SOME OBSERVATIONS OF WOOD DENSITY AND ANATOMICAL PROPERTIES IN A DOUGLAS-FIR SAMPLE WITH SUPPRESSED GROWTH[1]

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Abstract. This study used ring width correlations to examine the effects of tree-growth suppression on within-tree local wood density and tracheid anatomical properties. A wood core sample was taken from a 70-yr-old Douglas-fir that grew under various degrees of suppression in a natural forest setting. SilviScan and an imaging technique were used to obtain wood density and tracheid cross-section dimensions. The results indicated that wood and tracheid properties correlate to annual-ring width very well. The results also reveal that growth suppression may increase the uniformity of wood density and tracheid cell-wall thickness in both radial and tangential directions.

Keywords: SilviScan, tracheid, wood density, diameter, wall thickness, anisotropy, image analysis, resolution, suppressed growth, small diameter, thinnings, pulp.

INTRODUCTION

Decades of practicing forest fire suppression management in the United States have produced an overabundance of small-diameter trees grown under suppressed-growth conditions in many National Forests. Tree-stand overpopulation increases fuel loading in the forests and therefore increases the risk of catastrophic forest fires. Controlled burning to reduce fuel loading is not an option when forest lands are near communities. Selective forest thinning in these areas has been adopted as a strategy to reduce both fuel loading and the risks associated with these devastating fires, while benefiting local communities (Mason et al 2006). High-value, large-volume utilization of these small-diameter trees can mitigate the cost of expensive forest thinning operations. This is the key to making thinning strategies viable management tools for sustaining forest health.

Ideally, the production of solid wood products, such as dimensional lumber, poles, and posts, could substantially mitigate thinning costs. However, many trees removed in such thinnings are in small-diameter classes (less than 15-mm dia at breast height, DBH), which produce low lumber yields. Using these materials for biofuel is an option, but the potential economic returns

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are low. The production of paper is a good alternative use of thinned trees that can produce high values and use large volumes (Zhu et al 2007a). Ironically, there is a shortage of quality wood chips for papermaking in the western US (Reeve 2005). Therefore, a significant volume of the small-diameter thinning materials could be diverted to pulp mills with large saw logs going to lumber mills (Zhu et al 2007b). This would provide an opportunity to integrate the production of lumber and paper while minimizing taxpayer expense, satisfying both the management needs of the US Forest Service and the raw material needs of the forest products industry.

Forest thinning materials from unmanaged timber stands in the US National Forests are different from those in managed plantations. High juvenile wood content is the major detrimental characteristic of thinning materials from managed plantations. Juvenile wood content is associated with low mechanical strength of fibers, which is a major quality concern of the pulp and paper industry (Zobel and van Buijtenen 1989). Forest thinning materials from the US National Forests include many older trees experiencing decades of suppressed-growth. Although small in diameter, these trees are low in juvenile wood content. However, knowledge about the quality of wood chips for papermaking produced from these suppressed-growth trees is limited. Laboratory pulping studies (Myers et al 1999, 2003; Myers 2004) indicated that small-diameter trees from thinning can be used for thermomechanical pulp production. Conflicting results about pulp quality were reported in these studies and remain unexplained.

It is well known that fundamental fiber properties, such as anatomical dimensions, affect fiber processing and properties of end products (Seth 1990). Understanding the effects of suppressed-growth conditions on wood density and anatomical properties allows the scientific evaluation of the papermaking potential of affected trees. Related studies can also provide knowledge and guidance for pulping process optimization to achieve the material's potential. However, the only such studies available examined trees from managed plantations. Early studies on the effect of environment on wood properties are summarized in a comprehensive review by Koch (1972). Most of the work focused on plantation southern pine. Koch concluded that correlation between specific gravity and a factor such as stand density is usually poor. Only when an environmental factor becomes limiting does it affect tracheid size and /or wall thickening enough to show good correlation between that factor and the wood specific gravity. Recently, Kang et al (2004) quantified the effects of plantation density on wood density, fiber, and pulp properties in jack-pine plantations. They found that yield, wood and fiber properties can be improved through stand-density regulation. They also found that precommercial thinning has a positive effect on fiber properties. Yang and Hazenberg (1994), Hatton et al (1996), and Watson et al (2003) studied the effect of plantation spacing on relative wood density and fiber properties in black spruce, western red cedar, and western hemlock, respectively. They found that fiber coarseness and length were not affected by stand density for initial spacing between 0.9 × 0.9 m and 3.6 × 3.6 m. However, juvenile wood content increased when initial spacing was greater than 4.6 × 4.6 m.

Ring width is a measure of tree annual radial growth and should reflect the effects (if there are any) of environment on tree growth. It has been used to correlate wood density and fiber length (Dinwoodie 1965; Lindstrom 1996; Dutilleul et al 1998). The effects of thinning on wood and tracheid properties can be effectively demonstrated from these correlations (Dutilleul et al 1998; Makinen et al 2002). In a previous study, we used ring width to correlate the effect of tree stand density on wood density and anatomical properties of plantation red pine (Zhu et al 2007c). One goal of the study was to establish the approach of ring-width correlation to unmanaged tree stands under suppressed-growth in natural forests. The study also revealed different effects of stand density (ie growth suppression) on the relative growth of earlywood and latewood. High stand density resulted in increased uniformity of wood density and tracheid anatomy, beneficial to thermomechnical pulping (Rudie et al 1994). In the present study, the Ring-Profiler technique developed in our previous study (Vahey et al 2007) was employed to measure wood density and anatomical properties of a Douglas-fir wood core sample. The objectives are (1) to provide some understanding of the effects of growth suppression on the characteristics of within-tree wood density and tracheid anatomy, and (2) to verify the effectiveness of the approach of ring-width correlation (Zhu et al 2007c) to trees with growth suppression in a natural forest setting.

EXPERIMENTAL PROCEDURE

Sample

The sample from our previous study (Vahey et al 2007) was used. The core from a 70-yr-old Douglas-fir was first prepared and analyzed by the Commonwealth Scientific and Industrial Research Organization (Melbourne, Australia) using SilviScan. This tree was selected because its growth rings were greater than 1 mm from age 10–30 yr, then under 1 mm from 30–70 yr, with one exception. So the tree experienced various degrees of growth suppression. Figure 1 shows an image of the wood disk from which the sample was generated.

Measurements of wood density and anatomical properties

The SilviScan measurements reported in our previous study were carried out using the default measurement interval of 50 μm (Vahey et al 2007). The data obtained were not able to provide accurate measurements of wood density and anatomical properties for the very narrow rings of the sample. These data are not indicative of the capability of SilviScan, as the system is capable of producing much finer resolution than that which was chosen for these experiments. For these rings, the 50-μm measurement intervals produced results that are significantly aver-

FIGURE 1. The picture of the wood disk used in this study. All measurements were conducted on the right half of the wood core sample (2 mm in tangential direction) cut from the bottom.

aged over both the latewood and earlywood tracheids. Similar averaging is associated with the SilviScan line-of-sight measurements of curved rings near the pith. Therefore, the wood core sample was characterized by the Ring Profiler technique as a complement to SilviScan analysis. Detailed measurements of local wood density, tracheid diameter, and wall thickness in both the radial and tangential direction were reported in our previous study (Vahey et al 2007). The SilviScan-measured ring widths are in agreement with the measurements of the Ring Profiler; 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 wood density based on tracheid geometry using the following equation.

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

where D is the local tracheid density and is assumed local wood density by SilviScan, w_T is tangential wall thickness, R and T are radial and tangential tracheid diameter, respectively, α is the wall thickness anisotropy (equal to the ratio of tangential and radial wall thickness, $\alpha = w_T/w_R$), and d is the tracheid wall density (assumed to be 1500 kg/m^3). SilviScan uses the inverse of Eq (1) to determine an isotropic tracheid wall thickness from density, valid when $\alpha = 1.0$.

RESULTS AND DISCUSSION

The effect of growth suppression on tree annual radial growth

Ring width is a measure of the tree annual radial growth. The SilviScan annual ring widths of the Douglas-fir sample are presented in Fig 2. 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 Fig 1. Figure 2 clearly shows that the tree experienced various degrees of growth suppression throughout its life. The tree was under mild suppressed-growth between 30–50 yr. Annual ring widths as small as 300 μm were typical for 50–70 yr, indicating the tree was under severe suppressed-growth. Because of the 50-μm measurement intervals chosen for the SilviScan data for this sample, an error of 25% or greater will result in calculating the latewood volumetric fraction using the SilviScan density data for latewood bandwidth less than 200 μm. Analysis of latewood volumetric fraction was not attempted in this study.

Tracheid diameters

For the measurements conducted in the last 60 yr of tree growth, the Ring Profiler average latewood radial diameter is about half the corresponding earlywood radial diameter in the same ring (Fig 3). For suppressed-growth rings less than 1 mm in width, both the earlywood and latewood radial diameter decrease as annual ring width decreases. Between ring counts 10–30, where ring widths are greater than 1 mm (Fig 2), both the tracheid radial and tangential diameters decrease as ring width increases. Because juvenile wood dominates in the first 30 yr of the sample based on microfibril angles measured by SilviScan, data analysis was focused on the last 40 rings of the tree (age 30–70) for most parts of this study.

The Ring Profiler average earlywood tangential diameter was only slightly greater than the latewood tangential diameter (Fig 4). Both the average tracheid earlywood and latewood tangential diameters increased as annual ring width decreased. The increase in tangential diameter with the decrease in annual ring width simply reflects the radial growth of the tree. Recall that the annual ring width decreases almost monotonically as the tree grows (Fig 2).

Local wood density

The average local wood densities based on tracheid geometry (Eq (1)) of the earlywood and

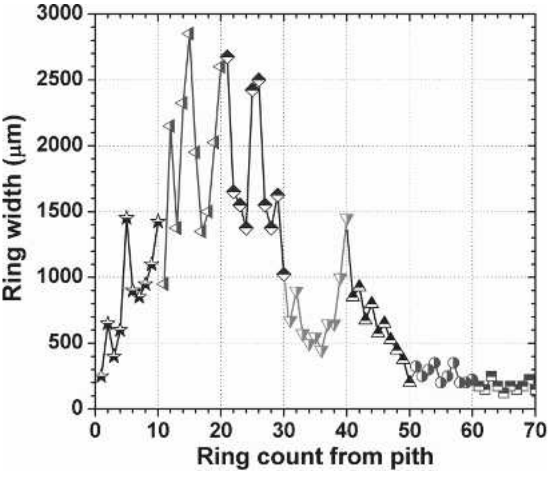

FIGURE 2. SilviScan measured annual ring width of the wood core sample.

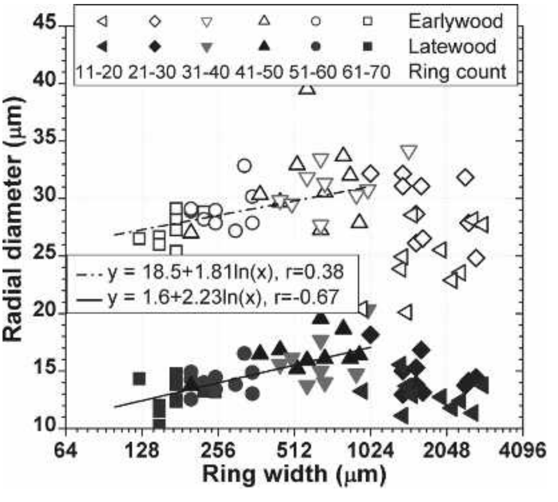

FIGURE 3. The correlations between Ring Profiler average tracheid radial diameter and annual ring width.

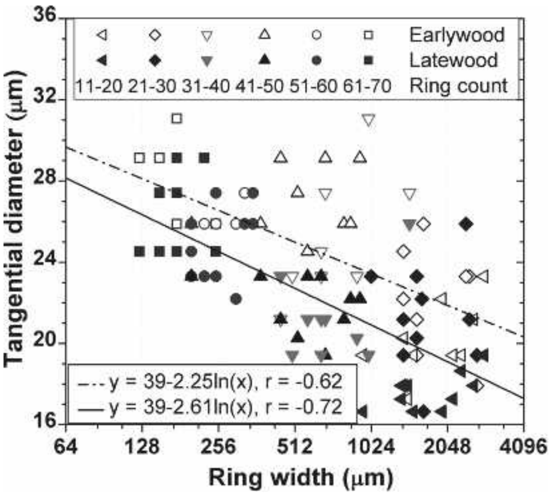

FIGURE 4. The correlations between Ring Profiler average tracheid tangential diameter and annual ring width.

latewood band were correlated to the corresponding annual ring width (Fig 5). The shapes of symbols identify the ring number group as shown in Fig 2. The results 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 due to growth suppression was similar to that observed in plantation red pines with higher stand densities in our previous study (Zhu et al 2007c). The effect of growth suppression is much more pronounced in reducing latewood density than in increasing earlywood density. Only the data from the last 40 yr of tree growth were used in performing the correlations.

Tracheid wall thickness

Figure 6 shows the Ring Profiler average earlywood and latewood tracheid wall thicknesses in both the radial and tangential directions. All the tracheid wall thicknesses decreased linearly as annual ring width decreased. However, the data indicate that the latewood tracheid wall thickness decreases more rapidly than the earlywood in both the radial and tangential directions. This is particularly true for the tracheid tangential wall thickness. The slope of the linear correlation between the wall thickness and the annual ring width for latewood was 3 times greater than the slope for earlywood in the tangential direction (only data from ring width less than 800 μm were used in the linear regressions), while in the radial direction, the slope for latewood is 2 times greater than for earlywood. The differences in the reduction of tracheid wall thickness between earlywood and latewood resulted in more uni-

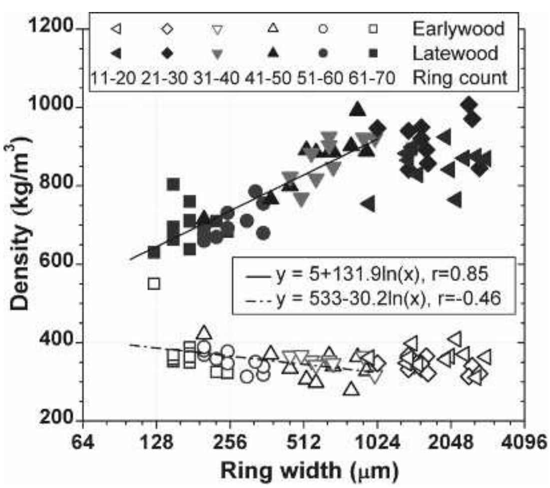

FIGURE 5. The correlation between calculated wood density based on tracheid geometry and annual ring width.

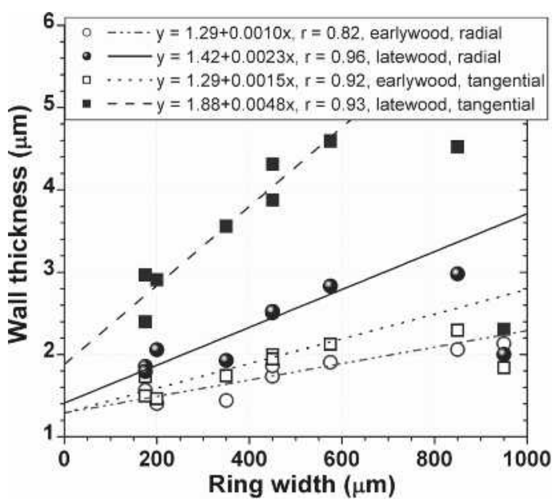

FIGURE 6. The correlations between earlywood and latewood tracheid wall thickness in both the radial and tangential directions and annual ring width.

form distributions of tracheid wall thickness in both the tangential and radial directions.

Comparison with literature results

We recognize that the results of the present study were obtained from only one sample. However, the results from the sample were consistent with other studies in the literature, as discussed below. Literature studies of the effects of tree-growing conditions on fiber properties are primarily focused on plantation forestry. However, qualitative comparison with the present study is possible if we equate the effects of drought in plantations with the effects of suppression growth in the natural forest. For example, it has long been recognized that drought contributes to a decrease in tracheid diameter and the formation of latewood (Larson 1963). Furthermore, drought exerts more influence on latewood than on earlywood development. These observations agree with the results shown in Fig 3; ie, radial diameter decreases with the decrease of annual ring width due to growth suppression. Moreover, wood density data in Fig 5 clearly show that growth suppression in our sample significantly reduced latewood density but did not reduce the density of earlywood. An accepted explanation of this effect on wood density is that earlywood forms rapidly and occurs at the expense of stored moisture, energy, or nutrients. If drought or growth suppression continues, a premature transition to latewood or false rings can occur (Zahner and Oliver 1962; Larson 1963; Zahner et al 1964) and the tree produces a small amount of latewood. Zahner and Oliver (1962) and Zahner et al (1964) revealed that the number of tracheid layers for both earlywood and latewood were significantly reduced when plantation red pines were grown under simulated drought or unthinned. They indicated that on average, earlywood tracheid layers were reduced from 160–110, or 31% in the upper bole for ring 20 (Zahner et al 1964), while latewood tracheid layers were reduced from 23–16, or 30% in the upper bole. Similar reductions were noted in the lower bole. This reduction in tracheid layers in both earlywood and latewood due to drought is similar to the effect of growth suppression on the sample tree used in this study as shown in Table 1. When comparing ring 40–39, and comparing ring 50–49, the effects of growth suppression can be clearly seen. From ring 39–40, growth suppression was somehow significantly reduced as indicated by the sudden increase in the width of ring 40 (Fig 2). At the same time, the numbers of earlywood and latewood tracheid layers increased accordingly from 20–31, and from 20–30, respectively (Table 1). From ring 49–50, growth suppression was increased as can be seen from the sudden reduction in the width of ring 50 (Fig 2). At the same time, the numbers of earlywood and latewood tracheid layers also decreased from rings 6–4 and 12–7, respectively, below the values for most of the 50–60 ring range.

Zahner and Oliver (1962) and Zahner et al (1964) also reported fewer total latewood tracheids with exceptional wall thickening (no quantitative data) under drought or without thinning. This also qualitatively agrees with what was observed in the present sample, shown in Fig 6; ie growth suppression significantly reduced latewood tracheid wall thickness more than earlywood. The data in Fig 6 also confirm

TABLE 1. *Comparison of the effects of tree growth conditions between the present study and literature results.*

	Zahner et al (1964)		Present study	
Species	Plantation red pine (among trees)		Natural grown Douglas fir (within one tree)	
Ring no.	20 (Upper bole)		39 → 40	49 → 50
Growth conditions	Irrigation	Drought	Growth suppression relieved	Growth suppression increased
Ring width (mm)	6.5	3.8	1.00 → 1.45	0.375 → 0.2000
Earlywood cell layers	160	110	20 → 31	6 → 4
Latewood cell layers	23	16	20 → 30	12 → 7

our discovery (Klungness et al 2006; Zhu et al 2007b) that growth suppression produces trees with more uniform tracheid wall thickness. In these studies, we compared the tracheid wall thickness distribution between a normal and a suppressed-growth lodgepole pine. There was a clear distinction between earlywood and latewood tracheid wall thickness in the normal lodgepole pine but not in the suppressed-growth sample.

CONCLUSIONS

This study demonstrates that ring-width correlations are an effective way to study the effects of tree-growth suppression in natural forests on wood density and tracheid anatomical properties. The results from this study suggest that growth suppression in natural forests creates a growing condition that results in fiber structure similar to drought with small radial and large tangential diameters for both earlywood and latewood. Growth suppression also produces more uniform wood density and tracheid wall thickness in both the tangential and radial directions. The increased material uniformity agrees with that observed in plantation red pine as stand density increased (Zhu et al 2007c). Increased material uniformity through growth suppression in natural forests suggests that chips from suppressed-growth trees may be suitable for pulp and paper production.

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