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Assessing the Within-Tree Variation in Stiffness from Ultrasonic Velocity and Specific Gravity Measurements in Douglas-Fir and Loblolly Pine

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Abstract

Roundwood is increasingly sourced from highly productive plantations that yield excellent growth. Information is needed on the wood properties from plantations because these trees will contain a higher proportion of low stiffness corewood compared to naturally regenerated trees of the same size. The objective of this study was to examine the within-tree variation in stiffness for Douglas-fir and loblolly pine grown in the United States through assessment of specific gravity (SG) and ultrasonic velocity (USV). Approximately 500 pith-to-bark radial strips collected from multiple height levels from each species were processed via a book-matched technique to yield a 2 mm tall (longitudinal) SG sample and an 8.5 mm tall USV sample. Ring-by-ring SG was measured using x-ray densitometry. Time-of-flight USV was measured in the longitudinal direction at 10 mm radial resolution using two 1-MHz delay line transducers with the distance between the two transducers measured at each radial location using a LVDT sensor. Patterns of USV followed the asymptotic patterns similar to the inverse of microfibril angle both radially and by height level. For Douglas-fir, radially at the pith and vertically at the stump, USV values averaged 3,750 m/s whereas at upper height levels at the pith USV values averaged 4,250 m/s. At the stump, USV reached asymptote values at 25 years compared to 15 years for other height levels. This

presentation will focus primarily on the measurement of the USV and the relationships discussed between USV with SG, tracheid length and microfibril angle.

Keywords: acoustic velocity, nondestructive testing, *Pinus taeda*, *Pseudotsuga menziesii*, wood and fiber quality

Introduction

Trees in forest plantations grow faster than their natural counterparts, and thus plantations allow for much shorter rotation lengths than in the past. As such, roundwood is increasingly being sourced from short rotation plantations as they provide a sustainable and consistent source of roundwood. However, the reductions in rotation age result in wood having a much larger proportion of corewood (juvenile wood) in the merchantable trees (Burdon et al. 2004; Moore and Cown 2017). Corewood, starting from the pith, and laid down outward, is the wood formed in young trees, while outerwood is formed later on as the tree matures (Burdon et al. 2004; Lachenbruch et al. 2011). Corewood is characterized by lower stiffness and strength, and higher longitudinal shrinkage, compared to outerwood (Larson et al. 2001).

The specific mechanism for the lower stiffness is dependent on a particular species because of different patterns of wood variability. Douglas-fir (*Pseudotsuga menziesii*) has arguably the most typical specific gravity (SG) radial trend whereby SG is high near the pith, decreases in the transition wood, and then increases in the outerwood (Kimberley et al. 2017). Hard pines, including loblolly pine, have an increasing trend of SG from pith to bark (Dahlen et al. 2018). For loblolly pine, the reason for the low SG near the pith is due to the low proportion of latewood to earlywood tracheids, lower cell wall thicknesses, and lower latewood SG (Megraw 1985; Larson et al. 2001; Dahlen et al. 2018). As the SG increases for loblolly pine, the width of the rings decrease (Dahlen et al. 2018). For Douglas-fir, the reasons for the decrease in SG are debatable, but it likely corresponds to an increase in the diameter of the tracheids without a comparative increase in cell wall thickness. Douglas-fir also has a decrease in ring width in approximately the first ten years, which corresponds to the decreasing SG during this period. While SG has variable patterns of radial variability, microfibril angle (MFA) appears to have a universal pattern radially regardless of species. MFA decreases from pith to bark and this decrease corresponds to an increase in wood stiffness (Larson et al. 2001). In addition to radial variation, wood properties of softwoods also vary with height for a given cambial age; Burdon et al. (2004) illustrated this point by differentiating between mature corewood higher in a tree and juvenile corewood at the base, the latter being formed when the tree was young. For a given cambial age, both Douglas-fir and loblolly pine displays a decrease in SG with increasing height (Megraw 1985). Regarding MFA, values of MFA are high in the butt log and decrease with increasing height (Jordan et al. 2007).

Measuring radial and longitudinal variation in SG is routine with the use of X-ray densitometry systems, and numerous laboratories have access to a variety of densitometer systems at reasonable costs (Jacquin et al. 2017). Measuring MFA is less routine due to the expensive hardware required for X-ray diffraction instruments (Evans 1999), and thus relatively few laboratories have access to in-house systems. One alternative to X-ray diffraction is to not measure MFA, and instead measure a surrogate property. To this end, measuring the longitudinal acoustic velocity is a promising alternative to measuring MFA since increasing AV is associated with decreasing MFA and increasing tracheid length (Hasegawa et al. 2011). The increasing AV is independent of changes in SG (Mason et al. 2017). Longitudinal velocity increases from pith to bark, whereas radial and tangential velocity do not (Hasegawa et al. 2011). Dynamic modulus of elasticity (MOE) can also be assessed by:

$$\mathrm{MOE_{dyn}} = \rho \mathrm{AV}^2 \tag{1}$$

where MOE_{dyn} is dynamic MOE, p is the density and V is the acoustic velocity (Ross 2015). Acoustic evaluation is common on standing trees using time of flight techniques. Here, a transmitting transducer sends a sound wave via a mechanical impact to a receiving transducer and the time to send is recorded (Grabianowski et al. 2006; Auty and Achim 2008; Mora et al. 2009; Wessels et al. 2011; Paradis et al. 2013). The time to send is combined with the length of the signal path to determine the acoustic velocity. Acoustics is also frequently employed in evaluating the velocity of logs, lumber and small clear samples using resonance techniques whereby the 1st harmonic frequency of an acoustic wave signal is measured (Carter et al. 2013; Moore et al. 2013; Wang 2013; Wang et al. 2013; Yang et al. 2015). Resonance approaches would not be suitable for assessing radial variability on in-tact samples, however the technique could be used if individual samples were cut from pith to bark. Most researchers want to avoid cutting a radial strip into smaller samples, since doing so will result in the radial measurements to not be automated, and care must be also taken with regards to keeping track of samples. Thus, time of flight systems are the most appropriate for assessing radial variability in acoustic velocity but challenges need to be overcome before doing so. One challenge with using time of flight approaches on small samples is the frequency of the transducer must be much higher than comparable tree-based systems; these systems typically employ transducers with frequencies in the low kHz ranges. Such an approach would be unsuitable for assessing samples collected from cores and disks due to the length of the wavelength generated at these frequencies, calculated by:

$$\Lambda = \frac{v}{f} \tag{2}$$

where Λ is wavelength with units of m, v is velocity with units of m s^{-1}, and f is frequency with units of Hz (s^{-1}). For example, measuring the velocity of wood near the pith with 3500 m s^{-1} velocity using a 10 kHz transducer would result in wavelength being approximately 350 mm in length, clearly much larger than the diameter of any core sample. To decrease the length of the wavelength, transducers with much higher frequencies are employed. Ultrasonic transducers utilize frequencies greater than 20 kHz (Senalik et al. 2014), and when assessing samples prepared from cores or disks frequencies between 500 kHz and 1 MHz are typically employed (Mason et al. 2017; Schimleck et al. 2019). For example, Mason et al. (2017) used 500 kHz transducers on disk samples 60 mm thick to evaluate MFA variability in disks, and they concluded this was an effective and lower cost alternative to an x-ray diffraction system. For assessing samples collected from 12-mm cores, a 1 MHz transducer would be suitable (Schimleck et al. 2019). Another challenge that needs to be overcome is the coupling between the transducer and the sample (Schimleck et al. 2019).

The objective of this work is to measure the longitudinal ultrasonic velocity (USV) from pith to bark and at multiple height levels for Douglas-fir and loblolly pine. The long-term objective of this work is to develop relationships between USV and MFA as well as tracheid length, and to develop models that explain the changes that occur with cambial age and height in the tree for USV. Combining USV models with models developed for SG will allow for the generation of tree maps for wood stiffness, similar to the SG maps generated by Dahlen et al. (2018).

Materials and Methods

Wood Samples

The Douglas-fir samples were acquired from a 41-year-old plantation from the Stand Management Cooperative (SMC) Type 1 installations. The objective of the Type 1 study was to provide data on the impact of pre-commercial thinning, commercial thinning, and fertilization on Douglas-fir grown throughout the Northwest United States. From the plantation sampled, eleven trees from nine plots were felled, and disks were collected at two fixed heights and three variable heights. The fixed height locations were at the stump and at the top of the first log (4.9 m height). The variable locations were at the base of the live crown, mid-point between the base of the live crown and the 10 cm top, and the 10 cm top. The loblolly pine samples were collected as part of a lumber study focused on assessing the quality of lumber produced from the most intensively managed operational plantations available for loblolly pine at the time (Butler et al. 2016; Butler et al. 2017; Dahlen et al. 2018). Trees from five stands, age 24 to 33 years, were felled and the 93 trees in the study were cut into 5.2 m logs for use in the lumber study. A 50 mm thick disk was cut from the bottom and top of each log at the stump (0.15 m), 5.2 m, 10.4 m, 15.6 m height, towards the top of the tree at the height equal to 13 cm stem diameter, and at 20.8 m if the 13 cm diameter height was above 20.8 m.

The disks were stored in plastic bags and frozen until processing. To process the disks, radial strips were cut from bark-to-bark using a band saw, gently dried at 40°C until the moisture content was below 20%, and then left to air dry until approximately 12%. The strips were cut in half at the pith, and glued in between two wood coreholders. The samples were then cut on a four-blade table saw with a power feed to yield a book-matched acoustic sample measuring 8.5 mm (longitudinal), a densitometry sample measuring 2 mm (longitudinal), and a third sample that was designated for tracheid analysis (15 mm). Some samples were not tall enough to yield a tracheid sample and thus were cut to yield only the densitometer and acoustic sample. The length of the coreholders was approximately 0.9 m and thus multiple samples were prepared at one time. After the book-matched cutting process but prior to cutting out the individual samples from the processed coreholders, the 8.5 mm tall (longitudinal) acoustic velocity samples were sanded with 320-grit sandpaper on both transverse faces using a modified Brynes thickness sander (Brynes Model Machines, United States). Sanding improves the contact between the transducers by correcting any surface quality issues that may have occurred during processing. The samples were equalized in a room at approximately 22°C at 52% relative humidity, equivalent to approximately 10% moisture content.

X-Ray Densitometry

The densitometry strips were scanned on a QTRS-01X Tree Ring Scanner (Quintek Measurement Systems, United States). The instrument was setup to scan with a 0.06 mm radial step resolution and the X-ray beam passed through the sample on the transverse face. The instrument was calibrated to express SG on an oven dry weight and green volume basis (basic specific gravity). On the instrument, latewood was differentiated from earlywood for ring counting purposes based on a threshold SG value of 0.45 for Douglas-fir and 0.48 for loblolly pine.

Ultrasonic Velocity

The acoustic velocity samples were scanned on an OPUS instrument (SoniSys, United States) at 10-mm radial resolution. The instrument uses two 1-MHz longitudinal delay line transducers with the top transducer transmitting the acoustic signal to the bottom transducer which receives the acoustic signal. The surface diameter of the delay lines is 10-mm, and they are attached to a 0.9 mm layer of neoprene using 3M #453 transfer tape (3M, United States). Neoprene as a couplant was first selected as alternative to gel couplants for testing paper, since gel couplants would absorb into paper and thus affect the velocity readings (Habeger et al. 1988). We have found that the neoprene is an effective couplant for solid wood samples, as well as the calibration materials tested here. The instrument is calibrated for thickness measurements using two reference shims using a linear variable differential transformer (LVDT) sensor, and calibrated against reference materials of aluminum (6320 m s^{-1}), brass (4430 m s^{-1}), and PVC (2395 m s^{-1}) blocks approximately 7.5 mm in height. For each acoustic reading, the instrument measures the thickness of the sample using the LVDT sensor, and the time required to transmit from the sending to receiving transducer; each time reading is an average value of 100 readings taken on the instrument. The acoustic velocity is then calculated by the time and the thickness measurements.

To move the sample from pith to bark, an automated movement system was built specific to the instrument. The system consists of a linear stage using a stepper motor which is controlled using a programmable logic controller and a touch screen interface. The programmable logic controller is programmed using C++ and the touch screen interface is programmed using Python, with communication between the two using serial communication. The touchscreen interface is used to input the length of the sample. When the last measurement reading is less than the 10 mm transducer diameter, the sample is moved the remaining distance of a sample. For example, if a sample is 127 mm, the sample is moved 12 times at 10 mm radial increments, and the final time at a 7 mm radial increment. The programmable logic control system will move the linear stage after each reading when the top transducer returns to the home position; this is done by way of a photoelectric U-Frame fork sensor.

Data Analysis

The statistical analysis and associated graphics were done in R statistical software (R Core Team 2019) with RStudio interface (RStudio 2019) and the tidyverse series of packages (Wickham and RStudio 2017) and gridExtra (Auguie 2016). At the time of writing this conference paper, two pieces of the studies are incomplete. The first is the densitometer work on the loblolly pine samples, and the second is the calibrations between the USV measurements and MFA using the SilviScan system (Evans 1999). As a temporary solution to this, we will report USV values in distance from the pith for both loblolly pine and Douglas-fir. And we will report estimated MFA using the model developed by Mason et al. (2017) on radiata pine. Following completion of the densitometry measurements, the USV data at 10 mm radial resolution will be matched with the densitometer data, and then the ring counts from the densitometer will be used to calculate ring, earlywood, and latewood level measurements for SG and width, and ring level USV measurements.

Results and Discussion

A total of 5,390 10 mm USV readings were conducted on Douglas-fir, and 4,387 readings for loblolly pine. A summary of the USV measurements for Douglas-fir and loblolly pine is shown in Table 1. The table shows the mean, minimum, and maximum USV values by height level for the first reading at the pith, and the last reading at the bark. Generally, the values for Douglas-fir are higher than loblolly pine, which matches the literature whereby Douglas-fir has generally lower MFA than loblolly pine. The values are particularly evident at the stump height, where the pith readings for Douglas-fir average 3738 m/s versus the 3261 m/s values for loblolly pine. Based on the USV to MFA equation developed by Mason et al. (2017), for Douglas-fir the mean predicted MFA at the pith is 26 degrees, with the stump having a predicted MFA of 29 degrees and the other height levels approximately 25 degrees. The MFA predictions are reasonable given that MFA was measured on breast height samples using an X-ray diffraction instrument at the Weyerhaeuser company, the pith samples at breast height averaged 28 degrees for these samples.

Table 1—Summary of ultrasonic velocity values measured from Douglas-fir and loblolly pine.

			Ultrasonic Velocity (m/s)					
			Pith Readings			Bark Readings		
Species	Height Description	Mean Height (m)	Mean	Min	Max	Mean	Min	Max
Douglas-fir	Stump	0.2 m	3738	2865	4720	5184	4516	5635
	First Log	4.3 m	4215	3052	4836	5519	4815	5925
	Base Live Crown	15.5 m	4160	3167	4848	5425	4455	5979
	Midpoint Live Crown	19.1 m	4257	3142	4876	5338	3923	6021
	10 cm Top	22.4 m	4230	3419	4952	5220	4179	5978
Loblolly Pine	Stump	0.15	3261	2703	3757	4971	4217	5553
	First Log	5.2	3582	2420	4158	5083	4265	5495
	Second Log	10.4	3689	2836	4210	5045	4307	5445
	Third Log	15.6	3815	2743	4191	4894	4231	5386
	Fourth Log	20.8	3787	2749	4220	4709	3804	5201
	13 cm Top	22.3	3770	3183	4184	4594	4096	4950

For loblolly pine, the mean predicted MFA at the pith is 30 degrees, with the stump having a predicted MFA of 34 degrees and with increasing height this decreases to 29 degrees. These predicted MFA values by height level are similar to the MFA values that Jordan et al. (2007) report for loblolly pine as measured using SilviScan (Evans 2001). Jordan et al. (2007) did not measure MFA at the stump height, but Schimleck et al. (2009) did and analyzing this dataset shows that the MFA values at the stump are similar to the predicted MFA reported here.

In addition to USV values at the pith and the bark, an important component of the work is determining how long the transition from low velocity values to higher velocity values takes in terms of ring number or distance from the pith (Figure 1). For Douglas-fir, the USV values uniformly increase with distance from the pith, although the rate of change for the stump height is slower than the other disks. For loblolly pine, the stump height rate of change is minimal for the first 5 cm, and then increases similar to the other disks. This results in USV values for the stump height that reach 5000 m/s approximately 15 cm from the pith. The other disks reach their asymptotic values approximately 7 cm from the pith. These MFA values match the typical patterns that Jordan et al. (2007) found whereby values in the first log take much longer to reach asymptotic values than in the rest of the tree.

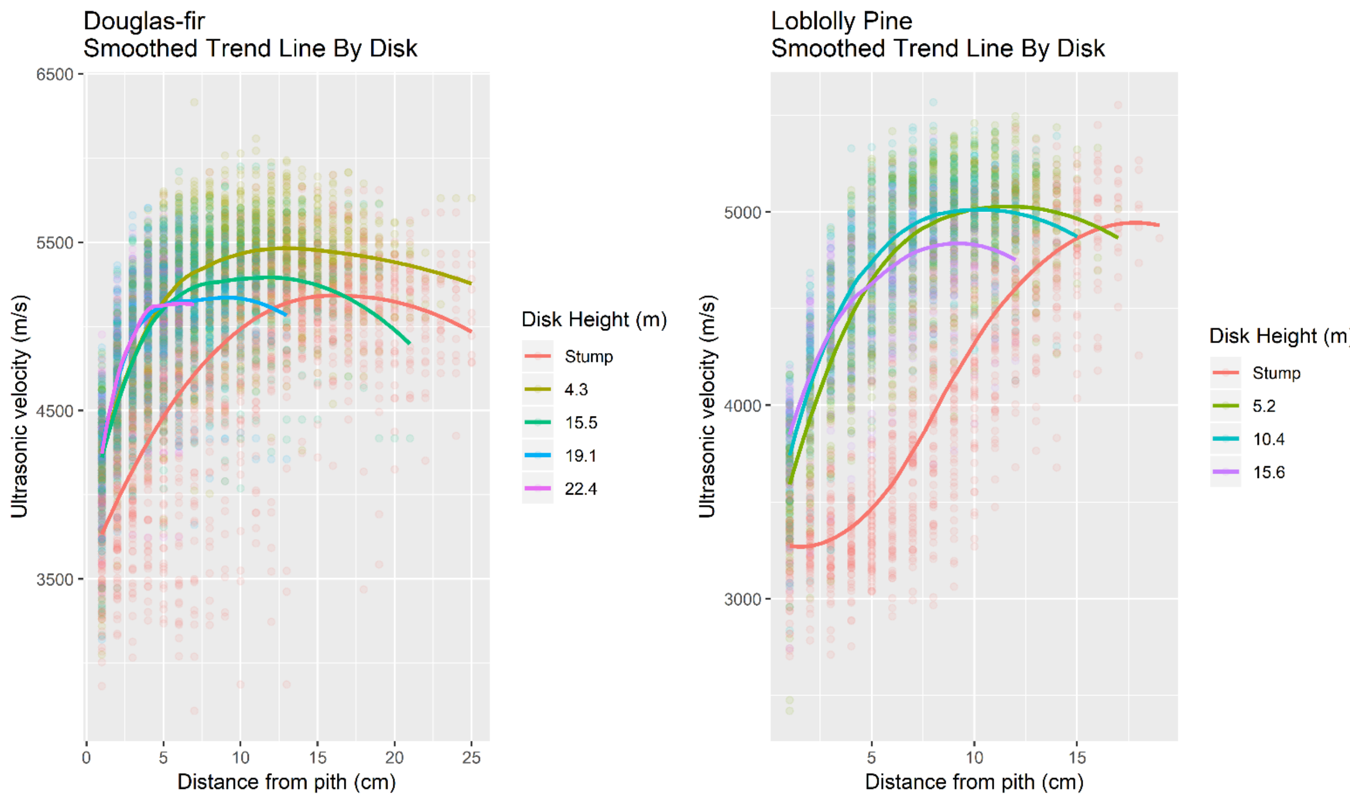

Figure 1—Ultrasonic velocity values based on distance from the pith for Douglas-fir and loblolly pine. The data points and smoothed lines are shown by disk height.

Conclusions

This work showed that USV measurements match the values that would be expected for MFA for Douglas-fir and loblolly pine. Generally, Douglas-fir had higher USV at the pith than did loblolly pine. The implication from this is that Douglas-fir would have lower MFA, higher stiffness and lower longitudinal shrinkage than loblolly pine. Future work will report USV values with cambial age rather than distance from the pith, however at the time of writing this the densitometer work for loblolly pine was not complete and thus the paper reports USV values in distance from the pith. Future work will also correlate USV readings with MFA measured using SilviScan, and tracheid length on macerated samples measured using a commercial fiber analyzer. Models will be developed that predict USV as a function of cambial age and height within tree and these models will be used to construct within tree variation maps for USV and wood stiffness calculated from SG and USV.

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