Effect of tree-growth rate on papermaking fiber properties

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ABSTRACT

Measurements of wood density and anatomical properties of wood disks were conducted by SilviScan (CSIRO Australia) and a new imaging technique. The disks included red pine obtained from a never-thinned experimental forest with five different plantation densities and Douglas-fir and lodgepole pine (one normal growth and the other suppressed growth) both supplied by a sawmill. The results indicated that the effect of tree-growing conditions can be effectively characterized by radial annual growth rate. Growth suppression produced wood with less distinction in wood density, tracheid radial diameter, and wall thickness between earlywood and latewood.

INTRODUCTION

It is well known that fundamental wood properties, such as ring structure and tracheid anatomical dimensions, affect both fiber processing and the end-use performance of paper and paperboard products [1, 2]. In many commercial conifer species and under plantation growing conditions, earlywood fibers are predominately larger in diameter and have thinner cell walls than the latewood tracheids in a single growth ring. These earlywood tracheids are desirable because they have good collapsibility in fiber processing, which can increase bonding in paper. However, they can also be severely damaged in thermomechanical pulping (TMP), making it difficult to optimize refining conditions. Therefore, a more uniform distribution of earlywood and latewood tracheid wall thickness can avoid a challenging refining conundrum; either the earlywood tracheids are severely damaged and shortened when refining is optimized for latewood, or the latewood is not well refined when refining is optimized for earlywood. Clearly, characterizing wood anatomical properties has significant importance in determining the most effective and efficient fiber processing conditions for papermaking.

There is good understanding of the properties of fibers produced from various tree species [3]. This understanding provides guidance in efficient utilization of different trees for specific paper and paperboard product applications. For example, spruce produces excellent mechanical pulps while loblolly pine produces good chemical pulps. The hardwood pulps with shorter fiber lengths are often used in printing and writing papers to improve smoothness and opacity.

Studies have shown that tree-growing conditions affect wood and tracheid properties. Early studies on the effects of various environmental conditions on wood properties are summarized in a comprehensive review by Koch [4]. Most of the work has focused on plantation southern pine. Koch concluded that the correlation between specific gravity and any factor, such as stand density, is usually poor. Only when an environmental factor becomes limiting does it affect tracheid size or wall thickening (or both) enough to show good correlation between that factor and the wood-specific gravity. Zahner and Oliver [5] found that thinning and pruning delays the initiation of latewood. Lanon [6] and Zahner et al. [7] indicated that the initiation of latewood of red pine (*Pinus resinosa* Ait.) was also affected under simulated drought and irrigation conditions. Recently, Antonova and Stasova [8] indicated that temperature and precipitation both affect radial cell expansion and secondary wall thickening of larch (*Larix sibirica* Ldb.) stems. Gindl et al. [9] concluded that lignification of the cell wall, ring width, and maximum densities are all susceptible to the influence of climatic variability. Wodzicki [10] revealed that tree thinning reduced competition for light, nutrients, and water and increased the volume and density of the timber (*Pinus sylvestris*) produced.

In plantation forestry, stand density is an important silvicultural tool used to maximize productivity. Several studies have been conducted on the effect of stand density on papermaking fiber properties [11-14]. Watson et al. [13] reported the effect of initial plantation density on wood and fiber (through Kraft pulping) properties of western hemlock. They found that initial stand spacing of greater than 3.6 m by 3.6 m had no effect on fiber length and coarseness properties of 38-year-old trees. Furthermore, juvenile wood content was not affected. Kang et al. [14] revealed that initial spacing affects the coarseness of pulp obtained from Kraft pulping of jack pine primarily because of the difference in growth rate.

Slow growth or severely suppressed growth has been the main characteristic of trees growing in U.S. National Forests. This is largely due to an overpopulation of trees (about 10,000 stems/acre or higher) as the result of decades of fire-suppression management practice. Unlike plantation forestry, where there are some measurable growing conditions such as stand density, the characterization of tree-growing conditions is very difficult in unmanaged natural forests. As a result, characterization of the effects of growth suppression on wood tracheid anatomical properties is not readily available. Yet given the overabundance of small-diameter, suppressed-growth trees and the urgent need to undertake thinning operations to restore the health of the forests, it is imperative to understand and characterize the constituent fiber properties to assess their value for papermaking.

In this study, we attempt to use tree-growth rate, an easily measurable parameter, to correlate the effect of tree-growing conditions on fiber properties for both plantation and unmanaged natural forests. Using tree-growth rate can eliminate the need to study how individual environmental factors affect wood and tracheid properties. This is necessary because it is difficult to define tree-growing conditions in natural forests and because certain environmental factors do not affect tree growth and therefore wood density, according to Koch [4]. Tree-growth rate has been represented by the averaged annual growth-ring width, which has been used to correlate wood density and fiber length [2, 14, 15]. The effects of tree-growing conditions such as thinning on wood and tracheid properties has been effectively demonstrated using these correlations [15, 16].

EXPERIMENTAL

Raw Materials

Three types of tree samples were used in this study: red pine from a research plantation forest, a Douglas-fir sample from an unmanaged natural forest that experienced different levels of growth suppression over several decades, and two lodgepole pine samples, one grown under normal conditions and the other that experienced severe growth suppression over its entire lifetime, both from an unmanaged natural forest. The red pine trees were obtained from a never-thinned 38-year-old research plantation in the Lake Superior State Forest (Michigan, USA): therefore. the age and thinning effects were eliminated. The plantation-stand density varied at 220, 320, 420, 620, and 820 stems/acre in five different plots, representing different levels of growth suppression. Ten trees were harvested from each of the plantation stand density plots. A 4.9-m butt log was bucked from each tree and shipped to the USDA Forest Products Laboratory (FPL) in Madison, Wisconsin, USA. A 61-cm section from each end of the butt log was retained. A 2.5-cm-thick disk was cut from each 61-cm section (Fig. 1). Two disks from each plantation density plot, a total of 10 disks from the 100 disks produced, were selected for basic wood property analysis by SilviScan (CSIRO Australia). The vertical heights of the disks were 0.6 and 4.3 m, respectively. The two representative disks were not necessarily from the same tree, but were carefully selected through visual observation of growth rates to be representative of the material in each plantation plot.

The wood disk of Douglas-fir was supplied by Ponderay Valley Fibers (now Vaagen Brothers, Usk, Washington). The disk was selected because its growth rings were greater than 1 mm from age 10 to 30, then under 1 mm from 30 to 70, with one exception at age 40. The tree experienced various degrees of growth suppression. Figure 2 shows an image of the wood disk from which the sample used for SilviScan and image analysis was generated. This Douglas-fir wood disk provides the opportunity to study the effect of within-tree variable growth rate on wood anatomical properties. The two disks of lodgepole pine trees (Fig. 3) were also supplied by Ponderay Valley Fibers. These two disks are used to verify the observed relations between growth rate and wood and tracheid properties from the previous two samples.

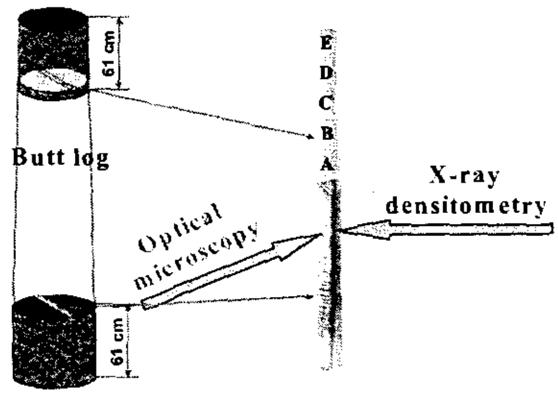

Figure 1. A schematic diagram showing the vertical location of two wood disks and the strips used in SilviScan analysis.

Figure 2. 70-year old Douglas-fir wood disk used in this study

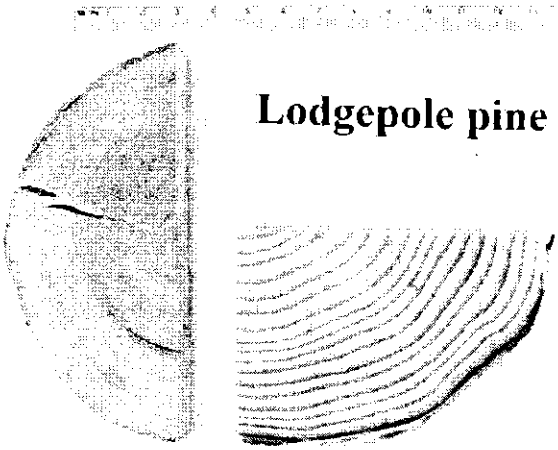

Figure 3. Lodgepole pine wood disks used in this study (left, 128 years old and right, 24 years old).

Measurements of Wood Density and Anatomical Properties

Two adjacent strips across the entire diameter were cut from each disk. The diameter was chosen with the least differentiation in radius between the two radii from the pith to bark. One strip was sent to the Tasmanian Forest Research Center, Commonwealth Scientific and Industrial Research Organization (CSRIO), Division of Forestry and Forest Products, Australia, for SilviScan analysis. SilviScan [17, 18] was developed for rapid analysis of wood density and anatomical properties. It provides good measurements of the red pine and the normal-growth lodgepole pine wood samples that have relatively large ring widths greater than 2 mm. For measurement consistency, the suppressed-growth lodgepole pine wood sample was also analyzed by SilviScan. However, SilviScan 'cannot provide accurate measurements of wood density and anatomical properties for samples with very narrow rings [19] because the 50-µm spatial resolution of SilviScan produces results that are averaged over both the latewood and earlywood tracheids. Similar averaging is associated with the SilviScan's line-of-sight measurements of curved rings. Therefore, the wood core sample of Douglas-fir was characterized by the Ring Profiler [19], an imaging technique developed to complement SilviScan analysis. Detailed measurements of local wood density, tracheid diameter, and wall thickness in both radial and tangential directions were reported in our previous study [19]. The SilviScan-measured ring widths are in agreement with the measurements of Ring Profiler; therefore, they were used in data analysis because SilviScan provided a more complete data set. The Ring Profiler measurements of tracheid geometry and wall thickness anisotropy were used to obtain a moditied SilviScan wood density based on

$$D = \frac{4w_T^2}{R\alpha T d}\left(\frac{R\alpha + T}{2w_T} - 1\right) \qquad (1)$$

where D is the local wood density, w_T is tangential wall thickness, R and T are radial and tangential tracheid diameters, respectively, α is the wall thickness anisotropy (equal to the ratio of tangential and radial wall thickness, $\alpha = w_G/w_R$). and d is the tracheid wall density (assumed to be 1,500 kg/m^3). SilviScan uses Eq. (1) to determine an isotropic tracheid wall thickness valid when $\alpha\alpha = 1.0$.

RESULTS AND DISCUSSIONS

Red Pine Samples

Average ring width

The arithmetic mean of the annual ring widths measured by SilviScan analysis is used in this study to represent the average annual growth rate. The terms average ring width and average annual growth rate will be used interchangeably in the discussion of the results for red pine samples. Growth suppression is nonexistent in early years for all plantation densities studied. Growth suppression becomes apparent only in the mature wood. Therefore, the annual ring-width data from the first 10 years were arbitrarily excluded in the calculation of average ring width. It was found that the annual ring width decreased significantly after year 10 from the peak at about year 6 for all the disks studied.

Wood physical properties

It was found that tree annual growth rate can be correlated to the plantation density. The average ring width (y in mm) decreased linearly as the plantation density (x in stems/acre) increased for the five plots studied: i.e., $y = 3159 - 1.77 \times$ ($r = 0.9$) and $y = 2709 - 1.71 \times$ ($r = 0.96$) for the disk sets from height of 4.3 m and 0.6 m, respectively. These correlations indicate that the average ring width is a reliable parameter to represent tree-growth conditions (plantation density in this case).

To study how growth suppression affected wood density, the mean earlywood and latewood densities were first calculated by integrating the SilviScan radial density profile over the entire disk area (assuming axial symmetry). The mean wood density is then correlated to the average annual ring width. It was found that the mean earlywood density increases while the mean latewood density and annual ring width decrease (Fig. 4). This indicates that the difference in wood density between earlywood and latewood becomes less distinct, or wood density becomes more uniform as a result of growth suppression in high density plantations. Further observations indicated that the differences in the mean wood densities between earlywood and latewood were smallest for wood disks from the highest stem-density plot (with the smallest average annual ring width) [20].

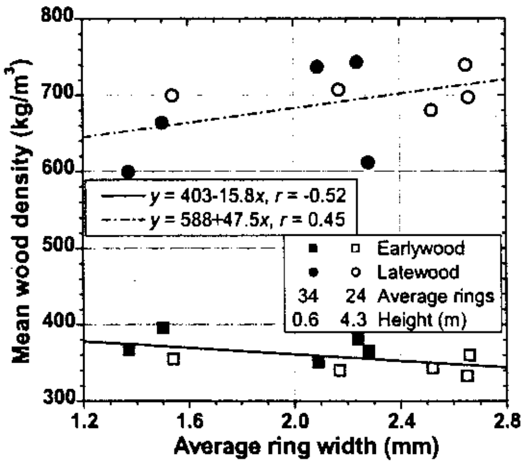

Figure 4. Effect of average radial growth rate on mean wood density of plantation red pine.

The average latewood mass fractions were calculated using the SilviScan data for the 10 disks studied. Latewood mass fraction is increased (Fig. 5) despite the fact that latewood density is decreased as average ring width decreases (Fig. 4), indicating increased latewood volumetric fraction as average radial growth rate decreases [20]. Larson [6] and Zahner et al. [7] suggested that the shift from earlywood to latewood in red pine can take place as a result of developing water stress, slowing crown growth, and declining auxin levels. Zahner and Oliver [5] and Zahner et al. [7] suggested that growth suppression caused early formation of flattened latewood tracheids. However, Zahner et al. [7] reported that latewood content was unchanged based on linear (radial) estimation using tracheids from year 20. The increase in latewood volumetric fraction at high-stand density can be attributed to growth suppression in the mature years.

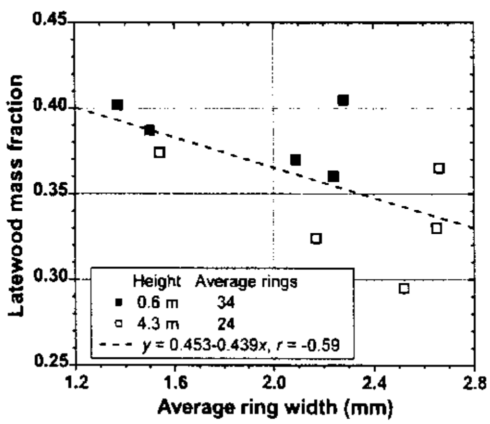

Figure 5. Effect of tree average growth rate on latewood content of plantation red pine.

Tracheiddiameters

Silviscan analysis revealed that the tracheid radial diameter varies significantly (as much as 100% for a given year) between earlywood and latewood [20]. However, the yearly averaged earlywood and latewood radial diameters remained a constant in the mature wood (after year 10) for a given tree. Therefore, the mean radial diameter of the tracheids across the entire diameter (excluding wood younger than 10 years) can be a good representation of the radial size of the tracheid. The tracheid number-weighted mean radial diameter of each disk was calculated using the SilviScan-measured linear-radial diameter and tracheid population profiles, excluding the first 10 years. It was found that both the earlywood and latewood mean tracheid radial diameter decreased as average ring width decreased (Fig. 6). which agrees with that observed under drought conditions by Larson [6]. The linear dependence of the mean tracheid radial diameter of earlywood on average annual radial growth (average ring width) is stronger than that of latewood (Fig. 6). As a result, trees with slow annual radial growth have a more uniform distribution of radial tracheid diameter.

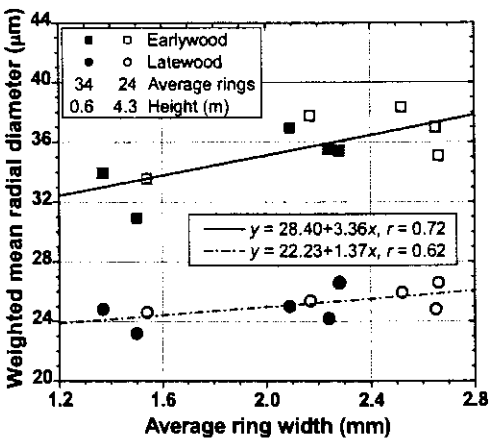

Figure 6. Effect of tree average growth rate on mean tracheid radial diameter.

The variation of tracheid yearly average tangential diameter between earlywood and latewood was only about 20%. The yearly average tracheid tangential diameter increases linearly with tree age [20]. The slope of the linear correlation is the average annual tangential tracheid growth rate. This average annual growth rate was observed from year 1; therefore, annual ring widths from the entire disk were used in calculating the average ring width in correlating the average annual tracheid tangential growth. For the five disks at height = 0.6 m and an average of 34 rings, the average annual tracheid tangential growth rate increases as average ring width increases for both earlywood and latewood (Fig. 7). A wide average ring width resulting from low-stand density in plantations also associated with a large tracheid tangential diameter. This suggests that the tree radial growth induced the growth of the tracheid tangential diameter.

Further analysis of the data from all 10 disks reveals that the average annual growth of tracheid tangential diameter of the earlywood and latewood are linearly correlated with a zero intercept and a proportionality constant of 0.81 with r = 0.96.

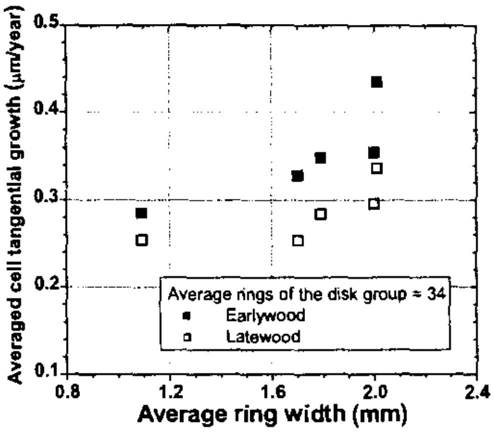

Figure 7. Effect of tree average growth rate on average tangential growth rate of plantation red pine.

Tracheid wall thickness

Tracheid wall thickness and its distribution is very important to mechanical pulp refining and is directly related to fiber collapsibility. The SilviScan revealed that tracheid wall thickness of a disk from a high-density plantation (820 stems/acre, with an average ring width of 1.37 mm) was thinner in general than the wall thickness of a disk from a low-density plot (220 stems/acre, with an average ring width of 2.24 mm) [20]. This effect is much more pronounced on latewood than on earlywood, especially in the last 10 years. As a result, the tracheid wall thickness for the disk with a narrower average ring width was more uniform. This uniformity can be illustrated by the wall-thickness probability-density distribution (Fig. 8) calculated using SilviScan-measured tracheid wall thickness and population. A bimodal distribution was observed for the disk from the 220 stems/acre plot with a very narrow and strong first peak corresponding to the earlywood and a broad second peak representing the latewood. The earlywood and latewood are indistinguishable from the wall thickness probability distribution for the disk from a 820 stems/acre plot. Furthermore, the distribution is fairly constant. These results on tracheid wall thickness agree qualitatively with data reported by Zahner and Oliver [5] and Zahner et al. [7], who found that growth suppression due to high-stand density or drought reduced the numbers of tracheids with exceptional secondary wall thickening.

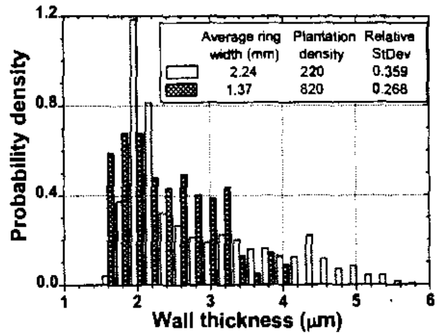

Figure 8. Probability-distribution density function of tracheid wall thickness for two red pine disks with different average ring widths

The Douglas-fir Wood Sample

Annual radial growth

The red pine data discussed above showed the relation between averaged annual radial growth-rate of trees from various plots of different plantation density to wood density and anatomical properties. The Douglas-fir wood sample discussed in this section shows the effect of annual radial growth rate on within-tree wood density and tracheid wall thickness. Figure 9 shows the SilviScan-measured annual ring widths of the Douglas-fir sample. A different symbol was used for every 10 rings for easy identification of tree age. The strip measured by SilviScan was cut from the lower right corner of the disk shown in Figure 2. The data clearly show that the tree experienced various degrees of growth suppression throughout its life. The tree experienced mildly suppressed growth between 30 and 50 years. Annual ring widths as small as 300 μm were typical from 50 to 70 years, indicating that the tree experienced severely suppressed growth at that time.

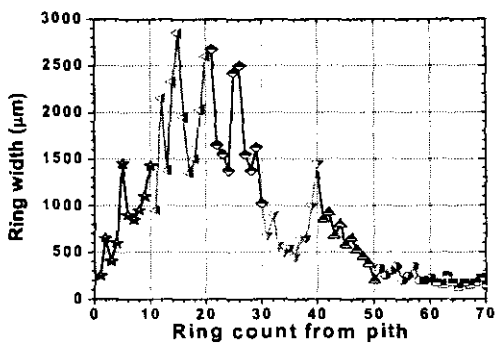

Figure 9. SilviScan measured annual ring width of the Douglas-fir wood core sample.

Local wood density

The modified SilviScan average local wood densities (Eq. (1)) of the earlywood and latewood band were correlated with the corresponding annual ring width (Fig. 10). The shapes of symbols identify the ring number group as shown in Figure 9. Results clearly show that latewood density decreases while earlywood density increases as ring width decreases, resulting in a more uniform distribution of wood density. This uniformity in wood density distribution due to growth suppression (within-tree) is very similar to that observed from plantation red pine samples (among-tree) shown in Figure 4. The effect of growth suppression is much more pronounced in reducing latewood density than in increasing earlywood density. This is indicated by the correlations, also similar to the results shown in Figure 4. Only data from last 40 years of the tree were used in performing the correlations.

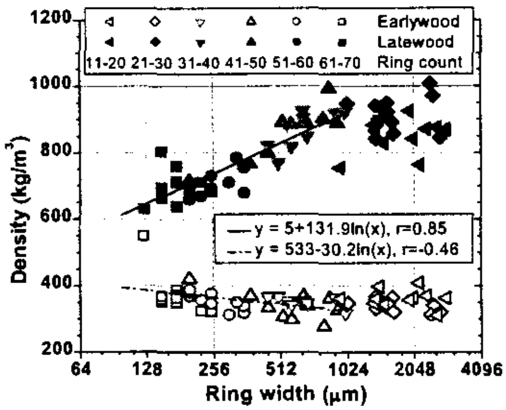

Figure 10. Effect of tree growth rate on latewood and earlywood densities of the Douglas-fir sample.

Tracheid wall thickness

With the Ring Profiler technique [19], tracheid wall thicknesses in both the radial and tangential directions were measured. It was found that the yearly average (within the measurement hand as described in [19]) earlywood and latewood tracheid wall thicknesses in both radial and tangential direction decrease linearly as annual ring width decreases (Fig. 11). However, the data clearly showed that latewood tracheid wall thicknesses decreased more rapidly than the earlywood in both radial and tangential directions. This was particularly true for the tracheid tangential wall thickness. The slope of the linear correlation between wall thickness and annual ring width for latewood was three times greater than the slope for earlywood in the tangential direction, whereas in the radial direction, the slope for latewood is two times greater than for earlywood. Only data from ring widths less than 800 0m were used in the linear regressions. The differences in the slopes between earlywood and latewood resulted in more uniform distributions of tracheid wall thickness in both tangential and radial directions. This agreed with the SilviScan measured isotropic tracheid wall thickness distribution in the red pine samples.

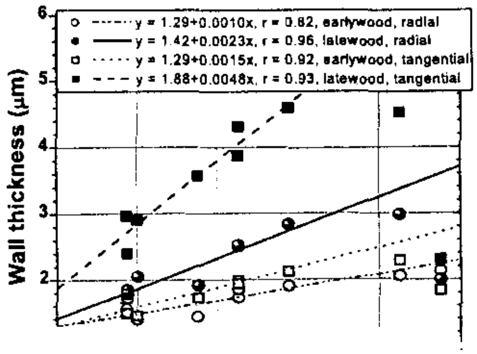

Figure 11. The correlations between earlywood and latewood tracheid wall thickness in both the radial and tangential directions and annual ring width.

The Lodgepole Pine Wood Samples

The two lodgepole pine samples were used in this study to verify the findings obtained from the among-tree and within-tree investigations, using red pine samples and a Douglas-fir sample, respectively. Figure 3 shows the images of the two wood disks. The normal-growth wood disk had 24 annual rings and suppressed-growth wood disk had 128 annual rings. The average ring widths for the two disks were 3.9 (normal) and 0.5 mm (suppressed), respectively. The SilviScan-measured wood density and tracheid population were used to calculate the wood density probability density (Fig. 12) for the two disks. Tracheid radial diameter and wall thickness probability density were also calculated (Fig. 13(a) and (b)) from SilviScan measurements. The results showed that the normal growth disk had bimodal distribution of wood density and tracheid radial diameter and wall thickness. The two peaks in the distributions represent the earlywood (large radial diameter, thin wall, and low density) and latewood (small radial diameter, thick wall, and high density). Therefore, clear distinction in tracheid radial diameter, wall thickness, and wood density between earlywood and latewood was seen. However, this clear distinction was not visible for the suppressed-growth wood disk. Furthermore, the distribution hands in and tracheid radial diameter, wall thickness, and wood density were narrower, indicating suppressed growth produced more uniform wood in terms of wood density and tracheid wall thickness.

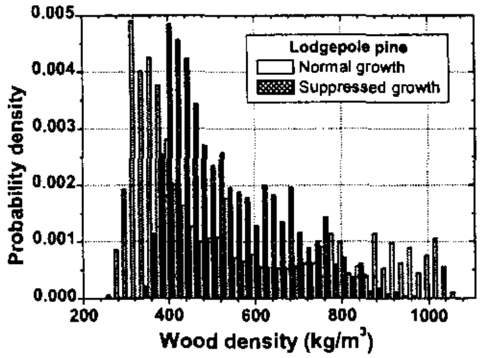

Figure 12. Effect of tree-growth condition on wood density distribution of two lodgepole pine samples.

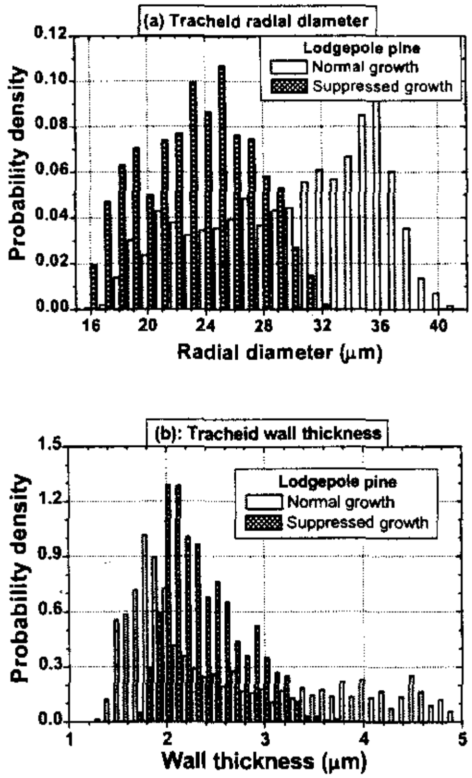

Figure 13. Effect of tree-growth condition on tracheid anatomical properties of two lodgepole pine samples.

CONCLUSIONS

The results presented in this study indicated that annual growth-ring width can be a unified parameter to characterize the effect of tree-growth rate on fiber properties. The ring-width correlation with wood density and anatomical properties can elucidate the effect of tree-growth conditions on wood physical properties. Specifically, the results from three types of samples through among-tree and within-tree analysis indicated that slow growth produced wood with less distinction between earlywood and latewood, and a more uniform distribution of wood density, tracheid radial diameter, and wall thickness. In other words, slow growth produced fibers with more uniform properties. The uniformity produced in a slow-growth environment can be beneficial for mechanical pulp production, because less distinction between earlywood and latewood reduces the degree or extent of cutting damage to earlywood fibers when refining is optimized. The study provides some fundamental observations of the effect of tree-growth rate on wood fiber properties and the implications to papermaking and paper physical properties.

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