ecology and Management* 112(1–2): 191–197.

Mäkinen, H., Uusvaara, O. 1992. Effects of fertilization on the branchiness and the wood quality of Scots pine. [Lannoituksen vaikutus männyn oksikkuuteen ja puuaineen laatuun]. – *Folia Forestalia*, 801. 23 p [in Finnish with an English summary].

Mäkinen, H., Saranpää, P., Linder, S. 2002. Wood-density variation of Norway spruce in relation to nutrient optimization and fibre dimensions. – *Canadian Journal of Forest Research*, 32(2): 185–194.

Malinen, J., Maltamo, M., Verkasalo, E. 2005. Stem and wood properties of Norway spruce on drained peatlands and mineral forest lands in southern Finland. – *Baltic Forestry*, 11(1): 21–38.

Mandre, M. 1995a. Changes in the nutrient composition of trees. In: M. Mandre (ed.). *Dust Pollution and Forest Ecosystems. A Study of Conifers in an Alkaline Environment.* Publication 3. Institute of Ecology, Tallinn, pp 44–65.

Mandre, M. 1995b. Effects of dust pollution on carbohydrate balance in conifers. In: M. Mandre (ed.). *Dust Pollution and Forest Ecosystems. A Study of Conifers in an Alkaline Environment.* Publication 3. Institute of Ecology, Tallinn, pp 78–95.

Mandre, M., Ots, K., Rauk, J. 1999. The state of the forest ecosystem in an area of oil shale mining and processing 1. Chemical composition of trees and environment. – *Oil Shale*, 16(3): 257–271.

Mandre, M., Kask, R., Pikk, J., Ots, K. 2008. Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust. *Environmental Monitoring and Assessment*, 138(1–3): 51–63.

Mason, W.L., Alia, R. 2000. Current and future status of Scots pine (*Pinus sylvestris* L.) forests in Europe. – *Investigación agraria. Sistemas y recursos forestales*, 9(1): 317–336.

Mason, W.L., Connolly, T., Pommerening, A., Edwards, C. 2007. Spatial structure of semi-natural and plantation stands of Scots pine (*Pinus sylvestris* L.) in northern Scotland. – *Forestry*, 80(5): 567–586.

Mattsson, S., Evans, R., Bergsten, U., Kubin, E. 2002. Wood density and microfibril angle in Scots pine (*Pinus sylvestris*) as affected by soil scarification method, tree type and height within tree. In: Mattsson, S. (ed.). *Effects of Site Preparation on Stem Growth and Clear Wood Properties in Boreal Pinus sylvestris and Pinus contorta.* Acta Universitatis Agriculturae Sueciae. Silvestria, 240: 1–37.

Megraw, R.A. (ed.). 1985. *Wood Quality Factors in Loblolly Pine.* TAPPI Press, Atlanta, Georgia. 88 p.

Mencuccini, M., Bonosi, L. 2001. Leaf/sapwood area ratios in Scots pine show acclimation across Europe. – *Canadian Journal of Forest Research*, 31(3): 442–456.

Mörling, T. 2002. Evaluation of annual ring width and ring density development following fertilisation and thinning of Scots pine. – *Annals of Forest Science*, 59(1): 29–40.

Mörling, T., Valinger, E. 1999. Effects of fertilization and thinning on heartwood area, sapwood area and growth in Scots pine. – *Scandinavian Journal of Forest Research*, 14(5): 462–469.

Mott, L., Groom, L., Shaler, S. 2002. Mechanical properties of individual southern pine fibers. Part II. Comparison of earlywood and latewood fibers with respect to tree height and juvenility. – *Wood and Fiber Science*, 34(2): 221–237.

Nikkola, A. 1985. Kasvatustiheyden ja lannoituksen vaikutus riukuvaiheen männiköiden laatuun. [Effect of stand density and fertilization on the branchiness and wood quality of pole stage Scots pine stands]. M.Sc. Thesis. Faculty of Agriculture and Forestry, University of Helsinki. Helsinki. 45 p [in Finnish with an English summary].

Nikolov, N., Helmisaari, H. 1992. Silvics of the circumpolar boreal forest tree species. In: Shugart. H.H, Leemans. R, Bonan. G.B, (eds.). *A Systems Analysis of the Global Boreal Forest.* Cambridge University Press, pp 13–84.

Ogner, G., Bjor, K. 1988. Concentrations of elements in annual rings of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) from Arendal, in southern Norway. *Meddelelser fra Norsk institutt for skogforskning*, 40(10): 1–8.

Ojansuu, R., Maltamo, M. 1995. Sapwood and heartwood taper in Scots pine stems. – *Canadian Journal of Forest Research.* 25(12): 1928–1943.

Olesen, P.O. 1977. The variation of the basic density level and tracheid width within the juvenile and mature wood of Norway spruce. – *Forest Tree Improvement*, 12: 1–21.

Olesen, P.O. 1982. The effect of cyclophysis on tracheid width and basic density in Norway spruce. – *Forest Tree Improvement*, 15: 1–80.

Omeis, E. 1895. Untersuchungen des Wachsthumsganges und der Holzbeschaffenheit eines 110 jährigen Kiefernbestandes. – *Forst Naturwissenschaftliche Zeitschrift*, 4(4): 137–170.

Ots, K. 2002. Impact of air pollution on the growth of conifers in the industrial region of Northeast Estonia. Doctoral dissertation. Estonian Agricultural University. 222 p.

Paavilainen, L. 1990. Importance of particle size - fibre length and fines - for the characterization of softwood kraft pulp. – *Paperi ja Puu*, 72(5): 516–526.

Pape, R. 1999. Effects of thinning regime on the wood properties and stem quality of *Picea abies*. – *Scandinavian Journal of Forest Research*, 14(1): 38–50.

Pereira, H., Graça, J., Rodrigues, J. 2003. Wood chemistry in relation to quality. In: Barnett, J.R. and Jeronimidis, G. (eds.). *Wood Quality and Its Biological Basis*. Blackwell Publishing Ltd, Oxford, UK, pp 53–86.

Pikk, J., Kask, R. 2004. Männipuidu omadused mõnedes metsakasvukohatüüpides [Pine wood properties in some forest site types]. Estonian Agricultural University, Forest Research Institute, Tartu, *Final report of grant project 4968*. 36 p [in Estonian].

Pikk, J., Seemen, H., Peterson, P. 1999. Pohlamännikute normaalse juurdekasvu taastumine pärast lämmastikuga väetamist. [Re-establishment of normal growth increment rate in Scots pine stands on *Vaccinium vitis-idaea* site type after fertilization with nitrogen]. – *Forestry Studies*, 31: 61–71 [in Estonian].

Pikk, J., Seemen, H., Valk, U. 2001. Toitumistingimuste järsust halvenemisest tingitud taandarengulised protsessid puistutes. [The retrogression processes in stands caused by steeply deteriorated growing conditions]. – EPMÜ Metsanduslik Uurimisinstituut, Tartu, *Final report of grant project* 2685. 96 p [in Estonian].

Pikk, J., Kask, R., Kuusepuu, T., Peterson, P. 2004. The effect of growth conditions on Scots pine (*Pinus sylvestris* L.) wood properties. – *Forestry Studies*, 40: 187–197.

Pushinskis, V., Hrols, J., Dolacis, J. 1998. Factors influencing the modulus of elasticity and strength limit in bending of pine (*Pinus sylvestris*) wood. In: *Wood Structure and Properties*. Symposium; 3rd, International Wood structure and properties. Zvolen, Slovakia, pp 163–168.

Rauk, J. 1995. Bioproductivity. In: Mandre, M. (ed.). *Dust Pollution and Forest Ecosystems. A Study of Conifers in an Alkaline Environment*. Publication 3. Institute of Ecology, Tallinn, pp 119–123.

Repola, J. 2006. Models for vertical wood density of Scots pine, Norway spruce and birch stems, and their application to determine average wood density. – *Silva Fennica*, 40(4): 673–685.

Riekkinen, M., Lukkarinen, A., Kärnä, J., Verkasalo, E. 2005. Visual and machining properties of Nordic Scots pine wood for joinery and furniture industry. In: Innes, J.L., Edwards, I.K. and Wilford, D.J. (eds.). *Forests in the Balance: Linking Traditions and Technology. XXII IUFRO World Congress, 8-13 August 2005, Brisbane, Australia. Abstracts. International Forestry Review* 7(5), p. 174.

Rikala, J. 2003. *Spruce and Pine on Drained Peatlands – Wood Quality and Suitability for the Sawmill Industry*. University of Helsinki, Faculty of Agriculture and Forestry, Department of Forest Resource Management. Publications 35. 147 p.

Romberger, J.A., Hejnowicz, Z., Hill, J.F. 1993. *Plant Structure: Function and Development*. Springer-Verlag. 524 p.

Saarela, K.E., Harju, L., Rajander, J., Lill, J.O., Heselius, S.J., Lindroos, A., Mattsson, K. 2005. Elemental analyses of pine bark and wood in an environmental study. – *Science of the Total Environment*, 343(1–3): 231–241.

Saarman, E. 1998. *Puiduteadus* [Wood science]. Tartu. 247 p [In Estonian].

Saarsalmi, A., Mälkönen, E. 2001. Forest fertilization research in Finland: a literature review. – *Scandinavian Journal of Forest Research*, 16(6): 514–535.

Saikku, O. 1975. The effect of fertilization on the basic density of Scots pine (*Pinus sylvestris* L.). A densitometric study on the X-ray chart curves of wood. – *Communicationes Instituti Forestalis Fenniae*, 85: 1–49.

Saladis, J., Aleinikovas, M. 2004. *Pušų medienos fizinių ir mechaninių savybių kintamumas bei koreliaciniai ryšiai tarp jų*. [Variability and correlation of physical and mechanical properties of pine wood] – *Miškininkystė*, nr. 1(55). Lithuanian Forest Research Institute, Kaunas, pp 60–67.

Saramäki, J., Silander, P. 1982. Lannoituksen ja harvennuksen vaikutus männyn latvukseen [The effect of fertilization and thinning on the crown of pines]. – *Metsäntutkimuslaitoksen tiedonantoja* 52. 42 p [in Finnish].

Saranpää, P. 1994. Basic density, longitudinal shrinkage and tracheid length of juvenile wood of *Picea abies* (L.) Karst. – *Scandinavian Journal of Forest Research*, 9(1–4): 68–74.

Saranpää, P., Vapaavuori, E., Peltola, H. 2000a. Metsien käsittelyn vaikutus puuaineen ominaisuuksiin. Effect of forest management on wood quality. In: Paavilainen, L. (ed.). *Metsäalan tutkimusohjelma*, *Wood Wisdom*. Yearbook 1999. Report 2/2000, pp 178–184.

Saranpää, P., Pesonen, E., Sarén, M., Anderson, S., Siiriä, S., Serimaa, R., Paakkari, T. 2000b. Variation of the properties of tracheids in Norway spruce (*Picea abies* (L.) Karst.). In: Savidge, R.A., Barnett, J.R. and Napier R. (eds.). *Cell and Molecular Biology of Wood Formation*. BIOS Scientific Publishers Limited, Oxford, pp 337–345.

Saranpää, P. 2002. Kuusen kuituominaisuuksien vaihtelu [Summary: Both tree age and growth rate affect fibre properties.] *Työtehoseuran metsätiedote* 3/2002 (646). 4 p [in Finnish].

Sauter, U.H., Mutz, R., Munro, B.D. 1999. Determining juvenile-mature *wood* transition in Scots pine using latewood density. – *Wood and Fiber Science*, 31(4): 416–425.

Savidge, R.A. 2003. Tree growth and wood quality. In: Barnett, J.R. and Jeronimidis, G. (eds.). *Wood Quality and Its Biological Basis*. Blackwell Publishing Ltd, Oxford, UK, pp 1–29.

Schwappach, A. 1897. *Raumgewicht und Druckfestigkeit des Holzes wichtiger Waldbäume. 1. Die Kiefer*. Springer-Verlag, Berlin, pp 1–133.

Seco, J.I.F.G., Barra, M.R.D. 1996. Growth rate as a predictor of density and mechanical quality of sawn timber from fast growing species. – *Holz als Roh- und Werkstoff*, 54(3): 171–174.

Sellin, A. 1994. Sapwood–heartwood proportion related to tree diameter, age, and growth rate in *Picea abies*. – *Canadian Journal of Forest Research*, 24(5): 1022–1028.

Seppälä, K. 1976. Relationship between the stem diameter of tree at time of draining and their post drainage increment. – *Suo*, 27(3): 55–60.

Sipi, M., Rikala, J. 2000. Tree stands on peatland, quality of wood raw material and suitability for different use objects. In: *Proceedings of the IUFRO Congress Posters*. Malaisia, pp 191–192.

Skuodene, L. 2005. *Stress of Trees and Its Physiological Estimate*. ARX Baltica Print House, Kaunas. 40 p.

Smith, W.H. 1990. *Air Pollution and Forests: Interactions Between Air Contaminants and Forest Ecosystems*, 2nd Ed. Springer, New York, pp 147–180.

Staaf, H., Tyler, G. (eds.). 1995. *Effects of Acid Deposition and Tropospheric Ozone on Forest Ecosystems in Sweden*. Ecological Bulletins 44. Munksgaard International Publishers Ltd. Copenhagen, Denmark. 368 p.

Tamminen, Z. 1962. Fuktighet, volymvikt m.m. hos ved och bark. I Tall. [Moisture content, density and other properties of wood and bark. I Scots pine]. Skogshögskolan, Institutionen för virkeslära, Rapporter och Uppsatser 41: 1–118.

Tamminen, Z. 1964. Fuktighet, volymvikt m.m. hos ved och bark. II Gran. [Moisture content, density and other properties of wood and bark. II Norway spruce]. Skogshögskolan, Institutionen för virkeslära, Rapporter och Uppsatser, 47: 1–124.

Tiitta, M. 2006. Non-destructive methods for characterisation of wood material. Doctoral dissertation. University of Kuopio. 70 p.

Uusitalo, J. 2004. Heartwood and extractive content of Scots pine in Southern Finland: models to apply at harvest. – *Wood and Fiber Science*, 36(1), 3–8.

Van Lear, D. H., Saucier, J.R., Goebel, N.B. 1973. Growth and wood properties of loblolly pine on a Piedmont subsoil as influenced by early fertilization. – *Soil Science Society of America Journal*, 37(5): 778–781.

Varhimo, A., Kojola, S., Penttilä, T., Laiho, R. 2003. Quality and yield of pulpwood in drained peatland forests: pulpwood properties of Scots pine in stands of first commercial thinning. – *Silva Fennica*, 37(3): 343–357.

Veermets, K. 1963. Kuusepuidu mehhaanilistest omadustest. [About mechanical properties of spruce wood]. *EPA teaduslike tööde kogumik*, 33: 164–179 [in Estonian].

Veibri, U., Kokk, A. 1980. Hariliku männi puiduniiskuse aastaringne muutumine. [The yearly variation in wood moisture of Scots pine]. *EPA teaduslike tööde kogumik*, 128: 90–94 [in Estonian].

Veibri, U. 1982. Hariliku kuuse puiduniiskuse aastaringne muutumine. [The yearly variation of wood moisture in Norway spruce]. *EPA teaduslike tööde kogumik*, 142: 63–67 [in Estonian].

Verkasalo, E., Leban, J-M. 2002. MOE and MOR in static bending of small clear specimens of Scots pine, Norway spruce and European fir from Finland and France and their prediction for the comparison of wood quality. – *Paperi ja Puu*, 84(5): 332–340.

Verkasalo, E., Nylinder, M., Roos, A. 2005. Specific wood and timber properties, competitive ability and advanced conversion of Nordic Scots pine in mechanical wood processing. In: Johansson, B. and Larsson, B. (eds.). *Wood Material Science Year Book 2005*. Finnish-Swedish Research Programme 2003–2007, Report 1/2005. Stockholm, pp 43–51.

Werberg, K. 1930. Lüli- ja maltspuu suhe männil. [Heartwood and sapwood proportion of pine wood]. – Tartu Ülikooli *Metsaosakonna toimetised* nr. 17. 184 p [in Estonian].

Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S.O., Grahn, T., Hedenberg, Ö., Olsson, L. 2002. Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. – *Scandinavian Journal of Forest Research*, 17(4): 330–350.

Wimmer, R. 1991. Relations between growth ring parameters and density of Scots pine wood. – *Holzforschung und Holzverwertung*, 43: 79–82.

Wimmer, R., Downes, G.M. 2003. Temporal variations of the ring width–wood density relationship in Norway spruce grown under two levels of anthropogenic disturbance. *IAWA Journal*, 24(1): 53–61.

Wodzicki, T.J. 2001. Natural factors affecting wood structure. – *Wood Science and Technology*, 35(1–2): 5–26.

Zālītis, P. 1999. The productivity of drained pine forests and pinewood quality. – *Baltic Forestry*, 5(2): 2–7.

Yearbook Forest 2009. 2010. Compiled and edited by The Estonian Environment Information Centre, Tartu. 217 p.

Боровиков, А.М., Уголев, Б.Н. 1989. *Справочник по древесине*. Лесная промышленность, Москва, 296 с [in Russian].

Вярбила, В.В., Шлейнис Р.И. 1981. Влияние удобрения сосновых насаждений на качество древесины – *Лесное хозяйство*, 12: 8–11 [in Russian].

Звирбуль А.П., Некрасова Г.Н., Полубояринов О.И. 1976. Влияние удобрения сосновых насаждений карбамидом на качество древесины. – *Лесной журнал*, 6: 18–22 [in Russian].

Кузьмин, С.Р., Ваганов, Е.А., Кузьмина, Н.А., Милютин, Л.И. 2008. Особенности трахеид древесины у климатипов *Pinus sylvestris* L. (*Pinaceae*) в географических культурах. – *Ботанический журнал*, 93(1): 10–21 [in Russian with an English summary].

Литаш, Н.П., Рябоконь, А.П. 1984. Физико-механические свойства древесины в сосновых древостоях в связи с рубками ухода различной интенсивности. – *Лесное хозяйство*, 7: 66–68 [in Russian].

Матюшкина, А.П., Коржицкая, З.М., Козлов, В.П., Агеева, М.И., Васильева, Н.А., Голубева, Л.В. 1974. Характеристика древесины сосны обыкновенной в зависимости от интенсивности роста. *Лесные растительные ресурсы Карелии*. Петрозаводск, с. 120–132 [in Russian].

Минин Н.С., Москалева С.А. 1986. Влияние рубок ухода на физико-механические свойства древесины культур сосны. – *Лесной журнал*, 2: 68–71 [in Russian].

Михайличенко, А.Л., Садовничий, Ф.П. 1983. *Древесиноведение и лесное товароведение*. Высшая школа, Москва. 206 с [in Russian].

Некрасова, А.А. 1994. Свойства древесины хвойных пород в зависимости от условий произрастания. – *Лесное хозяйство*, 2: 22–24 [in Russian].

Перелыгин, Л.М., Уголев, Б.Н. 1971. *Древесиноведение.* Лесная промышленность, Москва. 286 с [in Russian].

Пикк, Я. 1988. Лесоводственная эффективность применения минеральных удобрений на осушенных торфяно-болотных почвах в Эстонской ССР. Автореферат диссертации на соискание ученой степени кандидата сельскохозяйственных наук. Минск. 15 с [in Russian].

Полубояринов, О.И., Сорокин, А.М., Фёдоров, Р.Б. 2000. Базисная плотность древесины и коры лесообразующих пород европейской части России. – *Лесное хозяйство*, 5: 35–36 [in Russian].

Рябоконь А.П., Литаш Н.П. 1981. Физико-механические свойства древесины сосны в культурах разной густоты. – *Лесоведение*, 1: 39–45 [in Russian].

Сээмен, Х. 1987. Применение минеральных удобрений в сосняках-брусничниках и сосняках-черничниках Эстонской ССР. Автореферат диссертации на соискание ученой степени кандидата сельскохозяйственных наук. Минск. 15 с [in Russian].

Яхонтов, И.А. 1913. Технические свойства сосновой древесины из лесов Люблинской, Варшавской и Петроковской губернии. – *Труды по лесному опытному делу в России*, 49. 110 с [in Russian].

SUMMARY IN ESTONIAN

KASVUTINGIMUSTE MÕJU HARILIKU MÄNNI (*Pinus sylvestris* L.) PUIDU FÜÜSIKALIS-MEHAANILISTELE OMADUSTELE EESTIS

Sissejuhatus

Harilik mänd on Eestis enimlevinud puuliik ja seetõttu on selle kasvatamise ning ratsionaalse kasutamise vastu suur majanduslik huvi. Kahjuks piirdub see rohkem männipuidu töötlemise ja turustamise kvantiteediga, kvaliteedinäitajad ning nende uurimine on jäänud tagaplaanile. Saematerjali tugevusklasside määramiseks fikseerivad erinevate maade standardid mehaaniliste tugevusomaduste piirid (painde-, tõmbe-, survetugevus, elastsusmoodul, tihedus jm), sest täpsem teave annab parema ülevaate puitmaterjali hinnapakkumise kohta. Eestis on puidu omaduste kindlaksmääramisega tegeldud suhteliselt vähe. Käsiraamatute ja erinevate normide võrdlustabelites puuduvad Eestis kasvavate puuliikide puidu omaduste andmed. Sama puuliigi puidu omadused sõltuvad muuhulgas üsna palju geograafilisest piirkonnast ja kasvutingimustest, mistõttu ei saa naabermaade uurimistulemusi sageli otse üle võtta ning seepärast on vaja kohapealseid uuringuid.

Puude kasvutingimuste parandamiseks ja puidu juurdekasvu intensiivistamiseks puistutes on metsakasvatuses mitmeid võtteid. Enam levinud on puude kasvuruumi laiendamine puistute harvendamisega, toitainete kättesaadavuse parandamine liigniiske metsamaa kuivendamisega ja lisatoitainete andmine mineraalväetiste näol. Puude kasvu mõjutab oluliselt ka tolmu ja gaasidega saastatud õhk. 20. sajandi lõpu arvukad uuringud küll kirjeldavad happelise õhusaaste tekitatud kahju metsaaladele, kuid aluselisele saastele ei ole nii palju tähelepanu pööratud. Aluselise tolmusaaste mõju kohta tüvepuidu struktuurile ja tehnilistele omadustele puudub kättesaadav teave.

Käesoleva töö eesmärk on koondada Eestis kasvava hariliku männi puitu käsitlevate teadusuuringute tulemused ning analüüsida männipuidu omaduste sõltuvust kasvukohast ja metsakasvatuslikest meetoditest.

Töös püstitati järgnevad hüpoteesid:

1. parimad tehnilised omadused on viljakal kasvukohal kasvanud hariliku männi puidul;
2. metsakasvatuslike meetodite mõju männipuidu tehnilistele omadustele on varieeruv;
3. aluseline tolmusaaste mõjutab negatiivselt hariliku männi puidu tehnilisi omadusi.

Käesoleva doktoritöö eesmärgid on järgmised:

- määrata mõningate füüsikaliste ja mehaaniliste omaduste varieerumine männi peamistes kasvukohatüüpides (**I**, **IV**, **V**, **VI**);
- uurida puidu omaduste muutumist männitüve radiaal- ja pikisuunas (**I**, **V**, **VI**);
- uurida juveniilpuidu omadusi männitüves (**V**);
- selgitada välja mõnede metsakasvatuslike võtete (kuivendamine, väetamine) mõju männipuidu omadustele (**I**, **IV**);
- teha kindlaks pikaajalise tolmusaaste mõju männipuidu omadustele (**II**, **III**).

Materjal ja metoodika

Antud uurimustööks valiti looduses välja 41 erinevat männipuistut, mis paiknesid pohla, mustika, jänesekapsa-mustika, sambliku, kanarbiku, kõdusoo, kuivendatud madalsoo, kuivendatud siirdesoo, kuivendatud raba ja raba metsakasvukohatüübis. Neist kaheksal katsealal uuriti väetamise ja neljal tolmusaaste mõju männipuidu omadustele.

Mudelpuude valik puistus toimus ISO 4471:1982 nõuete kohaselt. Enne langetamist tähistati mudelpuudel põhjapoolne külg. Langetatud puudel mõõdeti pikkust, kümne viimase aasta ladvakasvu, elusa võra algust ja võra laiust ning tüve läbimõõte kõrguselt $h_{1,3}$, $h_{1/4}$, $h_{1/2}$ ja $h_{3/4}$. Uurimuse tarbeks langetati 202 mudelpuud, millest lõigati kõrguselt $h_{1,3}$, $h_{1/2}$ ja $h_{3/4}$ kokku 606 proovipakku pikkusega 1,2 m. Samal päeval lõigati igalt pakult ketas, millel määrati suhteline puidu niiskus lõuna- ja põhjaküljel ning keskosas. Hiljem tehti ketastel kindlaks lüliosa läbimõõt, kooreta läbimõõt ja aastaringide arv.

Proovipakkudest saeti lauad standardi ISO 3129:1975 kohaselt. Nendest valmistati pärast kuivatamist vastavate standardite järgi 7360 katsekeha paindetugevuse, paindeelastsusmooduli, survetugevuse, otspinna kõvaduse, aastarõngaste laiuse, sügispuidu protsendi ja absoluutkuiva puidu tiheduse määramiseks.

Katsed tehniliste omaduste määramiseks viidi läbi järgmiste standardite kohaselt: paindetugevus ISO 3133:1975, paindeelastsusmoodul ISO 3349:1975, survetugevus ISO 3787:1976, otspinna kõvadus ISO 3350:1975, puidu tihedus ISO 3131:1975 ja puidu niiskus ISO 3130:1975 järgi.

Tulemused

Puude kasvutingimused erinevates kasvukohtades mõjutavad oluliselt puidu omadusi. Männipuidu omaduste varieeruvus on suur nii puu tüves, puistus kui ka puistute vahel.

Puidu niiskus sõltub otseselt kasvukoha tingimustest. Niiskust on rohkem soomännikutes kui pohla- ja mustikamännikutes kasvavates puudes. Soomänni lülipuidus on puu poolel kõrgusel ja kõrgemal niiskussisaldus suurem kui rinnakõrgusel. Maltspuidus on rohkem niiskust tüve lõunaküljel ja see on selgelt eristatav võra piirkonnas.

Nõmmemetsades kasvanud hariliku männi puit on paremate ning rabades kasvanud halvemate omadustega: keskmine tihedus on vastavalt 513–545 kg/m^3 ja 414–464 kg/m^3, paindetugevus vastavalt 97–100 MPa ja 71–83 Mpa ning survetugevus vastavalt 55–56 Mpa ja 41–52 Mpa. Puu kõrgus määrab tugevusomaduste varieerumise tüve alumises pooles. Mida kõrgem tüvi, seda väiksem on tugevusomaduste varieerumine ladva suunas.

Kasvutingimuste muutmine mineraalväetiste lisamisel mõjutab aastarõngaste laiust suhteliselt lühikesel väetamisjärgsel perioodil ja võib mõnel juhul kutsuda esile puidu tiheduse muutumise paari protsendi ulatuses. Puidu paindetugevuse varieeruvus on sedavõrd suur, et tiheduse ja sügispuidu protsendi muutus väetamise tagajärjel ei kutsu puidu paindetugevuses esile suuri muutusi. Survetugevus võib mõnel juhul väheneda kuni 6%. Väetamine võib suurendada männikute tootlikkust, kuid sellega ei pruugi paraneda puidu kvaliteet. Kasvu parandamine suurendab okste ja okaste toodangut ning kasvu intensiivsust väiksema viljakusega kasvukohas, millest tulenevalt suureneb puistu harvendamise vajadus. Korduvalt väetatud keskealise puistu laasumine väheneb ja seetõttu halveneb ka esimese palgi kvaliteet. Suurem radiaalne juurdekasv pärast väetamist suurendab sügispuidu väiksema osakaaluga maltspuidu osa tüves. Väetamine toob kaasa puidu tiheduse vähenemise ja tehniliste omaduste halvenemise, kuid ei mõjuta tegelikult lülipuidu tekkeprotsessi kiirust.

Metsa kuivendamine vähendab puidu tihedust ja sügispuidu osa aastarõngas. Selline efekt ilmneb ainult esimestel kuivendamisjärgsetel aastatel. Hilisem mõju on vastupidine – sügispuidu osa ja tihedus suurenevad ning lõpuks saavutatakse paremad tehnilised omadused. Puidu tiheduse suurenemisega kaasneb maltspuidu suurem paindetugevus kuivendatud rabamännikus üksnes rinnakõrgusel ja intensiivse kuivendamisega rabas ka võra piirkonnas.

Aluseline keskkond ja aluselise tolmu pikaajaline heide tsemendivabrikutest on vähendanud ladva ja külgvõrsete ning tüve radiaalset juurdekasvu, kuid võib stimuleerida lülipuidu teket, puistu varasemat küpsemist ja vananemist. Sellega kaasneb kasvava puu niiskuse vähenemine. Antud uuringu põhjal saab väita, et aluselisel pinnasel, kus toitained ei ole tasakaalus, on otsene mõju puude kasvule ja tüvepuidu kvaliteedile. Mõõdukalt saastunud keskkond stimuleerib kasvava männi radiaalset juurdekasvu, kuid see ei too kaasa sügispuidu protsendimäära langust ega puidu tiheduse vähenemist. Saastunud puistu puidu paindetugevus ja survetugevus pikikiudu suurenevad. Mõnel juhul on täheldatav ka otspinna kõvaduse suurenemine. Puidu juurdekasv on suure tolmusaaste piirkonnas aeglasem, aastarõngad kitsamad ning tihedus ja sügispuidu osakaal suuremad võrreldes saastamata aladel kasvava puiduga. Puidu kaalutud keskmised tugevusnäitajad on väga suure saastega aladel tüve ristlõikes väiksemad kui saastamata puistutes.

Juveniilpuitu kasutatakse oma väiksemate tugevusnäitajate pärast vähem enamikus puidutöötlemise valdkondades. Juveniilpuidu tihedus moodustab 83,8% perifeerse maltspuidu tihedusest, paindetugevus on vastavalt 62% ja otspinna kõvadus 81,2%. Juveniilpuidu survetugevus pikikiudu väheneb ladva suunas kiiremini kui maltspuidu survetugevus.

Võrreldes lõunapoolsete naaberriikidega on Eestis head võimalused kasvatada juveniilpuidu väikese osakaalu ja heade omadustega männipuitu, sest uuritud mudelpuudel moodustas juveniilpuit suhteliselt vähem aastarõngaid.

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I

ORIGINAL PUBLICATIONS

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Second thinning Scots pine wood properties in different forest site types in Estonia.
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Second Thinning Scots Pine Wood Properties in Different Forest Site Types in Estonia

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Kask, R. and Pikk, J. 2009. Second Thinning Scots Pine Wood Properties in Different Forest Site Types in Estonia. *Baltic Forestry*, 15 (1): 97–104.

Abstract

The properties of Scots pine (*Pinus sylvestris*) wood were studied in 27 stands growing on sites of 9 different types in Estonia. Data were collected from 184 trees aged 60-80 years.

Pine wood is the strongest growing on heath and the weakest on raised bogs, its average density being 513-545 kg/m^3 and 414-464 kg/m^3, bending strength 97-100 MPa and 71-83 MPa and compression strength 55-56 MPa and 41-52 MPa, respectively. The heartwood percent is greater in pines grown on more fertile sites. Site type is a highly generalising predictor of strength properties, so site index must also be taken into account. On the contrary, site index may serve as a good predictor of relative strength indicators but only to a limited extent, within the range of adjoining types in the ordination scheme of forest site types.

Key words: Scots pine, site type, site index, heartwood, density, bending strength, compression strength, hardness

Introduction

Differences in properties of Scots pine (*Pinus sylvestris*) wood depending on growth site conditions have been observed for more than a century. The higher the nutrient content of the soil, the better the wood technical properties, other conditions being equal (Hartig1901). According to Jahntov (1913), deterioration in soil conditions leads to decreased wood density and compression strength. Beginning in the late 19th Century, researchers (Schwappach 1897, Omeis 1895, Werberg 1930, Kõresaar 1938) have correlated wood properties with growth site index. One of the best indicators of growth site fertility is site index; however, pine forests of site index 4-5 grow both in peatlands and dry heaths, where nutrition conditions vary widely. The effects of these conditions on wood properties are an issue of interest to today's theoreticians and practician. Averaged data on wood properties of main tree species have been concentrated into numerous handbooks and catalogues; however, they predominantly deal with mature trees. Fairly frequently, the data available characterise wood strength at breast height alone, disregarding the vertical variation of strength indicators in tree trunks.

Pine is a dominant tree species in Estonia's forests, taking up 33.6% of the total forest area and 29.1% of the growing stock. The average per-hectare volume was 104 m^3/ha in 1958 and reached 232 m^3/ha in 2006 (Yearbook…2008). Year by year, both wood supply, and demand, primarily for high-quality pine timber, are increasing. Yet the recorded data concerning the quality and properties of Estonian tree species are extremely scarce, and at times controversial.

In Europe, research has been focused on delving deeper into the wood properties of the most widespread tree species and exploring the physiological processes in wood formation (Wilhelmsson *et al.* 2001, Aleinikovas and Grigaliūnas 2006, Jelonek *et al*. 2006, Mandre *et al.* 2007). The structure and properties of wood are affected by genetic, environmental and anthropogenic factors acting during the formation of wood cell and tissue (Lindeberg 2001, Bektas *et al.* 2003). A number of authors (Andrews *et al.* 1999, Finér and Kaunisto 2000) have pointed out differences in the levels of nutrients and other elements found in stemwood, depending on the growth site. And the degree of nutrient retranslocation from senescing sapwood may be influenced by soil nutrient availability.

As early as 1897, Wijkander found that the technical properties of pine wood reach their maximum in annual rings formed at the age of 61-90. For this reason in the last ten years, pine wood properties have been researched in Estonia's younger, 60-80-year-old pine forests (Pikk *et al*. 2004, Mandre *et al*. 2007, Kask *et al.* 2008). Moreover, a fifth of the pine wood obtained comes from maintenance felling.

The rapidly changing economy, ever-modernising wood processing technology, warming climate, environmental pollution, etc. creates the need for constant regional research at stand, tree, macro- and microlevels. The objective of this paper was to concentrate the research results on pine wood in Estonia and summarize the variation in the properties of wood obtained from the second commercial thinning on the main Scots pine site types.

Materials and methods

The selected pine stands were situated on the most widespread types of pine sites in Estonia (Table 1). The existing classification of Estonian forest site types is from Lõhmus (1984). According to this classification, forests are divided into 22 forest site types. Each site type has as many subtypes as it has neighbouring site types (Lõhmus 1995). The site type index determines the average height of a stand at the age of 50.

Table 1. The number and characteristics of felled sample trees by forest site types

Site type	Site index	Number of sample plots	Tree age	DBH, cm	Height, m	Felled sample trees
Cladonia	3.5	2	81.5	18.9	17.3	12
Calluna	4.0	1	70.0	18.5	15.0	6
Rhodococcum	1.6	5	71.8	20.3	21.3	34
Myrtillus	1.4	10	70.7	24.0	22.7	60
Dry swamp	2.9	2	80.0	21.9	19.0	12
Drained birch fen	3.7	1	70.0	16.6	14.4	8
Drained transitional bog	3.6	2	70.0	20.7	17.7	12
Drained raised bog	5.2	2	88.0	15.0	14.1	24
Raised bog	5.3	2	77.5	14.1	10.9	16

In each of the 27 stands selected, 6-12 sample trees were felled. From these, specimens were prepared in compliance with international standards. More trees were felled in stands with a smaller average breast-height diameter (DBH). According to Saladis and Aleinikovas (2004), no less than six trees must be examined in a single forest stand in order to obtain wood properties with 10% accuracy. Sample blocks for determining wood properties were cut at the height of 1.3m ($h_{1.3}$), at half tree height ($h_{1/2}$) and at three-quarters of tree height ($h_{3/4}$); these stem sections roughly represent the butt log, the second log and the pulpwood, respectively

The following properties were subjected to study: annual ring width, latewood proportion, heartwood percent, oven-dry density, bending strength, compression strength and end-grain surface hardness.

The specimens for determining wood density were prepared in compliance with the requirements of ISO 3130-1975 and ISO 3131-1975. Experiments for determining mechanical properties were prepared and conducted in conformity with ISO standards 3131-1975, 3133-1975, 3787-1976 and 3350-1975. Strength tests were carried out using the universal test press INSTRON 3369.

The WinDENDRO™ software was used to measure annual ring widths and latewood proportions. Oven-dry density was determined in 7,360 specimens upon reaching a constant weight at 103 ʢC.

Seven thousand three hundred and sixty specimens (7,360) were prepared for the tangential static bending strength test and the same number for determining the compression strength parallel to grain. A total of 4,416 experiments were performed to establish the end-grain hardness. The mechanical testing took place with wood moisture content 8±0.5%. In the present paper, all the mechanical properties were reduced to a 12% wood moisture level. Weighted average strength indicators for each stand at three different heights, and then strength indicators were found for all the stemwood. For each site type, the vertical reduction of tree trunk strength properties was calculated in percentages.

Differences in the average wood properties between the site types were estimated using one-way ANOVA. The critical *P*-value was 0.05. Statistical calculations were performed with Excel 2003 (Microsoft Corp., USA). Regression trendlines and R-squared (R^2) were calculated to test the relationships between wood density and site index.

Results

The test results reveal great variations, which were due to the different horizontal and vertical structure of each individual tree trunk. Apart from that, wood formation during the growing season had been influenced by changes in growth conditions (thinning, draining, insect damage).

The weighted average stem strength indicators of the pine forests researched at three different heights were widely divergent (Table 2). The annual ring width increased but all the other strength indicators decreased towards the crown. The decrease was significantly more intensive than from breast height to half tree height than for $h_{3/4}$. Particularly great was the decrease in heartwood proportion in the crown part of the stem. Correlation between the strength indicators given in Table 2 was very strong (R= 0.85-1.00). A remarkable correlation between oven-dry density and site index was found (Figure 1).

The pine latewood at breast height was 30-43%. At half tree trunk height the proportion of latewood was significantly smaller, 22-33%, and, at three-quarters of tree trunk height there is even less latewood, 18-32%.

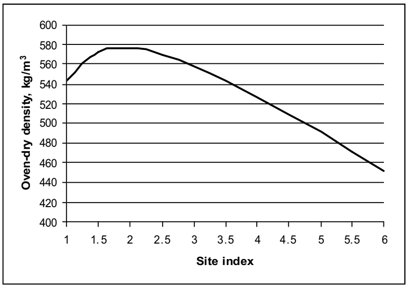

Figure 1. The oven-dry density of pine wood on DBH in different site index classes

Table 2. Wood average properties at three different stem heights and their alteration towards the top (%)

Relative height	Growth ring width, mm	Late-wood, %	Heart-wood, %	Oven-dry density, kg/m^3	Bending strength, MPa	Compress-ion strength, MPa	End-grain hardness, MPa
$h_{1.3}$	1.3	40.5	46.4	540.8	104.1	60.2	40.9
$h_{1/2}$	1.9	31.8	19.7	458.2	82.0	50.1	35.9
$h_{3/4}$	2.4	27.7	4.4	434.6	71.8	45.0	34.5
Alteration, %							
$h_{1.3}…h_{1/2}$	44.1	-21.5	-25.4	-15.3	-21.2	-16.7	-12.3
$h_{1/2}…h_{3/4}$	22.3	-12.8	-77.8	-5.2	-12.5	-10.1	-3.7

An analysis by individual site types revealed significant differences in stemwood strength indicators. Stands growing on fresh and dry soils showed good averages for stem strength indicators. The same indicators, however, were poor for trees growing in swamps and bogs. An exception among the technical properties appeared to be end-grain hardness, which manifested greater variations than the other characteristics; according to our findings, its variations were relatively greater on site types with poorer fertility (Table 3).

Variations in strength indicators between the site types were notable. As could be expected, they were greater in annual ring width and heartwood proportion. As for the other properties, the variations remained within the range of 8.4-10.9%.

The alteration of strength properties along the stem in percent per current metre from breast height to half tree height and then to $h_{3/4}$ also varied widely (Table 4), depending on the site and site index. The percent of per-metre deterioration of the properties up to half tree height was smaller in stands with best site index (up to class 3).

Table 4. The longitudinal decrease of strength properties (percent per meter)

Site type	Site index	Oven-dry density		Bending strength		Compression strength		End-grain hardness	
		$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$
Cladona	3.5	2.8	0.4	3.4	3.1	2.8	3.6	2.4	0.0
Calluna	4.0	3.0	1.8	3.7	4.4	3.5	5.1	2.4	2.2
Rhodococcum	1.6	2.2	1.0	2.4	3.0	2.3	2.1	1.8	0.2
Myrtillus	1.4	1.8	1.1	2.3	2.0	1.6	2.5	1.6	2.6
Dry swamp	2.9	2.3	0.3	2.7	1.9	2.2	0.9	0.9	0.7
Drained birch fen	3.7	0.7	0.0	3.6	1.4	2.1	1.9	1.0	0.9
Drained transitional bog	3.6	1.8	0.0	3.0	0.5	2.0	1.7	1.6	0.0
Drained bog	5.2	3.8	0.0	3.3	5.5	3.4	3.1	1.4	0.2
Raised bog	5.3	5.1	1.3	3.4	10.3	2.4	5.6	2.1	0.0
Average	3.5	2.6	0.7	3.1	3.7	2.5	3.2	1.7	0.7

The relation between longitudinal decrease of bending and compression strength and site index is notable. The relation is weak between decrease of hardness and site index (Figure 2).

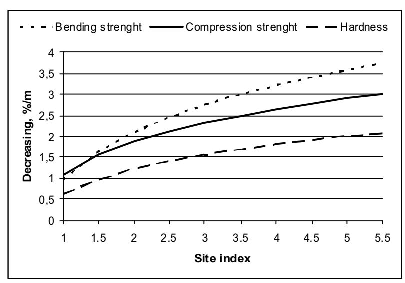

Figure 2. The longitudinal percent-per-meter decreasing of strength properties in different site index classes

Table 3. Pine stem average strength properties and heartwood proportion by different forest site types

Site type	Site index	Stem average						
		Odd, kg/m^3	Bs, MPa	Cs, MPa	Egh, MPa	Arw, mm	Lw, %	Hw, %
Cladonia	3.5	513±10	100.2±2.3	54.7±0.9	37.2±1.5	1.15±0.05	33.9±1.2	17.2±3.8
Calluna	4.0	545±12	97.1±4.1	55.7±1.7	36.9±1.7	1.42±0.06	35.8±1.1	14.3±2.1
Rhodococcum	1.6	479±14	86.9±4.3	56.4±2.8	27.1±1.0	1.71±0.08	31.9±1.4	17.3±3.2
Myrtillus	1.4	482±15	89.1±4.4	54.8±3.0	29.7±0.9	1.92±0.08	32.8±1.5	25.2±4.3
Dry swamp	3.3	464±12	80.2±3.0	49.8±1.5	31.9±1.1	1.70±0.05	35.5±1.0	21.5±1.7
Drained birch fen	3.7	446±15	79.3±4.5	48.7±2.3	34.2±1.5	1.65±0.09	35.9±2.0	13.2±2.1
Drained transitional bog	3.6	447±11	83.2±3.7	44.5±1.2	35.2±1.1	1.54±0.12	34.5±1.1	17.4±1.9
Drained raised bog	5.2	450± 8	77.7±2.0	52.1±1.1	34.7±1.4	1.62±0.06	31.3±0.9	10.7±1.7
Raised bog	5.3	414±13	71.6±3.4	41.4±1.8	33.7±1.6	1.54±0.06	27.0±1.1	7.1±1.6
Variation,%		8.4	10.9	10.3	9.9	13.5	8.6	34.1
ANOVA p-value		<0.0001	<0.0001	<0.0001	0.0025	<0.0001	<0.0001	<0.0001

Odd – Oven-dry density, Bs – Bending strength, Cs – Compression strength, Egh – End-grain hardness, Arw – Annual ring width, Lw – Latewood, Hw – Heartwood

Discussion and conclusions

The mechanical properties of wood are strongly correlated with its physical properties, the most important of which are the wood density, latewood proportion in annual ring and annual ring width. However, the great variations in our research results demonstrate that they are insufficient for estimating the mechanical properties of wood where growth rates are the same but growth conditions are different. Maybe consideration must also be given to fibre length, cell wall thickness, growth tensions, the levels of various elements and compounds, *etc.*

In Scots pine, the heartwood differs from sapwood by a number of properties and by chemical composition. Sapwood/heartwood proportions have an effect on technological properties: moisture content, density, shrinkage and water-vapour diffusivity (Allegretti *et al.* 1999). For this reason, heartwood and the phenomenon of its formation has been studied from various aspects (Ogner and Bjorn 1988, Helmisaari and Siltala 1989, Gjerdrum 2003). According to Bamber (1976), the heartwood formation is a developmentally controlled process functioning as a regulator of the amount of sapwood in the trunk, to keep it at the optimal level. According to the so-called "pipe model theory" (Shinozaki *et al*. 1964), the sapwood functions to guarantee the movement of required amounts of nutrients in the stem cross-section as determined by crown size. In this connection, age is the main factor in heartwood formation (Gjerdrum 2003). The correlation between the growth site and the heartwood content is weak (Björklund 1999). Additionally, the variation in the heartwood content between trees within the same DBH-class, growing in the same stand, is higher than the variation between stands.

Among the indicators researched in this paper, the heartwood proportion manifested the greatest variations between the site types as well as within a concrete site type (Table 2). For instance, in one *Myrtillus* site type stand, the heartwood content was 15% while in another it was 30%, although the average breast height diameter and the height of the stands as well as the stand densities were almost identical. If, however, the heartwood percent is the best indicator of tree maturity (Kärenlampi and Riekkinen 2002), and if the heartwood content is as widely varying under similar growth conditions as our findings show, it cannot be the best property to evaluate maturity.

Normally, the heartwood percent is higher under better growing conditions. Thus, our findings have not confirmed the position (Björklund 1999) that the heartwood formation is little affected by where it is grown, and only to a limited extent affected by how it is grown. Additionally, the vertical range of the heartwood may be affected by a number of factors, of which the tree crown appears to be the most important (Jelonek *et al.* 2006).

Sapwood area significantly decreased with decreasing soil moisture. According to some results, the pipe model theory is not valid (Mäkelä and Vanninen 2001). However, according to Rikala (2003) there is no clear evidence that the heartwood proportions of peatland trees are higher than those of trees grown on mineral soil sites. The heartwood percent was the lowest in our bog pine forests, where the soil moisture is high, stand density low and the tree crown volume is relatively big.

Wood density has the greatest influence on mechanical properties. According to Sipi and Rikala (2000), the basic density and amount of heartwood depend, *e.g.*, on geographic location, age and growth rate. At one and the same latewood percent and moisture level the density of the heartwood is usually greater than that of sapwood due to various substances (waxes, resins, tannins, *etc.*) accumulating in heartwood. As a result of the heartwood formation, the density of heartwood rises by 6-8% (Werberg 1930). However, wood density is often different at one and the same latewood percent. For instance, when comparing the density of site index 4 heath pine wood and that of the swamp pine wood of the same site index and latewood percent, the density of the latter was significantly lower (Table 3). It is known that the correlation between the growth site and the latewood content is weak (Björklund 1999). Here, consideration must be given to the effect of growing conditions, primarily the nutritional environment, on the accumulation of the chemical elements, which has been addressed in a number of studies (Helmisaari and Siltala 1989, Ogner and Bjorn 1988, Cave and Walker 1994, Andrews *et al.* 2004). Thus, in Finland the wood density of Scots pine increases from north to south while the opposite is true for spruce (Hakkila 1979, Kärkkäinen 1985).

Owing to variations in wood density, an analogous increase is not observable on the relatively small territory of Estonia. We can only note that the average pine wood oven-dry density in our experiments (471 kg/m^3) was similar to that of southern Finland, 470 kg/m^3 (Hakkila 1979). Surprisingly high is pine wood density in Poland, 540 kg/m^3 at the wood moisture level of 10% (Helinska-Raczkowska and Molinski 2003).

Noteworthy is the dependence of breast-height wood density on site index in some types of growth sites (Figure 1). One can see that due to intensive growth on very fertile sites, wood density there remains lower than on fresh sites with lower fertility. In a stand growing on mineral soils of a high site index

(1a) one can observe lower strength indicators, which is confirmed by data from the literature (Ericson 1960, Björklund and Walfridsson 1993). Hence, the site index is not a good wood oven-dry density predictor. According to our data, the strength of the relationship between stand average density and site index is characterised by determination coefficient R^2= 0.60.

The mechanical properties of softwoods decrease remarkably with increasing growth rate. The growth rate has a large effect on the mechanical properties, which can be accounted for by the affected oven-dry density. In addition to this indirect effect through specific gravity, the growth rate still has an additional effect on the mechanical properties that cannot be explained by oven-dry density (Zhang 1995).

The research results by site types (Table 3) manifest the dependence of mechanical properties (bending and compression strength and hardness) on wood density, while the latter was in turn largely influenced by the amount of latewood contained in the wood. As a rule, when a tree grows the amount of latewood in the annual ring at the same height is greater in each successive year than in the previous year, as a consequence of which the wood of older stems on average is denser and stronger than that of young trees.

The wide variations in the results were due to the heath pine forests, wood density and several strength properties which exceeded the respective indicators for other growth sites, even if the site index was relatively low (3.5-4). As another exception, Veermets (1960) points out the alvar pine forests, the wood compression strength which does not depend on wood density, as it does on sites of other types.

The strength properties of wood on sites of dry mineral soil types were better than on fresh soil sites. Peat soils, however, exhibited better wood strength properties on drained, more fertile sites. The strength properties of pine wood were clearly poorer on our low-fertility wet sites, as in Finland (Rikala 2003).

Site type is a highly generalising predictor of strength properties, so site index must also be taken into account. Site index may serve as a good predictor of wood relative strength indicators but only to a limited extent, within the range of adjoining types in the chart of ordinated forest site types.

The formation of wood properties is influenced by a number of silvicultural measures. Draining reduces basic density and the latewood proportion (Rikala 2003). In Estonia, such an effect is observable only in post-draining years, when draining results reduced the basic density and the latewood proportion. Later, the effect is opposite: the latewood proportion and the density increase and ultimately good results are achieved, as in Russia (Perelygin and Ugolev 1971).

Of mechanical properties, variations are the greatest in end-grain surface hardness. Hardness is highly dependent on grain direction. The strength of the radial and tangential surface is directly connected with the end-grain surface. For example, according to Mihailit□enko and Sadovnit□i (1983), end-grain strength exceeds tangential and radial surface hardness by 40%. According to Holmberg (2000), the hardness value of a radial surface, *i.e.* when load is applied in tangential direction, is about half the end-grain surface hardness.

In this research, greater variations in end-grain surface hardness were manifested in wood grown on more fertile sites, where, due to the greater width of annual rings, the test press ball might hit only early- or latewood. Accordingly, a smaller or greater result was obtained. The hardness of a wood end-grain surface with narrower annual rings therefore manifested less variation and was often greater than the average. With particularly wide annual rings, the probability of the ball hitting early wood was greater and the test result was therefore smaller.

The decrease in pine wood density and strength properties towards the tree-top has been widely covered in the literature (Veermets 1960, Sipi and Rikala 2000, Repola 2006). According to Repola (2006), the difference in wood density between the butt and the top in Scots pine stems is more than 100 kg/m^3. In this study, wood density in Scots pine decreased from $h_{1.3}$ to $h_{3/4}$, and the difference in wood density in pine stems was over 106 kg/m^3. This result is in agreement with previous studies (Hakkila 1966, Björklund 1984, Repola 2006).

In stands of site index 1 and 2 wood density and strength properties decreased towards the top by 1-2% per metre, whereas in stands of site index 5 the wood density and bending strength on average decreased by 3.5% per metre. On poorer sites, the reduction in compression strength and end-grain surface hardness towards the top was less intensive (3%). The extent of deterioration in the properties of wood obtained from tree stems depending on the site index is characterised in Figure 2. Of mechanical properties, bending strength had the strongest correlation with site index (R^2=0.75).

The longitudinal percent-per-metre reduction of bending strength, compression strength and end-grain surface hardness in tree stem is smaller on more fertile sites.

As early as in 1897, Wijkander in Sweden investigated pine technical properties at the heights of 1, 3, 10 and 12 m and ascertained that compression strength drops by 1.6% per current metre within the range of 1-3 metres, by 1.7% at 3-10 metres and by 1.2%

at 10-12 metres. The overall decrease from 1 to 12 metres was 16%. Apparently, the test material was obtained from a relatively fertile site type.

We have to take into account that the site index is determined based on age and height. The stands studied were of relatively similar ages, falling within one age group. In a sense, therefore, the site indexes given in the figures also indicate the different heights of the stands. The tree height, in turn, determines the variation of strength properties in the lower half of the stem. The longer the stem, the less the variance in strength properties of its timber.

In Estonia, the second thinning Scots pine wood is the strongest growing on heath and the weakest on raised bogs, its average density being 513-545 kg/m^3 and 414-464 kg/m^3, bending strength 97-100 MPa and 71-83 MPa and compression strength 55-56 MPa and 41-52 MPa, respectively.

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References

Aleinikovas, M. and Grigaliūnas, J. 2006. Differences of pine (*Pinus sylvestris* L.) wood physical and mechanical properties from different forest site types in Lithuanian. *Baltic Forestry* 12(1): 9–13.

Allegretti, O., Bernabei, M., Negri, M. and Piutti, E. 1999. Sapwood-heartwood proportion related to same technolocical properties in *Picea abies* (L.) Karst. Proceedings of the Fourth International Conference on the Development of Wood Science, Wood Technology and Forestry. 14-16 July, 1999, Missenden Abbey, UK. p. 475-485.

Andrews, J.A., Siccama, T.G. and Vogt, K.A. 1999. The effect of soil nutrient availability on retranslocation of Ca, Mg and K from senescing sapwood in Atlantic white ceder. *Plant and Soil* 208(1): 117-123.

Bamber, R.K. 1976. Heartwood, its function and formation. *Wood Science Technology* 10: 1–8.

Bektas, I., Alma, M.H., Goker, Y., Yuksel, A. and Gundogan, R. 2003. Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. *Forest Products Journal* 53(4): 48-50.

Björklund, L. 1984. Pulpwood basic density and it's dependence on different factors. Swedish University of Agricultural Sciences, Department of Forest Products. Report 155. 29 p.

Björklund, L. 1999. Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. *Silva Fennica* 33(2): 119-129.

Björklund, L. and Walfridsson, E. 1993. Properties of Scots pine wood in Sweden – Basic density, heartwood, moisture and bark content. The Swedish University of Agricultural Sciences. Department of Forest Products. Report 234: 1-67.

Cave, I.D. and Walker, J.C.F. 1994. Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. *Forest Products Journal* 44(5): 43-48.

Gjerdrum, P. 2003. Heartwood in relation to age and growth rate in *Pinus sylvestris* L. in Scandinavia. *Forestry* 76(4): 413-424.

Ericson, B. 1960. Studies of the genetical wood density variation in Scots Pine and Norway Spruce. Statens skogsforskningsinstitut, avdelningen för skogsproduktion, rapport 4. Forest Research Institute of Sweden, Department of Forest Yield Research. Report 4, 52 p.

Finér, L. and Kaunisto, S. 2000. Variation in stemwood nutrient concentration in Scots pine growing on peatland. *Scandinavian Journal of Forest Research* 15(4): 424-432.

Hakkila, P. 1966, Investigations on the basic density of Finnish pine, spruce and birch wood. *Communications Instituti Forestalis Fenniae* 61(5): 98 p.

Hakkila, P. 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. *Communications Instituti Forestalis Fenniae* 96(3): 1-59.

Hartig, R. 1901. Holzuntersuchungen. Altes und Neues. Springer-Verlag, Berlin, 99 S.

Helinska-Raczkowska, L. and Molinski, W. 2003. The effect of the Janka ball indentation depth on the hardness number determined for selected wood species. *Folia Forestalia Polonica* 34:27-36.

Helmisaari, H-S. and Siltala, T. 1989. Variation in nutrient concentrations of *Pinus sylvestris* stems. *Scandinavian Journal of Forest Research* 4: 443-451.

Holmberg, H. 2000. Influence of grain angle on Brinell hardness of Scots pine (*Pinus sylvestris* L.*). Holz als Roh- und Werkstoff* 58(1-2): 91-95.

ISO 3130:1975 Wood – Determination of moisture content for physical and mechanical tests. International Organization for Standardization. Switzerland. 1975. 2 p.

ISO 3131:1975 Wood – Determination of density for physical and mechanical tests. International Organization for Standardization. Switzerland. 1975. 2 p.

ISO 3133:1975 Wood – Determination of ultimate strength in static bending. International Organization for Standardization. Switzerland. 1975. 2 p.

ISO 3350:1975 Wood – Determination of static hardness. International Organization for Standardization. Switzerland. 1975. 2 p.

ISO 3787:1976 Wood – Test methods — Determination of ultimate stress in compression parallel to grain. International Organization for Standardization. Switzerland. 1976. 2 p.

Jahntov, J.A. 1913. Технические свойства сосновой древесины из лесов Люблянской, Варшавской и Петроковской губернии [The technical properties of pine wood in forests of Ljubljanskoj, Varshavskoj and Petrokovskoj province]. Санкт-Петербург, 132 p. (In Russian)

Jelonek, T., Pazdrowski, W., Tomczak, A. and Stypuła, I. 2006. Radial and axial variability of the proportion of sapwood and heartwood in stems of Scots pine trees (*Pinus sylvestris* L.) developed in conditions of former farmlands and typical forest sites. *Electronic Journal of Polish Agricultural Universities, Forestry* 9(3)#02.

Kask, R., Ots, K., Mandre, M. and Pikk, J. 2008. Scots pine (Pinus sylvestris) wood properties in an alkaline air pollution environment. *Trees* 22: 815–823

Kärenlampi, P.P. and Riekkinen, M. 2002. Pine heartwood formation as a maturation phenomenon. *Journal of Wood Science* 48(6): 467–472.

Kärkkäinen, M. 1985. Puutiede [Wood science]. Karisto, Hämeenlinna. 415 p. (In Finnish)

Kõresaar, J. 1938. Untersuchungen über die spezifischen Eigenschaften des Grunbenholzes aus den

Kiefärnwäldern von Alutaguse. *Mitteilungen der Forstwissenschaftlichen Abteilung der Univ.* No 30. Tartu, 161 S. (In Estonian with German summary)

Lindeberg, J. 2001. X-ray based dendro-analyses of wood properties. Rapporter - Institutionen for skogsskotsel, Sveriges Lantbruksuniversitet No.50, 18 p.

Lõhmus, E. 1984. Eesti metsakasvukohatüübid [The Estonian forest site types]. Tallinn. 88 p. (In Estonian)

Lõhmus. E. 1995. Conditions of forest growrh. Estonian forests and forestry. Tallinn. P. 6-20.

Mandre, M., Kask, R., Pikk, J. and Ots, K. 2007. Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust. *Environmental Monitoring and Assessment* 138(1-3): 51-63.

Mihailitšenko A.L., Sadovnitši F.P. 1983. Древесиноведение и лесное товароведение [Science of wood and forest products]. Москва, 206 p. (In Russian)

Mäkelä, A. and Vanninen, P. 2001. Vertical structure of Scots pine crowns in different age and size classes. *Trees* 15: 385-392.

Ogner, G. and Bjorn, K. 1989. Concentration of elements in annual rings of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) from Arendal, in southern Norway. *Canadian Journal of Forest Research* 19: 880-888.

Omeis, E. 1895. Untersuchungen des Wachsthumsganges und der Holzbeschaffenheit eines 110 jährigen Kiefernbestandes. *Forst Naturwissenschaftliche Zeitschrift* 4(4): 137–170.

Perelygin, L.M. and Ugolev B.N. 1971. Древесиноведение [Wood science]. Москва, 286 c. (In Russian)

Pikk, J., Kask, R., Kuusepuu, T. and Peterson, P. 2004. Kasvutingimuste mõju hariliku männi (*Pinus sylvestris* L.) puiduomadustele [The effect of growth conditions on Scots pine (*P.sylvestris* L.) wood properties]. *Forestry Studies*, 40. Tartu, p. 187-197. (In Estonian with English summary)

Repola, J. 2006. Models for vertical wood density of Scots pine, Norway spruce and birch stems, and their application to determine average wood density. *Silva Fennica*, 40(4): 673-685.

Rikala, J. 2003. Spruce and pine on drained peatlands - wood quality and suitability for the sawmill industry. University of Helsinki, Department of Forest Resource Management, Publications 35. 147 p.

Saladis, J. and Aleinikovas, M. 2004. Pušų medienos fizinių ir mechaninių savybių kintamumas bei koreliaciniai ryšiai [Variability and correlation of physical and mechanical properties of pine wood]. Lithuanian Forest Research Institute. *Miškininkystė* 1(55): 60 - 67. (In Lithuanian)

Schwappach, A. 1897. Raumgewicht und Druckfestigkeit des Holzes wichtiger Waldbäume. 1. Die Kiefer. Springer-Verlag, Berlin, 1–133.

Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T. 1964. A quantitative analysis of plant form. Pipe model theory. I. Basic analysis. *Japanies Journal of Ecology* 14: 97–105.

Sipi, M. and Rikala, J. 2000. Tree stands on peatland, quality of wood raw material and suitability for different use objects. Proc. 21th IUFRO World Congress, Malaysia, Poster abstracts 3: 191–192.

Veermets, K. 1960. Seaduspärasusi männipuidu tehnilistes omadustes [Regularities in technical properties of pine wood]. *Eesti Põllumajanduse Akadeemiateaduslike tööde kogumik* 17: 77–89. (In Estonian with German abstract)

Werberg, K. 1930. Das Verhältnis von Kern- und Splintholz bei der Kiefer. *Mitteilungen der Forstwissenschaftlichen Abteilung der Universität Tartu* No 17. 184 p.

Wijkander, A. 1897. Untersuchung der Festigkeits-Eigenschaften schwedischer Holzarten. *Materialpruefungsanstalt des Chalmers'schen Institutes ausgefuehrt* No 11. 178 S.

Wilhelmsson, L., Arlinger, J., Spangberg, K., Lundqvist, S.O., Grahn, T., Hedenberg, O. and Wodzicki, T.J. 2001. Natural factors affecting wood structure. *Wood Science and Technology* 35(1/2): 2-26.

Yearbook Forest 2007. Centre of Forest Protection and Silviculture, Tartu, 2008, 189 p.

Zhang, S.Y. 1995. Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. *Wood science and Technology* 29(6): 451-465.

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ТЕХНИЧЕСКИЕ СВОЙСТВА СОСНОВОЙ ДРЕВЕСИНЫ СРЕДНЕВОЗРАСТНОГО ДРЕВОСТОЯ В СВЯЗИ С УСЛОВИЯМИ МЕСТОПРОИЗРАСТАНИЯ В ЭСТОНИИ

Р. Каск и Я. Пикк

Резюме

Свойства древесины сосны (*Pinus sylvestris*) исследовали в 27 древостоях 9-ти типов местопроизрастания леса. Всего было взято 184 модельные деревья возрастом 60-80 лет. На срубленных деревьях выпиливались 3 пробные кряжи: на высоте груди, на середине высоты ствола и на высоте ствола 3/4.

Выяснилось, что наилучшими техническими показателями древесина сосны отличается на верещатниках и более низкими показателями - на верховом болоте. Средняя плотность соответственно была 513-545 кг/м^3 и 414-464 кг/м^3. Сопротивление на статический изгиб в тангентальном направлении соответственно было 97-100 МПа и 71-83 МПа и сопротивление на сжатие вдоль волокон соответственно 55-56 МПа и 41-52 МПа. Процент ядра в стволе наибольший у сосны, растущей на плодородных почвах.

При оценке технических свойств древесины основным определяющим показателем является тип местопроизрастания. Бонитет также может служить хорошим индикатором твердости древесины, однако ограниченно, только в отношении подобных типов местопроизрастания.

Технические свойства (изгиб, сжатие, твердость) от высоты груди до середины высоты ствола уменьшаются меньше в древостоях, растущих на плодородных почвах.

Ключевые слова: сосна обыкновенная, тип местопроизрастания, класс бонитета, ядро, плотность, изгиб, сжатие, твердость

II

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ORIGINAL PAPER

Scots pine (*Pinus sylvestris* L.) wood properties in an alkaline air pollution environment

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Abstract This paper examines the long-term influence on pine (*Pinus sylvestris* L.) wood properties of alkaline dust pollution (pH 12.3–12.7) emitted over 135 years from a cement plant in Estonia. A study of stemwood physical and mechanical properties in 70–80-year-old Scots pines growing in three zones of different air pollution levels showed serious deviations in comparison with a relatively healthy forest in an unpolluted area. Specimens from polluted trees evidenced smaller sapwood annual ring widths than those from the control trees. At the same time, the number of growth rings in sapwood at breast height increased under pollution. In the polluted areas, percentage of latewood in the annual ring widths was higher than in the unpolluted area. Small amounts of cement dust, which contains elements essential for the mineral nutrition of the trees, might have acted as fertilizer. Pine wood in the polluted stands exhibited increased density, bending strength across the grain, compression strength along the grain and, in some instances, hardness along the grain.

Keywords Scots pine · Dust pollution · Sapwood · Heartwood · Latewood

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Introduction

Numerous investigations describe the damage done by acidic air pollution to forest areas in many industrial countries towards the end of the twentieth century (Smith 1990; Staaf and Tyler 1995; Härtling and Schulz 1998). At the same time, research into the impact of different types of alkaline air pollution on forests has failed to attract as much attention as that of acid rain, SO_2, NO_x or O_3. Many authors have found serious deviations in plant metabolism and physiology (Auclair 1977; Lal and Ambasht 1982; Mandre 1995a, b; Klõšeiko 2003; Skuodene 2005) as well as in growth and productivity (Gluch 1980; Jäger 1980; Rauk 1995; Ots 2002) caused by alkaline dust pollution and alkalisation of the environment. However, no information is available on the effect of alkalisation of the environment and of alkaline dust pollution on the structure and mechanical and physical properties of stemwood, although it is known that growth conditions have a very strong impact on the structure and properties of wood (Nekrassova 1994; Lindeberg 2001; Wodzicki 2001; Pikk et al. 2004). Differences in sapwood and heartwood percentages may be due to ecological factors such as altitude, soil lime and organic matter content and soil type (Bektas et al. 2003).

The Kunda cement plant (longitude 26°32′E, latitude 59°30′N) became the primary source of alkaline air pollution in Northeast Estonia after expanding its production in 1962, when primitive air filters were first used.

The long-term exposure to dust pollution from the cement plant has resulted in a deterioration of the morphological properties of individual trees growing in middle-aged and mature conifer stands compared to those in unpolluted areas (Ots 2000). Calculations by Rauk (1995) show that in the peak years of emission from the Kunda cement plant in the early 1990s pollution accounted for a stemwood loss of 1,500 m^3 each year in the vicinity. On the other hand, many of the components contained in the dust have been valuable for trees as nutrients. Less research has been done on the magnitude of the changes in wood properties and their potential effect on wood utilisation technologies.

The objective of the present study was to find out whether long-term alkaline air pollution from the cement plant and soil alkalisation has an effect on some of the physical and mechanical properties of pine wood.

Methods

Area of study

The study was performed on a territory affected for over 135 years by a cement plant in Kunda, which was established in 1871. The sample plots were situated at the distances of 2.5 km (heavily polluted) and 5 km (less polluted) to the east and 3 km (less polluted) to the west of the emission source and the control sample plot was located under 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 to the west, opposite to prevailing winds. Pollution levels at the four sites indicate the pH of the soil upper horizon (30 cm): variant 2.5 km E, pH_{KCl} 7.86; variant 5 km E, pH_{KCl} 7.76; variant 3 km W, pH_{KCl} 6.68 and variant 38 km W, pH_{KCl} 3.84 (Mandre et al. 2007).

Dust emissions from the cement plant were extremely high in 1990–1992, totalling 80–100 kt per year (Estonian 1996; Environmental 2004). The emissions contained 87–91% technological dust and 9–13% gaseous pollutants (SO_2, NO_x, CO, etc.) (Mandre et al. 1994). The emitted dust contains 40–50% of CaO, 12–17% of SiO_2, 6–9% of K_2O, 4–8% of SO_3, 3–5% of Al_2O_3 and 2–4% of MgO, as well as Fe, Mn, Zn, Cu, B, etc. The water solution of the dust obtained from the electric filters has pH values from 12.3 to 12.7 (Mandre 2002). In 1993–1996 cement dust emissions from the plant decreased notably, thanks to the installation of efficient filters (Fig. 1). At present, they are below the permitted quantity (421 tons/year) (Environmental 2004).

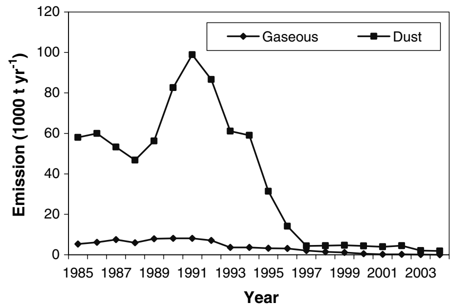

Fig. 1 Emission of dust and gaseous pollutants into the atmosphere from the cement plant in Kunda, Northeast Estonia

For this study, trees were sampled in 70–80-year-old mixed stands of *Myrtillus* site type (the dominant plant cover species is *Vaccinium myrtillus*), quality class (site index) II. For site type classifications see Cajander (1949). We have harvested trees of a single species, Scots pine (*Pinus sylvestris* L.), from which we obtained wood samples for our analyses.

Sampling

On each experiment plot, three average trees (breast height diameter 25.8 ± 0.3) were selected. Altogether, 12 trees fell in September 2005. From these, testing disks and sample blocks (1.2 m in length) were cut at 1.3 m ($h_{1.3}$), 1/2 of tree height ($h_{1/2}$) and 3/4 of tree height ($h_{3/4}$).

After drying at room conditions (temperature 21°C, relative humidity 65%) and surface sanding of cross-section disks, the annual radial growth increments were measured, as was the latewood percentage in the annual rings and the relative importance of heartwood and sapwood area was determined. The heartwood boundary of our Scots pines is visually clearly identifiable**.** The number of annual rings of heartwood and sapwood at different heights were determined (Table 1). More attention was paid to the sapwood, which in the polluted stands had developed under increased levels of air pollution. The program WinDENDRO™ (Ver. 2002a, Regent Instruments Inc., Quebec, Canada) and computer system was used for measuring the widths of annual rings and latewood. The age of the trees was determined from the stump disks.

To measure the absolute density of pine stemwood, 508 specimens (cross-section 20 × 20 mm and height 30 mm) were prepared at different stem heights in compliance with the requirements of ISO 3130 (1975a) and ISO 3131 (1975b). This method yielded 41–45 specimens per tree with respect to heartwood cross-section area at tree

Table 1 The age and number of annual rings (mean ± SE) in sapwood and heartwood at different heights

Stand	Tree age	Sapwood			Heartwood		
		$h_{1.3}$	$h_{1/2}$	$h_{3/4}$	$h_{1.3}$	$h_{1/2}$	$h_{3/4}$
38 km W	73.3 ± 1.7	33.7 ± 0.3	26.3 ± 1.3	18.3 ± 2.2	32.3 ± 2.5	18.0 ± 3.2	6.7 ± 2.0
3 km W	74.7 ± 1.2	42.0 ± 2.1*	29.3 ± 1.8	21.7 ± 1.5	27.7 ± 1.9*	19.0 ± 4.4	7.3 ± 0.9
2.5 km E	76.0 ± 2.0	46.3 ± 1.9**	34.3 ± 2.2	30.0 ± 0.6*	25.7 ± 3.3*	18.7 ± 4.0	6.0 ± 0.5
5 km E	75.3 ± 1.2	43.3 ± 0.3**	33.0 ± 2.0	27.7 ± 1.7**	29.7 ± 2.6	17.0 ± 2.3	9.3 ± 1.5
P value	0.6338	0.0023	0.0528	0.0039	0.0412	0.1217	0.2631

* Difference from control ($P < 0.05$)

** Difference from control ($P < 0.01$)

height $h_{3/4}$. The absolute density for each specimen was determined after a constant weight was achieved at 102°C. A total of 508 specimens were prepared for the static bending strength test and the modulus of elasticity test perpendicular to grain, and 508 specimens for the compression. The specimens from sapwood do not include wood from the five latest annual rings and heartwood specimens do not include two rings nearest the pith. Every set of specimens used for testing density, bending, and compression strength was obtained from the same preliminary material with cross-section 20 × 20 mm. Additionally, annual ring widths were measured and latewood percent was calculated for every specimen used to determine density, compression strength and bending strength. To determine the surface hardness, 596 tests were conducted in three directions (radial, tangential and transverse). All the mechanical properties in the present paper were adjusted to a 12% wood moisture level.

European Standard (2004) was applied to determine the mechanical properties and density. ISO standards 3131–1975b, 3133–c, 3349–d, 3350–e and 3787–1976 were applied in determining the mechanical properties and for the preparation of specimens. The bending test was made according to the prescription in the ISO standards using four points for pressure. The sample size for testing surface hardness was restricted to include a test point of rings situated on the edge of the sample. In testing at the Instron load cell capacity 50 kN and testing speed 1,350 ± 150 N/min (bending strength), 3–6 mm/min (static hardness) and 25,000 ± 5,000 N/min (compression strength) was used according to ISO standards.

All mechanical tests were conducted using an INSTRON Model 3369 (Instron Corp., Norwood, MA, USA).

Statistical analyses

Two-way analysis of variance was computed by the PROC GLM method (Cody and Smith 2006) with statistical analysis software SAS (Ver. 9.1, SAS Institute Inc., Cary, NC, USA).

Results

The best measure of the growth conditions is annual ring width (Mäkinen 1998). Dynamics of mean annual ring width of different stands are variable (Fig. 2). In the stand closest to the cement plant (2.5 km), the annual ring width in sapwood at breast height was 50% of that for the control stand, 68% in the stand 3 km to the west of the plant and 70% in the stand 5 km to the east (Table 2). In contrast, the means for heartwood annual ring width in the polluted stands proved to be considerably greater than the corresponding width for the control stand, by 26, 12 and 4%, respectively.

Sapwood contained a varying number of annual rings at breast height in the stands; the fewest in the control stand and the most in the various stands closest to the pollution source (Table 1). The proportion of latewood in sapwood growth rings was clearly higher in the polluted stands. On the other hand, only in the stand situated at 5 km from the plant did the percentage of latewood in heartwood exceed that of the control stand to a significant degree.

Wood density decreased from bark to pith and from stem bottom to top. The stands exhibited different wood densities at breast height and at half tree height. Sapwood

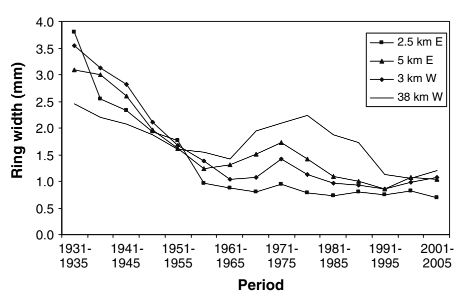

Fig. 2 Dynamics of mean annual ring width of different stands at different distances (km) and directions from the cement plant

Table 2 Physical properties and hardness of wood (mean ± SE) in different stands at breast height and different distances from the emission

Characteristic	38 km W	3 km W	2.5 km E	5 km E	*P* value
Sapwood					
Sapwood percentage (%)	75.4 ± 5.8	66.1 ± 4.3	50.5 ± 7.7**	67.9 ± 4.5	<0.0001
Annual ring width (mm)	1.69 ± 0.06	1.14 ± 0.06**	0.84 ± 0.05**	1.19 ± 0.06**	<0.0001
Latewood percentage (%)	38.0 ± 0.7	47.9 ± 0.7**	44.7 ± 0.6**	48.1 ± 0.6**	<0.0001
Absolute density (kg/m^3)	545 ± 5	586 ± 6**	536 ± 5	583 ± 5**	<0.0001
Cross-section hardness (MPa)	33.1 ± 0.6	36.2 ± 0.7**	32.9 ± 0.7	36.5 ± 0.7**	<0.0001
Tangential surface hardness (MPa)	30.2 ± 1.1	28.5 ± 1.9	30.6 ± 1.2	33.2 ± 2.1	0.2865
Heartwood					
Annual ring width (mm)	1.98 ± 0.15	2.21 ± 0.13**	2.49 ± 0.13*	2.06 ± 0.14*	<0.0001
Latewood percentage (%)	30.5 ± 1.4	32.3 ± 1.3	30.2 ± 1.2	33.2 ± 1.2*	0.0493

* Difference from control ($P < 0.05$)

** Difference from control ($P < 0.01$)

density reached the maximum predominantly at breast height ($h_{1.3}$ in Fig. 3). Sapwood density at breast height was 545 kg/m^3 in the control plot and 536–586 kg/m^3 in the polluted stands. The corresponding figures for heartwood density were 503 kg/m^3 and 466–495 kg/m^3, respectively. Sapwood density in the polluted stands exceeded the density of the control trees by upto 7.5% at breast height, upto 3.1% at half tree height and upto 3.0% at 3/4 tree height. Heartwood density in the polluted stands was lower than in the control stand at breast height (by upto 2.0%) but higher by upto 14.2% at half tree height and upto 11.1% at $h_{3/4}$.

Static bending strength, bending elastic modulus, compression strength parallel to grain and hardness are the key indicators of wood quality. The test results reveal great variability in the mechanical properties of the different parts of the stem between the experiment plots and individual trees (mean ± SE in Table 3). The trends in the variability of the mechanical properties in the tree stems

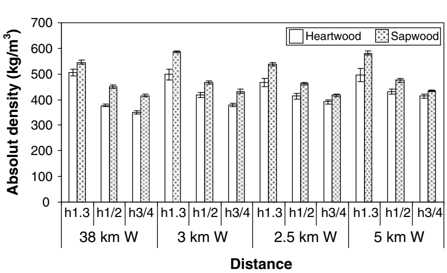

Fig. 3 The mean wood density and standard error of sapwood and heartwood at different heights and different distances from the emission (*h1.3* samples at height 1.3 m; *h1/2* samples at half of tree height; *h3/4* samples at 3/4 tree height)

and on the experimental plots largely coincide with the trends in the variability of the wood densities.

The air pollution had increased sapwood bending strength the most at breast height (by upto 16.3%); at greater heights the difference from the control trees decreased. No difference was found in the very heavily polluted stand when compared with the control stand. Heartwood bending strength in the heavily polluted stand proved to be insignificantly smaller than the control value at breast height; towards the top, however, the bending strength of the polluted trees exceeded that of the control trees by upto 25%.

To an even greater extent, alkaline air pollution increased sapwood bending elastic modulus, the changing trends of which resembled those of compression strength and bending strength. When the results were compared with those of the control variant, however, the difference exceeded 50% in some cases.

Values for sapwood compression strength parallel to grain considerably exceeded that of the control variant at breast height and half tree height (by 8–13%) in pines situated at the distances of 3 and 5 km from the plant. No difference was observed in the crown area. No significant difference was found between the control wood and the heavily polluted wood (2.5 km from the plant) (Fig. 4). The trends in the results obtained are largely similar to the changes in bending strength.

Heartwood compression strength parallel to grain at breast height, however, proved to be smaller than the control in the heavily polluted stand (12.3%) and greater than the control in the less polluted stand (1.1–2.4%). At half tree height, wood compression strength was significantly greater than the control value in the area of lower pollution (8–17%). Furthermore, heartwood compression strength was greater than the control value at $h_{3/4}$ in all the polluted stands.

Table 3 Bending strength perpendicular to grain (MPa) and modulus of elasticity (MPa) on different height of tree-stem (mean ± SE) and different distances from the emission source

Property and sampling height	38 km W	3 km W	2.5 km E	5 km E	*P* value
Sapwood					
Bending strength					
$h_{1.3}$	104.7 ± 1.6	120.7 ± 1.7**	99.3 ± 1.5*	119.3 ± 1.5**	<0.0001
$h_{1/2}$	88.1 ± 2.1	91.8 ± 2.3	87.9 ± 2.5	93.1 ± 2.2	<0.0001
$h_{3/4}$	78.3 ± 2.6	78.2 ± 2.23	77.3 ± 2.1	81.2 ± 2.1	<0.0001
Modulus of elasticity					
$h_{1.3}$	9,587 ± 242	14,246 ± 350	10,116 ± 216	10,935 ± 230	<0.0001
$h_{1/2}$	8,096 ± 337	10,986 ± 477**	8,477 ± 399*	8,677 ± 326*	<0.0001
$h_{3/4}$	7,506 ± 399	8,057 ± 420	7,638 ± 297	7,415 ± 306	<0.0001
Heartwood					
Bending strength					
$h_{1.3}$	89.6 ± 3.3	89.8 ± 3.3	77.5 ± 3.2	98.7 ± 3.2	0.2640
$h_{1/2}$	64.5 ± 4.9	72.2 ± 5.4*	68.3 ± 4.5	79.2 ± 4.3**	0.2640
$h_{3/4}$	55.8 ± 11.5	64.6 ± 11.4*	69.5 ± 7.2*	71.2 ± 8.1*	0.2640
Modulus of elasticity					
$h_{1.3}$	8,444 ± 491	8,500 ± 413	6,484 ± 506	8,916 ± 477	0.1089
$h_{1/2}$	6,828 ± 716	7,029 ± 827	7,101 ± 716	7,377 ± 640	0.1089
$h_{3/4}$	4,768 ± 432	5,172 ± 1,068	7,014 ± 906*	6,017 ± 514*	0.1089

* Difference from control ($P < 0.05$)

** Difference from control ($P < 0.01$)

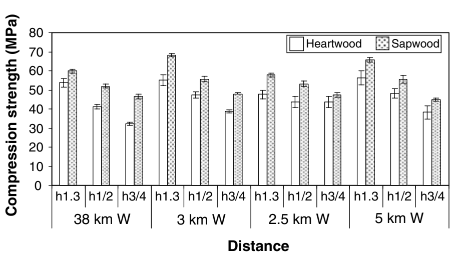

Fig. 4 The compression strength and standard error of sapwood and heartwood parallel to grain on different stands and different distances from the emission (*h1.3* samples at height 1.3 m; *h1/2* samples at half of tree height; *h3/4* samples at 3/4 tree height)

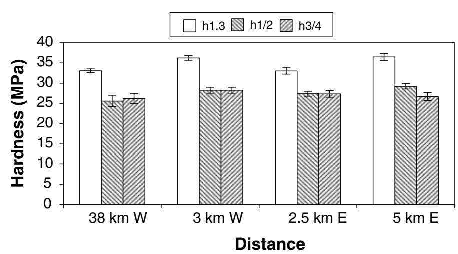

Fig. 5 The cross-section hardness and standard error of sapwood on different stands and different distances from the emission (*h1.3* samples at height 1.3 m; *h1/2* samples at half of tree height; *h3/4* samples at 3/4 tree height)

According to earlier studies, there is a very strong correlation between wood density and compression strength on cowberry and bilberry site types ($R = 0.95$) (Kask 2003). The present investigation reveals a strong correlation between wood density and compression strength in the control variant ($R = 0.93$); similar correlations are observed in the polluted pine forests ($R = 0.86 - 0.95$).

Greater differences between the trial variants appeared in sapwood hardness along the grain at breast height (Fig. 5). Sapwood cross-section hardness is strongly correlated with the hardness of the radial plane and the tangential plane. Heartwood manifested a weaker correlation (Table 4).

With regard to heartwood cross-section hardness at the same height, no statistically significant differences between the experiment plots were observed. The cross-section hardness ranged between 32.2 and 33.4 MPa ($P = 0.833$) at breast height and between 24.7 and 27.4 MPa ($P = 0.609$) at half tree height. Tangential plane hardness fell within the ranges of 18.5–23.9 MPa ($P = 0.335$) and 18.3–21.1 MPa ($P = 0.757$), respectively.

Table 4 The correlation coefficients of hardness between different wood surfaces

	Sapwood			Heartwood		
	Cross-section	Radial surface	Tangential surface	Cross-section	Radial surface	Tangential surface
Cross-section	1			1		
Radial surface	0.91	1		0.93	1	
Tangential surface	0.93	0.91	1	0.34	0.43	1

Table 5 Correlation coefficients of weighted mean (in cross-section) strength properties

	Absolute density	Compression strength	Bending strength	Modulus of elasticity	Cross-section hardness
Absolute density	1				
Compression strength	0.95	1			
Bending strength	0.96	0.97	1		
Modulus of elasticity	0.89	0.95	0.93	1	
Cross-section hardness	0.72	0.67	0.74	0.75	1

A correlation analysis of the test results showed a strong correlation between absolute density and mechanical properties (Table 5).

Discussion

Air pollution caused by alkaline dust has substantially stunted tree growth on the experiment plots in recent decades. The mean width of annual rings in sapwood of the heavily polluted stand (2.5E) was half that of the control stand. The mean annual ring width is also smaller for the other polluted stands. The width of annual rings has a certain limit (1–1.5 mm), above which triggers significant changes in wood strength properties (Vjarbila and Šleiniss 1981). On the basis of earlier research data, decreased radial increment and its dependence on the pollution load are clearly observable in zones strongly and significantly affected by the pollution from the cement plant (maximum reported load 1,000–2,700 g/(m^2 year) (Ots and Rauk 1999).

The study of heartwood annual ring width yielded the opposite result—in the stands of the polluted area annual rings are wider than in the unpolluted stand by 13–34%. Annual rings in heartwood have developed during a period when pollution was not particularly heavy. We may assume that on a *Myrtillus* site type, where the soil is acidic, moderate amounts of cement dust, which is rich in Ca, K and many microelements, may have enhanced radial increment growth.

Annual ring width is one of the criteria for wood density, modulus of rupture and modulus of elasticity in young stands (Mattsson 2002). In older pines, annual ring width is only of limited value in predicting 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 juvenile age (Mott et al. 2002).

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

It is noted that 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 in the experimental plots differed at breast height and half tree height. The higher the pollution load under which the tree has grown, the larger the proportion of heartwood in the cross-section. Although heartwood content is a far better criterion for the evaluation of the physiological maturity of a forest tree than age or size, it appears to be more independent of growth rate and tree size (Kärenlampi and Riekkinen 2002). Generally, heartwood percentage varies extensively between individual trees and stands and is weakly correlated with growth site, stand and tree properties; hence, inventory data do not provide a reliable basis for the selection of a forest rich in heartwood (Björklund 1999). Furthermore, the proportion of heartwood and the number of annual rings in heartwood cannot be increased by the thinning and fertilisation of the stand, since both results in increased proportions of sapwood (Mörlig and Valinger 1999).

The number of annual rings in sapwood at breast height pointed to the tendency that heartwood formation had decelerated in the more polluted stands. However, as annual ring width in sapwood was significantly smaller in the polluted stands compared to the unpolluted one, the proportion of heartwood in the cross-sections from these was nevertheless greater.

For that reason the stand maturation period may start earlier under the conditions of pollution. Whether this leads to shorter tree life remains unclear in the present study. Nevertheless, the increased latewood levels in the polluted stands suggest accelerated tree ageing.

Our findings show that under the conditions of alkaline dust pollution, the patterns of tree growth and the properties of the wood that formed were different in some respects from those manifested under conditions favourable for incremental growth. Major differences in stem density were observed between different stem zones in both sapwood and heartwood; the differences were smaller in the upper part of the stems. Mattsson (2002) also noted that variations from pith to bark are extensive in all wood parameters. Large differences in density are also found between middle and upper bole and between juvenile wood and heartwood (Duchesne et al. 1997). This means that wood density is not constant but depends on many external and internal factors. The variations in density were smaller in stem cross-sections. In the control variant, sapwood density exceeded heartwood density 1.08 times at breast height, 1.22 times at half tree height and 1.19 times at $h_{3/4}$. That pattern of density distribution did not change in the polluted stands. Correlation analyses showed a strong relation between latewood and the density of sapwood or heartwood in the pine stems obtained from the sample plots.

The mechanical properties of wood are most strongly affected by density and the amount of latewood (Wilhelmsson et al. 2002). Although density has a weaker correlation with annual ring width (Seco and Barra 1996), it is dependent on growth rate (Sipi and Rikala 2000). In a rapidly growing stem, the percentage of latewood in the annual rings and the density of wood are lower and the fibres are shorter and have thinner walls than in a slowly growing stem (Matjuškin et al. 1974; Paavilainen 1990; Hannrup et al. 2000; Mattsson 2002). However, it has been ascertained that pine wood properties vary from one geographical region to another (Polubojarinov et al. 2000; Verkasalo and Leban 2002). Very often, fertilisation has a negative effect on pine wood density, by upto 5.5% (Saikku 1975; Vjarbila and Šleiniss 1981).

Heartwood density on the control plot was equal to or lower than on the other plots and sapwood density was in all cases lower in the control plot than on the other plots. This indicates a trend analogous to that of latewood percentage and at the same time characterises the tree growth conditions during the different periods. In regard to site type conditions, the *Myrtillus* site type in Estonia is suitable for *Pinus sylvestris* and the wood grown there has good properties.

Since all the mechanical strength properties are dependent on density, the trends in the variation of these properties in the control stand from the tree base to top and from pith to bark are similar to the variations in density; however, the magnitude of variation in each individual strength property is different.

Bending strength perpendicular to grain and bending elastic modulus decrease in stem cross-section from bark to pith and from the tree base to top. In the control stand, sapwood bending strength was greater than heartwood bending strength by 16.8% at breast height and by 40.3% at $h_{3/4}$ whereas in the polluted stands the trend was the opposite (Table 3). In the bottom part of the stem the difference between sapwood and heartwood was greater and in the crown area it was smaller, consistent with the variations in wood density. In general, the bending strength of heartwood varies on a greater scale than that of sapwood. The reason is that the annual rings are wider in heartwood, and therefore specimens comprise varying numbers of latewood rings, whose density is higher. Apart from that, heartwood contains a significant share of juvenile wood, whose strength properties are inferior (Pikk and Kask 2004).

According to Kask (2003), the mean bending strength of 60–90-year-old pines fell in bilberry and cowberry site types in Estonia is 84.8 MPa. Based on previous literature, the bending strength of wood obtained from final felling is approximately the same, 72–88 MPa (Veermets 1960). If we want to compare the results with the mean values of neighbouring forests, then pine wood bending strength in Lithuania is 87.7 MPa, in Belarus 87.3 MPa and in northwest Russia 84.5 MPa (Borovikov and Ugoljev 1989). Based on this data, the mean weighed bending strength of pine wood in our polluted forest is greater than the corresponding figures in the neighbouring countries at breast height (103.7 MPa) and smaller in the crown part (76.6 MPa).

Compression strength parallel to the grain in the sapwood of trees situated in areas of moderate pollution may, according to our data, be greater by upto 12.9% at breast height and significantly greater at $h_{1/2}$. Growing under a greater pollution load, however, increases pine wood compression strength parallel to grain. In the control stand, sapwood compression strength at breast height was greater than that of heartwood by 10%, in the stand 5 km to the east by 17%, in the stand 3 km to the west by 24% and in the stand under the greatest pollution load, 2.5 km to the east, by 21%. At this point we remind the reader that the sapwood had grown under increased pollution levels and heartwood under low to moderate pollution levels.

Wood hardness largely determines the possibilities of wood utilisation and wood processing with cutting tools as well as the method of wood surface finishing. The cross-section hardness is deemed to be of greater importance, since the hardness of the radial plane and the tangential plane are in close correlation with cross-section hardness. In conifers, the hardness of the cross-section is normally 40% greater than the hardness of the tangential plane and of the radial plane (Mihailitšenko and Sadovnitši 1983).

In our tests, the cross-section hardness exceeded tangential plane hardness by barely 10.3% in the control variant and by 7.5–26.1% in the polluted stands. These percentages are significantly lower than those aforementioned. Sapwood cross-section hardness at breast height on the polluted plots exceeded the corresponding figure for the control stand by upto 10.4% (Fig. 5) and heartwood hardness by 0.5–3.7%.

Of the hardness properties of the polluted stands, bending strength perpendicular to grain and compression strength were very strongly correlated with absolute wood density whereas bending elastic modulus and the cross-section hardness were less so.

Changes in wood quality in extreme growth conditions require special attention, as the issue is of great significance for forestry and pulping technology.

Conclusions

Alkaline air pollution of trees may stimulate higher heartwood proportions and early stand maturation. Moderate pollution of a pine stand growing on acidic soil stimulates radial increment, but does not result in lower latewood percentages or wood density. In polluted stands, wood bending strength perpendicular to grain, compression strength parallel to grain and, in some cases, the cross-section hardness increase.

A drastic rise in dust pollution results in slower wood increment formation, narrower annual rings compared to the control variant and higher latewood percentages and wood density; in areas of very high pollution, however, weighted mean strength properties in stem cross-section are lower than those in unpolluted stands.

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References

Allegretti O, Bernabei M, Negri M, Piutti E (1999) Sapwood–heartwood proportion related to same technological properties in *Picea abies* (L.) Karst. Paper presented at Proceedings of the Fourth International Conference on the Development of Wood Science, Wood Technology and Forestry, Missenden Abbey, UK, pp 475–485, 14 July 1999

Auclair D (1977) Effects des poussièrs sur la photosynthèse. II. Influence des pollutants particulaires sur la photosynthèse du Pin sylvestre et du peuplier. Annales des Sciences Forestières 34:47–57

Bektas I, Alma MH, Goker Y, Yuksel A, Gundogan R (2003) Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. For Prod J 53(4):48–50

Björklund L (1999) Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. Silva Fennica 33(2):119–129

Borovikov AM, Ugoljev BN (1989) The wood handbook. Lesnaja promyšlennost', Moscow, Russia

Cajander AK (1949) Forest types and their significance. Acta Forestalia Fennica 56:1–71

Cody RP, Smith JK (2006) Applied statistics and the SAS programming language 5th edn. Pearson Education Inc., Upper Saddle River, USA

Duchesne I, Wilhelmsson L, Spangberg K (1997) Effect of in-forest sorting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) on wood and fibre properties. Can J For Res 27(5):790–795. doi:10.1139/cjfr-27-5-790

Environmental Review No.13 (2004) Kunda Nordic Tsement. Heidelberg Cement Group, Kunda, Estonia

Estonian Environment 1995 (1996) Ministry of the Environment of Estonia. Estonian Environment Information Centre, Tallinn, Estonia

European Standard (2004) EN 384:2004 Structural timber—determination of characteristic values of mechanical properties and density. CEN, Brussels

Gluch W (1980) Bioindikation mit produktionsbiologischen und morphometrischen Verfahren. Archiv für Naturschutz und Landschaftsforsch 20:99–116

Hannrup B, Ekberg I, Persson A (2000) Genetic correlation among wood, growth capacity and stem traits in *Pinus sylvestris*. Scand J For Res 15:161–170. doi:10.1080/028275800750014966

Härtling S, Schulz H (1998) Biochemical parameters as biomarkers for the early recognition of environmental pollution in Scots pine trees. I. Phenolic compounds. Zeitschrift für Naturforschung 53c:331–340

International Organization for Standardization (1975a) ISO 3130:1975 Wood—determination of moisture content for physical and mechanical tests. ISO, Switzerland

International Organization for Standardization (1975b) ISO 3131:1975 Wood—determination of density for physical and mechanical tests. ISO, Switzerland

International Organization for Standardization (1975c) ISO 3133:1975 Wood—determination of ultimate strength in static bending. ISO, Switzerland

International Organization for Standardization (1975d) ISO 3349:1975 Wood—determination of modulus of elasticity in static bending. ISO, Switzerland

International Organization for Standardization (1975e) ISO 3350:1975 Wood—determination of static hardness. ISO, Switzerland

International Organization for Standardization (1976) ISO 3787:1976 Wood—determination of ultimate strength in compression parallel the grain. ISO, Switzerland

Jäger HJ (1980) Indikation von Luftverunreinigungen durch morphometrische Untersuchungen an höheren Pflanzen. In: Schubert R, Schuh J (eds) Bioindikation, Teil 3. Kongress—und Tagungsberichte der Martin-Luther-Universität Halle—Wittenberg, Wissenschaftliche Beiträge 1980/26 (P 10), Halle, Germany, pp 43–52

Kärenlampi PP, Riekkinen M (2002) Pine heartwood formation as a maturation phenomenon. J Wood Sci 48(6):467–472
Kask R (2003) Mechanical and physical properties of Scots pine (*Pinus sylvestris* L.) wood on *Vaccinium vitis-idaea* and *Myrtillus* site type. M.Sc. Thesis, Estonian Agricultural University, Tartu, Estonia
Klõšeiko J (2003) Carbohydrate metabolism of conifers in alkalised growth conditions. Doctoral Thesis, Estonian Agricultural University, Tartu, Estonia
Lal B, Ambasht RS (1982) Impact of cement dust on the mineral and energy concentration of *Psidium guayava*. Environ Pollut (Ser A) 29:241–247. doi:10.1016/0143-1471(82)90065-4
Lindeberg J (2001) X-ray based dendro-analyses of wood properties. Rapporter—Institutionen for skogsskotsel, Sveriges Lantbruksuniversitet 50
Mäkinen H (1998) The suitability of height and radial increment variation in *Pinus sylvestris* (L.) for expressing environmental signals. For Ecol Manage 112(1/2):191–197. doi:10.1016/S0378–1127(98)00337–5
Mandre M (1995a) Changes in the nutrient composition of trees. In: Mandre M (ed) Dust pollution and forest ecosystem. A study of conifers in an alkaline environment. Institute of Ecology, Publication 3, Infotrükk, Tallinn, Estonia, pp 44–65
Mandre M (1995b) Effects of dust pollution on carbohydrate balance in conifers. In: Mandre M (ed) Dust pollution and forest ecosystems. A study of conifers in an alkaline environment. Institute of Ecology, Publication 3, Infotrükk, Tallinn, Estonia, pp 78–95
Mandre M (2002) Relationships between lignin and nutrients in *Picea abies* L. under alkaline air pollution. Water Air Soil Pollut 133:361–377. doi:10.1023/A:1012987503033
Mandre M, Tuulmets L, Rauk J, Ots K, Okasmets M (1994) Response reaction of conifers to alkaline dust pollution. Changes in growth. Proceeding of the Estonian Academy of Sciences. Ecology 4:79–95
Mandre M, Kask R, Ots K, Pikk J (2007) Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust. Environ Monit Assess 138:51–63. doi:10.1007/s10661-007-9790-3
Matjuškin AP, Koržidckaja ZA, Kozlov VA, Ageeva MI, Vassileva AN, Golubeva VL (1974) Characteristics of Scots pine wood in connection with growth intensity. Petrozavodsk, Russia, pp 120–132
Mattsson S (2002) Effects of site preparation on stem growth and clear wood properties in boreal *Pinus sylvestris* and *Pinus condarta*. Acta Universitatis Agriculturae Sueciae, Silvestria 240:1–37
Mihailitšenko AL, Sadovnitši FP (1983) Science of wood and forest product. Vysšaja škola, Moscow, Russia
Mörlig T, Valinger E (1999) Effect of fertilization and thinning on heartwood area, sapwood area and growth in Scots pine. Scand J For Res 14(5):462–469. doi:10.1080/02827589950154168
Mott L, Groom L, Shaler S (2002) Mechanical properties of individual southern pine fibers. Part II. Comparison of earlywood and latewood fibers with respect to tree height and juvenility. Wood Fiber Sci 34(2):221–237
Nekrassova AA (1994) Properties of wood of conifers as a function of the growth conditions. Lesnoe Khozyaistvo 2:22–24
Ots K (2000) Morphometric parameters of conifer needles and shoots in the areas near the Kunda cement plant. For Stud 38:158–176
Ots K (2002) Impact of air pollution on the growth of conifers in the industrial region of Northeast Estonia. Doctoral Thesis, Estonian Agricultural University, Tartu, Estonia
Ots K, Rauk J (1999) Scots pine (*Pinus sylvestris* L.) and impact of air pollution on it. Dendrological Researches in Estonia I, Tallinn, Estonia, pp 79–88
Paavilainen E (1990) Importance of particle size fiber length and fines for the characterization of softwood kraft pulp. Paperi ja Puu 72(5):516–526
Pikk J, Kask R (2004) Mechanical properties of juvenile wood of Scots pine *(Pinus sylvestris* L.*)* on *Myrtillus* forest site type. Bal For 10(1):72–78
Pikk J, Kask R, Kuusepuu T, Peterson P (2004) The effect of growth conditions on Scots pine (*Pinus sylvestris* L.) wood properties. For Stud 40:187–197
Polubojarinov OI, Sorokin AM, Fedorov PB (2000) Base density of wood and bark of the forest-forming species of European Russia. Lesnoe Khozyaistvo 5:35–36
Rauk J (1995) Bioproductivity. In: Mandre M (ed) Dust pollution and forest ecosystems. A study of conifers in an alkaline environment. Institute of Ecology, Publication 3, Infotrükk, Tallinn, Estonia, pp 119–123
Saikku O (1975) The effect of fertilization on the basic density of Scots pine (*Pinus sylvestris* L.). A densitometric study on the X-ray chart curves of wood. Communicationes Instituti Forestalis Fenniae 85:1–49
Seco JIFG, Barra MRD (1996) Growth rate as a predictor of density and mechanical quality of sawn timber from fast growing species. Holz als Roh—und Werkstoff 54(3):171–174
Sipi M, Rikala J (2000) Tree stands on peatland, quality of wood raw material and suitability for different use objects. Proceedings of IUFRO congress posters. Malaisia, pp 191–192
Skuodene L (2005) Stress of trees and it physiological estimate. Print House Arx Baltica, Kaunas, Lithuania
Smith WH (1990) Air pollution and forests. Interaction between air contaminants and forest ecosystems, 2nd edn. Springer, Berlin
Staaf H, Tyler G (1995) Effect of acid deposition and tropospheric ozone on forest ecosystems in Sweden. Ecological Bulletins 44. Munksgaard International Publishers Ltd., Copenhagen, Denmark
Veermets K (1960) Regularities in technical properties of pine wood. Trans Estonian Agric Acad 17:77–89
Verkasalo E, Leban J-M (2002) MOE and MOR in static bending of small clear specimens of Scots pine, Norway spruce and European fir from Finland and France and their prediction for the comparison of wood quality. Paperi ja Puu 84(5):332–340
Vjarbila VV, Šleiniss RI (1981) Effect of fertilizer application on the quality of wood in Scots pine stands. Lesnoe Khozyaistvo 12:8–11
Wilhelmsson L, Arlinger J, Spangberg K, Lundqvist SO, Grahn T, Hedenberg O, Olsson L (2002) Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. Scand J For Res 17(4):330–350. doi:10.1080/02827580260138080
Wimmer R (1991) Relations between growth ring parameters and density of Scots pine wood. Holzforschung und Holzverwertung 43(4):79–82
Wodzicki TJ (2001) Natural factors affecting wood structure. Wood Sci Technol 35:5–26. doi:10.1007/s002260100085
Zvirbul AP, Nekrassova GN, Polubojarinov OI (1976) Effect of urea fertilization on Pine stands on the wood quality. Lesnoi Zhurnal 6:18–22

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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.

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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, 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).

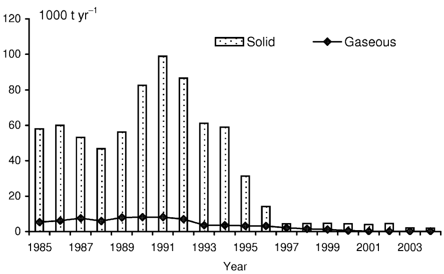


Fig. 1 Emission of dust and gaseous pollutants into the atmosphere from the cement plant in Kunda, Northeast Estonia

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

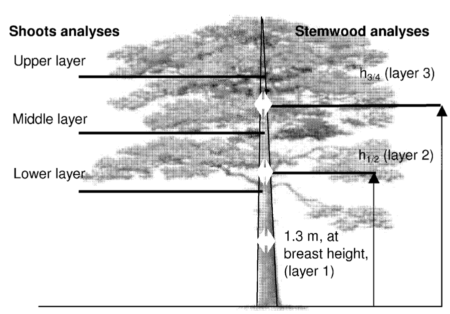


Fig. 2 Sampling of the material for Scots pine stem analyses

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

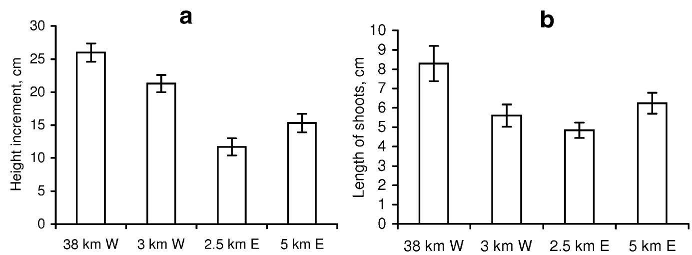


Fig. 3 Height increment of Scots pine in the last 10 years (**a**) and length growth of lateral shoots (**b**) (mean±SE) in the vicinity of Kunda cement plant and in the reference site area

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

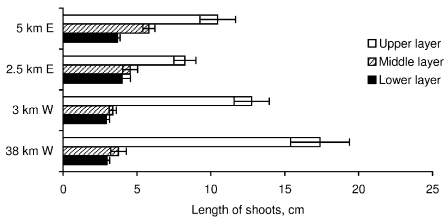


Fig. 4 Length growth of current-year shoots (mean±SE) in different layers of Scots pine crowns at different distances (km) and directions from the cement plant and in the reference site area in 2005

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

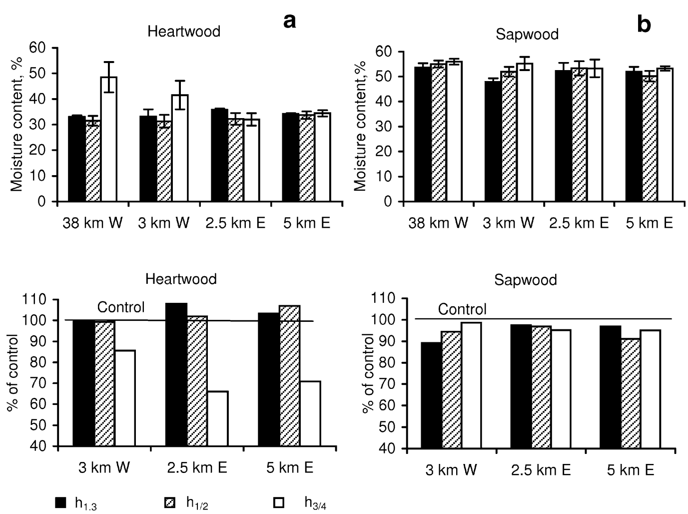
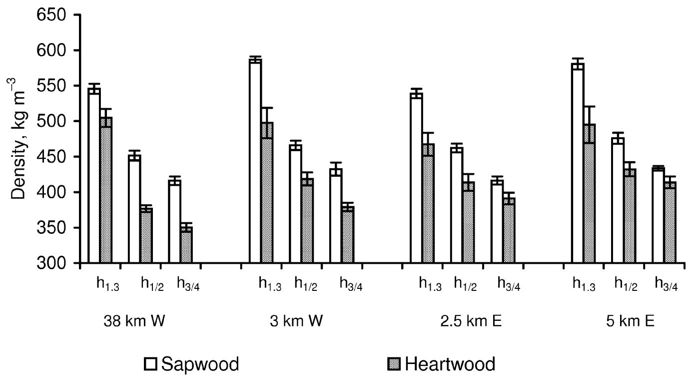


Fig. 6 Density of sapwood and heartwood of model trees on sample plots (±SE) on the different height and on the different distances from the emission source in September 2005



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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References

Allegretti, O., Bernabei, M., Negri, M., & Piutti, E. (1999). *Sapwood–heartwood proportion related to same technological properties in Picea abies* (L.) *Karst*. Paper presented at Proceedings of the Fourth International Conference on the Development of Wood Science, Wood Technology and Forestry, Missenden Abbey, UK (pp. 475–485), July.

Annuka, E. (1994). The impact of emission from cement plant on forest landscape. *Proceedings of the Estonian Academy of Sciences. Ecology, 4*, 118–127.

Auclair, D. (1977). Effects des poussièrs sur la photosynthèse. II. Influence des pollutants particulaires sur la photosynthèse du pin sylvestre et du peuplier. *Annales des Sciences Forestières, 34*, 47–57.

Bektas, I., Alma, M. H., Goker, Y., Yuksel, A., & Gundogan, R. (2003). Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. *Forest Products Journal, 53*, 48–50.

Chapin, F. S. III (1991). Effects of multiple environmental stresses on nutrient availability and use. In H. A. Mooney, W. E. Winner, & E. J. Pell (Eds.), *Response of plants to multiple stresses* (pp. 67–88). San Diego: Academic.

Duchesne, I., Wilhelmsson, L., & Spångberg, K. (1997). Effect of in-forest sorting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) on wood and fibre properties. *Canadian Journal of Forest Research, 27*, 790–795.

Environment ’90 (1991). *Tallinn* (in Estonian).

Environmental Review No. 13 (2004). Kunda: Kunda Nordic Tsement.

Estonian Environment 1991 (1991). *Environmental report 4*. Helsinki: Environment Data Centre, National Board of Waters and the Environment.

Estonian Environment 1995 (1996). Tallinn: Ministry of the Environment of Estonia, Environmental Information Centre.

Farmer, A. M. (1993). The effects of dust on vegetation – A review. *Environmental Pollution, 79*, 63–75.

Flanagan, P. W., & van Cleve, K. (1983). Nutrient cycling in forest ecosystems. In D. E. Reichle (Ed.), *Dynamic properties of forest ecosystems* (pp. 341–401). Cambridge: Cambridge University Press.

Flückiger, W., Braun, S., & Flückiger-Keller, H. (1982). Effect of the interaction between road salt and road dust upon water relations of young trees. In R. Bornkamm, J. A. Lee, & M. R. D. Seaward (Eds.), *Urban ecology* (pp. 331–332). Oxford: Blackwell Scientific Publications.

Gluch, W. (1980). Bioindikation mit produktionsbiologischen und morphometrischen Verfahren. *Archiv für Naturschutz und Landschaftsforschung, 20,* 99–116.

Hannrup, B., Ekberg, I., & Persson, A. (2000). Genetic correlation among wood, growth capacity and stem traits in *Pinus sylvestris*. *Scandinavian Journal of Forest Research, 15*, 161–170.

Härtling, S., & Schulz, H. (1998). Biochemical parameters as biomarkers for the early recognition of environmental pollution in Scots pine trees. I. Phenolic compounds. *Zeitschrift für Naturforschung, 53c*, 331–340.

Heath, R. L., & Castillo, F. J. (1987). Membrane disturbances in response to air pollution. In S. Shulte-Hostede, N. M. Darrall, L. W. Blank, & A. R. Wellburn (Eds.), *Air pollution and plant metabolism* (pp. 55–75). London: Elsevier.

Hillis, W. E. (1987). *Heartwood and tree exudates*. Berlin Heidelberg New York: Springer.

Hojatti, S. M., & Maleki, M. (1972). Effect of potassium and nitrogen fertilization on lysine, methionine and total protein contents of wheat grain. *Agronomy Journal, 65*, 46–48.

Huttunen, S., Karhu, M., & Torvela, H. (1983). Deposition of sulphur compounds on forests in southern Finland. *Aquilo Ser Botanica, 19*, 270–274.

Iliescu, E. (1981). Modificari in metabolismul plantelor de begonia sub actiunea pulberilor de la fabricile de ciment. *Analele Institutului de Cercetâri Pentru Protectia Plantelor, 16,* 437–441.

ISO 10390 (1994). *Soil quality – Determination of pH*.

ISO 11260 (1995). *Soil quality – Determination of CEC and base saturation*.

ISO 11261 (1995). *Soil quality – Determination of total nitrogen – Modified Kjeldahl method*.

ISO 3130 (1975). *Wood – Determination of moisture content for physical and mechanical tests*.

ISO 3131 (1975). *Wood – Determination of density for physical and mechanical tests*.

Jäger, E. J. (1980). Indikation von Luftverunreinigungen durch morphometrische Untersuchungen an höheren Pflanzen. In R. Schubert, & J. Schuh, (Eds.), *Bioindikation, 3: Wissenschaftliche Beiträge der Martin-Luther-Universität 26* (P1O) (pp. 43–52). Halle, Wittenberg.

Kannukene, L. (1995). Bryophytes in the forest ecosystem influenced by cement dust. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 141–147). Tallinn: Infotrükk.

Kärenlampi, P. P., & Riekkinen, M. (2002). Pine heartwood formation as a maturation phenomenon. *Journal of Wood Science, 48*, 467–472.

Kask, R., Pikk, J., & Kuusepuu, T. (2002). Scots pine (*P. sylvestris* L.) wood moisture and sapwood ratio on different forest site types. *Metsanduslikud Uurimused, 37*, 129–141.

Klõšeiko, J. (2003) Carbohydrate metabolism of conifers in alkalised growth conditions. Doctoral thesis, Estonian Agricultural University.

Knight, D. H. (1991). Pine forests: A comparative overview of ecosystem structure and function. In N. Nakagoshi & F. B. Golley (Eds.), *Coniferous forest ecology from an international perspective* (pp. 121–135). The Hague: SPB Academic Publishing.

Kokk, R. (1988). Alkalization of soils in NE Estonia. In *Soils of the Estonian SSR in figures, 7* (pp. 87–93). Tallinn: Eesti NSV Agrotööstuskomitee Info- ja Juurutusvalitsus) (in Estonian).

Kozlowski, T. T. (1991). Effects of environmental stresses on deciduous trees. In H. A. Mooney, W. E. Winner, & E. J.

Pell (Eds.), *Response of plants to multiple stresses* (pp. 391–411). San Diego: Academic.

Krigul, T., & Vaus, M. (1980). Measurement of trees and forest. In *Handbook of forestry* (pp. 46–62). Tallinn (in Estonian).

Lal, B., & Ambasht, R. S. (1982). Impact of cement dust on the mineral and energy concentration of *Psidium guayava*. *Environmental Pollution (Series A), 29*, 241–247.

Lassoie, J. P., Scott, D. R. M., & Fritschen, L. J. (1977). Transpiration studies in Douglas-fir using the heat pulse technique. *Forest Science, 23*(3), 377–390.

Lindeberg, J. (2001). *X-ray based dendro-analyses of wood properties*. Rapporter-Institutionen for skogsskotsel, Sveriges Lantbruksuniversitet 50.

Ludwig, B., Rumpf, S., Mindrup, M., Meiwes, K.-J., & Khanna, P. K. (2002). Effects of lime and wood ash on soil solution chemistry and nutritional status of a pine stand in northern Germany. *Scandinavian Journal of Forest Research, 17*, 225–237.

Magel, E., Hillinger, C., Höll, W., & Ziegler, H. (1997). Biochemistry and physiology of heartwood formation: role of reserve substances. In H. Rennenberg, W. Eschrich, & H. Ziegler (Eds.), *Trees – Contributions to modern tree physiology* (pp. 477–506). Leiden: Backhuys.

Mäkinen, H. (1998). The suitability of height and radial increment variation in *Pinus sylvestris* (L.) for expressing environmental signals. *Forest Ecology and Management, 112*, 191–197.

Mandre, M. (1989). Effect of dust pollution on the Scots pine and... *Estonian Nature, 11*, 723–731 (in Estonian).

Mandre, M. (1995a). Changes in the nutrient composition of trees. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 44–65). Tallinn: Infotrükk.

Mandre, M. (1995b). Effects of dust pollution on carbohydrate balance in conifers. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 78–95). Tallinn: Infotrükk.

Mandre, M. (2002). Relationships between lignin and nutrients in *Picea abies* L. under alkaline air pollution. *Water, Air and Soil Pollution, 133*, 361–377.

Mandre, M. (2005). Responses of Norway spruce (*Picea abies* L.) to wood ash application. *Metsanduslikud Uurimused, 42*, 34–47.

Mandre, M., & Korsjukov, R. (2002). Responses of the pigment systems of Norway spruce and Scots pine to alkalisation of the environment. *Metsanduslikud Uurimused, 36*, 95–106.

Mandre, M., & Tuulmets, L. (1997). Pigment changes in Norway spruce induced by dust pollution. *Water, Air and Soil Pollution, 94*, 247–258.

Mandre, M., Klõšeiko, J., Ots, K., & Tuulmets, L. (1999). Changes in phytomass and nutrient partitioning in young conifers in extreme alkaline growth conditions. *Environmental Pollution, 105*, 209–220.

Mandre, M., Rauk, J., & Ots, K. (1995). Needle and shoot growth. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 103–111). Tallinn: Infotrükk.

Mandre, M., Tuulmets, L., Rauk, J., Ots, K., & Okasmets, M. (1994). Response reaction of conifers to alkaline dust pollution. Changes in growth. *Proceedings of the Estonian Academy of Sciences. Ecology, 4*, 79–95.

Manning, W. J. (1971). Effects of limestone dust on leaf condition, foliar disease incidence, and leaf surface microflora on native plants. *Environmental Pollution, 2*, 69–76.

Manning, W. J. (2001). Air pollution and forest health: Establishing cause and effect in the forest. *The Scientific World, 1*, 391–392.

Manning, W. J., & Feder, W. A. (1980). *Biomonitoring air pollutants with plants*. London: Applied Science Publishers.

Matsuyama, N. (1975). The effect of ample nitrogen fertilizer on cell wall materials and its significance to rice blast disease. *Annals of Phytopathological Society of Japan, 4*, 56–61.

Mattsson, S. (2002). Effects of site preparation on stem growth and clear wood properties in boreal *Pinus sylvestris* and *Pinus contorta*. *Acta Universitatis Agriculturae Sueciae, Silvestria, 240*, 1–37.

Miidla, H. (1984). *Plant physiology.* Tallinn: Valgus (in Estonian).

Miidla, H. (1989). Biochemistry of lignin formation. In *Publications in plant physiology and plant biochemistry, 5. The formation of lignin in wheat plants and its connection with mineral nutrition* (pp. 11–23). Acta et Commentationes Universitatis Tartuensis, 845, Tartu.

Monties, B. (1989). Lignins. In P. M. Dey & J. B. Harborne (series Eds.), J. B. Harborne (Ed.), *Methods in plant biochemistry, Plant phenolics* (vol. 1, pp. 113–157). London: Academic.

Mott, L., Groom, L., & Shaler, S. (2002). Mechanical properties of individual southern pine fibers. Part II. Comparison of earlywood and latewood fibers with respect to tree height and juvenility. *Wood and Fiber Science, 34*, 221–237.

Nekrasova, A. A. (1994). Properties of wood of conifers as a function of the growth conditions. *Lesnoe Khozyaistvo, 2*, 22–24 (in Russian).

Nerg, A., Kainulainen, P., Vuorinen, M., Hanso, M., Holopainen, J. K., & Kurkela, T. (1994). Seasonal and geographical variation of terpenes, resin acid and total phenolics in nursery grown seedlings of Scots pine (*Pinus sylvestris* L.). *New Phytologist, 128*, 703–713.

Nilson, E. (1995). Species composition and structure of epiphytic lichen assemblages on Scots pine around the Kunda cement plant. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 134–141). Tallinn: Infotrükk.

Orlov, A. J., & Koshel'nikov, S. P. (1971). Soil ecology of Scots pine. Moscow: Nauka (in Russian).

Ots, K. (2000). Morphometric parameters of conifer needles and shoots in the areas near the Kunda cement plant. *Metsanduslikud Uurimused, 33*, 158–176.

Ots, K. (2002). Impact of air pollution on the growth of conifers in the industrial region of Northeast Estonia. Doctoral thesis, Estonian Agricultural University.

Ots, K. (2003). Impact of emission from oil shale fueled power plants on the growth and foliar elemental concentrations of Scots pine in Estonia. *Environmental Monitoring and Assessment, 85*, 293–308.

Ots, K., & Pöör, M. (1994). Influence of alkaline dust on shoot length of conifers. In *Forestry. Transactions of the Estonian Agricultural University, 173*, 130–133 (in Estonian).

Ots, K., & Rauk, J. (1999). Influence of climatic factors on annual rings of conifers. *Zeitschrift für Naturforschung, 54c*, 526–533.

Padu, E., Meiner, L., & Selgis, R. (1989). The activity of L-phenylalanine ammonia-lyase and peroxidase, and the biosynthesis of phenolic compounds in wheat under different condition of mineral nutrition. In *Publications in plant physiology and plant biochemistry, 5. The formation of lignin in wheat plants and its connection with mineral nutrition* (pp. 85–108). Acta Comm Univ Tartuensis, 845.

Pallardy, S. G., Cermak, J., Ewers, F. W., Kaufmann, M. R., Parker, W. C., & Sperry, J. S. (1995). Water transport dynamics in trees and stands. In W. K. Smith & T. M. Hinckley (Eds.), *Resource physiology of conifers* (pp. 301–389). San Diego: Academic.

Penel, C. (1986). The role of calcium in the control of peroxidase activity. In H. Greppin, C. Penel, & T. Gaspar (Eds.), *Molecular and physiological aspects of plant peroxidases* (pp. 155–164). Geneva: University of Geneva, Centre Botanique.

Polle, A., Otter, T., & Sandermann, H., Jr. (1997). Biochemistry and physiology of lignin synthesis. In H. Rennenber, W. Eschrich, & H. Ziegler (Eds.), *Trees – Contributions in modern tree physiology* (pp. 455–475). Leiden: Backhuys.

Rauk, J. (1995). Bioproductivity. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 119–123). Tallinn: Infotrükk.

Saarsalmi, A., Mälkönen, E., & Kukkola, M. (2004). Effects of wood ash fertilization on soil chemical properties and stand nutrient status and growth of some coniferous stands in Finland. *Scandinavian Journal of Forest Research, 19*, 217–233.

Saikku, O. (1975). The effect of fertilization on the basic density of Scots pine (*Pinus sylvestris* L.). A densitometric study on the X-ray chart curves of wood. *Communicationes Instituti Forestalis Fenniae, 85*, 1–49.

Schulte, E. E. (1995). Recommended soil organic matter tests. In T. J. Sims & A. Wolf (Eds.), *Recommended soil testing procedures for the Northeastern United States, Northeast Regional Bulletin 493* (pp. 47–56). Newark: Agricultural Experiment Station, University of Delaware.

Seco, J. I. F. G., & Barra, M. R. D. (1996). Growth rate as a predictor of density and mechanical quality of sawn timber from fast growing species. *Holz als Roh-und Werkstoff, 54*, 171–174.

Seeling, U. (2000). Ausgewählte Eigenschaften des Holzes der Fichte (*Picea abies* (L.) Karst.) in Abhängigkeit vom Zeitpunkt der Fällung. *Schweizerische Zeitschrift für Forstwesen, 151*, 451–458.

Sipi, M., & Rikala, J. (2000). *Tree stands on peatland, quality of wood raw material and suitability for different use objects*. Paper presented at the 21st IUFRO World Congress, Poster abstracts 3 (pp. 191–192). Malaysia, August.

Skuodene, L. (2005). *Stress of trees and it physiological estimate*. Kaunas: ARX Baltica Pribt House.

Smith, W. H. (1990). *Air pollution and forests. Interactions between air contaminants and forest ecosystems* (2nd ed.). Berlin, Heidelberg New York: Springer.

Staaf, H., & Tyler, G. (Eds.) (1995). Effects of acid deposition and tropospheric ozone on forest ecosystems in Sweden. Ecol Bull 44. Copenhagen: Munksgaard.

Teras, T. (1984). Impact of Kunda cement plant dust on the surrounding forest soils. In *Land Management 17* (pp. 11–22). Tallinn (in Estonian).

Thornley, J. H. M. (1991). A transport-resistance model of forest growth and partitioning. *Annals of Botany, 68*, 211–226.

Tohver, A., & Mandre, M. (1995). Influence of cement dust on phenolic substances in conifers. In M. Mandre (Ed.), *Dust pollution and forest ecosystems. A study of conifers in an alkaline environment.* Publ Inst Ecol 3 (pp. 96–102). Tallinn: Infotrükk.

Uzunovic, A., & Dickinson, D. I. (1998). Measuring and expressing moisture content in green timber. *Material und Organismen, 32*, 217–225.

Verbyla, V. V., & Šleinys, R. I. (1981). Effect of fertilizer application on the quality of wood in Scots pine stands. *Lesnoe khozyaistvo, 12*, 8–11 (in Russian).

Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S. O., Grahn, T., Hedenberg, Ö., et al. (2002). Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. *Scandinavian Journal of Forest Research, 17*, 330–350.

Wimmer, R. (1991). Relations between growth ring parameters and density of Scots pine wood. *Holzforschung und Holzverwertung, 43*, 79–82.

Wodzicki, T. J. (2001). Natural factors affecting wood structure. *Wood Science and Technology, 35*, 5–26.

Ziegler, H. (1997). Some open questions in tree physiology. In H. Rennenberg, W. Eschrich, & H. Ziegler (Eds.), *Trees – Contributions in modern tree physiology* (pp. 531–544). Leiden: Backhuys.

Zvirbul', A. P., Nekrasova, G. N., & Poluboyarinov, O. I. (1976). Effect of urea fertilization on pine stands on the wood quality. *Lesnoi Zhurnal, 6*, 18–22 (in Russian).

IV

Pikk, J., **Kask**, **R**., Peterson, P. 2006.
The wood quality of fertilized Scots pine (*Pinus sylvestris* L.) stands on
Vaccinium vitis-idaea and *Cladonia* site type.
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The wood quality of fertilized Scots pine (*Pinus sylvestris* L.) stands on *Vaccinium vitis-idaea* and *Cladonia* site type

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Abstract. Twenty four sample plots in artificial pine stands on productive and less productive site types in Estonia were investigated. It is possible to increase the productivity of pine stands with mineral fertilizers. Improving the quality of stands has a problematical value. Unsatisfying self-pruning in repeatedly fertilized middle-aged stands causes a low quality of first log. Great radial growth after fertilization increased sapwood ratio of the raw material from thinning origin. It might not contain so much latewood. Repeated fertilization has no practical influence on heartwood formation. Heartwood ratio has no relation with the diameter of trees, tree height, live crown length and volume of crone in even-aged pine stands of artificial origin.

Key words: pine, heartwood, latewood, site type, fertilization, self-pruning

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Introduction

Quality determines the price of raw timber and its usage. As the quality has been described mainly through the properties of wood, the necessity to do some research into those factors is evident. In general, it has been found that the wood properties depend on genetics, growing conditions and the age of a tree (Некрасова, 1994; Ojansuu, Maltamo, 1995; Wodzinci, 2001; Lindeberg, 2001; Bektas *et al.*, 2003). The quality of growing stands cannot be changed through their genotype, however, the change of growing conditions (thinning, fertilizing and drainage) of stands is the main way in silviculture to improve the growth and quality of stands.

There are many research papers on the importance of thinning for high-quality stands, but the fertilizing results are problematic and often vary on a large scale. Fertilization remarkably stimulates the growth of branches and needles that is a precondition for lush stem wood growth. The lush growth may influence wood properties. Therefore fertilization of young stands is not useful as it increases the diameter of branches and reduces the stem quality (Nikkola, 1985; Mäkinen, Uusvaara, 1992). Despite that, stand fertilization with the aim of reducing competition for the use of nutrients is recommended before thinning (Nikkola, 1985; Saarsalmi, Mälkonen, 2001). In addition to bigger branchiness the mechanical wood properties reduce and also the spread of stem rot has been spotted (Pape, 1999).

Most fertilization experiments have been established with the aim of increasing wood production and the following economical income from forestry. For example, the fertilization in Finland has increased the production of upland forests by 16 Mm^3

(Kukkola, Nöjd, 2000). It is known that the primary quality criteria for processing and commercial value of the stems and logs at sawmills are stem size, stem form, technical defects and branchiness. However, in addition to external qualities, the level and variation of the internal quality characteristics, such as annual ring width, wood density, proportions of heartwood and sapwood, proportion and diameter of possible juvenile wood and other internal defects (checks, pitch pockets, decay) are important, as well.

Annual ring width varies a lot among the trees and within a single tree, depending on the tree age, site fertility and seasonal growing conditions (Henttonen, 1984). Thereafter the radial growth rate is dependent on the available nutrient resources (Seppälä, 1976). High heartwood ratio is usually an advantage for the use of wood, since, for example, heartwood has good dimension stability and it is relatively resistant to decay. The heartwood proportion of pine correlates negatively with high growth rate, its high crown ratio and dominance of trees (Kärkkäinen, 1972).

The aim of this study was to investigate the influence of up to three-time application of mineral fertilizers on the quality of wood in stands of the Scots pine (*Pinus sylvestris* L.) in *Vaccinium vitis-idea* and *Cladonia* site types. We hypothesised that the development of a tree stand in the sandy soil depends on thinning and the nutrients applied, and that the effect of fertilization influenced some wood properties. The possibilities to forecast the proportion of heartwood and latewood percentage have been checked by means of external tree characteristics.

Materials and methods

A total of 24 research plots of pine were created in 1970-s with the area of à 0.1 ha on *Cladonia* and *Vaccinium vitis-idaea* site type, located in different parts of Estonia (58–59°N; 22–28°E) (Table 1). The main principle for our shoice of experimental stands was that one object would be situated in productive and the other in less fertile soil of the same site type. When the experiment was started the Pine stands on *Vaccinium vitis-idaea* site type had site index 1a and 2 (age 45 and 50 years respectively) and pine stands on *Cladonia* site type had site index 3 and 5 (age 50 and 21 years respectively). All the stands were single-storied artificial stands.

Diameter at breast height, tree height, the lowest dead branch and the height to the first live branch of all trees were measured on sample plots. The crown diameter was measured both in the north-south and west-east direction. Samples were taken at the breast height of all the trees using increment borer. The boring was done either from east to the west and from the west to the east. The growth ring widths of trees (early wood and latewood separately) were measured within 0.01 mm accuracy. The percentage of heartwood at breast height, the number of annual rings in sapwood as well as the relative importance of latewood were determined. Relations between the external tree characteristics that would help to make forecasts about the percentage of sapwood and heartwood were dealt with. The crown volume was calculated as follows: $v=\frac{2}{3}\pi R^2 L$, R – crown radius and L – crown length.

Correlation and regression analyze methods were used for data processing and a special program WinDendro was used for measuring radial growth. Estimating relations, the correlation was estimated as weak ($R<0.3$), moderate ($R=0.3–0.5$), medium ($R=0.5–0.7$), strong ($R=0.7–0.9$) or very strong ($R>0.9$).

Results and discussion

The dynamics of wood production in four experimental stands with fertilized and unfertilized experimental plots is shown in Figure 1. The mean productivity during the experimental period in pine stands on *Vaccinium vitis-idaea* site type makes up to 9.27–13.0 m^3/ha per year and in pine stands on *Cladonia* site type 8.41–10.37 m^3/ha per year. As shown in Table 2 there is no significant difference between the stand density, diameter and height of the trees in fertilized and unfertilized experimental plots. However, the mean production (Table 1) is bigger in the fertilized plots (1.1–2.1 m^3/ha $year^{-1}$) of Saare and Kubja trials.

Table 1. Production and growing stock of fertilized (F) and control (C) pine stands
Tabel 1. Tagavara ja tootlikkus väetatud (F) ja väetamata (C) männipuistutes

Object and site type *Objekt ja kasvukoha tüüp*	Variant *Katse-variant*	Fertilization years *Väetamise aastad*	Preliminary stock volume *Esialgne tagavara* m^3/ha	Production of experimental period *Katseperioodi produktsioon* m^3/ha	Annual production *Aastane juurdekasv* m^3/ha	Age *Vanus*	Growing stock m^3/ha and year *Puistu tagavara* m^3/ha *ja aasta*
Vastseliina 4	C		159.9	289.1	9.32	81	298-2004
Vaccinium vitis-idaea	F	1973,-89,-94	148.7	287.5	9.27		303
Kubja 3	C		190.0	359.9	11.20	82	380-2004
Vaccinium vitis-idaea	F	1972,-73,-74	181.9	415.1	13.00		449
Kubja 2	C		144.5	252.2	8.41	83	325-2002
Cladonia	F	1972	131.6	286.6	9.55		340
Saare 3	C		20.1	279.9	8.75	54	203-2003
Cladonia	F	1971,-86	21.8	331.8	10.37		238

Thinning and sanitation cuttings in middle-aged and older stands were carried out regularly, but the percentage of the thinned volume in the growing stock was relatively small accoding to the earlier silvicultural directions. The effect of fertilization on stand parameters, i.e. the diameter, height, productivity etc., and their variability during the stand growth is obvious. It is not clear how much fertilization affects self-pruning and thinning percentage in different stands. Cutting intensity on experimental plots has been limited to felling dead trees and light thinning (10–16%) only. So the stands have generally had a high stand density, which was also observed during the last measurement (Table 2). There is an exceptional pine stand of *Cladonia* site type with low soil fertility where, at the age of 54, the thinning of the control stand was 30% and the fertilized stand respectively — 43.6%. It should be mentioned that in certain cases the temporary increase of foliage mass and a higher degree of canopy cover after the fertilization may create an illusion of a growing need for thinning.

The quality of wood largely depends upon the number of branches and their thickness. When increasing the stand density the number of branches starts to diminish. Natural self-pruning has been aimed at in the cultivation of high-density stands. Much more thinning has been used in fertilized pine stands of *Cladonia* site type, whereas the degree of thinning has been a little lower in fertilized pine stands of *Vaccinium vitis-idaea* site type. During the experimental period the productivity of the fertilized stands of the three experimental areas has been higher compared to the unfertilized stands.

Table 2. Mean characteristics of the experimental stands (mean ± S.E.)
Tabel 2. Katsevariantide puistu keskmised iseloomustajad (keskmine ± st. viga)

Object and variant *Objekt ja katsevariant*		Stand density *Puistu täius*	Diameter $D_{1,3}$, cm	Stand height *Puistu kõrgus, m*	Crown length ratio *Võra suhteline pikkus, %*	First knot *Esimene kuiv oks, m*	Crown diameter *Võra diameeter, m*	Degree of canopy cover *Võra liitus, %*
Vastseliina 4	C	0.78	23.00±0,69	22.67±0.27	33.0	7.47±0.47	2.97±0,10	44.5
	F	0.78	23.34±0,51	22.59±0.25	32.0	7.09±0.21*	2.75±0,09	36.2
Kubja 3	C	0.78	27.42±0,53	28.73±0.29	30.7	10.88±0.36	3.25±0,13	40.0
	F	0.93	26.34±0,46	28.18±0.29	31.7	9.41±0.27*	3.04±0,11	45.7
Kubja 2	C	0.95	22.15±1,16	21.55±0.42	31.8	5.34±0.31	3.59±0,26	105.3
	F	0.95	22.27±0,98	21.62±0.54	35.5	5.47±0.34	3.40±0,26	94.0
Saare 3	C	0.65	19.99±0,52	18.53±0.26	44.7	2.62±0.14	3.23±0,12	53.2
	F	0.70	21.99±0,59	19.73±0.27	42.6	2.04±0.12*	3.56±0,12	57.5

*difference from control is significant (p<0.05) / *erinevus kontrollist oluline (p<0,05)*

The crown coverage density of the stands differs depending on the time that has passed since the latest thinning. The canopy is especially dense in Kubja 2 pine stands of *Cladonia* site type. During the last five years the thinning has reduced the canopy cover on other experimental areas although the thinning has had a modest effect on stand density. The tree crowns of dense stands have not had an opportunity to grow their diameter, which has generally been 2.75–3.59 m. The live crown length has been relatively normal. The directions of silviculture recommend to limit the crown coverage density in the way that the length of the crowns in those stands could form

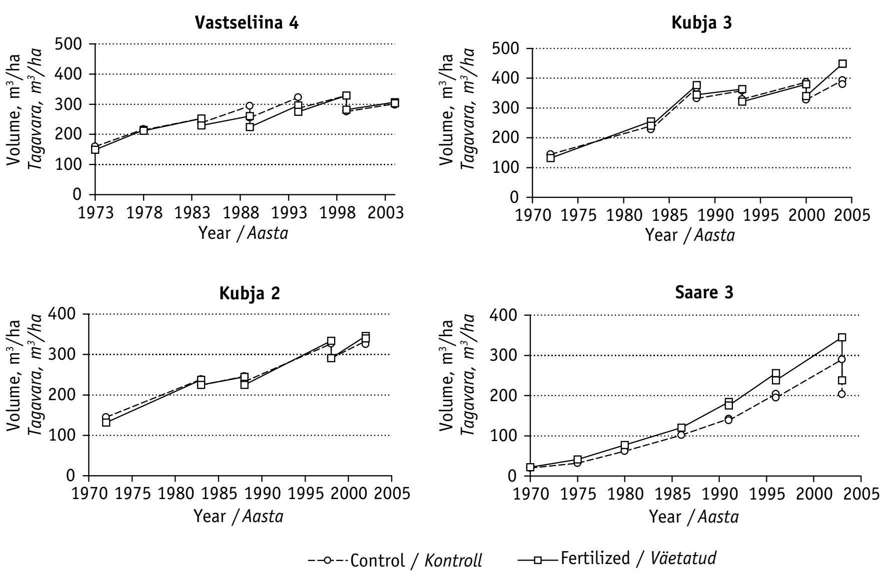

Figure 1. Production and the degree of thinning in unfertilized and fertilized stands
Joonis 1. Väetamata ja väetatud puistute tootlikkus ja väljaraie pärast katsete rajamist

⅓–¼ of the tree height, which has been achieved according to our measurement. The crown length forms up to 30.7–35.5% of the tree height on three experimental plots, but 42.6–44.7% in the pine stands of *Cladonia* site type with limited soil nutrient supply. The length of live crowns in fertilized experimental areas is higher than on unfertilized areas in three cases out of four. But this difference is not statistically significant. The base of live crown of almost all the trees is at the same level in cultivated stands, but the variety of this level of each diameter class is remarkable. The height of the pruned stem up to the first knot shows that a knot-free first log is rare in our stands (Figure 2). There is a negative correlation between the tree diameter and first knot height. Fertilization after the first thinning has no influence on branchiness of butt log, as recommended in the literature (Saranmäki, Silander, 1982; Nikkola, 1985). The fertilization of our three objects has been carried out after the first thinning but the results have been different. The fertilization done more than thirty years ago has influenced first branches so that the knots are still noticeable on the stems. Most trees have grown intensively and reacted well to fertilization especially in the pine stands of *Vaccinium vitis-idaea* site type. The gaps in the stands formed in the course of thinning the predominant trees with a great crown have influenced the existence knot stubs. Self-pruning around gaps slows down, which is a special feature of the stands with a higher site index. The pine stands of *Cladonia* site type have self-pruned in an equally unsatisfactory way and knots begin to appear at a two-meter height already. The self-pruned stem length in the stands repeatedly fertilized with N has been significantly shorter than in the control stands (Table 2). One-time fertilization has not influenced self-pruning (Kubja 2). Due to weak self-pruning it has been considered more useful to fertilize older pine stands (Nilsen, 2002). In general the knot-free stem length in the stands varies so greatly that it has had no remarkable relations with the other investigated external characteristics (live crown length, crown width, tree height, diameter at breast height).

An additional radial growth that has followed the fertilization of investigated stands has already been described earlier (Pikk *et al.*, 1999; Pikk *et al.*, 2001). It can be stated that re-fertilizing of pine stands of *Vaccinium vitis-idaea* site type often destroys the nutrient balance and after fertilization a radial increment period will be followed by a period when a radial increment of fertilized stands is lower than in unfertilized stands. It can be summarized with a fact that a fertilization effect decreases totally.

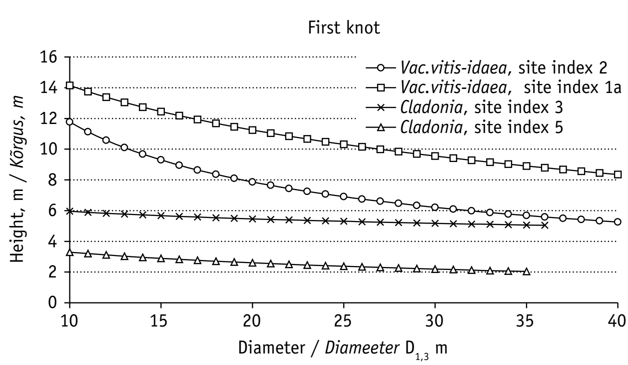

Figure 2. The first knot height relation with breast height diameter in fertilized stands
Joonis 2. Laasunud tüveosa kõrgus sõltuvalt puu rinnasdiameetrist katseobjektide väetatud puistutes

Therefore during a longer period an average annual ring in fertilized stands has not been remarkably wider than in control stands in most cases (Table 3).

Different results have become evident when studying the wood properties after fertilization. In Finland N fertilization (100–200 kg N ha^{-1}) increased the width of the annual rings by an average of 0.3–0.5 mm (Mäkinen, Uusvaara, 1992). The biggest influence has been spotted during the third or fourth year following the fertilization when the basic density of pinewood near the final cutting declined by 1–4% after N fertilization and depends on the site type to a certain extent (Saikku, 1975). In Novgorod region the wood density of pinewood decreased 8–11%, during the five years after fertilization and the annual ring width increased up to 168.6% whereby the latewood width increased only up to 17.6% (Звирбуль и др., 1976). In the course of fertilizing drainage bog pine stands it has been noticed that the latewood ratio has increased a couple of percent (Пикк, 1988; Pikk *et al.,* 2004). The scientific literature (Werberg, 1930; Звирбуль и др., 1976; Kairiūkštis, Malinauskas, 2001; Mäkinen *et al*., 2002) and our previous studies have verified a strong relationship between latewood and wood density, which is a precondition for getting wood with good strength properties (Kask, 2003).

The number of annual rings of sapwood at the moment of study was almost equal or even higher than in the run of the experimental period, which means that the wood growing after fertilization forms only inside the sapwood. The research of the width of annual rings after fertilization has shown a minimal decrease of latewood at breast height and thus, a decrease of wood density can be inferred during those years. As the following periods showed the opposite tendencies in growth the problem is of little importance. The basis of the consideration is the fact that wood grown after the beginning of the experiment (>30 years) has lower latewood percentage after fertilization only in two experimental areas. It is interesting to note that differences in the growth of the ring width resulting from thinning were not accompanied by significant differences in latewood percentage and wood basic density or they have had little influence (Loranca *et al*., 1996). The latewood/earlywood ratio depends on a tree position in the stand and varies like wood basic density (Kairiūkštis, Malinauskas, 2001).

Our results did not assure that the latewood ratio could depend on the tree position in a stand. The reasons can be the cultivated origin of the single-storied stands and the similar age of the trees. Heartwood, having better shape stability and fewer

Table 3. Internal characteristics of pine wood at breast height (mean ± S.E.)
Tabel 3. Männipuidu struktuuri iseloomustajad rinnakõrgusel (keskmine ± st.viga)

Object *Objekt*	Variant *Katse-variant*	Number of annual rings in sapwood *Aastarõngaste arv maltspuidus*	Annual ring width in sapwood *Aastarõnga laius maltspuidus, mm*	Heartwood *Lülipuit, %*	Latewood of experiment period *Katseperioodi sügispuit, %*
Vastseliina 4	C	49.8±0.8	0.95±0.04	53.7±0.9	40.5±0.6
	F	48.0±1.0	1.03±0.05	49.1±0.9*	38.1±0.5*
Kubja 3	C	40.0±1.9	1.30±0.05	53.1±2.1	40.1±0.8
	F	39.5±1.4	1.36±0.11	55.9±3.8	39.3±0.9
Kubja 2	C	41.8±1.3	1.08±0.06	52.9±1.9	37.2±0.5
	F	43.4±1.2	1.17±0.07	46.4±2.5	38.2±0.6
Saare 3	C	28.9±0.4	1.69±0.06	22.0±0.5	37.1±0.6
	F	29.6±0.4	1.77±0.05	22.5±0.5	39.5±0.5*

* difference from control is significant (p<0.05) / *erinevus kontrollist oluline (p<0,05)*

internal stresses is a much better raw material for many products than sapwood.

Pine heartwood formation is regarded as a sign of maturation in silviculture. The rate of heartwood is a much better indicator to determine maturation of the tree than the age and size, because the heartwood appears to be independent of growth rate and size (Karenlampi, Rikkinen, 2002). It is known that the pine has more heartwood in dense stands and it decreases remarkably according to relative tree growth (Ojansuu, Maltamo, 1995). The results by J. Uusitalo (2004) show that heartwood starts to form when the cambium age is roughly 20 years and after that it increases by two-thirds of the year ring annually.

According to such calculations, the sapwood of our experimental areas should have the following annual rings: Vastseliina 4 – 40.3, Kubja 3 – 40.7, Kubja 2 – 41.0 and Saare 3 – 31.3. As seen in Table 3 the results are similar in Kubja experimental areas. Pines in Vastseliina have relatively more annual rings in the sapwood and there are fewer rings in Saare pine stands of *Cladonia* site type. Heartwood forms slower in Estonia than in Finland because, according to E. Laas (2004), pine wood has generally more than 40 annual rings in sapwood and this fact could be supported by our previous studies carried out in middle-aged and older pine stands of *Vaccinium vitis-idaea* and *Myrtillus* site type (Kask, 2003; Pikk, Kask, 2004). Although the biggest number of annual rings in sapwood was not recorded in the stands with the highest site index, our results refer to the influence of nutrient conditions on sapwood formation that was already mentined by K. Werberg in 1930.

The heartwood ratio of repeatedly fertilized stands decreased in the breast height gross-section of the stems only in one case. The difference remained within the limits of a relative error in other experimental areas. Also, the co-influence of fertilizing and thinning has not had any remarkable effect on heartwood formation. There was a significant positive interaction effect of fertilization and thinning on the tree diameter under bark, sapwood area and relative heartwood area. The number of growth rings included in the heartwood at breast height was not affected by treatments. The possibility of affecting the amount of heartwood in individual trees by thinning and fertilization is limited (Mörling, Valinger, 1999). The 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). Our results support J. Lindeberg's (2001) opinion who wrote that both the environmental factor and the genotype have a considerable influence on the formation of heartwood (the latter appears in critical growth conditions).

Sapwood-heartwood ratios have been tried to forecast according to the external characteristics of a tree and of a stand (Kellomäki *et al.,* 1999; Fries, 1999). It has been noticed that the base of the crown correlates remarkably with the average growth of a tree and this is a more efficient characteristic to forecast the sapwood area in a cross-section than the diameter at breast height and the tree height (Ojansuu, Maltamo, 1995). According to our results the crown basis is very weakly related to the sapwood area measured at breast height (R=0.03–0.28). Also, the relation between the percentage of heartwood and the crown size is negative and weak. The relation between an average annual ring width of sapwood and the crown size was medium (R=0.58–0.64) and (R=0.76) in one case strong.

Pines on *Vaccinium vitis-idaea* and *Cladonia* site type have different wood structure. This already becomes evident at the early age of trees when juvenile wood begins to form at breast height. That rate is also one of the characteristics of raw timber. Annual rings near the pith at breast height are relatively wide and do not differ remarkably among the pines on both site types. However, the difference between their latewood

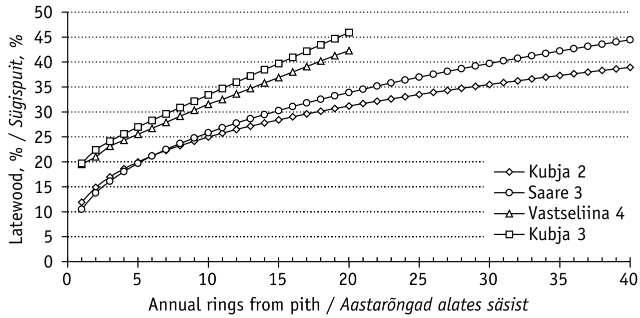

Figure 3. Latewood ratio from the pith to the outside of pines in different site types
Joonis 3. Sügispuidu osatähtsus aastarõngastes alates säsist erineva kasvukohaga männikutes

percentage is high (Figure 3). Latewood ratio in *Cladonia* site type was identified starting from 10% and in *Vaccinium vitis-idaea* site type from 20%. Comparing the data with the results obtained from the breast height in pine stands of *Myrtillus* site type studied earlier (8–12%) (Pikk, Kask, 2004), the stand site type cannot be considered as the only causal factor. The abundance or deficiency of some nutrient elements, genetics, growth intensity period, periodical climate conditions and other factors can also influence. It is noteworthy that the dynamics of the latewood increase starting from pith has been varied. The regression equations of latewood percentage (y) in relation with cambial age (x) in cross-section breast height are as follows:

Saare 3	$y=10.482x^{0.3917}$	$R^2=0.99$;
Kubja 2	$y=11.929x^{0.3207}$	$R^2=0.94$;
Vastseliina 4	$y=19.34665+1.215853x+0.44919/x$	$R^2=0.99$;
Kubja 3	$y=21.38823+1.233927x-2.92683/x$	$R^2=0.94$.

The increasing percentage of latewood of *Cladonia* site type stays relatively low after the sixth year but it has been proportionate to the age in the pine stands of *Vaccinium vitis-idaea*. Fertilization of middle-aged and older stands can influence wood properties of the crown area through the increase of juvenile wood. Also, it is possible to increase the percentage of juvenile wood fertilizing young stands of relatively low density but it is not recommended.

Conclusions

Fertilization can increase the productivity of pine stands but the possibility to improve the timber quality is questionable. Increase of productivity and intensive growth of branches and needles in a site type with poor fertility can make it seem that there is a stronger need for thinning in the stand. Self-pruning decreases in repeatedly fertilized middle-aged stands and it causes low quality of first log.

Bigger radial growth after fertilization increases the ratio of sapwood in raw timber got while thinning, where less latewood can exist. This wood has lower density and weaker wood properties. Fertilization has practically no influence upon the acceleration process of heartwood formation. Estimating heartwood-sapwood ratio in a stem by the external characteristics of trees is questionable.

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References

Bektas, I., Alma, M. H., Goker, Y., Yuksel, A., Gundogan, R. 2003. Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. – Forest Products Journal, 53 (4), 48–50.

Fries, A. 1999. Heartwood and sapwood variation in mature provenance trials of *Pinus sylvestris*. – Silvae Genetica, 48(1), 7–14.

Henttonen, H.1984. The dependence of annual ring indices on some climatic factors. – Acta Forestalia Fennica, 186, 1–38.

Kairiūkštis, L., Malinauskas, A. 2001. The influence of the initial density on spruce (*Picea abies* Karsten.) wood quality. – Baltic Forestry, 7 (2), 8–17.

Karenlampi, P. P., Rikkinen, M. 2002. Pine heartwood formation as a maturation phenomenon. – Journal of Wood Science, 48 (6), 467–472.

Kask, R. 2003. Hariliku männi (*Pinus sylvestris* L.) puidu mehaanilised ja füüsikalised omadused pohlaja mustika kasvukohatüübis. – EPMÜ. Magistritöö metsateaduste magistrikraadi taotlemiseks metsatööstuse erialal. Tartu, – 141 lk. Käsikiri metsandusteaduskonnas. [Mechanical and physical properties of Scots pine wood on *Vaccinium vitis-idaea* and *Myrtillus* site type].

Kellomäki, S., Ikonen, V. P., Peltola, H., Kolström, T. 1999. Modelling the structural growth of Scots pine with implications for wood quality. – Ecological Modelling, 122, 1/2, 117–134.

Kukkola, M., Nöjd, P. 2000. Kangasmetsien lannoituksen tuottama kasvunlisäys Suomessa 1950–1998. – Metsätieteen aikakauskirja, 4, 603–612. [Additional growth increment of fertilized mineral soil forests in Finland]

Kärkkäinen, M., 1972. On the proportion of heartwood in Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.). – Silva Fennica, 6(3), 193–208. [in Finnish, English summary].

Laas, E. 2004. Okaspuud. Atlex, Tartu, – 359 lk. [The coniferous trees].

Lindeberg, J. 2001. X-ray based dendro-analyses of wood properties. – Rapporter-Institutionen for skogsskotsel, Sveriges Lantbruksuniversitet (No.50), 18 pp. + Papers I-II.

Loranca, J. A. G., Oliva, A.G., Merino, M. V. B. 1996. Influence of thinning intensity on growth, volume production, and wood properties in a *Pinus sylvestris* L. reforestation. – Investigatcion Agraria, Sistemas y Recursos Forestales, 5 (2), 25–273.

Mäkinen, H., Uusvaara, O. 1992. Effects of fertilization on the branchiness and the wood quality of Scots pine. – Folia Forestalia, 801, 23. (in Finnish, English summary)

Mäkinen, H., Saranpää, P., Linder, S. 2002. Wood-density variation of Norway spruce in relation to nutrient optimization and fibre dimensions. – Can. J. For. Res., 32(2), 185–194.

Mörling, T., Valinger, E. 1999. Effects of fertilization and thinning on heartwood area, sapwood area and growth in Scots pine. – Scand. J. For. Res., 14, 5, 462–469.

Nikkola, A. 1985. Kasvatustiheyden ja lannoituksen vaikutus rikkuvaiheen männiköiden laatuun (Effect of stand density and fertilization on the branchiness and wood quality of pole stage Scots pine stands). – MSc. Thesis, Faculty of forestry, University of Helsinki. – 45 pp.

Nilsen, P. 2002. Fertilization experiments on forest mineral soils: A review of the Norwegian results. – Scand. J. For. Res., 16, 541–554.

Ojansuu, R., Maltamo, M. 1995. Sapwood and heartwood taper in Scots pine stems. – Can. J. For. Res., 25(12), 2008–2016.

Pape, R. 1999. Effects of thinning regime on the wood properties and stem quality of *Picea abies*. – Scand. J. For. Res., 14(1), 38–50.

Pikk, J., Seemen, H., Peterson, P. 1999. Pohlamännikute normaalse juurdekasvu taastumine pärast lämmastikuga väetamist. – Metsanduslikud uurimused XXXI. Tartu, 61–71. [Re-establishment of normal growth increment rate in Scots pine stands on *Vaccinium vitis-idaea* site type after fertilization with nitrogen].

Pikk, J., Seemen, H., Valk, U. 2001. Toitumistingimuste järsust halvenemisest tingitud taandarengulised protsessid puistutes. – EPMÜ Metsanduslik uurimisinstituut. Grandiprojekti 2685 lõpparuanne. Tartu, 96 lk. Käsikiri Eesti TA Raamatukogus. [The retrogression processes in stands caused by steeply deteriorated growing conditions]

Pikk J., Kask R. 2004. Mechanical Properties of Juvenile Wood of Scots Pine (*Pinus sylvestris* L.) on *Myrtillus* Forest Site Type. – Baltic Forestry, 10(1), 72–78.

Pikk J., Kask R., Kuusepuu T., Peterson P. 2004. Kasvutingimuste mõju hariliku männi (*Pinus sylvestris* L.) puiduomadustele. – Metsanduslikud Uurimused, 40, 187–197. [The effect of growth conditions on Scots pine (P. sylvestris L.) wood properties].
Saarsalmi, A., Mälkonen, E. 2001. Forest fertilization research in Finland: A Literature review. – Scand. J. For. Res., 16(6), 514–535.
Saikku, O. 1975. The effect of fertilization on the basic density of Scots pine (*Pinus sylvestris* L.). A densitometric study on the X-ray chart curves of wood. Densitometritutkimus puuaineen röntgenokuvista. – Commun. Inst. For. Fenn., 85 (3), 49.
Saranmäki J., Silander P. 1982. The effect of fertilization and thinning on the crown of pines. – Metsäntutkimuslaitoksen tiedonantoja, 52, 42. (in Fin with English abstr.)
Seppälä, K. 1976. Relationship between the stem diameter of tree at time of draining and their post drainage increment. – Suo, 27(3), 55–60.
Uusitalo, J. 2004. Heartwood and extractive content of Scots pine in Southern Finland: models to apply at harvest. – Wood and Fiber Science, 36 (1), 3–8.
Wodzinci, T. J. 2001. Natural factors affecting wood structure. – Wood Science and Technology, 1/2, 35, 5—26.
Werberg, K. 1930. Lüli- ja maltspuu suhe männil. – Tartu Ülikooli Metsaosakonna toimetised nr. 17. Tartu, – 184 lk. [Das Verhältnis von Kern- und Splintholz bei der Kiefer].
Звирбуль А. П., Некрасова Г. Н., Полубояринов О. И. 1976. Влияние удобрения сосновых насаждений карбамидом на качество древесины. – Лесной журнал, 6, 18–22. [Effect of urea fertilization on Pine stands on the wood quality].
Некрасова А. А. 1994. Свойства древесины хвойных пород взависимости от условий произрастания –Лесное хозяйство, 2, 22–24. [Properties of wood of conifers as a function of the growth conditions].
Пикк Я. Ю. 1988. Лесоводственная эффективность применения минеральных удобрений на осушенных торфяно-болотных почвах в Эстонской ССР. – Автореферат диссертации на соиск. уч. степени канд. сельскохозяйственных наук. Минск, 15 с.

Hariliku männi (*Pinus sylvestris* L.) puidukvaliteet pohla- ja sambliku kasvukohatüübis

Jaak Pikk, Regino Kask, Pille Peterson

Kokkuvõte

Väga palju on uuritud harvendusraiete olulisust kvaliteetsete puistute kasvatamisel, kuid väetamise tulemus on sageli suurelt varieeruv ja seetõttu puidukvaliteedi osas problemaatiline. Väetamine stimuleerib oluliselt okste ja okaste kasvu, mis on eelduseks jõudsale tüvepuidu kasvule. Kasvu vohamine võib aga mõjutada puiduomadusi. Uurimise alla võeti 1970. aastate alguses rajatud metsaväetamise katsealade 24 proovitükki suurusega à 0,1 ha sambliku- ja pohlamännikutes. Pohlamännikud kuulusid katsete rajamisel boniteediklassi 1a ja 2 (vanus vastavalt 45 ja 50 aastat) ning samblikumännikud boniteediklassi 3 ja 5 (vanus vastavalt 50 ja 21aastat). Kõik olid üherindelised kultuurpuistud

Proovitükkidel mõõdeti kõigi puude diameeter rinnakõrguselt, puude kõrgus, madalama kuivanud oksa kõrgus ja kõrgus esimese elava oksani. Võra läbimõõt määrati põhja-lõuna ja ida-lääne suunaliselt. Juurdekasvupuuriga võetud proovidel tehti kindlaks kõigi puude lülipuidu protsent rinnakõrgusel, aastarõngaste arv maltspuidus ning sügispuidu osakaal. Otsiti seoseid maltspuidu ja lülipuidu osatähtsuse ennustamiseks puu väliste tunnuste kaudu.

Katseperioodil aasta keskmine tootlikkus pohlamännikutes moodustas 9,27–13,0 m^3/ha aastas ja samblikumännikutes 8,41–10,37 m^3/ha aastas. Väljaraied katsealadel

on piirdunud kuivanud puude kõrvaldamisega ja nõrgaastmeliste (10–16%) harvendamistega. Nii on puistud kasvanud suhteliselt suure täiuse juures. Erandiks on samblikumännik toitainevaesel mullal (Saare 3), kus 54-aastaselt moodustas viimane väljaraie väetamata puistus 30% ja väetatud puistus 43,6%. Tootlikkuse suurenemine ja okste ning okaste intensiivsem kasv vähemviljakas kasvukohas võib tekitada puistu harvendamisel näiliselt suurema väljaraie vajaduse.

Väetatud katsevariantide puudel on kolmel juhul neljast elus võra pikem kui väetamata variantidel. Nimetatud erinevus pole aga statistiliselt usaldusväärne. Laasunud tüveosa pikkus esimese oksatüükani näitab aga olukorda, kus oksavaba jämedat esimest palki on meie puistutes vähe. Väetamisega on võimalik suurendada männikute tootlikkust, kuid puidu kvaliteedi parandamise võimalus on küsitava väärtusega. Rohkem kui kolmkümmend aastat tagasi tehtud väetamine on soodustanud alumiste okste kasvu sedavõrd, et tolleaegsete okste jäänused püsivad veel praegu tüve küljes. Mida jämedam puu, seda vähem on oksavaba tüveosa. Lämmastikuga korduvalt väetatud puistutes on iselaasunud tüveosa oluliselt lühem kui väetamata puistus. Ühekordne väetamine pole iselaasumist mõjutanud.

Eestis moodustub lülipuit aeglasemalt kui Soomes. Kuigi suurim aastarõngaste arv maltspuidus ei esinenud just kõige kõrgema boniteediklassiga puistus, viitavad meie tulemused toitekeskkonna teatud mõjule lülipuidu tekkimisel. Suurem radiaalne juurdekasv suurendab pärast väetamist harvendusraiest saadavas toormes maltspuidu osatähtsust, milles võib olla vähem sügispuitu. Toitekeskkonna parandamisel väetamisega väheneb lülipuidu osakaal puutüve ristlõikes rinnakõrgusel korduvalt väetatud puistus ainult ühel juhul. Teistel katsealadel jäi erinevus katsevea piiridesse.

Puutüves lüli- ja maltspuidu osatähtsuse hindamine puu väliste tunnuste kaudu on küsitava väärtusega. Meie andmetel krooni aluse kõrgus on väga nõrgalt seotud rinnakõrguse maltspuidu pinnaga (R=0,03–0,28). Ka võra suuruse (maht) ja lülipuidu protsendi vaheline seos oli negatiivne ja nõrk. Võra suuruse ja maltspuidu keskmise aastarõnga laiuse vahelise seose tugevus osutus keskmiseks (R=0,58–0,64 ühel juhul ka 0,76).

Juveniilpuidus fikseeriti erinev sügispuidu osatähtsus sõltuvalt kasvukohast ja sügispuidu osatähtsuse suurenemise erisugune dünaamika. Sambliku kasvukohatüübis moodustas sügispuit säsilähedastes aastarõngastes 10% ja pohla kasvukohatüübi männikutes 20%.

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Mechanical Properties of Juvenile Wood of Scots Pine (*Pinus sylvestris* L.) on *Myrtillus* Forest Site Type

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Variations in late wood percentage, juvenile wood and sapwood properties within trees and between stands of Scots pine from Northeast and South Estonia were analysed. The mean wood density of juvenile wood form 83,8% from sapwood density, static bending strength 62%, compression parallel to grain 68,6% and gross-surface strength 81,2% respectively. Investigations were conducted on the wood properties of trees from the 60-year-old stands determined the 5 year cambial age juvenile-mature wood transition in Scots pines in *Myrtillus* forest site type.

Key words: Pine, sapwood, late wood, bending strength, compressive strength, surface strength, density

Introduction

The properties of the pinewood differ in stems from pith to bark and from the roots to the top of the tree. To the same degree the amount of latewood and cells with thick walls increase from pith towards to the bark. During the cells and tissues formation process the structure and characteristics of the wood is influenced by the genetic, environmental (light intensity, nutrients, moisture) and anthropogenic factors (Stähl 1998, Saranpää 1999, Wodzicki 2001, Larson *et al.* 2001). For these reasons a material with different qualities can be obtained from same stem and the same wood for different users had different value. Earlier investigations discuss primarily the different qualities of heart- and sapwood and wood come of the crown. During recent years problems proceeding from properties of juvenile wood and superfluity of that in stem have become evident (Arlinger & Wlihemsson 1999, Larson *et al.* 2001, Jayawickrama 2001), as those factors decrease the general technical characteristics of the wood.

The juvenile wood forms a homogeneous cylinder in the central part of the stem and so almost all the top of the stem consists of the juvenile wood (Saranpää 2002). As the stem is getting older and diameter is increasing the heartwood is forming around the pith. The juvenile wood and also a part of the surrounding wood will change to heartwood, which is recognized by lower moisture level and higher containing of extractive matter.

The juvenile wood forms a little less than 10 annual rings around the spruce pith (Saranpää 2002), conifers have 5-25 annual rings (Lindström 2002), but the sources about pine tree are giving very different data. According to some authors the transition period of pines juvenile wood to the mature wood at cambial age approximately 22 years with the standard deviation of 5-7 years (Sauter *et al.* 1999). By E. Saarmann (1998) the juvenile wood is formed 10-20 nearest annual rings to the pith. S. Mattson (2002) remarks that variation was large for all wood property and the juvenile wood period seems to last for at least 16 years at 0,8 metre height. At the same time he has found out that there was no effect of the crown position in transition from juvenile to mature wood as judged by wood density and no evidence to support the concept that tree spacing and live-branch pruning have a significant effect on the cambial age in transition from juvenile to mature wood. (Gartner *et al*. 2002).

Sources give several constrained terms to juvenile wood that some authors have used synonymously (Amarasekara & Dene 2002). Also, there is no common position on how to determine the juvenile wood – should it be made according to density, modulus of elasticity or use acoustics approach when sorting out (Walker & Nakada 1999). For industry it is a question of utmost importance because for example the quality properties of paper (porosity, strength, density of sheets etc.) are affected by the raw material – as the butt log, middle log and top log have bigger differences in density and the juvenile wood as well as heartwood are playing there an important role (Duchesne *et al.* 1997). However, the top log of great pith consists lot of juvenile wood. First-thinning wood has different properties from the late- thinning wood (Hakkila *et al.* 1995). The reason comes from the great bunch of juvenile wood around the pith in a young tree with a small diameter. Early wood cells in such timber are short having thin walls, containing lots of lignin, having small amount of latewood and wood density is low. When drying wood, several increases and decreases cause lot of splits and timber can become warped. The most part of juvenile wood is not suitable material for construction works or building (Saarman 1998). As there are problems with many tree species used for economic purpose, the part of juvenile wood is tried to minimized by using forest selection and other methods of forestry, also the skillful sorting out of logs in mills are used (Jayawickrama 2001).

The aim of this study was to make evident the horizontal and vertical variation in some wood properties in *Myrtillus* site type of pine stems and to compare the characteristics of juvenile wood with mature wood and sapwood in the 60-year-old stands. There are relatively few data on raw material made of pole timber, but as the number of users has increased, the interest about the results is really high.

Material and methods

During the last decade when the felling extent is tripled more young wood have been started to from strong thinning and sanitation clearcut areas. This material should therefore contain more juvenile wood in comparison with the material cut from old forest. Taking that into account, the research objects with the 60-year-old pine trees in mixed stands on a *Myrtillus* site were chosen in North-East and South Estonia with the quality class I and II. The best strength properties were expected to get as according to the source pine forests on fresh soil and pine trees in mixed type forests have better strength qualities (Splawa-Newman 1994). On the other hand, it becomes evident that chosen trees have got relatively small diameter of juvenile wood in stem and number of annual rings (25) in sapwood, which makes a very big difference from the stands researched so far.

Twenty two model trees were chosen among the dominant trees, cutting of the testing disks and chopping blocks for preparing the testing samples of stem, from the highpoint of h1/4, h1/2, h 3/4. So the stub up to h ¾ was researched. In fresh cut trees the spreading of humidity was measured at above-mentioned levels. Room-dry dried and polished disks annual radial growth was measured, also the late wood percentage in the annual ring and heart- and sapwood relative importance as well as surface hardness in the three directions by the Janka method was measured. The program Win-Dendro was used for measuring the wideness of annual rings.

A total of 280 samples for measuring density and 764 experimental samples for determining the wood mechanical properties were made. Experimental samples of sapwood in cross-section were parcel out onto three groups by age of wood start from bark (sapwood 1, 2 and 3). All mechanical features in this research are explained at 12% of moisture level. All experimental data are processed using correlation and linear regression analyses with Microsoft Excel.

Experimental results

Physical characteristics

In mid October it was measured for the pine stems grown in North-East Estonia average sapwood relative moisture rate as 54,2±0,5% and heartwood 33,1±1,0% while the moisture rate of the juvenile wood (34,5±2,1) did not exhibit essential difference from the humidity rate of the heartwood. Humidity rate of the sapwood increased from the stump to the top of the stem statistically insignificant, but it was a remarkable increase in the case of heartwood.

At four levels of stems researched general width of annual ring (y) excluding 2-3 annual rings around pith, decreased linearly with increasing cambial age. It means the bigger the cambial age (x), then narrower is the annual ring in cross-section of the stem. The width of the annual ring at the level of h ¼ is explained as well:

$$y = 5,50049 - 0,09168x + 0,547463 * 1/x, \quad R^2=0,79$$

Different situation is with relative importance of latewood (y), which in annual rings near the pith is small but starting from the 5-th year cambial age starts to increase linearly with age (x) (Fig. 1). In research object in Northeast Estonia the stem level of height h ¼ explains this as follows:

$$y = 17,88949 + 0,527125x - 17,4225 * 1/x, \quad R^2=0,69$$

In the case of stub and the level of h ¼ the results gained from the late wood relative importance were almost similar, but at the half way of the tree and at the level of h ¾ the importance of the late wood decreases. We can see in the figure how the late wood is divided in comparison with two different stands. The stand with second quality class the latewood distribution is more equal. In the stand with the higher quality class the importance of latewood is increases equally with increasing cambial age and this case: $R^2 = 0,81…0,86$.

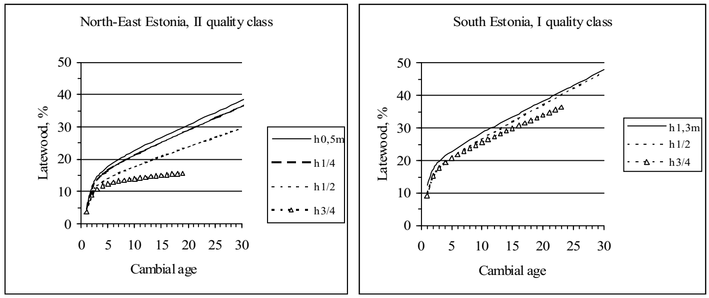

Figure 1. The distribution dynamics of latewood in different cross-sections of pine stem in Northeast and South Estonia on *Myrtillus* site

Density of the pinewood in stem decreases from the bark towards the pith and from stub towards the top (Fig. 2). The highest absolute dry density of sapwood was obtained under the bark from the butt log (535,2 kg/m³). Juvenile wood density at the same level was 448,6 kg/m³ e.g. 16,2% smaller.

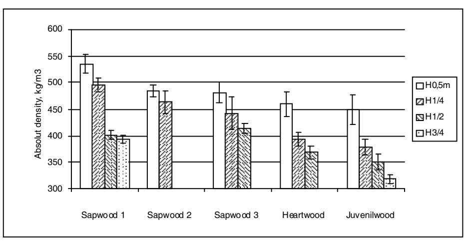

Figure 2. The pinewood absolute density at different height of stem from bark to pith

Density of the sapwood decreases towards the top and at the level of ¾ it was approximately 27% smaller than the density of butt examples. But even at that level the density of the sapwood is 1,2 times higher than in juvenile wood. Density of the juvenile wood in the stem decreases towards the top to the level h¾ even 29%. So the density of juvenile wood varies in the stem 318,3…448,6 kg/m³.

Mechanical properties

Static bending strength, compression strength parallel to grain, surface strength and impact strength are the most significant quality characteristics of the material (Tab. 1). Mechanical strength properties depend mainly on density as the trend of changes from the butt log towards the top log and from pith towards the bark are similar to the change of density as shown in Figure 2.

The average compression strength parallel to grain of juvenile wood was 30,7±2,4 MPa and 46,5±1,7 MPa in the outer layer of sapwood e.g. 1,5 times bigger. Variations range from 27,8 to 69,6 MPa and from 16,9 to 46,1 Mpa, respectively. It gave difference to compression strength along stem of sapwood 2,5 times and of juvenile wood 2,7 times.

Resistance of pinewood to impact strength does not qualify as main characteristics of wood and it is not taken into account when calculating wood constructions. But it is important characterizer for comparing wood material quality (Михайличенко, Садовничий 1983). Relying on experimental results it can be said that in juvenile wood of Northeast Estonian pine impact strength (37,8 ± 3,0 kJ/m³) in comparison with other wood layers in the stem on average (52,1±1,2 kJ/m²) was 27% smaller. In comparison with peripheral sapwood, the difference was 2,4 times. It means that impact strength in juvenile wood decreases towards the top faster than in sapwood.

Surface strength by the Janka method was identified at three levels: along to grain (Tab. 1), radial surface and tangential surface. The average results in sapwood and heartwood were bigger on along to grain, followed by tangential surface strength and the weakest was radial surface. It was complicated to identify strength technically at along to grain and radial surface because the testing point on experimental material (50x50x50 mm) situated near the line of juve-

Table 1. Values of wood properties in different parts of stem

Quality, example level	Unit	Exterior sapwood	Intermediate sapwood	Interior sapwood	Heartwood	Juvenile wood
Bending strength						
h0,5m	MPa	101,5±3,1	87,9±2,4	88,9±2,6	77,9±5,7	61,0±6,9
h1/4	"	94,2±2,3	77,8±4,5	67,0±3,3	62,6±3,4	53,8±3,3
h1/2	"	70,6±2,0		65,7±2,0	51,7±2,0	43,7±3,6
h3/4	"	59,4±4,4				44,3±0,4
Compression strength						
h0,5m	"	52,6±3,1	47,1±1,8	50,1±2,0	40,5±2,3	38,1±8,0
h1/4	"	54,3±1,5	46,7±2,3	38,8±1,3	36,8±3,6	29,7±3,5
h1/2	"	38,5±1,2	38,7±1,8	35,9±2,6	31,0±3,0	27,0±3,6
h3/4	"	32,7±2,2				27,3±0,3
Cross-surface strength						
h0,5m	"	36,6± 1,0			30,3± 1,4	
h1/4	"	30,9± 1,3			25,5± 0,6	
h1/2	"	29,3± 0,4			22,9± 0,5	
h3/4	"	26,8± 1,4			21.5± 0.5	

nile and mature wood. Mean strength was 19,6±0,6 MPa and 21,0±0,5 Mpa, respectively. Tangential strength (30,3±1,0) was 5,9% smaller and radial strength (27,0±0,6) 16,1% smaller than sapwood surface strength (32,2±0,6). Tangential strength (21,0±0,5) of heartwood was 19,2 % smaller and radial strength (18,30,5) ± 29,6% smaller than surface strength along to grain (26,0±0,6). Those regularities are widely used in cutting theories and elaborating cutting regimes but absolute maximum of strength depends on lots of factors where the main one is density.

Discussion

Individual trees are remarkably different from other when comparing the moisture content of wood. Depending on the season and felling month the moisture level differs in outside and inside of sapwood and also it differs in highpoints (Seeling 2000). Most of these differences are caused by density of the wood (Uzunovic & Dickinson 1998). If we exclude the effect of basic wood density and using the percentage saturation method for measuring the humidity significant differences related to increased moisture content appear with increasing tree height as pointed out by above mentioned authors.

According to our data on stem crosscuts no differences of sapwood were noticed in the rate of moisture but remarkable change of moisture was noticed in relation to height. Humidity rate in mature heartwood crosscut was similar to that in juvenile wood.

Nutrition conditions, growing space and age of tree are most clearly indicated by the width of the annual ring. It is also one of the most important visual evidence when estimating the wood quality, because increased radial growth resulted in the reduced fiber length, fiber diameter, cell wall thickness, wood density and modulus elasticity (Mattson 2002). But exist investigations where growth rate did not appreciably influence the density and bending properties of timber, and so its utility as predictor of their mechanical quality of timber is very low (Seco & Barra 1996).

Taking into account the width of annual rings in our felled model trees we can say that those trees were grown in normal conditions, with no influences of thinning or hyper-density periods of stand. Juvenile wood period is not distinguishable in the width of annual rings, but percentage of latewood increases from pith until the 5-th year smoothly and after that increases proportionally to the age (Figure 1). On the basis of gained results it is possible to estimate the existence of juvenile wood in those stems only in the frame of 5 annual rings which forming a cylinder with a diameter approximately 50 mm of around the pith. Starting form the pith in the frame of 5 annual rings mean width and content of latewood from stub to the top change not much. Differences appear with increasing cambial age in relation to the height in the case of heartwood.

The width of annual ring in the stem that has been growing fast has smaller late wood than in a stem that has been growing slower. Longer fibers are in outward annual rings (Saranpää 1999). So the annual ring gets suddenly wider when the thinning takes place and density of wood decreases in negative correlation between the width of annual rings (Morling 2002). After thinning in an average tree the density might be smaller than 17% (Минин, Москалева 1986). That is why it has become evident that younger stands must be kept thick because the best pinewood grows in light thinned stand where grow 1300-1400 trees per hectare at the age of 43-47 (Литаш, Рябоконь 1984).

According to the sources wood density is most influenced by the frequency of annual rings and percentage of latewood (Wilhelmsson *et al.* 2002). The width of annual rings has less influence (Seco & Barra 1996) that also fits with our results where the relation of density to the annual rings is characterized by the correlation coefficient R= -0,44 and latewood percentage R= 0,80 (Tab. 2). Density may have strong connection with the annual rings in a freely grown tree, but in periodically thinned and fertilized soil the density varies. According to the some sources (Veermets 1963) wider annual rings do not decrease mechanical characteristics but the importance of latewood percentage remains. Here we cannot exclude that during faster growth building and resistance of wood cells change as also has called attention P. Saranpää (1999) and T. Morling (2002).

Table 2. Correlation coefficients between wood properties

Quality	1	2	3	4	5	6
1. Wood density	1					
2. Impact strength	0,41	1				
3. Compression strength	0,87	0,55	1			
4. Annual ring width	-0,44	-0,62	-0,58	1		
5. Latewood %	0,80	0,43	0,77	-0,53	1	
6. Bending strength	0,95	0,41	0,86	-0,42	0,79	1

Carrying out investigations about properties between juvenile and mature wood among 10 tree species in China considerable differences were found (Bao *et al.* 2001). Comparing in our research juvenile wood density with a beside growing heartwood no remarkable statistical changes were identified except some tendency in increase of density toward bark can be assumed as shown in the Figure 2. Therefore, the relationship of outer sapwood density with juvenile wood density remains constant (1,2) over three-quarters of stem height, is notable.

When characterizing the construction materials then bending strength is one of the most important properties. Reducing all researched bending strength data of crosscuts to butt log's crosscut (Figure 3) we get a row with linear characteristics where bending strength of juvenile wood forms only 62% of the bending strength of the wood near the bark. So the bending strength factor in juvenile wood has 1.2 times bigger relative standard error of middle value that can be explained by existence of stronger latewood in experimental pieces because of wider rings of juvenile wood.

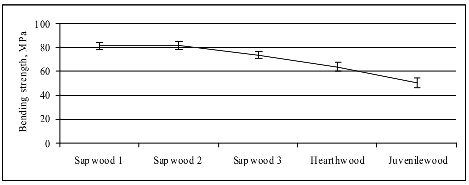

Figure 3. Mean static bending strength (with standard error) in cross-section of stem from bark to pith

According to K. Veermets (1960) the relation between wood mechanical properties (moisture W=15%) and density appears in parabolic equation as the curve of parabolic is usually small the direct line that could be used in practice for the 120-year-old pinewoods the bending strength (B) and density (m) is: B=2500m-450. But according to our data the relation between bending strength (y) and density (x) compared with direct line (Fig. 4) and is better explained by equation as follows:

$y=-212,765+0,473484x+33500,86*1/x, \ R^2= 0,90$

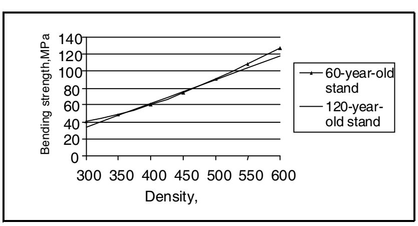

Figure 4. Relation between bending strength and density of the 60-year-old (Northeast Estonia) and 120-year-old (South Estonia) pine stands on *Myrtillus* site

The larger part of the curve in the graphic characterizes the part with lower density in the juvenile wood. Despite that the results of the investigations in the 120- and 60-year-old pinewoods match and exclude the age as a determinative factor, and the density is of utmost important.

The average bending strength in Estonian *Vaccinium vitis-idaea* and *Myrtillus* site type pinewoods have been compared. In 55-90-year-old felled trees it is 84,8±0,7 MPa (Kask 2003). At the age of 120 the bending strength is 902 kg/cm² (101,0 MPa if w=12%) (Веэрметс 1959).

The bending strength of mature pine stands in Lithuania is generally 87,7 MPa, in Byelorussia 87,3 MPa and in North-west Russia 84,5 MPa (Боровиков, Уголев 1989). Based on above - mentioned data our bending strength of the pinewood is already similar to those at the age of 60. One of the increasing factors may be generally smaller consistence of juvenile wood in stem as of neighbours.

After the static bending strength density has also strong correlation with compressive strength parallel to grain (R=0,87) but much weaker connection with impact strength (R=0,41).

Compression strength parallel to grain has good connection (R=0,77) with the percentage of latewood and weak correlation (R=0,58) with the width of the annual rings. Mean compression strength of juvenile wood makes up only 68,6% of the strength of outer layer of sapwood.

In a great part the surface strength of the wood dictates the possibilities for use and the last touch of wood surface. More frequently the surface strength parallel to grain is described in the literature. Strength of the radial and tangential surface is directly connected with the surface strength parallel to grain. For example, according to A. Mihailitšenko and F. Sadovnitšij (Михайличенко, Садовничий 1983) the surface strength parallel to grain that forms up to 40% of tangential and radial surface strength.

According to our data surface strength parallel to grain (y) of sapwood decreases in line with the height of stem crosscut (x):

$y= 29,0791-1,04403x+8,507463*1/x, R^2=0,99$ and in juvenile wood correspondingly:

$y= 23,43433-0,99552x+7,880597*1/x, R^2=0,82$

The most varying is surface strength parallel to grain that is confirmed by annual ring weakest connection to the surface strength (Tab. 3). In the case of wide annual rings the results are influenced by the

Table 3. The correlation coefficients characterise the relation between growth ring width and pinewood strength of radial, tangential and cross surface

Quality	1	2	3	4
1. Gross-surface strength	1			
2. Radial surface strength	0,84	1		
3. Tangential surface strength	0,86	0,86	1	
4. Annual ring width	-0,50	-0,62	-0,61	1

testing part that may be totally in early wood or partly in latewood.

Differentiation of pinewood properties influenced by geographical heritage is clearly defined by several researchers (Saarman 1998, Jayawickrama 2001) but in Estonia there are few data on it. In the framework of this research no remarkable differences in the mechanical properties in collected testing materials between Northeast and South part of Estonia were identified. This can be taken as normal as the distance between the areas is only 220 km.

Conclusions

Summing up the results it can be said that the juvenile wood is less favoured in most areas of wood use because of weaker strength characteristics. Density of the juvenile wood makes up 83.8% of the sapwood near the bark, bending strength 62% and surface strength 81,2% in the 60-year-old stands. Compression strength parallel to grain in juvenile wood decreases faster towards the top log as than in sapwood.

In comparison with the southern neighbouring states, Estonia has good possibilities for growing pinewood with low content of juvenile wood and good properties because of the tested model trees had it relatively few annual rings. It is not possible to avoid juvenile wood in pine stems but definitely it can be reduced by forest growing methods.

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References

Amarasekara, H., Denne, M. 2002. Effect of crown size on wood characteristics of Corsican pine in relation to definitions of juvenile wood, crown formed wood and core wood. - Forestry - Oxford. 75,1, 51-61.

Arlinger, J., Wilhelmsson, L. 1999. Wood analysis - an aid to meeting the needs of the mills.- Results SkogForsk. 1, 4.

Bao. F. C., Jiang, Z. H., Jiang, X. M., Lu, X. X., Luo, X. Q., Zhang, S. Y. 2001. Differences in wood propeties between juvenile wood and mature wood in 10 species grown in China. - Wood Science and Technology, 35, 4, 363-375.

Duchesne, I., Wilhelmsson, L., Spangberg, K. 1997. Effect of in-forest sorting of Norway spruce (Picea abies) and Scots pine (*Pinus sylvestris*) on wood and fibre properties. - Can. J. F. R. 27, 5, 790-795.

Gartner, B. L., North, E. M., Johnson, G. R., Singleton, R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. - Can. J. F. R. 32, 3, 439-447.

Hakkila, P., Kalaja, H., Saranpää, P. 1995. Etelä-Suomen ensiharvennusmänniköt kuitu- ja energialähteenä [First-thinned pine stands as the fibre and energy source in South Finland]. Metsätutkimuslaitoksen Tiedonantoja 582, 100 s. (in Finnish)

Jayawickrama, K. J. S. 2001. Breeding radiata pine for wood stiffness: review and analysis. - Australian Forestry, 64, 1, 51-56.

Kask, R. 2003. Physical and mechanical properties of Scots pine (Pinus sylvestris) on bilberry and cowberry forest site types. Abstract of M.Sc. Thesis. Tartu. 24.

Larson, P. R., Kreutschmann, D. E, Clark, A., Isebrands, J. G. 2001. Formation and properties of juvenile wood in southern pines: a synopsis. General technical report forest products laboratory, USDA Forest Service. FPL-GTR-129, iii, 42.

Lindström, H. 2002.Intra-tree models of juvenile wood in Norway spruce as an input to simulation software. Silva Fennica 36(2): 521-534.

Mattsson, S. 2002. Effects of site preparation on stem growth and clear wood properties in boreal Pinus sylvestris and Pinus condarta. - Acta Universitatis Agriculturae Sueciae -Silvestria. 240, IXXXVII, 37

Morling, T. 2002. Evaluation of annual ring width and ring density development following fertilization and thinning of Scots pine. - Annals of forest science. 59, 1, 29-40.)

Saarman, E. 1998. Puiduteadus [Wood science]. 247.

Saranpää, P. 1999. Effect of forest management on wood quality.-Metsäalan tutkimusohjelma. Raportti 2. Helssinki, 178-185.

Saranpää, P. 2002. Kuusen kuituominaisuuksein vaihtelu [Exchanges of fibre properties of spruce]. Työtehoseuran metsätiedote. 3(646), 1-4. (in Finnish)

Sauter, U. H, Mutz, R., Munro, B. D. 1999. Determing juvenile-mature wood transition in Scots pine using latewood density. - Wood and Fiber Science. 31, 4, 416-425.

Seco, J. I. F. G., Barra, M. R. D. 1996. Growth rate as a predictor of density and mechanical quality of sawn timber from fast growing species. Holz als Roh- und Werkstoff 54, 3, 171-174.

Seeling, U. 2000. Ausgewählte Eigenschaften des Holzes der Fichte (Picea abies (L.) Karst.) in Abhängigkeit vom Zeitpunkt der Fällung. - Schweizeische Zeitschrift für Forstwesen, 151, 11, 451-458.

Splawa-Neumann, S. 1994. Selected properties of Scots pine (Pinus sylvestris L.) wood in dependence upon forest stand type and age of the trees. Prace Institutu Technologii Drevna. 38, 1-2, 19-28.

Stähl, Erik-G. 1998. Changes in wood and stem properties of Pinus sylvestris caused by provenance transfer. -Silva Fennica, 32(2):163-172.

Uzunovic, A., Dickinson, D. I. 1998. Measuring and expressing moisture content in green timber. - Material und Organismen, 32, 3, 217-225.

Veermets, K. 1960. Seaduspärasusi männipuidu tehnilistes omadustes [Relationships between technical properties of pine wood]. EPA teaduslike tööde kogumik 17. Tartu, 77-89. (in Estonian)

Veermets, K. 1963. Kuusepuidu mehhaanilistest omadustest [About mechanical properties of spruce wood]. EPA teaduslike tööde kogumik 33. Tartu, 164-179. (in Estonian)

Walker, J. C. F., Nakada, R. 1999. Understanding corewood in some softwoods: a selective review on stiffness and

acoustics. - International Forest Review. 1: 4, 251-259; 284-285.)
Wilhelmsson, L., Arlinger, J., Spangberg, K., Lundqvist, S. O., Grahn, T., Hedenberg, O., Wodzicki,T. J. 2001. Natural factors affecting wood structure. - Wood Science and Technology, 35,1/2, 2-26.
Боровиков, А.М., Уголев, Б.Н. 1989. Справочник по древесине[The Wood Handbook]. Москва, 296. (in Russian)
Веэрметс, К. 1959. О технических свойствах сосновой древесины [About technical properties of pine wood]. - Сборник научных трудов ЭСХА 11б. Тарту, 70-80. (in Russian)
Литаш, Н.П., Рябоконь, А.П. 1984. Физико-механические свойства древесины в сосновых древостоев в связи с рубками ухода различной интенсивности [Physical and mechanical properties of the wood in Scots pine stands in relation to thinnings of different intensity]. – Лесное хозяйство, 7, 66-68. (in Russian]
Минин, Н.С., Москалева, С.А. 1986. Влияние рубок ухода на физико-механические свойства древесины культур сосны [Effect of thinning on the physical and mechanical properties of wood in Scots pine plandations]. – Лесной журнал, 2б 68-71. (in Russian)
Михайличенко, А.Л., Садовничий, Ф.П. 1983. Древесиноведение и лесное товароведение [Science of wood and forest product]. Москва, 206. (in Russian)

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МЕХАНИЧЕСКИЕ КАЧЕСТВА ЮВЕНИЛЬНОЙ ДРЕВЕСИНЫ СОСНЫ ОБЫКНОВЕННОЙ (*P. SYLVESTRIS* L.) В СОСНЯКАХ ЧЕРНИЧНИКАХ

Я. Пикк, Р. Каск

Резюме

По литературным данным ювенильная древесина образуется вокруг серцевины из 5–25 годичных слоев. Относительно большой объем ювенильной древесины в деловой древесине приводит к неблагоприятным явлениям для потребителей в деревообрабатываемом производстве. Феномен ювенильной древесины и возможности сокращения влияния ювенильной древесины в сырье в Эстонии вообще мало изучены.

Целью данного исследования является изучения варьирования некоторых показателей качества в стволах деревьев 60-летних сосняков-черничников в Северовосточной и Южной Эстонии. У господствующих деревьев были вырезаны кряжи на высоте 0,5 м, h1/4, h1/2 и h3/4. Для определения абсолютной плотности было подготовлено 280 образцов и для определения механических свойств древесины -764 образца.

Одной из основных характеристик качества древесины является содержание поздней древесины в годичном слое. Содержание поздней древесины пяти годичных слоев вокруг сердцевины ниже чем у остальных слоев до коры. Плотность древесины снижается в направлении от коры до серцевины и по стволу от пня до верхушки. Прочность ювенильной древесины при статическом изгибе (при влажности 12%) на высоте h1/4 значительно ниже чем у заболони. Статический изгиб (y) тесно связан с плотностъю (x) древесины: y= -212,765+0,473484x+33500,86*1/x, R^2=0,90. Довольно тесная связь имеется между плотностью и прочностью на сжатие вдоль волокон и мало связано с ударной вязкостью. Ширина годичного слоя в какой-то степени связана со статической твердостью. Установлено, что плотность ювенильной древесины составляет соответственно 83,8% от заболони, изгиб 62% и сжатие вдоль волокон 68,6%.

Ключевые слова: сосна, заболонь, поздняя древесина, статический изгиб, прочность на сжатие, плотность.

VI

Kask, **R**., Pikk, J., Kuusepuu, T. 2002.
Hariliku männi (*P. sylvestris* L.) puiduniiskus ja maltspuidu osatähtsus
erinevates kasvukohatüüpides.
Forestry Studies, 37: 129–141.

Hariliku männi *(P. sylvestris* L.*)* puiduniiskus ja maltspuidu osatähtsus erinevates kasvukohatüüpides

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Kask R., Pikk J., Kuusepuu T. 2002. Scots pine (*P. sylvestris L.*) wood moisture and sapwood ratio on different forest site types. – Metsanduslikud uurimused XXXVII, 129–141. ISSN 1406-9954.

Abstract. The relationship between pine wood physical properties and tree characteristics were studied. One hundred and sixty six model trees were felled from 21 different pine stands. Blocks of stem were cut as samples at breast height, half of tree height and 3/4 of tree height. Wood moisture content and sapwood ratio were determined. Correlation and regression analysis were used to test for significant relationship between tree and site type characteristics and sapwood area. There is more wood moisture in pines growing on peatlands than in those growing on *Vaccinium vitis-idaea* or *Myrtillus* site types. On peatlands, heartwood moisture content in pines is higher at half of tree height than at breast height. Sapwood moisture content is higher on the south side of the stem than on the north side. This difference is great in the crown part of the stem. A close correlation was observed between sapwood ratio and stand quality class and age. The correlation between sapwood ratio and tree crown volume is moderate.

Key words: Scots pine, sapwood, moisture, site type, relationship

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Sissejuhatus

Harilik mänd on meil enamlevinud puuliik ja seetõttu majanduslik huvi selle kasvatamiseks ja ratsionaalseks kasutamiseks viimasel aastakümnel on suur. Kahjuks piirdub huvi rohkem männipuidu töötlemise ja turustamise kvantiteediga, kvaliteedinäitajad ja nende uurimine on jäänud tagaplaanile. Siiski on rahvusvahelises puidukaubanduses hakatud rohkem nõudma puidu kvaliteedinäitajate ja päritolu täpsemat esitust. EU standard LVS EN 338 näeb ette saematerjali tugevusklasside (C14 kuni C40) määramiseks mehaaniliste tugevusomaduste piirid (painde-, tõmbe-, survetugevus, elastsusmoodul, tihedus jm), sest täpsem teave võimaldab paremini orienteeruda puitmaterjali hinnapakkumises. Meil aga on puiduomaduste kindlaksmääramisega tegeldud suhteliselt vähe. Varasemad andmed on lünklikud, sest rohkem kasutati GOST-ides ettekirjutatud üldistatud andmeid ja puudus seetõttu uute uuringute vajadus. Nii ongi meil praegu vastavasuunaline uurimistöö jäänud maha praktika vajadustest.

Sama puuliigi puiduomadused sõltuvad muuhulgas suuresti geograafilisest piirkonnast ja kasvutingimustest (Mencuccini, Bonosi, 2001). Looduslike tingimuste erisuse tõttu pole naabermaade uurimistulemused sageli otseselt ülevõetavad, mistõttu vajatakse kohapealseid uuringuid. Sellesuunalisi uurimistöid on viimastel aastatel uuesti intensiivistatud Soomes (Saranpää, 1999; Sipi, Rikala, 2000), Lätis (Zalitis, 1999; Pushinskis *et al.*, 1998) ja Rootsis (Lindstrom, 1996).

Uuringute taasalustamist lihtsustab meil toetumine varem väljatöötatud rahvusvaheliselt tunnustatud metoodikale, puiduproovimise eeskirjadele ning olemasolevate uurimistööde läbitöötamisele. Põhjalikke puiduomaduste uurimusi on avaldanud K. Veermets (varem K. Werberg) alates 1930. aastast. Enne K. Werbergi töid puudusid Eesti männi tehniliste omaduste kohta andmed. Hiljem on puiduomadusi Eestis käsitlenud A. Kasesalu (1965), O. Henno (1963), U. Veibri (1973, 1982), Ü. Tamm (2000) jt. Arvestades, et tegemist on väga suurt füüsilise töö mahtu nõudvate uurimistega, on katseobjektide arv enamikul juhtudel jäänud suhteliselt tagasihoidlikuks. Selle tõestuseks olgu märgitud, et K. Werbergi doktoritöö "Lüli- ja maltspuu suhe männil" katsematerjaliks olid 29 mudelpuud, lüli- ja maltspuidu osatähtsus 453 kännus ja 444 palgis ning 132 tüvest saadud sortimentides. Suurem osa materjalist koguti ülikooli õppemetskonnast ja 132 tüve mõõtmisest Kivinõmme metskonnas. Kokku käsitletakse kuut erinevat vanemas kasvueas männipuistut boniteediga I–IV.

Männipuidu tehniliste omaduste uurimise eesmärgil langetatud mudelpuude koguarv Eestis, hinnatuna kirjandusallikate põhjal, ei ületa 150 puud. Kui see arv jaotada erinevate kasvukohatüüpide, boniteediklasside, vanuseklasside ja kasvuklasside vahel, siis igasse neist jääb katseandmeid suhteliselt vähe. Selliselt pihustunud andmestik ei võimalda saada täielikku ülevaadet meie männipuidu omadustest. Muidugi ei suuda seda lünka täita ka käesolevaga alustatud uurimistöö, mille esimeses etapis püütakse selgitada puiduniiskuse erinevust ja maltspuidu osatähtsust puu erinevates osades ning selle võimalikku seost takseertunnustega mõnedes kasvukohatüüpides. Järgnevas käsitletakse männi füüsikalisi omadusi peamiselt harvendusealistes ja männi peenpalki andvates puistutes ning püütakse leida maltspuidu osatähtsuse määramise võimalust puu takseertunnuste abil.

Uurimismetoodika ja uurimisobjektid

Kirjandusallikate põhjal selgusid puiduomaduste uurimise katseobjektide valikul erisugused lähenemised ja põhjendused. Nii on enamasti peetud olulisemaks kasvukohta, mõnel juhul aga boniteediklassi või vanuseklassi. Uuritud on puiduomadusi kasvuklasside lõikes, kuid on piirdutud ka keskmiste mudelpuude valikuga. Mudelpuudest proovipakkude lõikamise koha valik on samuti erinev. Kui rinnakõrgus (h1,3) ja puu pool kõrgust (h1/2) on kõigil uurijatel olnud peamiseks, siis teised kõrgused on leidnud erinevaid põhjendusi. Puutüve üldiseks uurimiseks on proovipakkude lõikamiseks valitud sagedamini kännukõrgus, kõrgus h3/4, võraosa algus ja elusa võra algus. Proovipaku lõikamist 12 cm diameetri kohalt põhjendatakse puhttehniliselt ehituspalgi ladvadiameetri miinimumiga.

Puiduniiskuseks (absoluutne) on niiskuse massi suhe antud puidumahu juures absoluutkuiva puidu massiga, väljendatuna protsentides. Selles töös kasutatud suhteline niiskus on aga niiskuse massi suhe antud puidumahu juures märja puidu massiga. Praktikas määratakse niiskus kuivatusmeetodiga või elektrilise niiskusmõõtjaga.

Käesolevaks tööks valiti looduses välja 21 erinevat männipuistut, mis paiknesid pohla, mustika, kuivendatud kõdusoo, kuivendatud madalsoo, kuivendatud siirdesoo, kuivendatud siirderaba ja raba metsakasvukohatüübis (tabel 1). Katsematerjal pärineb Elva (Konguta), Kaansoo, Kabala, Kubja, Laeva (Tähtvere), Saare, Surju, Sõmerpalu, Misso (Vastseliina) ja Väätsa metskonnast ning Järvseljalt.

Tabel 1. Katseobjektid ja mudelpuude keskmised takseernäitajad
Table 1. Experimental objects and model tree mean characterisics

Objekt *Object*	Tüüp *Site type*	D1,3	Vanus *Age*	Täius *Stand density*	Boniteedi klass *Quality class*	Võra maht *Crown volume*, m^3	Tüve maht *Trunk volume*, m^3	Vormiarv *Form factor*
Tähtvere	Rb	13,7	85	0,6	5,5	12,6	0,0922	0,577
Tähtvere	Krb	14,7	88	0,8	5,3	16,6	0,1283	0,536
Surju	Krb	15,8	70	0,6	5	28,5	0,1024	0,476
Tähtvere	Ksrb	15,7	88	0,9	5,0	11,4	0,1296	0,483
Surju	Kss	21,4	120	0,6	4	43,2	0,3378	0,472
Kaansoo	Kss	21,1	90	0,8	4	65,8	0,2593	0,434
Väätsa	Kss	18,1	80	0,7	3	21,1	0,2462	0,519
Väätsa	Kmds	16,6	70	0,7	4	32,5	0,1486	0,481
Kabala	Kks	18,5	90	0,8	3	33,0	0,2621	0,483
Väätsa	Ms	18,9	73	0,8	2	30,4	0,2788	0,467
Järvselja	Ms	24,2	79	0,8	1	46,2	0,5367	0,461
Saare	Ms	25,1	109	0,8	2	42,3	0,5163	0,415
Kubja	Ms	20,3	55	1,0	1	56,0	0,3244	0,453
Konguta 2	Ms	25,7	72	0,8	1	45,0	0,5365	0,439
Konguta 1	Ms	19,5	59	0,9	1	35,6	0,2688	0,446
Sõmerpalu 1	Ms-ph	17,6	67	0,75	2	36,8	0,2112	0,459
Sõmerpalu 2	Ph	18,5	66	0,7	1	36,1	0,2879	0,511
Misso 1	Ph	22,5	77	0,7	1	46,3	0,4552	0,451
Misso 2	Ph	20,9	72	0,8	2	46,7	0,3262	0,457
Surju 1	Ph	26,4	150	0,7	3	61,9	0,5471	0,443
Surju 2	Ph	22,4	70	0,9	2	64,9	0,3108	0,380

Metskonnas väljavalitud puistusse rajati esmalt ajutine proovitükk suurusega 0,1 ha. Selle keskmise rinnasdiameetri järgi valiti proovitükilt 6-12 mudelpuud. Mudelpuude arv sõltus puistu hooldamisest. Hästihooldatud puistust, kus kluppimise järgi esines vähem diameetriastmeid, valiti vähem mudelpuid. Halvemini hooldatud puistutes langetati keskmise diameetriga puudele lisaks ka mõned peenemad ja jämedamad mudelpuud. Mudelpuudel tähistati enne langetamist põhjapoolne külg. Langetatud puul mõõdeti pikkus, kümne viimase aasta ladvakasv, elusa võra algus ja võra laius ning tüve diameetrid kõrguselt h1,3, h1/4, h1/2 ja h3/4. Kokku langetati 166 mudelpuud, millest lõigati proovipakud (l,2 m pikad) kõrguselt h1,3, h1/2 ja h3/4. Samal päeval lõigati igalt pakult ketas, millel määrati suhteline puiduniiskus lõuna- ja põhjaküljel ning keskosas, et hiljem selgitada tehniliste omaduste erinevuse võimalikke põhjusi, mida on leidnud O. Henno (1963) kasepuidu uurimisel. Niiskuse määramiseks kasutati elektrilist niiskusemõõtjat Hydromette HT 85T. Ketastel määrati lüliosa diameeter, kooreta diameeter, maltsaosa aastaringide arv. Seoste hindamisel loeti korrelatsioon nõrgaks, kui $R < 0,3$, mõõdukaks, kui $0,3 < R < 0,5$, keskmiseks, kui $0,5 < R < 0,7$, tugevaks, kui $0,7 < R < 0,9$, ja väga tugevaks, kui $R > 0,9$.

Võra pikkuse ja läbimõõdu järgi määrati võra suurus pöördkeha valemiga. Puutüve maht leiti Simony valemiga (Krigul, 1972): $v = (h/3)*(2*g_{1/4} - g_{1/2} + 2*g_{3/4})$ ning puu vormiarv valemiga $f = v/(g_{1,3}*h)$; kus: g – ristlõikepind vastaval kõrgusel ja h – puu kõrgus.

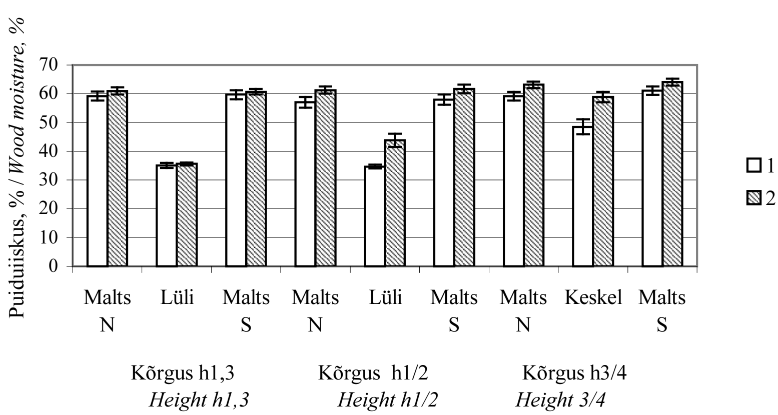
Puu niiskusesisaldus

Puu kasvuks ja ainevahetuseks on niiskuse olemasolu kasvavas puus vajalik, kuid raiutud puidus on niiskuse olemasolu ebasoovitav, sest see võib soodustada seente, värvimuutuste, kõverdumise jt ilmingute teket. Puiduniiskus avaldab suurt mõju puidu füüsikalis-mehaanilistele ja tehnoloogilistele omadustele, olles üheks kvaliteedinäitajaks (Veibri, 1982).

Värskeltraiutud pohla- ja mustikamännikute puidus on niiskust oluliselt vähem kui soopuistutest raiutud puidus (joonis 1). Siinkohal tuleb märkida, et rinnakõrgusel malts- ja lülipuidu osas oluline erinevus puudus, kuid ladva suunas erinevus suurenes. Tõsi küll, paljudel juhtudel ei olnud kõrgusel h3/4 lülipuitu selgepiiriliselt välja kujunenud, mistõttu võeti siin kasutusele mõiste "keskosa niiskus", mis mõõtmisel oli selgelt erinev maltspuidu niiskusesisaldusest. Nii jäi pohla- ja mustikamännikutes lülipuidu niiskus rinnakõrgusel ning puu poolel kõrgusel samaks, kuid kõrgusel h3/4 oli niiskuse protsent oluliselt suurem. Ilmselt võrapiirkonnas võtab ka lülipuit teatud määral elutegevusest osa, millele on viidanud mitmed uurijad (Veibri, Kokk, 1980; Перелыгин, Уголев, 1971). Varasemates uurimustes märgib aga K.Werberg (1930) viitega Danckelmanni (1890) ning Hartigile (1885), et niiskuse hulk lülipuidus ei sõltu kõrgusest, kuid üldine vee hulk tüves suureneb kiiresti alt üles.

Meie andmetel on soopuistutes juba puu poolel kõrgusel lülipuit niiskem kui rinnakõrgusel ja niiskusesisaldus ladva suunas suureneb veelgi. See seletub osaliselt sellega, et soopuistutes on elusa võra algus madalamal kui hästi laasunud pohla- ja mustikamännikutes. Soopuistutes märgiti elusa võra alguseks keskmiselt 0,6 h ning pohla- ja mustikamännikutes 0,7 h.

Maltspuidu niiskusesisaldus suureneb ladva suunas (joonis 1). Rinnakõrguselt puu poole kõrguseni on see vähemärgatav, kuid edasi juba oluline. Samuti vähemärgatav oli keskmine puiduniiskuse erinevus põhja- ja lõunapoolses tüveosas. Erinevus suurenes ladva suunas, kuid kõrgusel h3/4 oli lõunapoolses maltsaosas

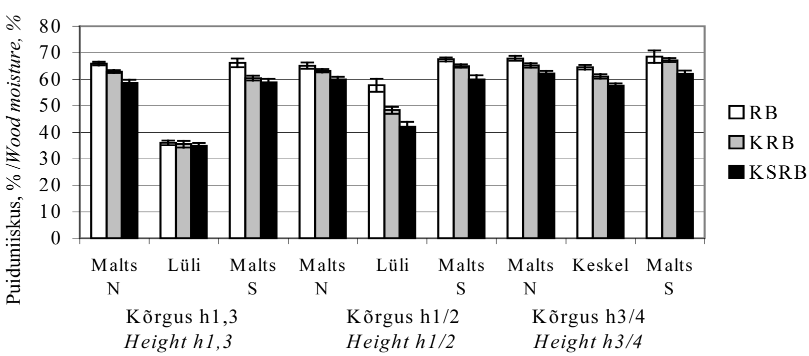


Joonis 1. Keskmine puiduniiskus kasvava puu erinevates osades pohla- ja mustikamännikutes (1) ning soomännikutes (2)

Figure 1. Mean moisture content in pine wood of different tree part growing on Vaccinium-vitis idaea and Myrtillum site type (1) and on peatlands (2)

niiskust pohla-mustikamännikutes rohkem vaid 3,3% ja soomännikutes 1,4%. Tulemus on analoogne kirjanduse andmetega, kus ilmakaarte suhtes puiduniiskuse erinevus maltspuidus kännu- ja rinnakõrgusel puudub, küll aga on poolel kõrgusel ja ladvas puiduniiskus madalaim põhjapoolses tüveosas ja maksimaalne läänekaares: vastavalt vahe 7% ja 2%. Lülipuidus see seaduspärasus puudub, sest puidu soojuse ühtlustumine välispinnalt lülipuitu on väga aeglane (Перелыгин, Уголев, 1971). Kirjanduse andmetel on aga puiduniiskus suurem nooremates puudes ja selle kõikumine aastas on suurem kui vanadel puudel (Михайличенко, Садовничий, 1983; Ванин, 1945), millest tulenevalt võiksid antud töös uuritud soomännikute ja pohlamustikamännikute niiskuses olla veelgi suuremad vahed, kui viia sisse keskmise vanuse (vastavalt 86,8 ja 79,1 aastat) erinevusest tulenevad paranduskoefitsiendid. Pohla- ja mustikamännikute puiduniiskuse sõltuvus kasvukoha niiskusest on tõestamist leidnud juba varem (Kask, 2001), mistõttu vaatleme järgnevas puiduniiskust rabamännikutes. Võib eeldada, et rabamännikutes on vett küllaldaselt ja puiduniiskuses erinevused seetõttu puuduvad. Katsetulemused Tähtvere 85–88-aastastest puistutest näitasid aga siiski mõningaid puiduniiskuse erinevusi, mida saab põhjendada vaid kasvukoha erineva niiskusega. Joonisel 2 on esitatud keskmised tulemused rabamännikutest võetud mudelpuude niiskusest. Katseobjektide lõikes puudub rinnakõrgusel ja puu poolel kõrgusel maltspuidu põhja- ja lõunapoolse tüveosa niiskuse erinevus, samuti on maltspuidu niiskus ühesugune rinnakõrgusel ja puu poolel kõrgusel. Võraosas on niiskust maltspuidus rohkem kui tüve alumistes osades ja mõne protsendi võrra on niiskust rohkem lõunapoolsel küljel, kus soojust on rohkem ja elutegevus seetõttu aktiivsem, nagu märgiti eespool.

Kirjanduse andmetel on kõige rohkem niiskust kasvavas puus talveperioodil (nov–veebr) ja minimaalselt suvekuudel (juuli–august). Niiskusesisaldus tüves muutub ka ööpäeva jooksul – hommikul ja õhtul on niiskust rohkem kui päeval (Михайличенко, Садовничий, 1983; Ванин, 1945). Niiskusesisalduse perioodiline muutumine puutüves iseloomustab puus toimuvate füsioloogiliste protsesside intensiivsust ja kaitsereaktsioonide aktiivsust (Перелыгин, 1969). Eestis on kindlaks



Joonis 2. Kasvava puu niiskus (koos suhtelise veaga) raba, kuivendatud raba ja kuivendatud siirderaba kasvukohatüübis erineval kõrgusel puu põhjakülje maltspuidus, lülipuidus ja lõunakülje maltspuidus

Figure 2. Moisture content of growing pine in different cross-section in North-side of sapwood, in heartwood and South-side sapwood on raised bog (RB), drained raised bog (KRB) and on drained transitional raised bog (KSRB)

tehtud maltspuidu suurima niiskuse olemasolu 75–80-aastasel siirdesoomännil novembris (Veibri, Kokk, 1980)

Erinevalt rabamännikutest suurenes puiduniiskus kasvavas puus Kabala kuivendatud kõdusoomännikus ja Kaansoo kuivendatud siirdesoomännikus 29.11.2000. a maltspuidus ladva suunas märgatavalt, kuid lülipuidu osas kuni poole puu kõrguseni jäi samaks. Puiduniiskuse absoluutväärtused osutusid kõigis mõõtmiskohtades väiksemaks, kui need olid kindlaks tehtud kuivendatud siirdesoo- ja karusambla-mustikamännikus eelmisel aastal (tabel 2). Saadud tulemustest võib järeldada, et kasvava puu niiskus sõltub mõõtmisele eelnenud pikema perioodi sademetest. Kui 1999. a sügisel katseobjektidele lähemate vaatlusjaamade keskmisena esines sademeid mudelpuude lõikamisele eelnenud kahel kuul kokku suhteliselt rohkem (166,5 mm), oli suurem ka puiduniiskus. Aasta hiljem esines rohkem sademeid suvel, kuid novembri lõpus mudelpuude raiumisele eelnes suhteliselt kuivem periood (oktoobris sademeid 61 mm; novembris 48 mm), mistõttu puiduniiskus Kabala ja Kaansoo objektil saadi tunduvalt väiksem kui eelmisel sügisel. Puutüve ulatuses on aga puiduniiskus sõltuv lülipuidu osakaalust tüves, st mida vanem puu, seda suurem on lülipuidu osa ja seda väiksem on puidu keskmine niiskusesisaldus.

Langetatud keskmistel mudelpuudel samas puistus ilmnes puiduniiskuse suur varieeruvus. Selgitamiseks püüti leida lineaarseid seoseid üksikpuude niiskuse ja teiste parameetrite vahel. Eeldati, et suhteliselt suurema võraga puu vajab elutege-

Tabel 2. Puiduniiskuse keskväärtused erinevates puistutes sõltuvalt ilmakaarest
Table 2. Wood moisture mean values in cross-section depending on stand side and height

Katse-objekt *Object*	Kasvu-koha-tüüp *Site type*	Puiduniiskus, % / *Wood moisture %*								
		Kõrgusel h 1,3 m *Height*			Kõrgusel h 1/2 *Height*			Kõrgusel h 3/4 *Height*		
		Põhi *North side*	Lüli *Heart-wood*	Lõuna *South side*	Põhi *North side*	Lüli *Heart-wood*	Lõuna *South side*	Põhi *North side*	Keskel *Center-wood*	Lõuna *South side*
Tähtvere	Rb	65,9	36,0	66,2	65,1	57,7	67,5	67,9	64,5	68,5
Tähtvere	Krb	62,9	35,5	60,4	63,2	48,3	65,0	65,2	61,1	67,2
Surju	Krb	62,5	34,4	60,6	65,0	51,0	64,2	64,6	63,1	64,5
Tähtvere	Ksrb	58,6	35,0	58,9	60,0	42,1	60,0	62,2	57,6	62,1
Surju	Kss	61,1	34,3	59,2	58,1	35,4	57,7	59,2	60,1	60,2
Kaansoo	Kss	45,0	31,4	48,6	45,7	30,4	47,1	46,9	44,7	46,7
Väätsa	Kss	60,0	37,8	61,6	61,6	34,0	60,9	62,4	52,0	65,3
Väätsa	Kmds	56,3	36,4	58,0	56,1	38,0	56,7	60,5	53,3	60,4
Kabala	Kks	45,6	28,8	47,3	46,4	31,7	48,0	48,0	47,7	48,0
Väätsa	Ms	65,0	35,5	63,3	60,7	35,4	64,1	66,2	59,1	66,4
Järvselja	Ms	54,8	32,4	53,6	49,7	32,0	51,5	54,0	33,9	56,6
Saare	Ms	63,5	38,1	62,7	62,7	35,0	64,3	64,0	44,2	68,2
Kubja	Ms	48,6	31,9	48,9	46,8	32,9	48,1	50,3	42,6	52,0
Konguta 1	Ms	59,7	37,3	59,4	58,0	36,8	58,7	60,1	54,7	59,8
Konguta 2	Ms	60,6	36,8	60,5	59,1	38,5	60,6	57,9	60,4	63,1
Sõmerpalu	Ms-ph	58,8	34,9	58,8	57,2	36,6	54,1	58,1	55,0	59,5
Sõmerpalu	Ph	60,6	35,3	63,3	55,0	34,4	53,0	60,6	51,4	58,3
Misso 1	Ph	63,8	35,0	64,9	63,0	33,9	62,9	64,2	44,7	64,7
Misso 2	Ph	67,9	41,5	69,4	67,9	37,3	68,6	67,0	54,4	69,4
Surju 1	Ph	52,3	31,7	54,9	51,7	30,6	55,3	54,2	33,6	57,3
Surju 2	Ph	54,3	30,2	56,5	52,2	32,4	55,0	62,9	48,5	57,4

vuseks rohkem vett ja tema puiduniiskus on suurem kui väiksema võraga puul. Suurem võra on aga tavaliselt hõredamas puistus, kus täistüvelisus on suurem ja lülipuidu osatähtsus võiks olla suurem ning kogu puu puiduniiskus seetõttu väiksem.

Mudelpuude võra diameetriga oli rinnasdiameetri seos nõrgem kui tüve diameetriga kõrgusel h3/4 ja h1/2. Näiteks, Tähtvere rabamännikus andis võra diameeter mõõduka seose (R = 0,30) üksnes tüve diameetriga kõrgusel h1/2. Kubja mustikamännikus ja Väätsa kuivendatud siirdesoomännikus oli seos tugev (R = 0,87) diameetriga kõrgusel h3/4 ning Väätsa kuivendatud madalsoos kõrgusel h1,3 ja h1/2.

Metoodika kohaselt valiti puistutest peamiselt keskmisi mudelpuid. Sõltuvalt kasvukohatingimustest on puistute keskmine rinnasdiameeter sama vanuseklassi puistutes suuresti varieeruv. Varieeruv oli ka võra diameeter, mida mõjutab lisaks kasvukohatingimustele veel täius ja hooldusraied. Tulemuste analüüsil selgus, et rinnasdiameetri seos võra läbimõõduga erineval ajal hooldatud mineraalmaapuistutes on nõrgem, kui see on hooldamata soopuistutes (vastavalt R = 0,57 ja R = 0,75).

Võra ruumala sõltub suhteliselt valguselembelisel männil elusa võra pikkusest, ehk millises tiheduses on puistu kasvanud. Võra suurem ruumala on eelduseks laiema aastaringi kasvamiseks ning on seetõttu otseses seoses puiduomadustega. Kui hooldamata rabamännikutes oli seos rinnasdiameetri ja võra mahu vahel väga nõrk, siis Väätsa harvendatud kuivendatud siirdesoomännikus oli see keskmine (R = 0,56) ning madalsoomännikus mõõdukas (R = 0,40). Hooldatud Kubja mustikamännikus oli nimetatud seos tugev (R = 0,79). Siit nähtub tugevama tüve diameetri ja võra dimensioonide seose kujunemine puistu hooldamise tagajärjel, mille arvestamine on praktikas ammu rakendamist leidnud.

Vormiarv võib mõjutada sortimentide väljatulekut, kuid üldjuhul ei loeta seda puiduomaduste mõjutajate hulka. Kuna käesolevas uurimuses on keskmisi mudelpuid paljudest puistutest, siis on vormiarvu esitus siin üldistavat laadi. Nagu tabelist 1 selgub, on keskmine vormiarv ühevanuselistes männikutes suuresti erinev. Metsakasvatuse põhitõdedest on teada, et puistu vormiarv suureneb boniteediklassi alanedes ja väheneb samas boniteediklassis vanuse suurenedes. Puistu täiuse vähenedes vormiarv väheneb. Kuid on ka erandeid, nagu näeme tabeli 1 viimasest reast, kus 70-aastases luitemännikus tehti kindlaks suhteliselt väiksem vormiarv kui teistes puistutes.

Kasvukohatüübi viljakuse parimaks iseloomustajaks on boniteediklass. Tabelist 3 näeme keskmist seost (R = 0,53) boniteedi ja vormiarvu vahel. Samas on aga vormiarvul tugev negatiivne korrelatsioon võra mahuga (R = –0,79).

Tabel 3. Puistu ja mudelpuu takseernäitajate vahelist seost iseloomustavad korrelatsioonikordajad
Table 3. Correlations between stand and tree characteristics

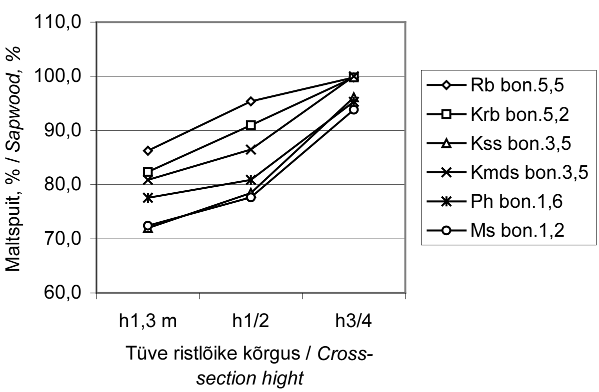
Nr/*No* Parameeter / *Parameter*	1	2	3	4	5	6	7
1. Rinnasdiameeter / *Diameter breast height*	1						
2. Vanus / *Age*	0,25	1					
3. Täius / *Stand density*	0,19	−0,36	1				
4. Boniteet / *Quality class*	−0,57	0,34	−0,42	1			
5. Võra maht / *Crown volume*	0,71	0,16	0,27	−0,52	1		
6. Tüve maht / *Trunk volume*	0,8	0,36	0,15	−0,68	0,64	1	
7. Vormiarv / *Form factor*	−0,64	−0,04	−0,47	0,53	−0,79	−0,58	1

Maltspuidu seos puiduniiskuse ja takseernäitajatega

Lüli- ja maltspuidu vahekord määrab antud puidu kasutamisvõimalused. Liiprites ja postides on suurem lülipuidu hulk kasulik, kuid oluliselt tumedama värvusega ja suurema vaigusisaldusega lülipuit ei ole sageli soositud mööblitööstuses. Tumedamavärvilisem lülipuit on väiksema kahanevusega. K. Werbergi (1930) andmetel on tume värv lülipuidus ka harilikult suurema kestvusea tunnus, sest tema õhukuiv tihedus, kõvadus, vastupanu mädanemisele on suurem kui sama puu pehmel ja kergel maltsaosal. Samas on aga lülipuidu painduvus tunduvalt väiksem kui maltspuidul.

Juba varem on kindlaks tehtud, et Eestis kasvaval männil maltsaosa aastaringide arv ei ole samas puus püsiv suurus ja lülipuidu piir ei kulge aastaringi mööda. Lülipuidu piirjoon tüves nihkub kõrgusega (ülespoole) järjest hiljem tekkinud aastaringidesse, paremates boniteetides on selle piirjoone aastaringide vahe ladvas ja kännul suurem, halvemates aga väiksem (Werberg, 1930). Kirjanduses on maltspuidu osatähtsust ristlõikepinnas seostatud männi okkamassiga (Albrektson, 1984), samuti leidub andmeid okkapinna (ka okkamassi) ja maltsapinna suhte märkimisväärsest seosest kasvukohatingimustega (Livonen *et al.*, 2001; Berninger, Nikinmaa, 1994; Grier, Waring, 1974), siit loogilise jätkuna peaks maltspuidu osatähtsust mõjutama ka võra maht. Samuti asjaolu, et okaste ja maltspuidu ristlõikepinna suhe Euroopas sõltub kliimast (Mencuccini, Bonosi, 2001) võiks põhjustada mõningat maltsa osatähtsuse erinevust ka soopuistutes ja mineraalmaal kasvavates ühevanuselistes ja sama boniteediklassiga puistutes.

Käesolevas uurimistöös määrati maltspuidu osatähtsus ja aastaringide arv maltspuidus puude ristlõikepinnal kõrgusel h1,3, h1/2 ja h3/4. Sõltuvalt kasvukohast ja boniteediklassist on maltspuidu osatähtsuse muutumine ladva suunas 55–90-aastastes männikutes erinev (joonis 3). Paljudel juhtudel, eriti kuivendatud puistute



Joonis 3. Maltspuidu osatähtsus 55–90-aastastes puistutes puutüve ristlõike erineval kõrgusel sõltuvalt metsakasvukohatüübist ja boniteediklassist. Rb – raba, Krb – kuivendatud raba, Kss – kuivendatud siirdesoo, Kmds – kuivendatud madalsoo, Ph – pohla, Ms – mustika kasvukohatüüp

Figure 3. *Sapwood ratio in 55...90-year-old pine stands at different cross-section heights depending on the site type and quality class. Rb – raised bog, Krb – drained raised bog, Kss – drained transitional bog, Kmds – drained birch fen, Ph – Vaccinium vitis-idaea site type, Ms – Myrtillus site type*

puudel, kõrgusel h3/4 koosnes ristlõikepind täielikult maltspuidust. Kõigi katseobjektide järgi määratuna oli maltspuidu osatähtsus suurem nooremates puistutes, seos vanusega oli mõõdukas kuni keskmine, R = –0,40…–0,53. Nende hulgas parim tulemus saadi pohla- ja mustikamännikute mudelpuudega (joonis 4).

Maltspuitu moodustavate aastarõngaste arv rinnakõrgusel sõltus peamiselt puistu vanusest. Nooremas puistus leiti maltspuidus aastaringe vähem kui vanemas, puu vanuse ja aastaringide arvu vahel maltspuidus registreeriti mõõdukas seos (R = 0,45…0,55). Boniteediklassi ja maltspuidu aastaringide arvu vahel saadi keskmise tugevusega seos (R = –0,14…–0,33), paremas kasvukohas on aastaringe maltsas rohkem. Maltspuidu protsendi ja boniteediklassi positiivne seos ilmnes rinnakõrgusel ja puutüve poolel kõrgusel, vastavalt R = 0,40 ja R = 0,56. Puu 3/4 kõrgusel oli seos keskmine (R = 0,48). Kuna boniteediklass on üheks olulisemaks kasvukohatüübi iseloomustajaks, siis võib eeldada maltspuidu osatähtsuse ja kasvukohatüübi vahelise seose olemasolu.

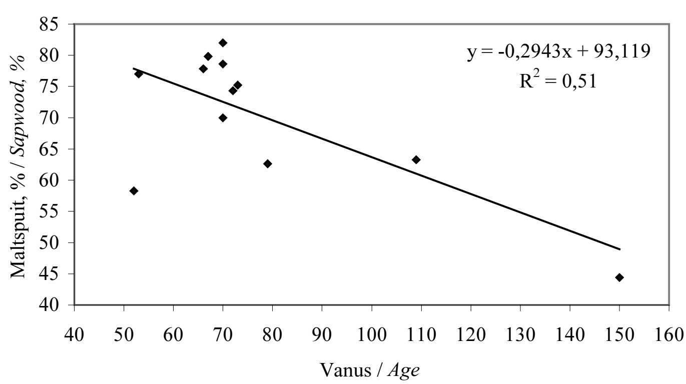
Keskealiste ja valmivate puistute boniteediklassi ja maltspuidu osatähtsuse tugev positiivne korrelatsioon tehti kindlaks rinnakõrgusel ja puu poolel kõrgusel, vastavalt R = 0,80 ja R = 0,83. Puu kõrgusel h3/4 on seos märgatav (R = 0,65).

Soopuistutes iseloomustas küllaldaselt hästi maltspuidu osatähtsuse (y) seost boniteediklassiga (x) sirge võrrand (joonis 5):

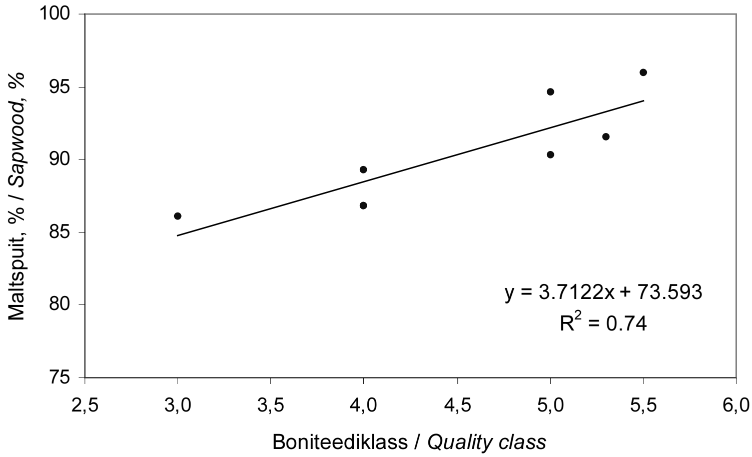
$y = 73,593 + 3,7122*x.$

Pohla- ja mustikamännikutes sarnast seost ei täheldatud. Kui aga opereerida boniteedi (x) ja vanusega (x_1), saab maltspuidu osatähtsust iseloomustada väheinformatiivse seosega: $y = 62,98948 + 11,16207*x – 0,35392*x_1$, kus R = 0,77…0,89.

Võramahu ja maltspuidu protsendi vaheline mõõdukas seos (R = –0,40…–0,50) tehti kindlaks üle 55 aasta vanustes puistutes. Kindlasti ei või seda tulemust üle kanda noorendikele, kus lülipuit puudub. Samas aga puu biomassi jaotuse põhimõtet interpreteeritakse veejuhtivuse mudeli teooria alusel (Shinozaki *et al.*, 1964; Grier, Waring, 1974), kus vastavalt lehepinnale (massile) on igal puul vastav maltsaringi pindala. Kuna lehepinna suurus ja mass on sõltuv võra suurusest, siis kontrolliti võramahu seost maltsapinna suurusega. Tähtvere rabamännikutes osutus aga nimetatud lineaarne seos suhteliselt nõrgaks (rinnakõrgusel R = 0,37, puu poolel



Joonis 4. Maltspuidu osatähtsuse seos vanusega pohla- ja mustikamännikutes
Figure 4. The relationship between relative sapwood area and stand age in pines growing on Vaccinium vitis-idaea and Myrtillus site types



Joonis 5. Maltspuidu osatähtsuse seos boniteediklassiga männi soopuistutes kõrgusel h1/2
Figure 5. The relationship between sapwood area % and quality class at h1/2 in pine stands growing on peatlands

kõrgusel R = 0,51), kui seda võrrelda näiteks kuuse uurimisel (Eckmüller, Sterba, 2000) saadud tulemustega, kus korrelatsioonikordaja on üle 0,9.

Võramaht oli männil negatiivses korrelatsioonis ka maltspuidu niiskusega kogu puu ulatuses (R = –0,47…–0,55). Võib oletada, et suurem võra kasutab rohkem vett, mida aga sügistalvisel perioodil transporditakse tüve mööda vähem. Seos maltspuidu niiskuse ja maltspuidu osatähtsuse vahel puutüve erinevates kõrgustes puudub (R = 0,10…0,27). Samuti ei leitud seost maltspuidu niiskuse ja maltspuidu aastaringide arvu vahel.

Võramahu ja maltsaosa aastaringide arvu vaheline seos analüüsitud katsematerjali alusel puudus rinnakõrgusel, mõõdukalt positiivne seos saadi puu poolel kõrgusel ja võraosas (h3/4).

Võramahu ja maltspuidu protsendi suhtel ning boniteediklassil oli seos statistiliselt mõõdukalt negatiivne, mis tugevneb ladva suunas: kõrgusel 1,3 m R = –0,52, kõrgusel h1/2 R = –0,57 ja kõrgusel h3/4 R = –0,58. Negatiivne seos tuleneb boniteediklassi negatiivsest seosest nii maltspuidu protsendi kui ka võramahuga. Ilmselt meie tingimustes ei asenda männi võramaht lehepinda ja okkamassi analoogsetes uuringutes.

Järeldused

Üksikpuu kasvu puistus mõjutavad paljud tegurid, mistõttu puu takseertunnused ja puidu füüsikalised omadused on samas kasvukohas varieeruvad. Varieeruvus on suur ka paljudelt kasvukohtadelt kogutud andmete summaarses analüüsis. See lubab eeldada, et uurides kasvukohatüüpide viisi puiduomadusi, on võimalik tuua välja iseloomulikke füüsikalisi omadusi, mis võimaldavad hinnata mehaanilisi omadusi lihtsamalt, kui seda on puiduomaduste määramine proovikehade abil. Selleks peab aga olema põhjalikumalt läbitöötatud katseobjektide andmestik.

Puiduniiskus sõltub otseselt kasvukohatingimustest. Kasvavas puus on puiduniiskust rohkem soomännikutes kui pohla- ja mustikamännikutes. Soomänni lülipuidus puu poolel kõrgusel on niiskust rohkem kui rinnakõrgusel, mida ei esinenud kuivemates kasvukohtades kasvavatel mändidel. Maltsaosa suurem niiskus lõunaküljel, võrreldes põhjaküljega, on selgelt eristatav võra piirkonnas.

Maltspuidu osatähtsus on suurem parema boniteediga ja nooremates puistutes. Paremas kasvukohas on maltsarõngas aastaringe rohkem. Võramahu ja maltspuidu protsendi vahel esineb mõõduka tugevusega seos, mis ei võimalda hinnata maltspuidu osatähtsust kasvavas puus võramahu järgi kuigi suure täpsusega.

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Kirjandus

Albrektson A. 1984. Sapwood basal area and needle mass of Scots pine (Pinus sylvestris L.) trees in Central Sweden. – Forestry, 57, 35–43.

Berninger, F., Nikinmaa, E. 1994. Foliage area – sapwood area relationships of Scots pine (Pinus sylvestris) trees in different climates. – Canadian Journal of Forest Research, 24, 2263–2268.

Grier, C. C., Waring, R. H. 1974. Conifer foliage mass related to sapwood area. – Forest Science, 20, 205–206.

Eckmüller, O., Sterba, H. 2000. Crown condition, needle mass and sapwood area relationships of Norway spruce (Picea abies). – Canadian Journal of Forest Research, 30, 10, 1646–1654.

Henno, O. 1963. Kasepuidu tehnilistest omadustest. – EPA teaduslike tööde kogumik, 33. Tartu, 180–189.

Kasesalu, A. 1965. Kasepuidu füüsikalis-mehaanilistest omadustest erinevates kasvukohatüüpides. – Metsanduslikud uurimised IV. Tallinn, 149–186.

Kask, R. 2001. Eesti männipuidu omaduste uurimine. – EPMÜ Metsandusteaduskonna toimetised, 34. Tartu, 59–64.

Krigul, T. 1972. Metsatakseerimine. Tallinn, 358 lk.

Lindstrom, H. 1996. Basic density in Norway spruce. Part III. Development from pith outwards. – Wood and Fiber science, 28, 391–405.

Livonen, S., Rikala, R., Vapaavuory, E. 2001. Seasonal root growth of Scots pine seedlings in relation to shoot phenology, carbohydrate status and nutrient supply. – Canadian Journal of Forest Research, 31, 9, 1569–1578.

Mencuccini, M., Bonosi, L. 2001. Leaf/sapwood area ratios in Scots pine show acclimation across Europe. – Canadian Journal of Forest Research, 31, 442–456.

Pushinskis V., Hrols J., Dolacis J. 1998. Factors influencing the modules of elasticity and stength limit in bending of pine (Pinus sylvestris) wood. – Wood Structure and Properties, 98. Zvolen, Slovakia, 163–167.

Saranpää, P. 1999. Effect of forest management on wood quality. – Metsäalan tutkimusohjelma. Raportti 2. Helssinki, 178–185.

Shinozaki, T., Yoda, K., Hozumi, K., Kira, T. 1964. A quantitative analysis of plant form - the pipe model theory. I Basic analyses. – Japan Journal of Ecology, 14, 97–105.

Sipi, M, Rikala, J. 2000. Tree stands on peatland, quality of wood raw material and suitability for different use objects. – XXI IUFRO World Congress 7.–12.8.2000, Proceedings of Posters. Malaysia, 191–192.

Zalitis P. 1999. The productivity of drained Pine Forests and Pinewood Quality. – Baltic Forestry, 5, 2, 2–7.

Tamm, Ü. 2000. Haab Eestis. Tartu, 257 lk.

Veibri, U. 1973. Hooldusraiete mõjust kuusepuidu mahukaalule. – EPA teaduslike tööde kogumik, 89. Tartu, 155–158.

Veibri, U. 1982. Hariliku kuuse puiduniiskuse aastaringne muutumine. – EPA teaduslike tööde kogumik, 142. Tartu, 63–67.

Veibri, U., Kokk, A. 1980. Hariliku männi puiduniiskuse aastaringne muutumine. – EPA teaduslike tööde kogumik, 128. Tartu, 90–94.

Werberg, K. 1930. Lüli- ja maltspuu suhe männil. – Tartu Ülikooli Metsaosakonna toimetised, 17. Tartu, 184 lk.

Ванин С. И. 1945. Древесиноведение. Москва, 35 с.

Михайличенко А. Л., Садовничий Ф. П. 1983. Древесиноведение и лесное товароведение. Москва, 206 с.

Перелыгин Л. М. 1969. Древесиноведение. Изд. 3-е. Переработанное и дополненное Б. Н. Уголевым. Москва, 286 с.

Перелыгин Л. М., Уголев Б. Н. 1971. Древесиноведение. Москва, 286 с.

Scots pine (*P. sylvestris* L.) wood moisture and sapwood ratio on different forest site types

Kask R., Pikk J., Kuusepuu T.

Summary

In Estonia, relatively little research has been done on wood properties. As appears from literature, the total of model trees felled in Estonia for studying pine wood technical properties does not exceed 150.

The first half of this ongoing research dealt with the determination of wood moisture differences and sapwood ratios in different tree parts and their potential correlations with tree survey criteria on some site types. Pine physical properties were investigated mainly in thinning-age and poletimber-tree stands. The possibility of determining sapwood ratio from tree survey criteria was also examined.

In nature, we selected 21 different pine stands growing on cowberry (*Vaccinium vitis-idaea*), bilberry (*Myrtillus*), full-drained bog, drained birch fen, drained transition bog, drained transition raised bog and raised bog site types (Table 1). Six to twelve model trees were selected by the stand mean breast height. Altogether, 166 model trees were felled, from which sample blocks (1.2 m in length) were cut at 1.3 m, 1/2 of tree height and 3/4 of tree height.

Pine wood freshly felled on *Vaccinium vitis-idaea* and *Myrtillus* site types contained considerably less moisture than that on bog site types (Figure 1). Differences in sapwood and heartwood contents were insignificant at breast height but increased towards the top.

In pine stands growing on *Vaccinium vitis-idaea* and *Myrtillus* site types, heartwood moisture content was identical at breast height and half of tree height but considerably higher at 3/4 of tree height. Apparently, heartwood in the crown region participates to some extent in organic life.

Our findings showed that heartwood moisture in stands growing on bog site types was higher at half of tree height than at breast height and kept rising towards the top.

Similarly, sapwood moisture increased towards the top. The change was slight from breast height to half of tree height yet considerable higher up. The difference in mean wood moisture was slight between the south and the north side of the stem. It increased towards the top, yet at 3/4 of tree height sapwood moisture on the south side was higher by just 3.3% on *Vaccinium vitis-idaea* and *Myrtillus* site types and

1.4% on bog site types.

Supposedly, raised bog stands should evidence no differences in wood moisture as they are exposed to plenty of water. The results from 85…88-year-old stands, however, demonstrated some differences in wood moisture, which can only be explained by differences in site type soil moisture content (Figure 2).

The absolute wood moisture values proved smaller in all measurement sites in which the felling was preceded by a longer period of low precipitation (the objects of Kubja, Kaansoo and Kabala) (Table 2).

A greater crown volume obviously results in a wider annual circle, which, in turn, bears direct relationship to wood properties. While the correlation between pine breast height diameter and crown volume was very weak in untended bog stands it was strong in tended *Myrtillus* stands.

The best indicator of site type fertility is the quality class. Table 3 shows the mean correlation ($R = 0.53$) between quality class and form factor. At the same time, however, the form factor exhibits a strong negative correlation with crown volume ($R = -0.79$).

Depending on the site type and the quality class, changes in sapwood ratio towards the top reveal some differences in 55…90-year-old pine forests (Figure 3). In many cases, particularly in trees of drained stands, the cross section at 3/4 of tree height was fully composed of sapwood. Results from all the experimental objects showed that sapwood ratio was higher in younger stands; the correlation with age was moderate to medium ($R = -0.40…-0.53$). In these stands, the best results were gained from model trees growing on *Vaccinium vitis-idaea* and *Myrtillus* site types (Figure 4).

Younger stands evidenced fewer annual rings in their sapwood than older stands; a moderate correlation was registered between tree age and sapwood annual ring number ($R = 0.45…0.55$). A medium correlation was observed between quality class and sapwood annual ring number ($R = -0.14…-0.33$); a higher-quality site evidenced more annual rings in sapwood. A positive correlation between sapwood percentage and quality class was observed at breast height and half of tree trunk height ($R = 0.40$ and $R = 0.56$, respectively).

In bog stands, the correlation between sapwood ratio (y) and quality class (x) was adequately characterized by a linear equation (Figure 5). No similar correlation was observed in *Vaccinium vitis-idaea* and *Myrtillus* stands.

Crown volume and sapwood percentage appeared to be moderately correlated, which renders it possible to roughly assess the sapwood ratio of a tree by its crown volume.

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2012–2014	SA Keskkonnainvesteeringute Keskuse (KIK) projekt 8-2/T12199MIMT: Kasvavate puude laasimise mõju puidu kvaliteedile. Põhitäitja.
2009–2012	Baasfinantseeritav teema 8-2/T9002MIMI: Metsakorralduslikud uuringud. Põhitäitja.
2005–2008	Baasfinantseeritav teema 8-2/T5085MIMI05: Puit – formeerumine, omadused ja kasutamine. Põhitäitja.
2002–2004	ETF grant nr. 4986: Männipuidu omadused erinevates metsakasvukohatüüpides. Põhitäitja.

LIST OF PUBLICATIONS

Publications in journals indexed in the Thomson Reuters Web of Science database

Tamme, V., Muiste, P., **Kask**, **R**., Padari, A., Tamme, H. 2012. Experimental study of electrode effects of resistance type electrodes for monitoring wood drying process above fibre saturation point. – *Forestry Studies*, 56: 42–55.

Ots, K., Mandre, M., Pärn, H., **Kask**, **R**., Pikk, J. 2009. Changes in the allocation of nutrients and biomass in Scots pine (*Pinus sylvestris* L.) canopy in an area of cement industry in Northeast Estonia. *Baltic Forestry*, 15(2): 237–247.

Kask, **R**., Pikk, J. 2009. Second thinning Scots pine wood properties in different forest site types in Estonia. – *Baltic Forestry*, 15(1): 97–104.

Mandre, M., **Kask**, **R**., Pikk, J., Ots, K. 2008. Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust. – *Environmental Monitoring and Assessment*, 138(1–3): 51–63.

Kask, **R**., Ots, K., Mandre, M., Pikk, J. 2008. Scots pine (*Pinus sylvestris* L.) wood properties in an alkaline air pollution environment. – *Trees – Structure and Function*, 22(6): 815–823.

Papers published in other peer-reviewed journals

Pikk, J., **Kask**, **R**., Peterson, P. 2006. The wood quality of fertilized Scots pine (*Pinus sylvestris* L.) stands on *Vaccinium vitis-idaea* and *Cladonia* site type. – *Forestry Studies*, 44: 9–19.

Pikk, J., **Kask**, **R**. 2004. Mechanical properties of juvenile wood of Scots pine (*Pinus sylvestris* L.) on *Myrtillus* forest site type. – *Baltic Forestry*, 10(1): 72–78.

Pikk, J., **Kask**, **R**., Kuusepuu, T., Peterson, P. 2004. Kasvutingimuste mõju hariliku männi (*Pinus sylvestris* L.) puiduomadustele. – *Forestry Studies*, 40: 187–197.

Kask, **R**., Pikk, J., Kuusepuu, T. 2002. Hariliku männi (*P. sylvestris* L.) puiduniiskus ja maltspuidu osatähtsus erinevates kasvukohatüüpides. – *Forestry Studies*, 37: 129–141.

Other scientific publications

Tamme, V., **Kask**, **R**., Muiste, P., Tamme, H. 2012. Puidu niiskusmõõtjate võrdlus laiendatud mõõtepiirkonnas. – *Taastuvate energiaallikate uurimine ja kasutamine*, 14: 98–108.

Kask, **R**. 2001. Eesti männipuidu omaduste uurimine. Metsandusteaduskonna magistrantide ja doktorantide teaduslike tööde kogumik. – *EPMÜ Metsandusteaduskonna toimetised*, 34: 59–64.

Conference proceedings

Siim, K., **Kask**, **R**., Lille, H., Täkker, E. 2012. Study of physical and mechanical properties of birch plywood depending on moisture content. In: *Proceedings of the 8th International Conference of DAAAM Baltic, Industrial Engineering: 8th International DAAAM Baltic Conference, Tallinn, Estonia, 19–21 April 2012*. (Ed.) Otto, T. Tallinn University of Technology, Tallinn, Estonia, 19–21 April 2012, pp 735–740.

Tamme, V., Muiste, P., **Kask**, **R**., Padari, A., Tamme, H. 2012. The research of electrode effects on wood drying above fiber saturation point. In: *Proceedings of the 12th International IUFRO Wood Drying Conference. Challenges and Opportunities Related to Tropical Lumber Drying. WDC 2012 12th International IUFRO Wood Drying Conference*, *Belém*, *Pará*, *Brazil, July 30 to August 03 2012*. (Ed.) Jankowsky, I.P. Instituto de Pesquisas e estudos Florestais, Belém, Pará, Brazil, 30.07.12–03.08.12, p. 47.

Padari, A., Mitt, R., Pärn, L., Savi, H., **Kask**, **R**., Muiste, P. 2011. Degrading of properties of birch wood during long-term storage in Estonian conditions. In: *ICFFI News, 13(1). International Centre of Forestry and Forest Industries.* St. Petersburg State Forest Technical University, St. Petersburg, Russia, 9–11 November 2011, p. 23.

Kask, **R**., H. Lille., K. Siim., P. Paabo., K. Sillaste. 2011. Study of physical and mechanical properties of oriented stand board depending on moisture content. In: *Civil Engineering' 11 Proceedings of 3rd International Scientific Conference. Vol. 3.* Jelgava, Latvia, 12–13 May 2011, pp 91–94.

Kask, **R**., Lille, H., Ryabchikov, A., Ljahov, J., Rebane, A., Reial, A. 2009. The dependence on moisture content for the physical and mechanical properties of particleboard. In: *Proceedings of the 16th Baltic Building Symposium*. Estonian University of Life Sciences, Department of Rural Building, Tartu, Estonia, 28–29 May 2009, pp 70–76.

Kask, **R**. 2000. Investigation of properties of Estonian pine wood. In: *Proceedings from the NSV-meeting at Røros 2000*. Norsk institutt for skogforskning. Røros, Norway, 27–29 May 2000, pp 35–39.

APPROBATION

Presentations at international conferences and meetings

30.07.–03.08.2012. Tamme, V., Muiste, P., **Kask**, **R**., Padari, A., Tamme, H. The research of electrode effects on wood drying above fiber saturation point. WDC 2012 - 12th International IUFRO Wood Drying Conference. Belém, Para, Brazil.

9.–11.11.2011. Padari, A., Mitt, R., Pärn, L., Savi, H., **Kask**, **R**., Muiste, P. Degrading of properties of birch wood during long-term storage in Estonian conditions. Conference "Ecosystem Design for Multiple Services – with an emphasis on Eurasian Boreal Forests". St. Petersburg, Russia.

Presentations at local conferences and meetings

08.11.2012. Tamme, V., **Kask**, **R**., Muiste, P., Tamme, H. Puidu niiskusmõõtjate võrdlus laiendatud mõõtepiirkonnas. Conference "Taastuvate energiaallikate uurimine ja kasutamine XIV". Eesti Maaülikool, Tartu.

26.10.2010. **Kask**, **R**. Second thinning Scots pine wood properties in different forest site types in Estonia. Conference "Eesti metsandus – tänapäev ja tulevikuperspektiivid". Eesti Maaülikool, Tartu.

VIIS VIIMAST KAITSMIST

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Dotsent **Enn Lauringson**, vanemteadur **Malle Järvan** (Eesti Taimekasvatuse Instituut)
27. veebruar 2015

JULIA JEREMEJEVA

PROSTAGLANDIN F2*α* AND PARENTERAL ANTIBIOTICS AS A TREATMENT OF POSTPARTUM METRITIS AND ENDOMETRITIS, AND POSSIBLE RELATION OF ACUTE PHASE PROTEINS WITH SUBSEQUENT FERTILITY IN DAIRY COWS
PROSTAGLANDIINI F2*α* JA ANTIBIOOTIKUMIDE LIHASTESISENE VÕI NAHAALUNE KASUTAMINE POEGIMISJÄRGSE METRIIDI JA ENDOMETRIIDI RAVIS LÜPSILEHMADEL NING TAASTIINESTUMISE VÕIMALIK HINDAMINE AKUUTSE FAASI PROTEIINIDE MÄÄRAMISE KAUDU
Dotsent **Kalle Kask**
16. aprill 2015

KADRI KASK

DISTRIBUTION AND HABITAT PREFERENCES OF CLOUDED APOLLO BUTTERFLY [*Parnassius mnemosyne* (L.)] IN ESTONIA
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