Research paper

Effect of growth conditions on wood properties of Scots pine (*Pinus sylvestris* L.)

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Abstract. The study material of Scots pine sample trees originated from five different forest site types (*Cladonia, Calluna, Myrtillus,* natural raised bog and drained raised bog) in Estonia. Altogether, 60 trees were sampled from 10 stands. From these, test disks and sample blocks (1.2 m in length) were cut at 1.3 m height, 1/2 of tree height and 3/4 of tree height. We analysed the effect of forest site type on the growth of tree ring width, proportion of late- and heartwood, oven-dry density, bending and compression strength and wood hardness. Wood properties in stands of the same age showed great variability. Significant differences were found in the wood properties between site types. Wood density and strength characteristics were higher in samples from heath site types than from the sites more optimal for pine (e.g., *Myrtillus*). The quality of the wood from peatland stands was lower than from trees grown on mineral soil. The decreasing trend in strength properties towards the top of trees was steeper in the wood formed under poor nutrient conditions. Latewood proportion increased with tree age. However, in the case of equal latewood percentages, heartwood density was higher than sapwood density.

Key words: wood density, latewood, bending strength, compression strength, hardness.

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Introduction

Knowledge of the properties and quality of raw material is a key factor for any wood-based product and production. In the industrial timber procurement and processing chain this knowledge increases the efficiency of manufacturing as the raw material can be allocated to the right product segment as early as needed.

A significant impact of environmental and growth conditions on the horizontal and vertical variability of wood properties in tree stem is shown by a number of authors (Moore & Cown, 2015). In addition, geographical variations in wood properties of tree species and the dependence of the properties on soil type, soil reaction, genetic provenance, tree position in the storey, tree age and many other factors are generally known (Bektas *et al.*, 2003; Lindeberg, 2001; Nekrasova, 1994; Osman, 2013; Ståhl, 1998; Wodzicki, 2001). However, a study in Lithuania (Aleinikovas & Grigaliūnas, 2006) found that the wood density of pine trees (aged 85–110 years) from three forest

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sites did not differ significantly, but the estimated bending strength and compression strength parallel to wood grain from a normal humidity poor site were the highest and significantly differed from those of a normal humidity very poor site and normal humidity fertile site.

In Estonia, strong correlations have been observed between wood properties and site index in juvenile and maturing stands in *Rhodococcum* and *Myrtillus* site types (Kask, 2015; Lõhmus, 2004). However, using site index for predicting wood properties in stands growing in extreme conditions is problematic. There is a great variability of growth conditions in Scots pine habitats, as Scots pine is a species with wide ecological amplitude. In different site conditions, the availability and supply of nutrients are clearly different for trees. On overmoist sites, there may be sufficient levels of nutrients in the soil, but their availability is restricted by periodic or seasonal waterlogging. After the periodic waterlogging it still may appear that the availability of plant active phosphorus, potassium or nitrogen is low. In the pine stands on heath sites, a general shortage of nutrients may occur (Osman, 2013). Yet in pine stands on *Cladonia* and *Myrtillus* site type higher wood N and P levels can be recorded in comparison to peatland pines (Sazonova & Pridacha, 2005). The NPK levels are lower in heartwood than in sapwood, and Ca and Mg levels exhibit high variability (Meerts, 2002). Consideration should be given to fibre length, cell wall thickness, internal bond strength, crystal structure, etc. Some influence to wood strength properties also comes from the growth site soil NPK and Ca content availability during the period of wood formation (Ots, 2002; Sazonova & Pridacha, 2005). Other studies indicate that climatic, water-related and nutrient-related factors do not always have a consistent effect on radial growth and wood density (Bergès *et al.*, 2008).

The objective of the current study was to analyse and describe the main differences in the physical and mechanical properties of Scots pine wood forming in peatland and heath forests when age, tree dimensions and site index of trees were similar.

Material and methods

The study material was collected from 10 natural regenerated stands aged 65–75 years growing on sites suitable for pine in Estonia (58–59° N; 22–28° E). Six sample trees (healthy trees with a width of an average diameter in the stand) were selected and felled for analysis from each of three heathland pine stands on Haplic Podzol (*Cladonia* and *Calluna* site type, site index class 4) as for the control, two drained raised bog pine stands on Dystric Histosol (site index class 4), one raised bog pine stand on Dystric Histosol (site index class 5.2) and four *Myrtillus* site type pine stands on Umbri-Densic Podzol (site index class 1) were also sampled for the comparison of wood properties. The sample trees were selected according to the method described by Saladis & Aleinikovas (2004), with the requirement that at least 6 trees and 42 samples from every tree must be examined to obtain the wood properties with 10% accuracy for a single forest stand.

In managed stands, a mean tree by its dimensions that can serve as a good indicator of the stand is usually on the borderline between the dominant and the co-dominant trees. For comparison we selected sample trees in *Myrtillus* site type pine stands growing in relatively optimal growth conditions and in raised bog pine stands in extremely poor conditions. The site type classification by Lõhmus (2004) is used in this study.

To prepare samples, sample blocks and test disks were cut from each stem at breast height ($h_{1.3}$), at the half-tree height ($h_{1/2}$) and from the crown ($h_{3/4}$) at 75% of tree height. The disks were room-dried (8.4% relative humidity). After they were dried, annual radial increment was measured

Table 1. Determination of wood properties.

Property	Used standard	Number of tests
Oven-dry density	ISO 13061-2:2014 (2014)	1.478
Static bending strength across-the-grain	ISO 13061-3:2014 (2014)	1.136
Compression strength along-the-grain	ISO 13061-17:2017 (2017)	1.484
Hardness along-the-grain	ISO 13061-12:2017 (2017)	952

and annual ring latewood percentage as well as heartwood and sapwood proportions were determined. Relative humidity was measured using a Hydromette HT85T device (Gann GmbH) and a computer system with WinDENDRO TM software (Ver. 2002a, Regent Instruments Inc.) was used to measure annual ring widths. The annual radial increment was measured to the nearest 0.01 mm.

In mechanical sampling from sample blocks the heart boards were cut in the direction of two mutually perpendicular diameters. Samples for determining wood oven-dry density, along-the-grain hardness, tangential bending strength and along-the-grain compression strength were prepared separately from sapwood and heartwood (Table 1). All the mechanical properties in the present paper were adjusted to 12% wood moisture level.

Differences in the average wood characteristics between site types were estimated by the one-way ANOVA (Analysis of Variance). The critical *p*-value was 0.05. Regression trend lines and determination coefficients (R^2) were calculated to test relationships between wood density and latewood percentage.

Results

Wood physical properties

Under lack or insufficient availability of soil nutrients the annual tree ring widths in heartwood were relatively small in heath and peatland sites compared to the annual rings of the same age of the trees growing in *Myrtillus* site type (Table 2). The mean annual ring widths in heath pine forest heartwood were close to or less than in trees growing in raised bog and drained raised bog pine stands; however, the proportion of latewood in annual rings was larger in heath pine forests. The proportions of latewood in heartwood and sapwood in heath stands even exceeded the corresponding values for *Myrtillus* site type stands at all the heights under study. In peatland stands, the proportions of latewood were considerably smaller.

Unlike heartwood, the mean annual ring widths in sapwood in the three cross-sections of the tree stem were broadly similar in heath and *Myrtillus* site type stands. In heath pine stands in sapwood, however, the number of annual rings was greater than in the other site types. In tree stem cross-sections the number of annual rings in sapwood is normally not identical in different directions. With height, stem heartwood boundary increasingly shifts towards the latest annual rings.

At $h_{1/2}$, heartwood percentages had decreased by 5% in the heath pine stands, 8% in the raised bog pine stand, 4% in the drained raised bog pine stands and 4% in the pine stands on *Myrtillus* site type.

At $h_{3/4}$ heartwood contained relatively more wood weaker in strength properties around the pith. There were many trees where the heartwood had not yet formed at that height, which accounts for the high variability of heartwood proportions at that height. In general, the variability in the heartwood percentage was higher between trees in individual stands than between stands.

It is common knowledge that there is

Table 2. Pine wood physical properties (mean ± SE) at different heights.

Characteristic and unit	Sampling height	Site type				*P*-value, ANOVA
		Heath	Drained raised bog	Raised bog	*Myrtillus* site type	
Diameter at breast height, mm	$h_{1.3}$	164.4±3.5	156.5±2.0	124.2±2.0**	226.3±3.2**	<0.0001
Heartwood annual ring width, mm	$h_{1.3}$	1.37±0.08	0.92±0.08**	0.88±0.05**	2.19±0.11**	<0.0001
	$h_{1/2}$	1.74±0.15	2.72±0.16**	2.12±0.25	2.72±0.24**	0.0002
	$h_{3/4}$	2.13±0.43	1.88±0.30	1.95±0.03	2.61±0.18	0.5127
Sapwood annual ring width, mm	$h_{1.3}$	0.95±0.06	1.20±0.07**	0.99±0.04	1.23±0.09**	0.0142
	$h_{1/2}$	1.29±0.10	1.86±0.07**	1.77±0.06*	1.20±0.09	<0.0001
	$h_{3/4}$	1.81±0.14	2.51±0.13**	2.18±0.07	1.71±0.17	0.0003
Latewood in heartwood, %	$h_{1.3}$	36.6±1.4	26.9±1.3**	25.7±1.4**	33.1±1.1	<0.0001
	$h_{1/2}$	26.7±1.6	16.7±1.1**	16.0±1.9**	23.3±0.9	<0.0001
	$h_{3/4}$	24.1±3.0	19.6±3.8	16.6±6.2	22.7±0.9	0.6653
Latewood in sapwood, %	$h_{1.3}$	44.6±0.9	36.3±1.3**	31.4±2.1**	42.1±0.9	<0.0001
	$h_{1/2}$	34.2±1.1	30.9±0.8*	24.2±0.9**	31.9±0.9	<0.0001
	$h_{3/4}$	29.0±1.1	23.8±0.9**	23.0±2.2*	25.6±1.0*	0.0034
Proportion of heartwood, %	$h_{1.3}$	22.3±2.3	17.7±2.2	12.4±1.3*	36.2±4.1**	<0.0001
	$h_{1/2}$	17.3±2.2	9.1±1.1**	4.0±0.9**	32.2±4.6**	<0.0001
	$h_{3/4}$	2.9±0.7	0.6±0.1**	0.1±0.1*	10.9±2.2**	<0.0001
Number of annual rings in sapwood, pcs	$h_{1.3}$	49.8±2.5	35.7±1.4**	42.5±3.4	40.9±1.4*	<0.0001
	$h_{1/2}$	33.9±1.9	21.2±0.4**	24.5±1.0*	30.2±1.2	<0.0001
	$h_{3/4}$	24.3±1.9	14.90.5**	15.3±0.8**	23.8±1.5	<0.0001
Oven-dry density of heartwood, kg/m^3	$h_{1.3}$	553±11	457±0**	425±21**	489±8**	<0.0001
	$h_{1/2}$	442±10	378±10**	371±15**	410±11*	<0.0001
	$h_{3/4}$	444±13			391±10**	0.0043
Oven-dry density of sapwood, kg/m^3	$h_{1.3}$	583±7	497±12**	441±26**	563±10	<0.0001
	$h_{1/2}$	469±8	420±8**	408±13**	464±10	<0.0001
	$h_{3/4}$	445±9	381±6**	370±10**	424±9	<0.0001

a strong correlation between latewood percentage and oven-dry density. In our results, the determination coefficient in a stand (R^2) as an indicator of correlation ranged from 0.70 to 0.90 both for sapwood and heartwood. There was a moderate linear correlation between annual ring width and density (R^2 = 0.40). The distribution of mean oven-dry density values on the tested samples in the study is presented in Table 2 and it shows similar results with latewood percentages.

Because of higher latewood levels in heath pine forests the heartwood and sapwood density there exceeds wood density in the corresponding parts of the stem in other stands. Although it is clear that there is normally less latewood in heartwood than in sapwood, heartwood density was higher than sapwood density at equal latewood percentages (Figure 1). The results show that the difference is variable in different site types. It was smallest in *Myrtillus* site type pine stands (1%), followed by the raised bog pine stand (5.7%), heath pine stands (8.2%), and drained raised bog pine stands (11.2%). The difference in drained raised bog pine stands is greater at smaller densities, which is contrary to *Myrtillus* site type pine stands (Figure 2), where the difference is greater at higher wood densities. In heath pine stands and the natural raised bog pine stand the difference in density between heartwood and sapwood was constant, which did not change with variations in latewood proportion.

Wood mechanical properties

Significant differences were observed between the stands under study in wood

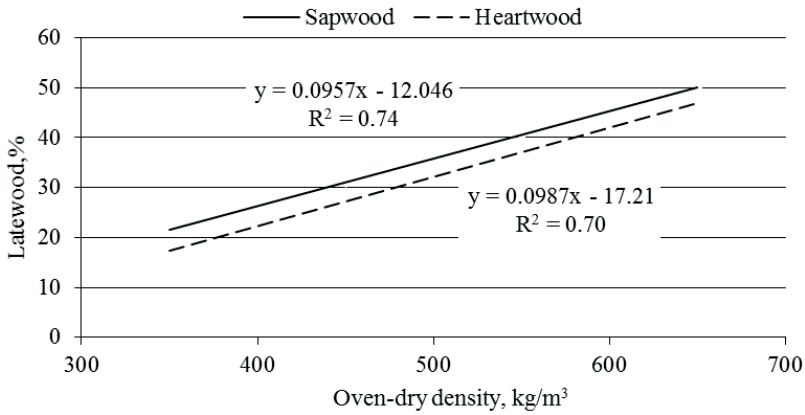


Figure 1. Heartwood and sapwood oven-dry density (kg/m3) at the same latewood percentage in heath pine forests.

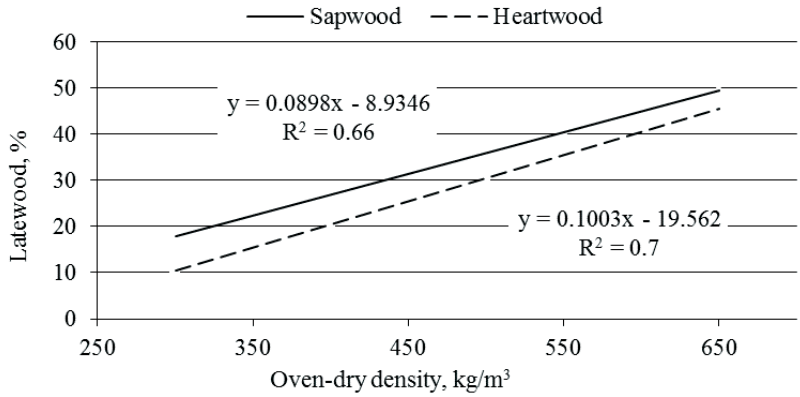


Figure 2. Heartwood and sapwood oven-dry density (kg/m3) at the same latewood percentage in drained raised bog pine forests.

bending strength, compression strength and hardness. If we take the heartwood bending strength of the heath site type pine stands as 100%, then the bending strength of samples taken from the *Myrtillus* site type pine stands is 85.4%, from the raised bog pine stand 69.9%, and from the drained raised bog pine stands 70.8%. The distribution of sapwood bending strengths by site types was roughly analogous: 100%, 90.2%, 66.7% and 74.8%, respectively. Smaller differences were observed in compression strength, and even smaller ones in wood along-the-grain hardness. All the strength properties studied in heath pines at breast height and stem relative heights ($h_{1/2}$, $h_{3/4}$) presented in Table 3 exceed the corresponding wood properties of trees from the other site types. However, the sample tree breast height diameters in heath pines and drained raised bog pines were similar (16.4 and 15.7 cm, respectively). The mean breast height diameter of pines from the raised bog stand was smaller than these (12.4 cm) while in the *Myrtillus* site type pines it was larger (22.6 cm).

Increased wood density does not have similar effects on mechanical properties. The effect of density was the strongest on bending strength and compression strength (Figures 3–4) and relatively weak on along-the-grain hardness (Figure 5).

Table 3. Pine wood mechanical properties (mean ± SE) at different heights.

Characteristic	Sampling height	Site type				*P*-value, ANOVA
		Heath	Drained raised bog	Raised bog	*Myrtillus* site type	
Bending strength of heartwood, MPa	$h_{1.3}$	103±3	73±2**	72±6**	88±3**	<0.0001
	$h_{1/2}$	82±3	54±3**	54±3**	71±2**	<0.0001
	$h_{3/4}$	74±2	53±0**		67±2	0.0004
Bending strength of sapwood, MPa	$h_{1.3}$	123±2	92±3**	82±7**	111±4**	<0.0001
	$h_{1/2}$	92±2	73±2**	70±4**	91±2	<0.0001
	$h_{3/4}$	80±2	57±2**	53±5	79±2	<0.0001
Compression strength of heartwood, MPa	$h_{1.3}$	60.5±1.5	52.5±1.5**	46.5±4.5**	53.0±1.5**	<0.0001
	$h_{1/2}$	48.5±4.0	39.5±1.0**	39.5±2.0**	45.5±1.5	<0.0001
	$h_{3/4}$	44.5±2.0			40.5±2.0	0.1092
Compression strength of sapwood, MPa	$h_{1.3}$	69.0±1.0	59.0±1.5**	52.0±5.5**	63.0±2.0**	<0.0001
	$h_{1/2}$	54.5±1.0	48.5±1.0**	47.5±2.5**	54.0±1.5	0.0003
	$h_{3/4}$	46.5±1.0	41.5±1.0*	40.5±1.5	48.0±1.5	0.0008
Hardness of heartwood, MPa	$h_{1.3}$	38±2	34±1	33±2	33±1*	0.0269
	$h_{1/2}$	31±1	28±1*	30±1	26±1**	0.0072
	$h_{3/4}$	31±1	28±1*	31±1	26±1	0.0034
Hardness of sapwood, MPa	$h_{1.3}$	41±1	36±1*	34±3**	35±1**	0.0022
	$h_{1/2}$	34±1	34±1	32±2	28±1**	0.0003
	$h_{3/4}$	32±1	33±1	32±1	27±1	0.0021

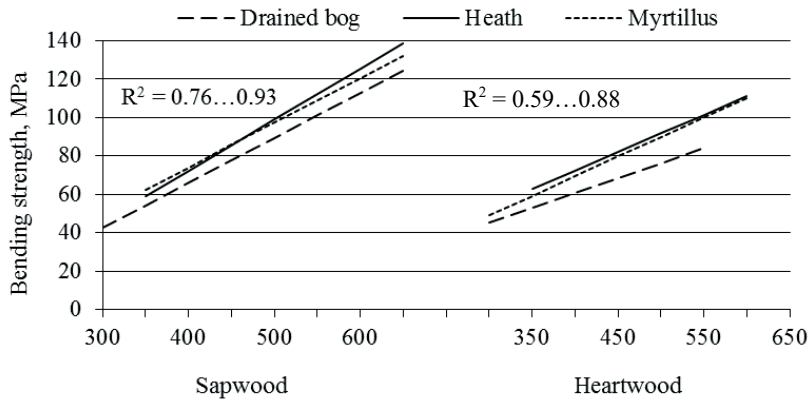


Figure 3. Scots pine heartwood and sapwood across-the-grain bending strength (MPa) in various forest site types at the same oven-dry density (kg/m3).

Comparison of the bending strength in heartwood and sapwood at the same density showed that it was greater in sapwood in all the site types. At the same oven-dry density the bending strength was almost identical in heath and *Myrtillus* site type pines. The bending strength of wood originating from drained raised bog pine stands proved to be significantly smaller (Figure 3).

Study of along-the-grain compression strength at the same density yielded an identical result in three site types for both sapwood and heartwood (Figure 4). In contrast, along-the-grain hardness of heartwood and sapwood at the same wood density proved to be the greatest in wood from the drained raised bog pine stands (Figure 5).

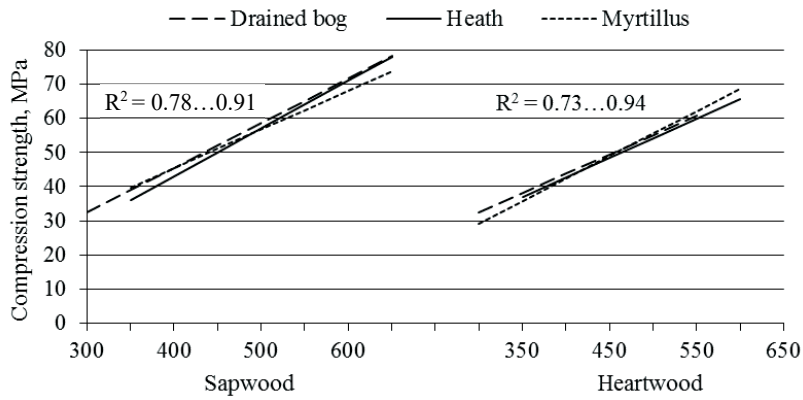


Figure 4. Scots pine heartwood and sapwood along-the-grain compression strength (MPa) in various forest site types at the same oven-dry density (kg/m3).

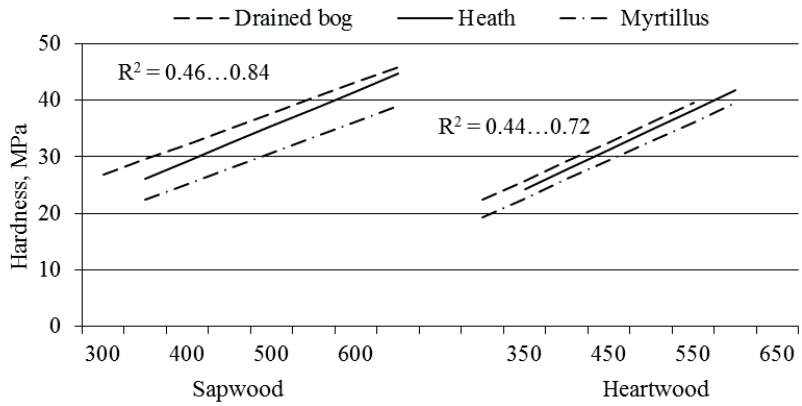


Figure 5. Scots pine heartwood and sapwood along-the-grain hardness (MPa) in various forest site types at the same oven-dry density (kg/m3).

Discussion

Wood physical properties

Growth conditions in different stands can be best characterised by annual height growth or ring width (Mäkinen, 1998; Metslaid *et al.*, 2011) and wood properties often, but not always, by latewood percentage and density. Thus, in younger stands annual ring width has a significant effect on wood density, modulus of rupture and modulus of elasticity (Mattsson, 2002). In older pines, annual ring width only has a limited value for determining wood properties; there, wood properties are characterised to a significant degree by latewood percentage (Seco & Barra, 1996; Wilhelmsson *et al.*, 2002; Wimmer, 1991). With age, latewood percentage increases in pine. A number of authors have observed a very weak correlation between latewood content and growth site as well as between stand and single tree variables (Björklund, 1999; Björklund & Walfridsson, 1993; Metslaid *et al.*, 2018; Uusvaara, 1974). Based on our results, it may be maintained that in trees of the same age latewood percentage in both heartwood and sapwood may depend on the growth site.

The transition from sapwood to heartwood is a steady occurrence, and heartwood boundary does not necessarily go

past an annual ring (Yang & Hazenberg, 1991). The difference between heartwood and sapwood is primarily chemical and on the border of heartwood replacing of some elements occurs, which may influence bonds and the growth stress division between heartwood cells and thus affect wood properties (Bowyer *et al.*, 2003; Werberg, 1930). In Scots pine trees growing in poorer conditions the share of heartwood was highly variable. Trees growing on more fertile sites, however, contained higher proportions of heartwood. In same-age stands of higher heartwood proportions on more fertile soils coincide with previous results from a number of authors (Bektas *et al.*, 2003; Havimo *et al.*, 2009). Based on our findings, differences at breast height may be as great as threefold. Compared to breast height values, heartwood proportions decreased towards the top.

Climate is a significant factor in heartwood development. Wider heartwood occurs in drier climate types (Climent *et al.*, 2002). The amount of heartwood also depends on the geographical location, age and growth rate (Savva *et al.*, 2008). Therefore, the differences in heartwood proportions between our dry and moist growth sites were something to be expected. Other tree species, too, have fairly significant differences in sapwood to heartwood ratios between growth sites (Bektas *et al.*, 2003). Our results and the references given herein do not confirm the view of Kärenlampi & Riekkinen (2002) that heartwood content is independent of tree growth rate and tree size. Rather, one may agree that site conditions have little effect on heartwood formation on more fertile sites (Björklund, 1999; Mörling & Valinger, 1999). According to some studies, heartwood formation in Scots pine begins from 15 years of cambial age on (Björklund, 1999; Fries & Ericsson, 1998; Mörling & Valinger, 1999). This is a considerably earlier age than those found by other authors (Lappi-Seppälä, 1952; Werberg, 1930). The diversity in the results may be due to site moisture and site fertility if we compare trees of the same age in our research.

In addition to latewood percentage, density is another key characteristic of tree properties (Wilhelmsson *et al.*, 2002). In pine, basic density decreases from stub to top (Lagana *et al.*, 2008) and from pith to bark (Havimo *et al.*, 2009). Significant is the correlation between basic density and site quality or cambial age (Oliva *et al.*, 2006), as well as the dependence on the geographical location, age and growth rate (Konofalska *et al.*, 2021; Mattsson, 2002). Results have been obtained to the effect that basic density is independent of growth rate or even negatively correlated with annual ring width, and is only dependent on cambial age (Kärenlampi & Riekkinen, 2004). This is at variance with the increase in wood density in Finland from north to south (Hakkila, 1979; Kärkkäinen, 1985), which indirectly points to the impact of growth conditions, which are poorer for pine towards the north. However, wood of equal density values contains very different proportions of latewood in different geographical regions (Zvirbul *et al.*, 1976).

It is well known that silvicultural methods influence wood formation. Drainage of peat bogs leads to a number of changes in wood properties. Wood formed before drainage has greater density than wood formed after drainage (Varhimo *et al.*, 2003). After forest drainage, wood basic density and annual ring latewood content decrease and the variability in all wood properties is higher than on mineral soils (Rikala, 2003). Raised bog pine forests drainage results in an increment that is relatively small under Estonian circumstances. Accordingly, the effect on wood density is small, and the present study did not ascertain any decrease in it.

One of the factors influencing density is cell wall thickness. Cell wall thickness is directly correlated with the length of the growth period (Antonova & Stasova, 1993) and with factors of influence during the time of wood cell and tissue formation

(Wodzicki, 2001).

The difference in density during the period of heartwood formation cannot be caused by wood macroscopic structure, since cell wall thickness remains the same in the process of heartwood formation (Crivellaro & Ruffinatto, 2021). However, the process sees the accumulation in heartwood of various substances, the quantities of which are influenced by growth conditions. Among these, consideration is given primarily to resins, dyes, tannins and other substances (Bowyer *et al.*, 2003). The process of heartwood formation is accompanied by the accumulation of Ca into heartwood. As there is relatively little Ca in raised bog soil, it is certain to affect the accumulation of Ca in heartwood.

Wood mechanical properties

Our results harmonise with those of Aleinikovas and Grigaliūnas (2006), according to which wood bending and compression strengths were the highest on poor sites with normal moisture, and significantly different from corresponding values for fertile sites with normal moisture.

Improvement in growth conditions after drainage may reduce basic density and latewood percentage. However, as the period of intensive growth in a raised bog is relatively short compared to tree age, then, according to our previous studies, reduced density ultimately has relatively little effect on wood mechanical properties (Pikk *et al.*, 2004). Changes in wood properties after forest drainage on mineral soils and swamps are similar in Finland; however, the variability of the results from peatlands is higher and the wood from there is clearly poorer in quality (Rikala, 2003). The same conclusion can be drawn from data collected in the present study.

The findings obtained cast doubt on the hypothesis that the wood of stunted swamp pines has the greatest strength. Do the findings coincide with those showing that wood obtained from fresh forests and from fresh mixed forests containing deciduous trees is the best (Spława-Neyman, 1994)?

Our test results had large variation and showed statistically weaker relations of density with wood hardness than bending strength and compression. We found that although the most important factor affecting mechanical properties was wood density, there were other important factors (annual ring width, proportion of heartwood, proportion of latewood) influencing strength properties.

From the perspective of practical wood utilisation, a reduction in along-the-grain mechanical properties is of importance. Percentage wise, the reduction in strength properties from breast height ($h_{1.3}$) up to ¾ of tree height ($h_{¾}$) per one metre was the highest for sapwood bending strength in natural raised bog pines (5.0%), followed by drained raised bog pines (4.0%), heath pines (3.2%) and *Myrtillus* site type pines (1.9%). The reduction in sapwood compression strength ranged from 3.2% to 1.5% and in hardness from 0.8% to 2.0%. At this point, it should be noted that the reduction in strength properties from breast height to half-tree height is smaller than toward the top from there on, to ¾ of tree height. The poorer the tree nutrition conditions, the greater the variability in mechanical properties in the same tree stem.

Conclusions

This study provided some new information on the quality of wood from different site conditions and coincides with earlier studies and findings concerning differences in pine wood properties between neighbouring regions.

Wood density and strength properties are greater in wood growing in heath pine stands, exceeding the corresponding values for wood from sites optimal for pine (*Myrtillus* site type). Wood from peatlands has lower mechanical properties than

from stands grown on mineral soils. Hardness, bending strength and compression strength in the same tree stem cross-section are greater in sapwood than in heartwood. The reduction in strength properties towards the top is greater in wood formed under poorer nutrient conditions.

The proportion of latewood increases with tree age; however, at the same latewood percentage heartwood density is greater than sapwood density by an average of 1.0–11.2% depending on the site type. At equal oven-dry densities wood obtained from different site types manifests significant differences in bending strength and hardness. The results of the study can be applied in selecting pine stands with good quality roundwood.

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