

Tracheid Cross-sectional Dimensions in Scots Pine (*Pinus sylvestris*) – Distributions and Comparison with Norway Spruce (*Picea abies*)

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Cell wall thickness and tracheid radial and tangential diameter are important characteristics in papermaking. These fibre cross-sectional dimensions affect paper properties such as light scattering, and tear and tensile indexes. In the authors' previous article, the mean values and distributions of tracheid cross-sectional dimensions were obtained for Norway spruce (*Picea abies*). This article characterises the cross-sectional tracheid properties of Scots pine (*Pinus sylvestris*) using exactly the same methodology as in the previous study on Norway spruce, which enables the comparison between the tree species. The distributions for Scots pine cell wall thickness and tracheid radial diameter were similar: a narrow peak due to earlywood tracheids, and a wide peak due to latewood tracheids. The tangential diameter distributions for Scots pine were very similar in both earlywood and latewood, having one wide peak. Also, the distributions in whole stem, top pulpwood and sawmill chip assortments were quite similar. The differences between Scots pine and Norway spruce tracheid cross-sectional dimensions were fairly marginal. This is at least the case when comparing large tracheid populations, in which differences tend to even out. The situation may be different on a more detailed level of observation, for example, when individual annual rings in the different tree species are compared.

Keywords cell wall thickness, radial diameter, tangential diameter, Scots pine, Norway spruce, distribution

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1 Introduction

Scots pine (*Pinus sylvestris* L.) is a common raw material for chemical pulps, and furthermore, a raw material for various paper grades. Paper properties including strength and light scattering depend, among other things, on cross-sectional tracheid properties; i.e. cell wall thickness, and radial and tangential tracheid diameter. For example, in kraft pulp handsheets, the tear and tensile indexes depend mainly on cell wall thickness (Paavilainen 1993, Braaten and Molteberg 2004). An increase in cell wall thickness increases the tear index, but decreases the tensile index. However, it should be noted that these observations may be confounded by the correlation of cell wall thickness with fibre length, which is also an important factor in the tear and tensile indexes. The light scattering coefficient is also known to depend on the cell wall thickness; an increase in the cell wall thickness reduces light scattering (Scallan and Borch 1973, Middleton and Scallan 1992, Braaten and Molteberg 2004).

Cross-sectional tracheid dimensions vary greatly. This was recently characterised on Norway spruce (*Picea abies* L. Karst.) (Havimo et al. 2008). As Scots pine is another important tree species for the Nordic forest industry, this study focuses on its cross-sectional tracheid properties. Another focus is the comparison of tracheid dimensions of Scots pine and Norway spruce, because chips of these species are often mixed in the chemical pulping process. For maintaining comparability with the previous study, sampling, measurements and data analysis were repeated exactly the same way as was done with Norway spruce (Havimo et al. 2008). The study stand is also the same; thus, growth conditions like site quality or forestry practices do not cause differences between species.

The analysis of cross-sectional tracheid dimensions of Norway spruce showed that most of the variation in the cell wall thickness and tracheid radial diameter is due to the differences between earlywood and latewood tracheids (Havimo et al. 2008). In earlywood, the cell walls are narrow and radial diameters wide, whereas in latewood the cell walls are thicker and radial diameter narrow. In contrast, the tracheid tangential diameters of earlywood and latewood are similar.

The variation in wood properties influences the properties of pulp and paper, which has stimulated an interest in controlling this variation. Two control methods have been proposed: sorting of logs before pulping (e.g. Wilhelmsson 2001), or separation of fibres after pulping (e.g. Paavilainen 1992). For controlling the cross-sectional tracheid dimensions of spruce, the separation of fibres after pulping was found to be a more efficient method than sorting of logs (Havimo et al. 2008).

2 Material and Methods

2.1 Sample Collection and Measurements

The wood samples were taken from the same mixed pine-spruce stand as in the previous study (Havimo et al. 2008). In order to maintain the comparability between the tree species, the sampling, sample preparation and measurements were also similar to the previous study. The study stand located in Southern Finland near Hyytiälä Forestry Station (University of Helsinki). The stand was even-aged and the site was a *Vaccinium myrtillus* type in Cajander's classification system (Cajander 1926). The stand was sparse, having a stand density of 310 stems ha⁻¹.

All the trees in a sample plot of 10 000 m² were measured for obtaining diameter at breast height (dbh) distribution. The distribution was divided into five classes of equal intervals, and one sample tree was randomly selected from each class. The dbh of the smallest tree was 39 cm, and that of the largest tree 59 cm. The average age of the sample trees was 140 years.

Sample discs from each tree were sawn from nine height levels, at regular intervals representing relative heights of the tree between 0 to 88%. One additional sample disc was taken from the breast height (1.3 m). The total number of sample discs was 50. The sample discs were stored in a freezer before further processing. The samples to be measured were prepared by sawing a bar from the pith to the bark of each disk, and the bars were then air dried under weight to prevent cracking.

Tracheid cross-sectional dimensions were measured with the SilviScan device at STFI-Packfors (Stockholm, Sweden). Evans (1994) describes the

device in detail. The device measured tracheid radial and tangential diameters, and an average of radial and tangential cell wall thicknesses. The bars were measured at 50 μm intervals, so that a very accurate picture of tracheid cross-sectional dimensions from the pith to the bark could be constructed.

2.2 Data Analysis

The analysis follows the previous study (see Havimo et al. 2008), and is only briefly summarised here. The measurement data was processed with a program written with Mathematica (Wolfram Research Inc., IL, USA). The analysis began with a construction of virtual trees from the measurement data. The virtual trees were then divided into assortments, and mass distributions were calculated.

The virtual trees were constructed by dividing the measurement points, first into annual rings, and then further to earlywood and latewood. The earlywood/latewood was divided into individual tracheids; the dimensions of tracheids were obtained from the measurement data with regression analysis. Regression curves for all three cross-sectional dimensions were obtained by fitting a linear equation to each earlywood/latewood ring. The dimensions of tracheids in different parts of annual rings were calculated with these linear equations.

At this stage, a line of tracheids from the pith to the bark was ready. A virtual disc was then constructed from the line, by extending each tracheid on the line to a circle of tracheids. The radius of the circle was the tracheid's distance from the pith. The disc was then extended to a bolt, whose length was the distance between two successive measurement heights in the trunk. Using this method, the mass and properties of tracheids in each sample tree were determined. To calculate the mass of tracheids in the whole stand, the number of tracheids was multiplied by the number of trees in each size class.

The dividing of virtual trunks into sawmill chip and top pulpwood assortments was done by assuming pulpwood to have top diameter of 6 cm, and saw logs to have top diameter of 15 cm. The saw logs had lengths from 3.3 m to 6 m in 0.3 m

modules. The saw logs were posted with a simple method, in which the largest possible square was fitted into the top end of the log. The part of the trunk which was outside of the square was considered as sawmill chips.

The distributions were formed from the assortments in the last stage of the analysis. Five characteristics described the tracheids: mass, cross-sectional dimensions, number in the stand, position in the trunk, and whether the tracheid was formed in earlywood or latewood. The position in the trunk determined whether the tracheid belonged to top pulpwood or sawmill chips. For presenting the distributions, the tracheids were divided into 50 classes. To obtain the mass proportions, the mass of tracheids in a class was divided by the total mass of all classes in the assortment. The differences between earlywood and latewood were illustrated by expressing their share of the total mass, i.e., their combined shares were normalised to unity.

3 Results

The differences in fibre property distributions between earlywood and latewood are shown in Figs. 1–3. The distributions were calculated for the whole tree assortment, i.e. for all the trees within the stand. Both cell wall thickness (Fig. 1) and tracheid radial diameter (Fig. 2) distributions had two peaks, one mainly formed by earlywood tracheids, and the other formed by latewood tracheids. The earlywood peaks were narrow in both cases, which means that in the earlywood both the cell wall thickness and the tracheid radial diameter have small internal variations. In contrast, the latewood peaks were wide and flat, indicating that the internal variation in cell wall thickness and radial diameter within latewood is large.

The shape of the tracheid tangential diameter distribution differed from the two other dimensions, because there was no major difference between earlywood and latewood (Fig. 3). Both of the distributions were normally distributed, with similar variation and only a slight difference in the mean value (30.3 μm for earlywood and 29.4 μm for latewood).

The fibre property distributions of different

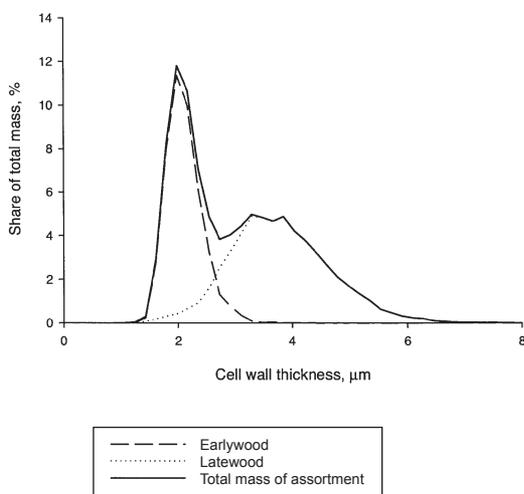


Fig. 1. Scots pine cell wall thickness in the whole stem assortment. The assortment includes all tracheids in the stand.

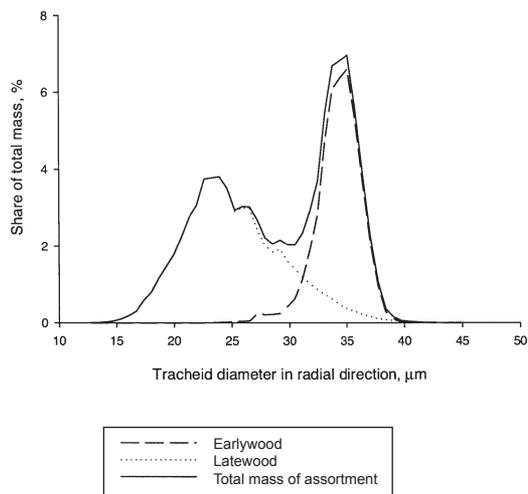


Fig. 2. Scots pine tracheid radial diameter in the whole stem assortment. The assortment includes all tracheids in the stand.

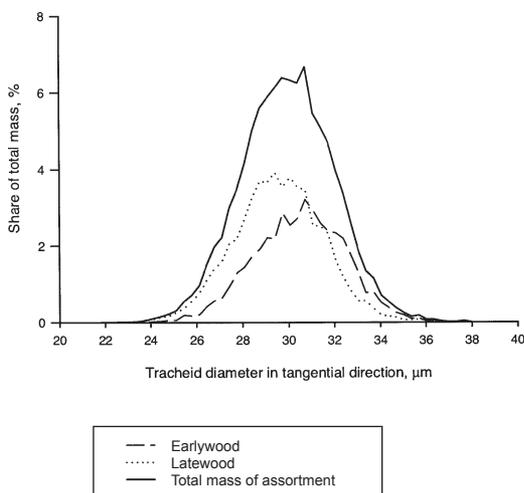


Fig. 3. Scots pine tracheid tangential diameter in the whole stem assortment. The assortment includes all tracheids in the stand.

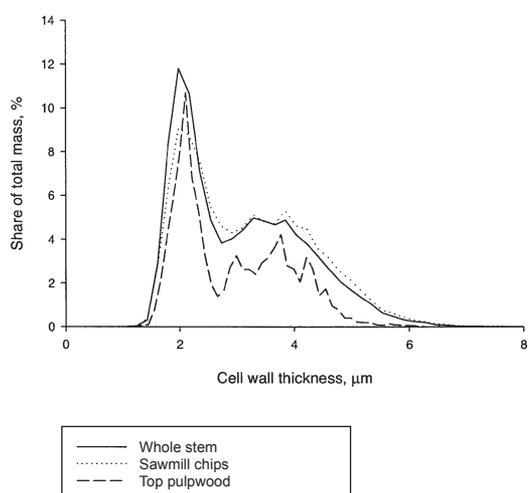


Fig. 4. Scots pine cell wall thickness in all assortments.

assortments are compared in Figs. 4–6. Cell wall thickness distributions were very similar between the whole stem and the sawmill chip assortments (Fig. 4). The top pulpwood assortment was somewhat different by having a narrower earlywood

peak, and a flatter latewood peak. A slight difference in tracheid radial diameter was observed between the assortments (Fig. 5). In the top pulpwood assortment, the earlywood peak was clearly centred around a lower average than in the other

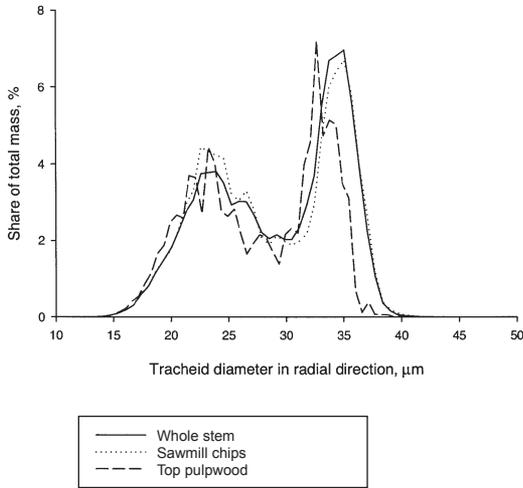


Fig. 5. Scots pine tracheid radial diameter in all assortments.

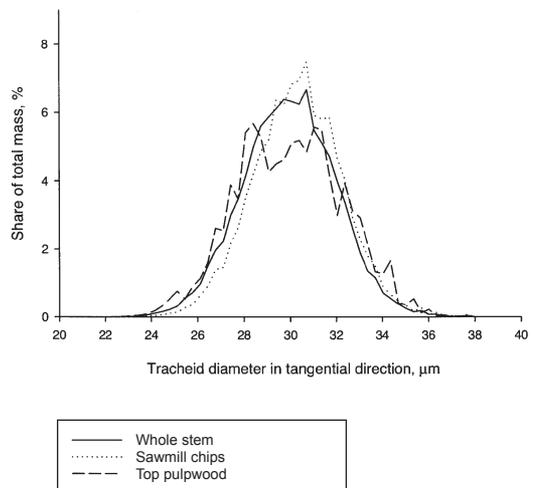


Fig. 6. Scots pine tracheid tangential diameter in all assortments.

Table 1. Mass weighted average values and standard deviations for cell wall thickness, and radial and tangential diameters in Scots pine.

	Whole stem		Top pulpwood		Sawmill chips	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Cell wall thickness, µm						
Earlywood	2.0	0.31	2.0	0.25	2.1	0.35
Latewood	3.7	0.89	3.5	0.76	3.8	0.91
All tracheids	3.0	0.69	2.9	0.60	3.1	0.75
Radial tracheid width, µm						
Earlywood	33.9	2.0	32.6	2.0	34.3	1.7
Latewood	24.9	4.3	23.7	4.0	24.9	4.3
All tracheids	28.9	3.5	27.5	3.6	28.6	3.5
Tangential tracheid width, µm						
Earlywood	30.3	2.0	30.7	2.1	30.8	1.9
Latewood	29.4	2.0	29.2	2.2	29.8	1.8
All tracheids	29.8	2.0	29.8	2.2	30.2	1.9

two assortments. In spite of this, the difference in average diameters between the assortments was quite small (average diameter was 34.3 µm for sawmill chips and 32.6 µm for top pulpwood).

The tangential tracheid diameter distributions were also very similar in the whole stem and sawmill chip assortments, but the top pulpwood

assortment again differed by having a flatter distribution (Fig. 6).

The average values for each dimension and assortment are presented in Table 1. The averages strengthen the view obtained from the distributions: there is no major difference in cross-sectional tracheid dimensions between assortments.

For example, the earlywood cell wall thickness varies only 0.1 μm between the assortments.

4 Discussion

In all assortments earlywood and latewood differed from each other considerably in cell wall thickness and tracheid radial diameter (Figs. 1 and 2). The difference caused the distributions to have two peaks, one narrow and high for tracheids that were mainly earlywood, and another wide and flat, consisting latewood tracheids. The cell wall thickness distribution was similar to the measurements of Reme and Helle (2002). The tracheid tangential diameter was quite similar between earlywood and latewood (Fig. 3).

The latewood and earlywood distributions in Scots pine were very similar to the previously published Norway spruce distributions (Havimo et al. 2008). The main difference is in average dimensions: spruce has thicker cell walls, and wider tangential diameters. On the other hand, earlywood tracheids are wider in radial direction in Scots pine than in Norway spruce. However, differences in cell wall thicknesses are ca. 0.1 μm , and in radial and tangential diameters ca. 1 μm . Previous measurements support this observation: in the study of Ollinmaa (1956) the largest difference between pine and spruce was in the tangential diameter (3 μm), whereas the difference in radial direction was only 0.5 μm and in cell wall thicknesses 0.15–0.23 μm .

Differences in cross-sectional dimensions between the species are fairly small. This is the case when the species are compared at the stand level: distributions in both species are similar, and the average cross-sectional dimensions are near each other. The cell wall thickness and radial diameter distributions are bimodal both in Norway spruce and Scots pine (see Havimo et al. 2008). Also, the tangential diameter has nearly bell shaped distribution in both species. However, pronounced differences can be found, if the level of comparison is more detailed. For example, if annual rings at a given height are compared, pine and spruce may show great differences, but in large populations of tracheids, i.e. on the stand level, the differences even out. For

pulp- and papermaking, stand level distributions and average values are more appropriate than those of annual ring level, because of the large wood volumes used in the industrial processes.

This study suggests that Norway spruce and Scots pine cross-sectional dimensions are near to each other, when the trees have grown in the same stand. Growth rate affects the cross-sectional dimensions (Sirviö 2000, Sirviö 2001, Lundgren 2004), which may result differences between stands. However, thinning and fertilisation experiments with spruce have shown that only a slight decrease in cell wall thickness was gained after modest growth rate enhancement (Jaakkola et al. 2005, Jaakkola et al. 2007). Therefore, growth conditions are probably also less important from a practical point of view.

The difference between latewood and earlywood resulted in large variation within the assortments, but the variation between the whole tree, sawmill chips and top pulpwood assortments were only moderate (Figs. 4–6). All cross-sectional dimensions were very similar in the whole tree and sawmill chip assortments. The top pulpwood assortment differed from the others mainly by having a narrower radial diameter (Fig. 5), and a flatter tangential diameter distribution (Fig. 6). It is probable that these differences between assortments are mainly caused by the larger proportion of juvenile wood in the top pulpwood assortment.

The large within assortment variation, as well as small between assortment variation, was also found in Norway spruce (Havimo et al. 2008). We can make the same conclusion as in the case of spruce: sorting of logs into different assortments has only a moderate effect on the cross-sectional dimensions of pulp fibres. Fractionation of tracheids after pulping into earlywood and latewood classes appears to be much more efficient method. This is because the largest variation in cross-sectional properties is between earlywood and latewood, and this variation can be efficiently controlled only by fractionation of individual fibres. Paavilainen (1992) has studied fractionation on a laboratory scale, and concluded that with multistage fractionation it is possible to produce pulps with properties that are notably different compared to the original pulp. However, the efficiency of the fractionation is at the

moment somewhat theoretical, because there are no industrial scale fractionators, at least to the authors' knowledge. Also, final paper properties may in some cases be effectively altered with the sorting of logs (Braaten 1997).

5 Conclusions

The previously made conclusions (Havimo et al. 2008) about the structure and methods for controlling the variation of cross-sectional dimensions of spruce tracheids are also applicable to pine tracheids.

The distributions of cell wall thickness and radial tracheid diameter have a large internal variation due to earlywood and latewood. The variation is small within the earlywood class, whereas in the latewood class it is relatively large. Both distributions approximate normal distributions. Tangential tracheid diameter distributions are very similar in earlywood and latewood: both are normal, and the average values are nearly alike. There are not many differences between pulpwood and sawmill chips, since in both assortments average values and distributions are almost identical. The results suggest that separation of fibres after pulping is a far more efficient method for controlling cross-sectional fibre properties than sorting of logs before pulping. On the other hand, there seem to be no mill scale fractionators at the moment, so the possibility to efficiently fractionate fibres is somewhat theoretical.

It was also found that the average cross-sectional dimensions of spruce and pine tracheids are very similar. This is at least the case when large tracheid populations are compared, but if the level of comparison is more detailed, differences can be found.

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