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Fiber length characteristics of Norway spruce (*Picea abies*) trees with fast height growth

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Abstract: Pulp fiber lengths are important in the mechanical behavior of paper and paperboard materials. The length affects the total number of bond sites in fiber networks and thus indirectly the paper strengths. In a case study at Mölnbacka Sweden, fiber lengths of wood samples from 38-year-old trees of Norway spruce (*Picea abies*) with fast height growth were investigated. The fiber length of the samples was compared with literature values, and some reference example material. The hypothesis was that the sampled trees with fast height growth may have longer fibers, and thus provide longer pulp fibers, compared to lengths previously reported. The work highlights and critically examines the impact of different preparations, measurements, and analysis methods of fiber lengths. The results from this study show that the 21-year-old sampled wood had longer fibers than expected when compared to previous reports for Norway spruce wood grown in Sweden. The samples also showed to have skewed distributions with proportionally more long fibers than expected, also shown by higher mode values to describe central tendencies. About 75 % of the manually measured Mölnbacka fibers were longer than 3.1 mm with a mode value of 3.77 mm.

Keywords: fiber length; paper and paperboard strength; Norway spruce; *Picea abies*; softwood; fast height growth

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1 Introduction

Conifers, often called softwoods, consist of elongated tracheid fibers aligned mainly along the tree's length direction, interconnected for fluid transportation by openings known as pits. Tracheids are the major building blocks in softwood trees and can, after a variety of different processing, be used to produce materials such as paper and board, plastic-like materials, be spun into textile fibers, and molded into various shapes for packaging applications. The tracheids are also often referred to as wood fibers, when liberated from the wood by for example pulping, also including other cells such as for example parenchyma cells, and smaller fragments of tracheids, especially in pulp and paper industries and research. For many applications these wood fibers are an excellent replacement for fossil-based materials as they are renewable, recyclable, and biodegradable. The fiber dimensions are important to paper and board product properties (Hubbe 2014; Larsson et al. 2018; Lindström et al. 2005), especially the strength properties of the materials, where the ratio between length and width increase the possibilities for higher number of fiber–fiber bond sites, and long slender fibers thus are preferred for high-strength performance (Lindström et al. 2005). Another factor influencing the bonding capacity is the fiber swelling and flexibility, where both chemical and mechanical treatments as well as other fiber parameters such as fiber wall thickness, fiber width and fiber collapsibility are crucial for the formation of fiber–fiber bonds (Hubbe et al. 2024).

The distributions and volumes of conifer fiber sizes in the wood and thus the raw material mixes are of utmost importance for the kraft pulp industry. Several regions in Sweden have large kraft pulp and paper industry clusters, utilizing mainly Norway spruce (*Picea abies*) in their production. Of the total and average annual gross growth of almost 120 Mm^3 in Sweden during the last decade, over 50 Mm^3 were Norway spruce wood according to the Swedish forest inventory (Swedish NFI- National Forest Inventory 2024). In the province of Värmland, the annual average growth volume was almost 4.6 Mm^3 of Norway spruce, which corresponds to almost 55 % of the total gross volume growth

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in the province (Swedish NFI- National Forest Inventory 2024). The growth of the forest is the basis for the long-term potential harvesting wood volumes, and thus industrial wood. It is therefore relevant to focus some research on the development of the naturally given fiber properties of the resource, and the distributions and proportions within the resources. When discussing fiber lengths, it is crucial to differentiate between the relative intact softwood tracheids found in wood and the liberated fibers whose average length have been shortened by industrial chipping and pulping processes. Chemical pulping operations use wood pieces known as chips (Gard Timmerfors et al. 2020). In chemical processes, this is essential to ensure uniform distribution of chemicals and heat throughout the wood. Since wood is cut across the fibers during chipping, it reduces the average fiber length. The shorter the chips, the higher reduction in fiber length. For this reason, the nominal chip length in a chipper is typically not set below 18–20 mm, with a common range being 20–30 mm (Brännvall 2009). The same effect of cut fibers occurs with increment borers which in principle provide one "chip", however with a uniform dimension and in one preset direction. With this information it is possible to model the total length population including any missing fragments and pieces of original tracheids, at least if the true distributions of fiber lengths are known (Svensson et al. 2007). Few studies have been found by the authors concerning the effects on fiber lengths by the pulping itself, but Scallan and Green (1975) reported a reduction in fiber length of 2–6 % originating from the pulping, although for other softwood wood species than Norway spruce. Eckes-Shephard et al. (2022), Lachenbruch et al. (2011) and Larson (1994) has reviewed numerous wood formation models that has been published over the past 150 years. A lot of research refer to the transverse cell division and cell wall developments including annual growth patterns with the transition from thin walled early wood (spring) to thicker late wood fibers (summer). Brändström (2001) also reviewed some of the most established models for wood fibers including reported tracheid lengths, and explored 3D models of fiber walls (Brändström 2002).

The average length of tracheids in wood and liberated pulped fibers has been reported by many sources, and with a rather wide span. Average lengths of <3 mm were reported from Norway spruce grown in Sweden (Brännvall 2009; Henriksson et al. 2009; Larsson et al. 2018; Lundqvist et al. 2005). Others, however, have reported longer fibers, primarily from larger and older European spruce wood with e.g. averages ranging between 2 mm and 4.2 mm (Fabisiak et al. 2020). In a review by Buksnowitz et al. (2010) the average lengths ranged between 2 mm and 6 mm within stems for Norway spruce, influenced by trends associated with tree age, height, cambial age, and radial distance from the pith. They showed that fiber lengths in two well-documented samples of larger and older Norway spruce in central Europe increase notably with diameter, cambial age, and tree age over 30 years. In some cases, the maximum average length occurs after 50 years, before starting to show a slight decline (Buksnowitz et al. 2010).

Softwoods in the Pacific Northwest have been reported to have formed the longest fibers (Panshin and de Zeeuw 1980). Among those softwood species reported to have the longest fibers are species, that are also growing to the tallest trees, such as the Redwoods (*Sequoia*), Douglas fir (*Pseudotsuga*) and Sitka spruce (*Picea sitchenis*). However, reports and comparisons within and between softwood species are often somewhat confusing, as stated by Lachenbruch et al. (2011) in a large review of wood forming theories. The reported values for the same species often differ due to both place of growth (site), measurement methods, and sampling methods. Research into tracheid fiber lengths often focus on finding a transition from juvenile to mature wood (Kucera 1994). An increase of up to four times longer fibers between the most juvenile inner wood to the outer wood can be found according to Lachenbruch et al. (2011). Another specific aim of research into fiber length has been to get early indicators to enable genetic improvements. Hannrup et al. (2004) stated that "tracheid length showed no, or positive, genetic correlations with volume" and had a comparable low heritability. The study however mainly sampled and studied cambial young wood, and was summarized in the review by Buksnowitz et al. (2010) as a "juvenile wood" material with shorter average tracheids. Some other studies have analyzed the effects of fertilization and thinnings, and reported shorter mean fiber lengths in Norway spruce as an effect of an increased growth rate (Mäkinen et al. 2002, 2015).

Woody stems, branches, and roots overall display large progressive changes in both structure and function from the pith outwards. The differences in wood properties within the stems have led to much research on wood properties in and development of the cambial activity as the trees grow. Lachenbruch et al. (2011) however stated that the knowledge of drivers, and the universality of the typical radial pattern, is rather limited despite 150 years of research. They explain and summarize a number of existing theories to explain the typically radial patterns within the stems, but conclude that there seem to be two rather opposing hypotheses to explain the radial changes in wood properties such as the length of fibers. Some hypothesis uses the increasing cambial age (measured from the pith) as the main explanatory variable, while others use tree size as the main explanatory factor. Conceptual models of wood formation can also suggest that trees with large crowns produce wood with reduced

mechanical properties due to enhanced auxin production, but few studies have explicitly examined the relationship between crown dimensions and wood properties or come to significant differences in more even grown forests (Kuprevicius et al. 2013). The difference in tracheid length between the bulk of wood fibers formed early in the year (spring wood) and later (summer) has been reported to be rather limited regardless of the position in the stems. Buksnowitz et al. (2010) and Lachenbruch et al. (2011). The tree size hypothesis is sometimes exemplified by the height and growth rate factors of the world's tallest trees, especially fiber dimensions such as length (Williams et al. 2019).

There are also known challenges to correctly measure and describe the natural distributions of pulp fiber dimensions. A complication when trying to investigate the fiber dimensions is also that fiber lengths are measured differently in various studies and sometimes is done on other wood samples, than those used for measuring e.g., density, cell wall thickness and lumen size (Donaldson 2008). The fiber length is commonly measured on separated fibers either manually utilizing a light optical microscopy, or in automated image processing equipment on fiber flows. Challenges in comparing values from different methods and equipment have been described by Ferritsius (2021) and Hirn and Bauer (2006).

A portion of the Norway spruce resource in Värmland has since long been recognized as originating from some of Sweden's naturally most fertile Norway spruce sites and thus tall trees, not seldom located near the early pulp and paper industries of the province (Tamm 1921). Some of the sites studied by Tamm, with young Norway spruce stands and a fast height growth (FHG), were on the hillsides of hyperite bedrock near Mölnbacka in Värmland, located about 30 km north of Karlstad. Around 100 years later it happened that some of the tallest standing trees of Sweden were found and measured at the same hill. The majority of the forest stands around Mölnbacka have been owned and managed by forest industry companies since before year 1,650.

The genetic origin of the stands, or other commercially planted forests in Scandinavia is not very well known. It is at Mölnbacka expected to be of a mixed seed origin from Sweden and central or eastern Europe. Plants are since long provided from the nearby nurseries, run by the forest owning company. A foreign seed origin is also likely for the over 100-year-old spruce trees, planted or sown downhill from our stand. The possible foreign seed origin is indicated by the mixed in larch trees not native in Sweden, Myking et al. (2016). Similar FHG Norway spruce trees, stands and fertile sites can be found also further north in the region, where the genetic origin would be rather different, and possibly more locally developed. Chen et al. (2019). To investigate some wood properties in light of the different wood-forming hypotheses including tall and large trees, a limited case study at Mölnbacka was set up, where some 38-year-old trees with fast height growth (FHG) were available for wood sampling after felling. The aims of the study were twofold: (i) to measure fiber lengths in these FHG samples, comparing the results to reference example materials and literature values, with the hypothesis that these FHG trees might form longer tracheids, thus giving longer fibers than previously reported, and (ii) to highlight and critically examine the impact of different preparations, measurements, and analysis methods including describing fiber length distributions.

2 Materials, methods, and basic wood properties

2.1 Tree selection

There are a number of challenges to handle in order to investigate the length of fibers in a variable and dynamic wood resource. For this work, the focus was on wood from FHG trees. A specific location in Sweden was selected, known for having some of the tallest trees in the country, and related to a diabas bedrock often called "hyperite". In Sweden it is known to often produce very fertile forest soil conditions (Tamm 1921). A specific and commercially established stand of trees was selected, because the trees were scheduled to be harvested by the landowner the same year. The location is below the highest historic coast line, and the soil a lightly washed morain and a locally rather fast weathering process provides the current soil structure.

The Norway spruce trees of the stand were planted in 1985, thus 38 years old at the time of felling according to the forest owners' stand register. The stand had grown exceptionally fast in height for Swedish conditions. For the height increment rate of the sampled trees, they were estimated to reach a height around 39 m at 100 years of age (Hägglund and Lundmark 1977). Such a height increment corresponds to about 15 m^3 per hectare and year, about three times the mean forest site productivity in Sweden (Appiah Mensah et al. 2023; Lundgren 2003; Swedish NFI- National Forest Inventory 2024).

Wood samples for pulping and fiber length measurements could be gathered from eight individual trees that all seemed to have been planted at the same time, four from each side (North and South) of a small utility line (Figure 1). The tree samples are denoted S1-4 and N1-4. The location for

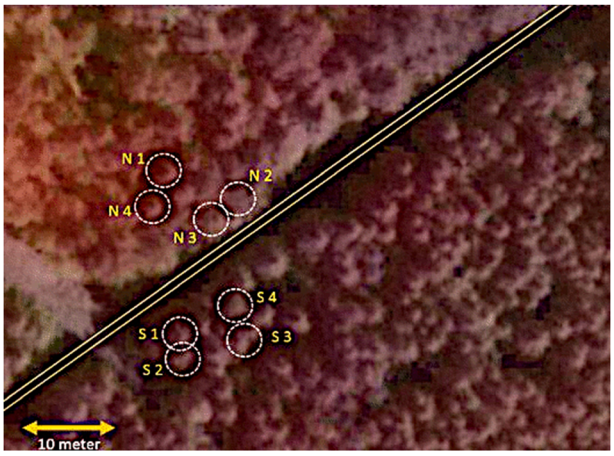

Figure 1: Location of each tree north and south of the utility line. North is up on the map.

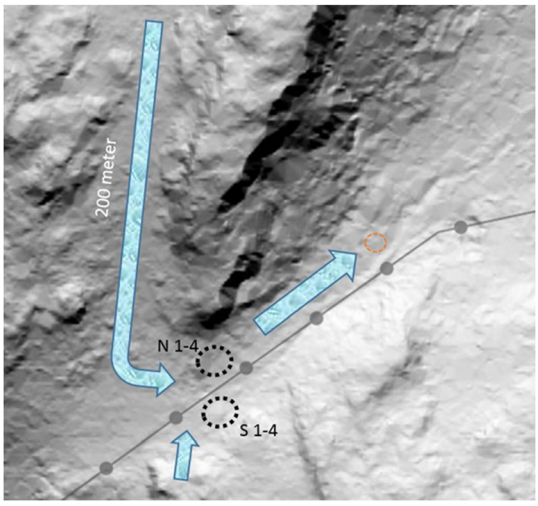

Figure 2: Approximate water flow pattern along the slope of the hyperite bedrock and for the trees on both side of the utility line indicating they have had the same water supply. The location of the tallest known Norway spruce tree to the northeast is marked by a smaller circle. North is up on the map. Approx. GPS: WGS84 decimal (lat, lon) 59.66, 13.55.

sampling trees with fast height growth was chosen based on the fact that the tallest known Norway spruce tree in Sweden grew less than 100 m further down the same hillside. The sampled trees would thus to a large extent utilized the same weathered water (Figure 2) flowing on the hyperite bedrock. The sampled trees stood within 200 m of the ridge. The reason for sampling on both sides of the utility line was mainly to find enough undamaged similar size trees from practical felling and transport reasons, utilizing the same weathered water. There are also some differences between the two sides of the utility line in regards to water flow, light from the south, etc. that could influence the results.

The provenance and genetic material are not known but are expected to be of a normal mixed commercial seed origin as of 1985 at the regional nursery at Sjögränd. No tests for genetic origin on the sampled trees have been done.

The heights of the two groups of trees were between 22 and 26 m (Table 1), as measured after felling. The tallest trees from each group were 26 m. Given the structure of the forest and crown development, the sampled trees could be considered to be dominating or sub-dominating. The branches of sampled trees did not show any obvious visual influence from the utility line caused by e.g. extra light exposure.

The trees were planted with an average 2-m spacing. There were no signs or records of any commercial thinning, and any pre-commercial thinning would also be limited given many existing tall hardwood trees and also small hardwoods (mainly birch) mixed into the stand. The tallest of the sampled trees were observed to be straight based on visual inspection and showed no signs of damaged tops, and thus would be rather near the natural theoretical height maximum (Hägglund and Lundmark 1977). All sampled trees could be regarded as co-dominant since they were not the thickest trees at breast height. Some nearby trees with larger

Table 1: Tree heights and breast height diameter of all eight sample trees.

Tree ID	Height, h (m)	Breast height diameter, d (cm)
S1	24	32
S2	26	35
S3	24	32
S4	22	30
N1	26	31
N2	22	26
N3	22	35
N4	26	32

diameters were left standing. Those trees were positioned closer to the nearby opening of the utility line. The cleaning of the five meters wide utility line opening in the west-to-east direction could have influenced the wind and light exposure of the trees to some extent.

In this study, two other Norway spruce material reference examples were available for comparisons of the cooking and measurements of fiber lengths. One individual reference example spruce sample (Ref ex. tree), 58 years old, was collected at a location farther north in Sweden WGS Decimal (lat, lon) 63.81, 20.23 obtained with previous research work on wood fibers (Sjöstrand et al. 2022). An additional reference example pulp (Ref ex. pulp): an industrially manufactured, commercially available, bleached, unrefined chemical kraft softwood pulp from a mix of spruce

and pine mainly from thinnings, flash dried to a solids content of approximately 95 %.

2.2 Sampling of material and basic wood properties

A 40 cm long chunk of wood was cut from the top end of the butt logs, approximately 4.9 m from the stump, see Figure 3. After debarking manually using a knife, a 70–90 mm thick knot-free slice was cut for the measurement of the mechanical properties. From the remaining material, the wood outside annual ring number 17 was sliced off for the measurement of fiber length. The average cambial age for the wood samples was determined taking into account the cross-section area of each annual ring. The resulting median cambial age for the samples from the eight trees was 21 years.

The idea was that this material would represent more outer/mature wood from a limited range of cambial age, to enable a more stringent comparison with other studies of fiber length, and given the typically strong radial trend associated with cambial age (Buksnowitz et al. 2010). The sampling of the wood position in this type and size of logs resembles what comes as sawmill chips as described and calculated by in e.g. Hyll et al. (2024), even the cambial age is more like wood from commercial thinnings in Sweden (Persson et al. 2024).

Radial trend in annual ring width RW and density $D_{12,12}$ was determined on specimens cut from the defect-free slice from pith to bark. The material was conditioned in a constant climate at a relative humidity of 65 % and a temperature of 20 °C for 2 months before measurement, which means that the reported density is based on weight and volume at approximately 12 % moisture content.

Average area-weighted ring width from pith to bark was RW = 4.8 mm with a similar decreasing radial trend for trees north and south of the utility line, see Figure 4. For the mature wood outside ring #17 for the fiber length measurement, the average ring width was 2.8 mm. As expected, the density increased radially with an area-weighted average of $D_{12,12}$ = 390 kg/m^3. For the mature wood, the average density was $D_{12,12}$ = 450 kg/m^3.

The average growth ring size is larger than the average levels for southern Sweden, especially during the first 15 years (Swedish NFI-National Forest Inventory 2024). Ring widths are normally measured at breast height and not at 4.9 m. The radial trends in ring width and density in the sampled FHG trees are then accentuated with larger than average changes, probably since the stand had not been thinned.

2.3 Fiber separation by kraft cooking

The wood samples for fiber measurements (Figure 3) were dried at 60 °C for 36 h before being hand sorted to remove any knots or indication of reaction wood and then sawn with a band-saw into smaller pieces and cut with a chisel to produce hand-cut chips; with an average width of 23.1 ± 0.5 mm, length of 26.6 ± 0.9 mm, and a thickness of 4.9 ± 0.3 mm for an average volume of 2.9 ± 0.1 cm^3. The Ref ex. tree outer wood sample was chipped at MoRe Research in a pilot chipper

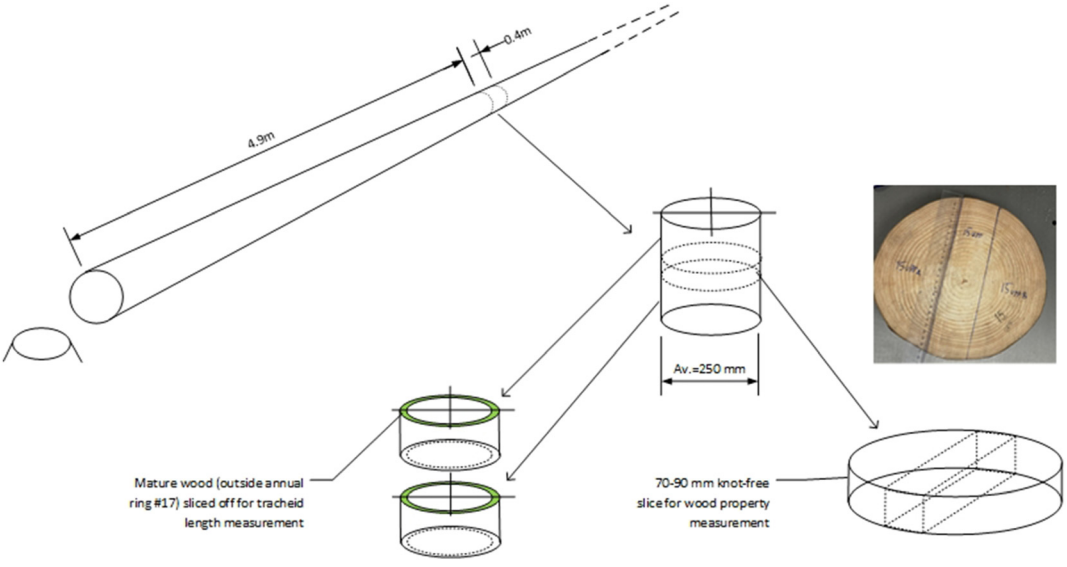

Figure 3: Sampling of material from the top end of butt logs for measurement of fiber length and wood properties.

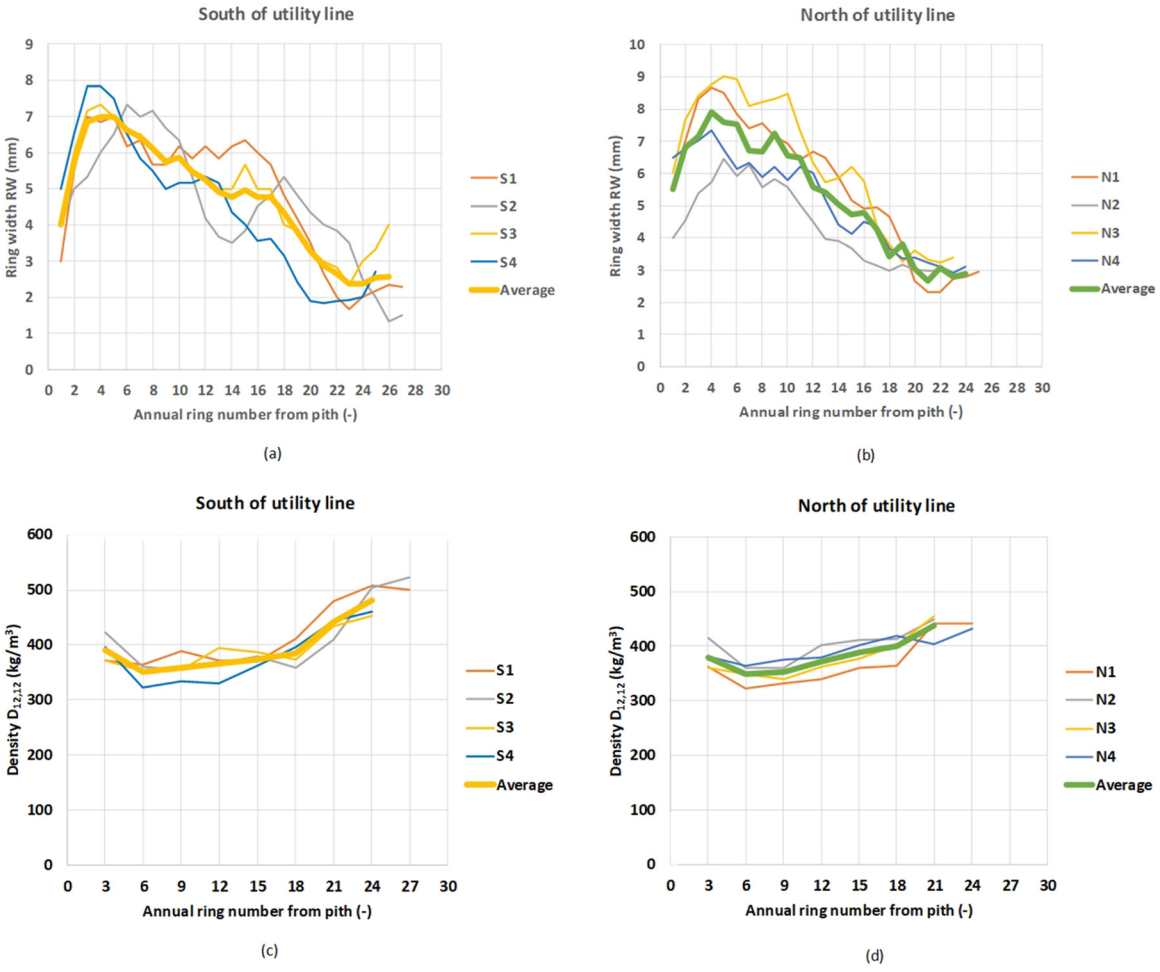

Figure 4: Radial variation in annual ring width RW and density $D_{12,12}$ (weight and volume at 12 % moisture content) for trees, north and south of the utility line, based on samples taken at 4.9 m from the stump.

Table 2: Chip size distribution and density.

	Ref ex. Tree	S1	S2	S3	S4	*N1*	*N2*	*N3*	*N4*
Width (mm)	22.1 ± 2.4	22.9 ± 1.5	23.3 ± 1.3	25.5 ± 1.1	23.2 ± 1.7	21.6 ± 1.4	24.3 ± 2.8	21.3 ± 1.2	22.9 ± 1.0
Length (mm)	22.2 ± 1	21.2 ± 1.1	28.2 ± 1.1	22.2 ± 1.2	30.6 ± 0.7	23.7 ± 3.3	32.7 ± 5.6	25.1 ± 2.1	30.2 ± 0.8
Thickness (mm)	3.9 ± 0.5	5.8 ± 0.75	3.8 ± 0.3	5.6 ± 0.8	5.2 ± 0.4	5.5 ± 1.9	3.8 ± 0.7	3.9 ± 0.4	5.3 ± 0.6
Density (g cm^{-3})	271 ± 14	395 ± 11	341 ± 22	367 ± 14	405 ± 18	376 ± 16	415 ± 31	337 ± 14	400 ± 18

Average values of approximately 20–50 chips are shown with variation shown as 95 % confidence intervals.

(Bruks Mekaniska AB, Sweden). Size distribution and density of all chips are shown in Table 2. The reference example pulp was chipped, cooked, and ECF-bleached industrially. The typical average chip in Sweden size of 15–30 mm in width, 20–30 mm in length and 3–8 mm in thickness, and (Brännvall 2009).

The cooking process was carried out in a steam-heated autoclave digester. Chemical composition during cooking was 20 % effective alkali and 35 % sulfidity at a liquor-to-wood ratio of 4. The initial temperature was set at 100 °C, with a gradual increase of 1 °C per minute until the final cooking temperature was 165 °C. The chips were then cooked for 2 h, resulting in a total H-factor of 1,300. To ensure no systematic errors affecting the fibers during the cooking, tree S2 was cooked three separate times, and tree nr N1 was cooked twice.

Post-cooking, autoclaves were rapidly cooled by submersion in cold water to halt any further reactions. Black

liquor was collected for each sample. Cooked chips were washed with deionized water in a siphon bath for 10 h. Pulp was produced by subjecting washed chips to water jet defibration at 2 bar pressure using an NAF (Nordiska Armaturfabriken) defibrator connected to a Wennberg sieve. Defibrated pulp was dewatered using a centrifuge to 28 % dry content and stored cold.

Pulp was analyzed for Kappa number (ISO 302:2015) and viscosity (ISO 5351).

2.4 Fiber testing

Pulp samples from the FHG samples (S1-4 and N1-4), the reference example tree, and the reference example pulp were characterized using a Valmet Fiber Image Analyzer (Valmet FS5, Valmet AB, Karlstad, Sweden), as well as in a polarized-light optical microscopy (Olympus BX51, Tokyo, Japan). For the fiber lengths, the results from the FS5 were complemented by manually counting and measuring 150 randomly selected fibers from the FHG samples and each reference example, with at least 10 measurements from each FHG tree sample (S1-4 and N1-4). Pulp suspensions diluted to 0.2 % consistency were prepared, drops of the suspensions were placed on glass slides with cover glass and a magnification of 5X was used. For measuring lengths, the software ImageView, version *x*64 (4.11.19367.20210815), was used.

2.5 Statistical methods

The data from FS5 was relative frequencies for fiber length ranges (steps) of 0.2 m, normalized so that the sum of the relative frequencies was equal to 100 for each sample, see Figure 6a This means that the area under a histogram curve is the same for all samples and thus comparable.

Figure 5 illustrates the variations in fiber length between the different cooking processes for the repeated cooks of samples S2 and N1 in order to indicate a seemingly limited effect from sampling and cooking in those two trees.

The fiber lengths for all measurements are shown in Table 4 with and without fines below 0.7 mm. It can be noted that the box plots in Figures 5, 7, and 8 show the three quartiles Q1-Q3 within the box and the maximum and minimum value indicated by whiskers. According to these standard plotting rules, values above Q3 plus 1.5 times the inter-quartile range IQR (Q3-Q1), are considered to be outliers and the whisker for the maximum is instead set at this limit. This limit came into action for the maximum in all box plots in Figures 5, 7, and 8. However, for the minimum the

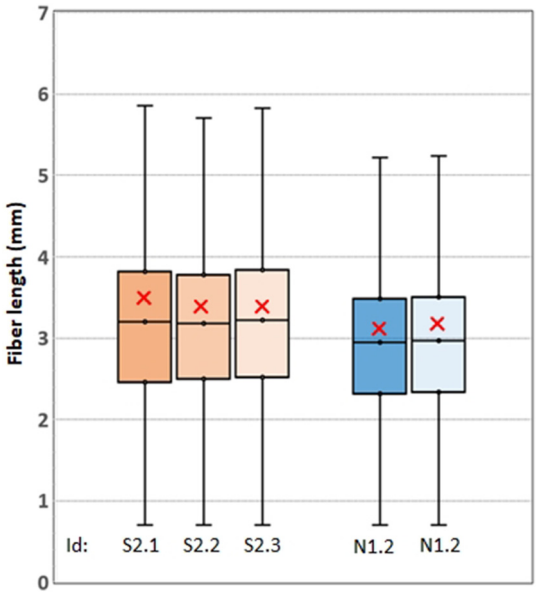

Figure 5: Box plot of fiber lengths comparing parallel cooks from the same trees as measured by FS5. Fines shorter than 0.7 mm are excluded. Mode values are marked with a red cross.

corresponding limit (Q1-1.5·IQR) did not govern. Due to the truncation of fines below 0.7 mm, it became the minimum value at which the whiskers were plotted. The choice of truncation limit also influences the quartiles, but to a lesser degree. The mode, representing the most frequently occurring value in the dataset, is marked with a cross in Figure 5.

The mode is defined as the most frequent data value in a data set and has advantages compared to the average and the median as it is typically not influenced by outliers or truncations. However, a challenge is highly variable data for which random individual peaks can lead to a mode value that do not reflect the central tendency in a proper way.

One way to address this problem is apply a moving average to smooth the histogram data, but the result is sensitive for the choice of averaging width. A second way is to fit a polynomial function to the histogram data and locate the maximum, but this method is sensitive for the choice of data range and local peaks at the end of the chosen range.

The method proposed in this paper is based on the fact that the mode, by definition, is the data value where we have greatest inclination in a cumulative frequency plot. First, a polynomial function (4th order) is fitted to the central range of the cumulative frequency plot (no averaging involved), see Figure 6b. Then, the derivative of this function is calculated using the spreadsheet software Excel (Microsoft). Finally, the mode is found as the local maximum of this polynomial expression of the derivative. The start and stop of the central range of the cumulative frequency plot are

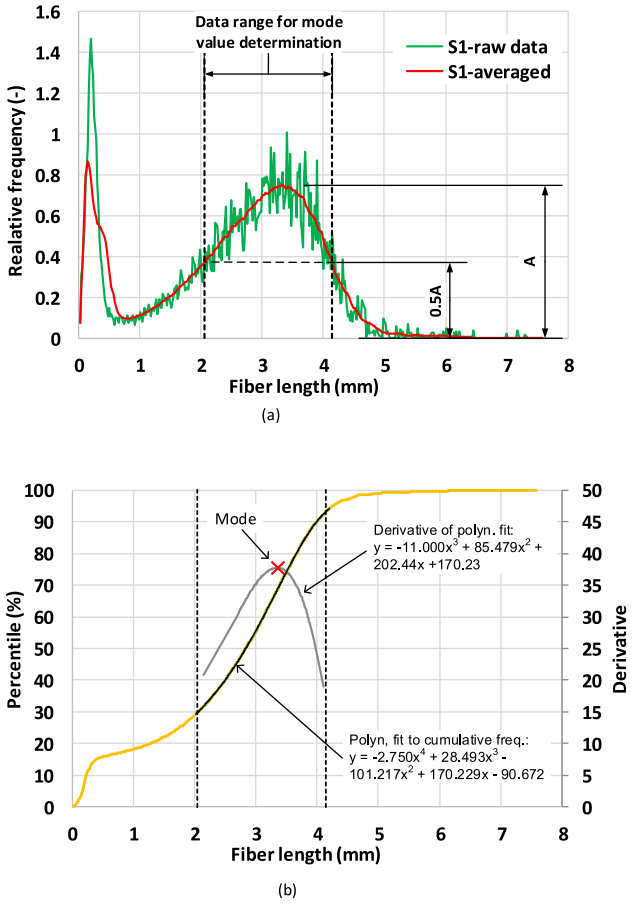

Figure 6: Relative frequency plot (a) and cumulative frequency plot (b) for FS5-data for FHG tree no. S1 with illustration of methodology to determine the mode value. Mode is based on the derivative of a 4th order polynomial regression line fitted to the central part of the cumulative frequency distribution.

defined as the fiber lengths where the histogram frequency is approximately half of the maximum level, see Figure 6a. This method seems to give a more stable mode value.

3 Results

The outcomes of the cooking procedure are shown along with variations between samples in Tables 3 and 4 and Figure 7. Table 4 presents the statistical data for the fiber lengths measured using the FS5 method, both with and without truncation of fines shorter than 0.7 mm. It should be pointed out that the choice of truncation limit has a profound influence on the average and standard deviation, whereas the median and quartiles are less influenced. As expected, the mode value is not influenced at all by the truncation which highlights the advantage of mode as a measure of the central tendency for this kind of experimental data. To characterize the variation, the interquartile range (IQR) might be a better parameter than standard deviation as it is less influenced by outliers and truncation of fines.

Wood chips from the outer annular rings of the eight FHG samples (approximately 20 years of cambial age) and the reference example tree (approximately 40 years of cambial age) were subjected to kraft pulping for 2 h at 165 °C. The yield after cooking varied between 47 % and 50 %, and the number of rejects (shives) varied between 0.2 % and 2.2 %. The average kappa value of all the FHG samples was 30 ± 1 and the corresponding single value for the reference tree was 30 (Table 3). No significant variations in viscosity (η) were observed between the FHG samples (η = 1,041 ± 99 ml/g) and the reference example tree (η = 947 ± 111 ml/g). The overall variations during cooking, although small, are attributed to either the size of the chips, their density, or the occurrence of small amounts of reaction wood.

Figure 7 shows variations between pulp fiber lengths, as measured by the FS5, also between the south and north groups, compared with the average lengths for the same groups. This figure is mainly shown to illustrate that the FHG wood samples are without large intra-variation and that the material might be used to compare with other reported values.

The comparison between the Mölnbacka average fiber lengths FS5 measurements for the FHG samples and the two reference samples are shown in Figure 8a–c in three different ways. Figure 8a illustrates the distribution of all observed fibers, while fines below 0.7 mm in length are omitted in the box and percentile plots, Figure 8b and c. Fines are defined as fine particles, small particles of cellulose, hemicellulose and lignin that pass through a 200 mesh screen, including broken fiber fragments and fibrillar material.

Table 3: Cooking results.

	Ref ex. Tree	S1	S2	S3	S4	N1	N2	N4
Yield	49.4 %	48.9 %	47.9 ± 1.0 %	47.1 %	48.1 %	49.6 ± 1.6 %	49.2 %	47.8 %
Reject	0.32 %	0.91 %	0.18 ± 0.16 %	2.16 %	0.32 %	0.42 ± 0.53 %	0.26 %	0.93 %
Kappa	30	29	30 ± 2	30	35	27 ± 5	30	28

Variation is shown as 95 % confidence intervals for S2 and N1, based on three and two values respectively.

Table 4: Fiber lengths from FS5, both with fines shorter than 0.7 mm omitted, and with no fines omitted.

Tree ID	Fiber length (mm)						
	Avg.	Std. dev.	1st quart. (25th perc.)	Median	3rd quart. (75th perc.)	Mode	Interquartile range IQR
Fines below 0.7 mm omitted							
S1	3.01	0.92	2.38	3.06	3.62	3.32	1.24
S2.1	3.13	0.97	2.46	3.20	3.82	3.51	1.36
S2.2	3.13	0.90	2.50	3.18	3.78	3.39	1.28
S2.3	3.17	0.94	2.52	3.22	3.84	3.38	1.32
S3	2.97	0.93	2.30	2.98	3.62	3.13	1.32
S4	3.16	0.97	2.48	3.20	3.86	3.34	1.38
N1.1	2.91	0.79	2.32	2.94	3.48	3.10	1.16
N1.2	2.92	0.73	2.34	2.96	3.50	3.17	1.16
N2	3.14	0.85	2.54	3.22	3.76	3.58	1.22
N3	2.99	0.78	2.42	3.04	3.60	3.08	1.18
N4	3.19	0.93	2.52	3.26	3.86	3.61	1.34
South average	3.07	0.92	2.42	3.10	3.72	3.35	1.30
North average	3.06	0.85	2.44	3.10	3.70	3.34	1.26
All FHG	3.06	0.89	2.42	3.10	3.70	3.34	1.28
Ref ex. Tree	2.78	0.80	2.14	2.82	3.40	3.06	1.26
Ref ex. Pulp	2.08	0.637	1.44	2.0	2.60	1.93	1.16
No fines omitted							
All FHG	2.68	1.69	1.94	2.90	3.60	3.34	1.66
Ref ex. Tree	2.42	1.45	1.64	2.60	3.30	3.06	1.66
Ref ex. Pulp	1.82	0.94	1.08	1.82	2.50	1.93	1.42

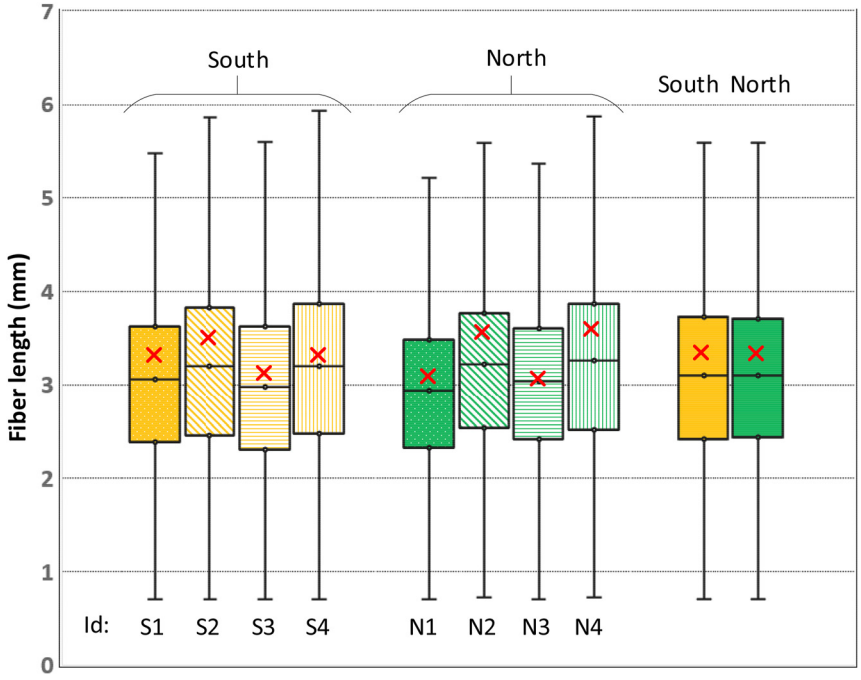

Figure 7: Box plot for fiber lengths for all FHG samples, as measured by the FS5, grouped in north and south origin of the trees. Box plots for all samples in each group to the right. Mode values are marked by a red cross. Fines shorter than 0.7 mm are excluded.

The distribution of fiber lengths in the sample from the reference tree were similar to total distribution of FHG-fibers, while the distribution of the commercial reference pulp had shorter fibers. Even if the reference tree was rather close and only one sample it can be noted that all statistical measures (mode, average and median) were lower than all

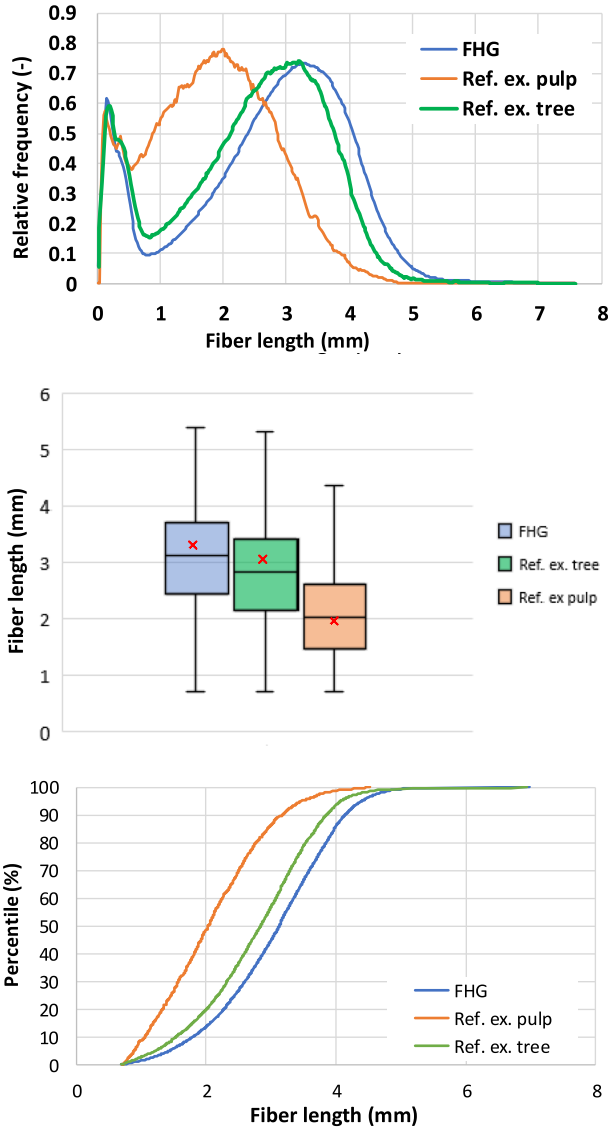

Figure 8: Relative frequency plot (top) for all data (a, top), box plot (b, middle), and cumulative frequency plot (c, bottom) without fines below 0.7 mm in length. Reference example tree (Ref ex. tree) and reference example pulp (Ref ex. pulp) as measured by FS5 are included for comparison. Mode in the boxplot indicated with a red cross. A moving average filter of ±0.3 mm was used for the relative frequency plot to facilitate comparisons.

the individual FHG sampled trees (see Figures 5 and 7). To eliminate some doubts about the method for measuring fiber lengths, a manual measurement was performed in parallel to the FS5. The same principal results and trends are shown even more clearly in the manual measurements in Table 5 and in Figure 8. The histograms in Figure 9 also show that the form of the distributions differ.

The results from the manual measurements in Table 5 e.g. show that almost 80 % of the manually measured 150 FHG fibers were longer than 3 mm, 25 % longer than 4.4 mm, and that the typical fiber length value (mode) was 3.77 mm. In the commercial reference example pulp, the typical fiber length was 1.49 mm, with the same calculated mode. The lengths of the 150 measured fibers from the reference tree sample was intermediate.

4 Discussion

Even if the sample size was limited as well as the reference material, the results do point at some interesting findings: Regardless of preparation method and measurements, the fast height growing trees from Mölnbacka, FHG samples, to a large extent had longer pulp fibers than the reference examples, contrary to what was expected based on literature review. The same trends and relative rankings observed for fiber lengths were present in both FS5 and manual measurements. The FHG trees studied have had an exceptional height growth by Swedish standards, where they are expected to be potentially around 40 m tall at 100 years. It could also be noted that parts of the sampled wood fibers were formed 2018 and after, a summer of drought that have had effects on overall forest growth in Sweden. The fiber lengths from the wood samples fits the hypothesis, that fast growth in height might lead to longer fibers, and the international research compiled in recent years that long fibers can start to be formed before 20 years of cambial age in e.g. FHG trees. Thus, the results support theories that Lachenbruch et al. reviewed (2011) that measures of tree height and/or tree volume influence fiber lengths.

The sampled trees and limited knowledge of the stand history, near a small utility line did not provide good means to investigate any effects from the distance to the living crown. However, in our case with wood from an un-thinned stand with FHG trees, the distance to living branches was moving fast upwards when the sample wood was formed. Norway spruce is also a secondary forest specie that can grow well also partly shadowed, e.g. Lundqvist et al. (2013).

The results of the FHG in this study is in line with expected fiber lengths of sawmill pulp chips, even if the wood from the FHG-trees have grown tall and into sawlog dimensions much younger than normal, and in comparison, with previously measured and modelled materials (Hyll et al. 2024). It is a rather complicating fact that fiber measurements done by different methods and tools are difficult to compare, and that some other reference materials e.g. have been measured with different image processing machines and settings. Hirn and Bauer (2006) reported that the deviations in (length weighted) average fiber length between the tested systems were around 15–20 %, and therefore did not recommend absolute comparisons of results.

Table 5: Fiber length from manual measurements of 150 randomly selected fibers in an optical microscope.

	Average	Std. dev.	1st quart. (25th perc.)	Median	3rd quart. (75th perc.)	Mode	Interquartile range IQR
FHG samples	3.68	0.98	3.10	3.78	4.40	3.77	1.31
Ref ex. Tree	2.58	0.86	2.03	2.56	3.23	2.42	1.20
Ref ex. Pulp	1.90	0.72	1.31	1.85	2.45	1.49	1.14

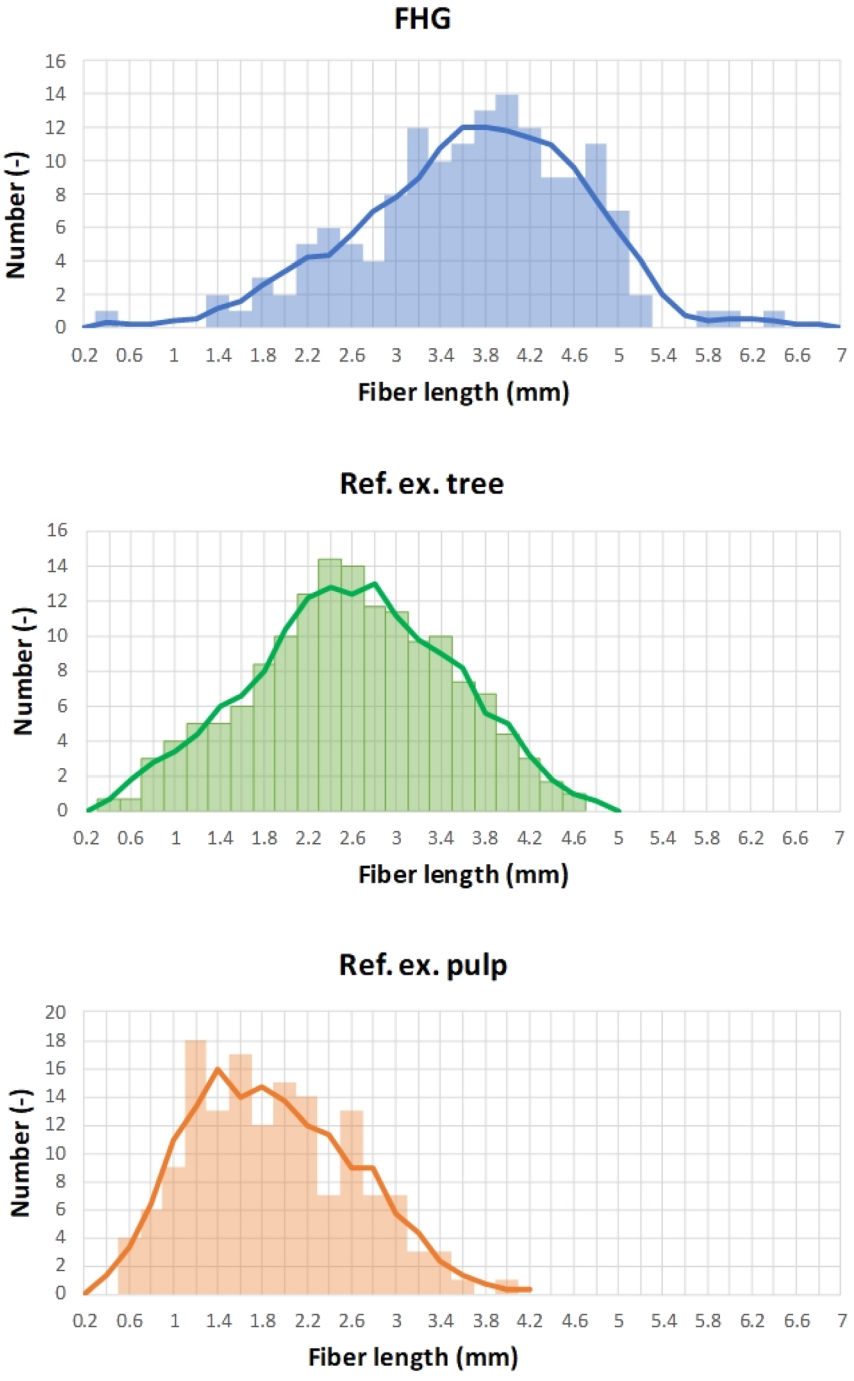

Figure 9: Fiber length distribution (mm) of Mölnbacka tree samples (mix of all samples), reference tree (Ref. tree) and reference pulp (Ref. pulp), from manual measurements.

It was not intended to use the reference examples as direct comparisons of raw material sources but rather to explore measurement factors. That it is difficult to compare can also be seen in this study, and the used commercial reference example pulp have changed the specified average length value over time and with different commercially used machines.

The measured commercial reference Pulp was specified as a pulp from thinnings, which in Sweden often is specified or modelled to have average fiber lengths that are 0.5 mm shorter than pulp from e.g. sawmill chips. Wood from commercial thinnings in the southern regions of Sweden would most often come from 30-year-old stands (Persson et al. 2024), and thus the median cambial age of the fibers would be well over 15 years, not so far from the 21 years in our FHG samples. Commercial pulp from thinnings or tops of trees do however include down to zero in cambial age, and thus a portion of short juvenile fibers. Looking at the distributions of length in our study do not suggest that the difference in cambial age can explain the whole difference in e.g. mode-the typical fiber length. The measured reference tree is only outer wood from an average size older tree grown in the north of Sweden. We do not know exactly the average cambial age or distribution in the sampled wood. The measured values of them are however according to the expectations and the distribution, less skewed. It might strengthen the idea that the younger fibers from FHG samples are different, especially in terms of the form of the distribution and the mode value. Another explanation of the special distribution could be that the sample is a very narrow in terms of position and cambial age of sampled wood, even if from eight different trees.

The results from the manual measurements using an optical microscope also include uncertainties. On the one hand, it confirms the trend and relative ranking between the FHG samples and the two reference examples, but the absolute observed values may be too large. The manual microscope measurements were conducted on 150 fibers of the FHG samples, which were extracted from a small portion of the samples even if randomly. Additionally, it is possible that operator bias could influence the results, even though the intention was to select fibers in each of the images randomly. In comparing the data, it appears that the measures of the two reference samples are lowered in the manual measurements, while the FHG manual measures are higher when compared to the FS5 measurements. With only 150 fibers examined for each group, compared to around 20,000 fibers in FS5, small variations in selection can impact the apparent fiber length distribution, making it harder to generalize findings across the entire pulp batch. Therefore, while the trends align well with those observed in FS5 measurements, the differences observed should be interpreted cautiously. For pulp quality analysis, correct sampling is essential to obtain a representative view of fiber characteristics.

The mode value could be a very suitable measure for evaluating pulp fiber lengths, as a complement to the mean and median values. The mode is unaffected by where the boundary for fines is set, see Table 4. The method of automatically identifying the mode from the derivate of the maximum inclination (derivative) of a polynomial function (4th order) fitted to the cumulative frequency plot is also suitable for large data sets with a large share of fines, which is typical for commercial pulp fiber analysis.

The results from this study suggest that more research is needed to understand how and why longer fibers are naturally formed in certain forests. It also appears that the natural potential for long fibers in relatively young Norway spruce wood grown in Sweden, both in terms of average and mode values, is greater than previously established knowledge has indicated. Moreover, increased use of mode, established by use of a polynomial fit within Q1 to Q3, could be valuable in better describing the length distribution of cultivated fibers and pulp fibers.

The mode could be highly relevant for pulp and paper producers, as well as for equipment and machine manufacturers, as it enables the presentation of a very relevant measure. When commercial pulps are marketed as containing long fibers, relying solely on mean values can be problematic because it does not clearly indicate how long the typical fiber in the flow or raw material batch actually is. The mode's advantage lies in its ability to represent the most frequently occurring fiber length, which provides a clear and consistent point of reference. Unlike the mean and median, which can be skewed by exceptionally long or short fibers and fines, the mode reflects a more stable characteristic length, offering a realistic measure for industrial applications. This distinction is particularly useful in quality control processes, where understanding the typical fiber length is critical for maintaining product consistency. For those involved in manufacturing and machine design, having access to mode-based data on fiber length distribution allows for better-informed decisions, particularly when tuning equipment to handle specific fiber types. In essence, utilizing the mode for fiber length evaluation supports a more accurate portrayal of fiber characteristics, helping to ensure that specifications for long fiber products truly meet market demands. In papermaking, long fibers give the possibility to form sheets with higher number of fiber-fiber bond sites compared to short fibers, and thus higher mechanical strength (Hubbe 2014; Larsson et al. 2018; Lindström et al. 2005). Especially long slender fibers are preferred for high-strength performance (Lindström et al. 2005).

5 Conclusions

- Trees with fast height growth (FHG samples) from the Mölnbacka region produced longer fibers at low cambial age compared to previously reported values, regardless of the production method used.
- The results indicate a greater natural potential for longer fibers in young Norway spruce grown in Sweden than previously reported, highlighting the need for further research into the factors that promote longer fiber formation.
- The mode value offers a characterization of the central tendency of the fiber length that is more stable and less influenced by fines (or omission of them) compared to the average or the median values.

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