



Whole-tree tracheid property maps for loblolly pine at different ages

Laurence R. Schimleck¹ · Finto Antony² · Christian Mora³ · Joseph Dahlen²

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Abstract

Maps developed using Akima's interpolation method, and representing average data for trees aged 13 and 22 years, were used to compare patterns of within-tree variation for *Pinus taeda* L. (loblolly pine) tracheid properties: coarseness (C), specific surface (S), radial (R) and tangential (T) diameter and wall thickness (w). SilviScan-calibrated near-infrared (NIR) spectroscopy provided data for the analysis with C ($R_c^2 = 0.85$, $R_p^2 = 0.85$), S ($R_c^2 = 0.83$, $R_p^2 = 0.76$), and w ($R_c^2 = 0.89$, $R_p^2 = 0.93$) models having very good calibration / prediction statistics, while those for T and R diameter were moderate ($R_c^2 = 0.79$, $R_p^2 = 0.57$) and poor ($R_c^2 = 0.64$, $R_p^2 = 0.19$), respectively. C , S , and w maps were similar to the density maps for *P. taeda* and indicate the properties increase radially at all heights. The T diameter map was similar to maps reported for microfibril angle except that T diameter increased radially and with height whereas microfibril angle decreased radially and with height. The map for R diameter increased with height and was unlike the other properties examined; caution is recommended regarding any interpretations based on the R diameter map owing to the weak statistics observed for the NIR model. Changes observed between the two ages are consistent with the asymptotic progression of properties associated with maturation.

✉ Laurence R. Schimleck
Laurence.Schimleck@oregonstate.edu

¹ Department of Wood Science and Engineering, College of Forestry, Oregon State University, Corvallis, OR 97331, USA

² Warnell School of Forestry and Natural Resources, University of Georgia, 180 E. Green Street, Athens, GA 30602, USA

³ Fibraconsult, 4030000 Concepcion, Chile

Introduction

Examination of the within-tree variation of wood properties has been an ongoing topic of research for many years. A knowledge of how wood properties vary within trees is critical in developing an understanding of the effects of tree age on wood formation and for the optimal utilization of wood as a raw material. However, such studies are costly, time-consuming and difficult owing to the large number of samples required to achieve the level of detail necessary to describe radial and longitudinal variation accurately. Subsequently, few properties, other than perhaps density determined by X-ray densitometry, have been explored in detail in large numbers of trees.

SilviScan has made it possible to examine the within-tree variation of a range of additional wood properties at high spatial resolution. Unfortunately, SilviScan analysis can be prohibitively costly if examination of a large number of trees or multiple heights per tree is required. Near-infrared (NIR) spectroscopy, calibrated with SilviScan data, provides an alternative method for examining within-tree variation of wood properties. An approach for developing NIR calibrations applicable to *Pinus taeda* L. (loblolly pine) trees at multiple heights and radial positions was described by Schimleck et al. (2009). Models for density, microfibril angle (MFA) and stiffness (MOE), based on NIR spectra collected in 10 mm increments from selected sections of selected radial strips at specific heights, were developed. The models were used to predict the three properties in 10 mm increments for all strips (411) at all heights (the number of heights sampled ranged from 9 to 13) for 18 trees aged 13 years and another 18 trees aged 22. Mora and Schimleck (2009) utilized the NIR-predicted data to explore the use of three spatial interpolation algorithms (Akima, universal kriging and semiparametric regression methods) for mapping density and MFA variation within the 13-year-old trees. More recently, Schimleck et al. (2018) utilized the Akima interpolation method to compare how patterns of within tree variation for density, MFA and stiffness in *P. taeda* changed between the ages of 13 and 22.

The determination of density, MFA and stiffness by SilviScan is based on measurements from X-ray densitometry and X-ray diffraction equipment, and these properties are most frequently measured. An image analysis system provides additional data; however, the cost of analysis is higher owing to preparation of the transverse surface of radial strips for radial strips and the time required to examine samples. Radial (*R*) and tangential (*T*) diameter are measured using the image analysis system, and these direct measurements combined with density data, provide information on coarseness (*C*) a measure of tracheid mass per unit length (Li et al. 2014), specific surface (*S*) a measure of tracheid surface area per unit mass (Li et al. 2014) and wall thickness (*w*). These properties are not associated with solid wood products directly; however, tracheid size and wall thickness are related closely to density (Burdon et al. 2004) and all are important in determining pulp quality and paper performance, for example, low coarseness is associated with improved properties of Kraft and mechanical pulps (Burdon et al. 2004).

Few studies have reported maps for these properties. Examples include coarseness, perimeter (P , and where $P = 2(R + T)$) and wall thickness in *Pinus radiata* D. Don (radiata pine) (Evans et al. 1995), and coarseness in *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) (Defo et al. 2009). While Mäkinen et al. (2007) and Dahlen et al. (2020) developed maps of tracheid length and width for Norway spruce (*Picea abies* (L.) Karst.) and *P. taeda*, respectively, and Ikonen et al. (2008) developed maps for tracheid length for Scots pine (*Pinus sylvestris* L.). To the best of the authors' knowledge, the only maps that exist for *P. taeda* tracheid properties were reported by Lundqvist et al. (2005). In addition, the authors are not aware of maps comparing patterns of tracheid property variation at different ages.

Potentially maps can be developed for *P. taeda* tracheid properties based on NIR-predicted data, utilizing the methods described in Schimleck et al. (2009) and Mora and Schimleck (2009). Schimleck and Evans (2004) and Jones et al. (2005) have reported NIR calibrations for tracheid properties based on spectra from radial strips for *P. radiata* and *P. taeda*, respectively. A common aspect of both studies was that the calibration samples were obtained from breast height only and therefore are not applicable to samples from multiple heights. If the within-tree variation of tracheid properties is to be predicted, predicted using NIR spectroscopy, multiple height calibrations are required. Hence, the objectives of this study were to:

- develop multiple height NIR-based calibrations for C , S , R diameter, T diameter and w ;
- use Akima's interpolation method as employed by Mora and Schimleck (2009) to develop maps showing the within-tree variation of C , S , R diameter, T diameter and w for *P. taeda* trees aged 13 and 22 years and;
- compare maps for the five properties for trees aged 13 and 22 years.

Materials and methods

Sample origin

Two groups of eighteen *P. taeda* trees, aged 13 and 22 years, respectively, were sampled from a half-sib progeny trial planted at International Paper's (IP) Southlands facility located in the lower coastal plain near Bainbridge, GA. For *P. taeda*, large industrial landowners typically perform a first thinning from 11 to 16 years after establishment, a second thinning from 16 to 21 years, and a final harvest from 22 to 27 years. Thus, the data represent trees from a first thinning and a final harvest scenario.

The trees were a subsample of two larger populations selected to encompass the range of cellulose, lignin and specific gravity variation as measured by IP. Selected trees were felled, and samples were removed for wood property and NIR analyses. Disks (25 mm thick) were taken at 1.5 m intervals along the stem of each tree, giving 9 to 13 disks per tree (number depended on tree height). A total of 191 disks were collected from trees aged 13 years, while 220 were obtained from the 22-year-old trees, giving a total of 411 disks.

Sample preparation: radial strips

Pith-to-bark radial sections were cut from each disk using a bandsaw. Section dimensions were 12.5 mm longitudinally by 12.5 mm tangentially with the radial length corresponding to the length of the sample. Radial sections were gently dried, glued into core holders and cut using a twin-blade saw to give strips 2 mm thick (tangentially) using the methodology described in Jordan et al. (2008).

Near-infrared spectroscopy and SilviScan analysis

Schimleck et al. (2009) provide a detailed description of the methodology used to collect NIR spectra and develop predictive NIR models for air-dry density, MFA and MOE, and the same approach was used in this study for tracheid properties.

Briefly, NIR spectra were collected in 10 mm increments from the radial-longitudinal face (consistent with the orientation of the sample for SilviScan analysis) of each radial strip using a FOSS NIRSystems Inc Model 5000 scanning spectrometer. The utilization of radial-longitudinal face NIR spectra for models has provided slightly better results than transverse surface spectra (Schimleck et al. 2005).

The total number of spectra collected was 2569 (1114 from 13-year-old trees and 1455 from trees aged 22 years). A subsample of 72 strips (two from each tree and representing different heights) was selected for SilviScan determination of the following tracheid properties (Evans 1994, 1999, 2006):

- Tracheid radial (R) and tangential (T) diameters were measured in 25-micron intervals using image analysis (Evans 1994); and
- Tracheid coarseness (C), specific surface (S) and wall thickness (w) (also in 25-micron intervals) were estimated using the following relationships (Evans 1994):

$$C = RTD \quad (1)$$

$$S = P/C \quad (2)$$

$$w = P/8 - 1/2(P^2/16 - C/d)^{1/2} \quad (3)$$

Note: D , air-dry density and was determined using X-ray densitometry on SilviScan (Evans 1994), P , perimeter ($P = 2(R + T)$) and d is approximately equal to 1500 kg/m^3 for all softwoods (Kellogg et al. 1975).

SilviScan data were averaged over 10 mm sections from pith-to-bark for correlation with the 10 mm NIR spectra data (477 in total, representing 179 and 298 spectra from trees aged 13 and 22 years, respectively) as shown in Schimleck et al. (2018).

Tracheid property calibrations: phase 1

The two groups combined to give a total of 477 spectra (set 1 = 179 spectra (one section was only 40 mm long explaining why there was not 180 spectra) and set 2 = 298 spectra) and then split into calibration (320 spectra) and prediction (157 spectra) sets. The calibration set was comprised of samples from 24 trees (12 each from set 1 and set 2), while samples from 12 trees (6 each from set 1 and set 2) were present in the prediction set. A statistical summary of the calibration and prediction sets is given in Table 1. Note wood property calibrations (air-dry density, MFA and stiffness) are reported in Schimleck et al. (2009).

Tracheid property calibrations were developed using the Unscrambler (version 9.2) software package (Camo AS, Norway). Untreated spectral data were used to create the calibrations using partial least square (PLS) regression. Calibrations were developed with four cross-validation segments.

Calibration performance was assessed using the following parameters:

- Standard error of calibration (SEC) determined from the residuals of the final calibration;
- Standard error of cross-validation (SECV) determined from the residuals of each cross-validation phase;
- Coefficient of determination (R^2), the proportion of variation in the calibration set that was explained by the calibration;
- Ratio of performance to deviation (RPD_c) (Williams and Sobering 1993), calculated as the ratio of the standard deviation of the reference data to the SECV.
- Standard error of prediction (SEP) determined from the residuals of predictions of a parameter of interest for a set of samples not included in the calibration set.
- Coefficient of determination for the prediction set (R_p^2), the proportion of variation in the independent prediction set explained by the calibration; and
- RPD_p (which is similar to the RPD_c) but uses the standard deviation of the prediction set reference data and the SEP.

Table 1 Statistical summary of SilviScan-measured properties, the calibration and prediction sets

Wood Property	Calibration set (320 spectra)				Prediction set (157 spectra)			
	Minimum	Maximum	Av	SD	Minimum	Maximum	Av	SD
Coarseness ($\mu\text{g}/\text{m}$)	287.0	812.0	523.3	120.3	322.4	730.8	513.5	99.2
Radial diameter (μm)	25.1	41.0	32.7	2.9	34.3	39.3	32.6	2.4
Specific surface (m^2/kg)	165.4	391.9	263.9	50.5	175.9	368.7	264.0	44.6
Tangential diameter (μm)	23.3	37.3	30.4	2.8	24.3	37.7	30.2	2.6
Wall thickness (μm)	1.8	5.4	3.3	0.8	2.0	4.7	3.2	0.7

Determination of RPD allows comparison of calibrations for different properties that have differing data ranges and units, the higher the RPD the more accurate the data are described by the calibration or predicted.

Tracheid property calibrations: phase 2

Following phase 1, all samples were combined and used to develop tracheid property calibrations with all 477 spectra. The calibrations were then used to predict the wood properties of all 411 strips in 10 mm increments. As the calibration samples were a subsample of all samples, the subsequent calibrations were directly applicable to the spectra collected from the 411 strips.

Estimation of whole-tree averages

Mean tracheid properties for each age was calculated by weighting the volume of each radial point compared to the overall volume and then summing each respective height.

Maps of wood property variation within trees

Mora and Schimleck (2009) provide a detailed description of the methodologies they used to develop maps of within-tree variation for air-dry density, MFA and MOE. Three different methods were explored: Akima's interpolation, Universal kriging and semiparametric smoothing. Mora and Schimleck (2009) reported that for *P. taeda*, maps generated by Akima's interpolation method provided good representation of the expected trends in air-dry density and MFA. In addition, they reported that a principal advantage of Akima's algorithm over Universal kriging and semiparametric smoothing techniques was that only straightforward procedures were required, and there were no problems concerning computational stability or convergence. Owing to these features, only Akima's interpolation method was used to provide the maps that were used to compare tracheid property variation within trees aged 13 and 22 years.

Data analysis

The within-tree maps and data summaries were produced in the *R* statistical programming environment (R Core Team 2018) with the RStudio interface (RStudio 2018), and the *akima* (Akima and Gebhardt 2016), *dplyr* (Wickham and Francois 2016), *fields* (Nychka et al. 2015), and *lattice* (Sarkar 2008) packages. Correlations were explored between the tracheid properties here and the additions of density, MFA, and stiffness from Schimleck et al. (2018) at 13 and 22 years.

Results and discussion

Multiple height wood property calibrations: phase 1

Multiple height, tracheid property calibrations, developed using SilviScan data averaged in 10 mm increments and 320 NIR spectra are summarized in Table 2.

Strong calibration statistics were obtained for C , S , and w , however, only the w calibration had statistics similar to those reported for MFA and stiffness (Schimleck et al. 2009). Statistics for T diameter were moderate, while R diameter had a weak relationship even though 9 factors were recommended. Despite being developed with samples representing many different heights, the relationships reported in Table 2 agree well with those based on radial strips from a single height (breast height) for *P. radiata* (Schimleck and Evans 2004) and *P. taeda* (Jones et al. 2005).

When used to predict the tracheid properties of the test set, the performance of the calibrations varied. Predicted w had statistics better than those obtained for the calibration set ($RPD_p = 3.5$ versus $RPD_c = 2.67$), while those for C and S were similar to those reported for their respective calibrations. Predicted T diameter provided results ($R_p^2 = 0.57$, $RPD_p = 1.63$) that were weak compared to the corresponding calibration statistics and predicted R diameter had a very weak relationship with the equivalent SilviScan data. The relative performance of calibrations for each tracheid property (predicted w the strongest relationship and predicted R diameter the weakest) is consistent with results reported by Schimleck and Evans (2004) for *P. radiata* and Jones et al. (2005) for *P. taeda*. Nabavi et al. (2018) predicted tracheid width as measured on macerated tracheids using a fiber analyzer and found similar results ($R_p^2 = 0.61$, $SEP = 1.6 \mu\text{m}$) to the T diameter presented here; it is important to note that fiber analyzers do not differentiate between radial and tangential diameter as the measurements are done on macerated tracheids. Nabavi et al. (2018) found much stronger relationships with tracheid length ($R_p^2 = 0.87$, $SEP = 0.23 \text{ mm}$) with the results comparable to the C and w models found here.

Table 2 Summary of the multiple height *P. taeda* wood property calibrations developed for each wood property

Wood property	Calibration set (320 spectra)					Prediction set (157 spectra)		
	# factors	R^2	SEC	SECV	RPD_c	R_p^2	SEP	RPD_p
Coarseness ($\mu\text{g/m}$)	6	0.85	46.1	47.8	2.52	0.85	51.6	1.92
Radial diameter (μm)	9	0.64	1.7	1.9	1.53	0.19	2.3	1.04
Specific surface (m^2/kg)	3	0.83	20.7	21.3	2.37	0.76	20.4	2.19
Tangential diameter (μm)	9	0.79	1.3	1.4	2.00	0.57	1.6	1.63
Wall thickness (μm)	3	0.89	0.3	0.3	2.67	0.93	0.2	3.50

The numbers of factors used was identified by the Unscrambler software

Multiple height tracheid property calibrations: phase 2

Multiple height tracheid property calibrations developed using all available NIR spectra (477) are summarized in Table 3. Generally, calibrations based on all 477 spectra were as good, or better, than those presented in Table 2, the exception being *R* diameter despite an additional factor being used. These calibrations predicted tracheid properties of all 411 radial strips (set 1: 191 radial strips / 1114 spectra and set 2: 1455 spectra / 220 radial strips) in 10 mm increments. Summary statistics for predicted tracheid properties are given in Table 4 and concur with those reported in Table 1.

Whole-tree averages

Table 5 reports whole-tree averages for each tracheid property and for both the 13- and 22-year-old trees. Most properties increased with maturity but *S* decreased. Proportionally, *C* showed the greatest increase (27.3%) followed by *w* (20.7%). Percent changes for *R* and *T* diameter were 10.7 and 14.1%, respectively. The greater relative changes in *C* compared to tracheid dimensions explain why *S* decreased with age. Probability (density) plots (Fig. 1) show the variation of the predicted tracheid properties for the two data sets and allow observation of age-related shifts in property means. Based on the heights and diameters used to determine tracheid property maps, the 22-year-old tree has 52% more volume than the 13-year-old tree. The difference would have been larger, but the height of the

Table 3 Summary of the multiple height *P. taeda* wood property calibrations developed for each wood property using all 477 NIR spectra

Wood property	Calibration set (477 spectra)				
	# factors	R^2	SEC	SECV	RPD _c
Coarseness (μg/m)	7	0.86	42.7	44.2	2.57
Radial diameter (μm)	10	0.58	1.8	1.9	1.42
Specific surface (m ² /kg)	3	0.83	20.3	20.6	2.36
Tangential diameter (μm)	10	0.78	1.3	1.3	2.15
Wall thickness (μm)	3	0.90	0.3	0.3	2.67

The numbers of factors used was identified by the Unscrambler software

Table 4 Summary statistics of *P. taeda* wood properties predicted by NIR spectroscopy

Wood property	Minimum	Maximum	Average	SD
Coarseness (μg/m)	223.5	800.4	500.2	99.0
Radial diameter (μm)	22.9	37.7	32.6	2.5
Specific surface (m ² /kg)	127.6	382.5	274.2	40.7
Tangential diameter (μm)	23.5	35.6	30.0	2.5
Wall thickness (μm)	1.8	5.4	3.1	0.7

Table 5 Whole-tree averages for each *P. taeda* tracheid property for set 1 (aged 13 years) and set 2 trees (aged 22 years)

Tree	Coarseness ($\mu\text{g}/\text{m}$)	Radial diam. (μm)	Specific surface (μm)	Tangential diam. (μm)	Wall thickness (μm)
<i>13-year-old trees</i>					
1	506.8	32.0	248.0	28.9	3.4
2	497.2	30.7	249.6	28.0	3.3
3	469.2	30.5	276.1	27.5	3.0
4	478.3	30.4	270.5	28.1	3.1
5	450.0	30.7	292.3	28.9	2.8
6	450.2	31.0	288.7	28.4	2.8
7	447.5	29.9	275.4	27.4	2.9
8	444.6	31.2	282.6	29.3	2.9
9	469.6	30.2	266.0	27.8	3.0
10	416.4	31.9	301.5	29.2	2.6
11	437.4	30.8	291.3	27.9	2.7
12	431.3	29.9	286.7	27.9	2.8
13	454.3	30.4	283.4	28.6	2.9
14	428.0	30.4	301.8	27.9	2.7
15	446.9	30.4	285.8	27.8	2.9
16	445.9	31.6	291.8	28.9	2.8
17	426.9	30.8	296.3	28.2	2.7
18	464.6	31.4	270.5	28.5	3.1
Average	453.6	30.8	281.0	28.3	2.9
Std dev	23.9	0.62	15.6	0.57	0.21
CV	0.05	0.02	0.06	0.02	0.07
<i>22-year-old trees</i>					
1	589.6	32.7	242.6	31.9	3.5
2	577.0	35.6	258.7	32.8	3.5
3	580.9	33.6	251.7	31.6	3.4
4	632.3	34.5	230.9	33.1	3.8
5	550.4	34.0	250.4	32.5	3.3
6	573.2	34.8	256.1	33.3	3.4
7	529.9	35.0	259.2	32.3	3.0
8	559.6	33.7	258.4	31.7	3.3
9	605.9	32.5	233.4	31.8	3.8
10	574.1	33.1	251.2	31.9	3.6
11	596.0	33.0	236.8	32.1	3.7
12	580.7	33.5	251.7	31.9	3.6
13	546.4	33.9	262.0	31.6	3.4
14	587.8	33.5	243.0	32.6	3.6
15	578.5	35.1	247.2	32.7	3.6
16	595.9	34.4	248.3	33.0	3.6
17	550.3	35.3	263.7	32.7	3.3

Table 5 continued

Tree	Coarseness ($\mu\text{g}/\text{m}$)	Radial diam. (μm)	Specific surface (μm)	Tangential diam. (μm)	Wall thickness (μm)
18	586.3	34.9	249.3	32.1	3.5
Average	577.5	34.1	249.7	32.3	3.5
Std dev	24.1	0.93	9.5	0.54	0.2
CV	0.04	0.03	0.04	0.02	0.06

Summary statistics for all trees at each age are also provided

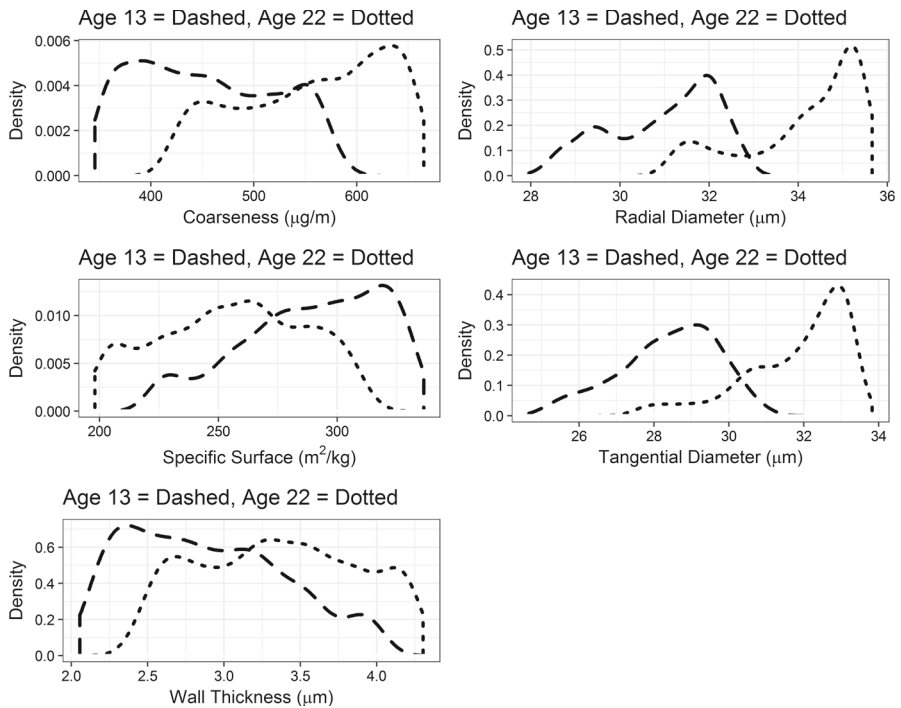


Fig. 1 Probability (density) plots showing the variation of the predicted tracheid properties for the two data sets. The area under the density curves has a probability of one

22-year-old tree was limited to 15 m to match the merchantable height of the 13-year-old tree.

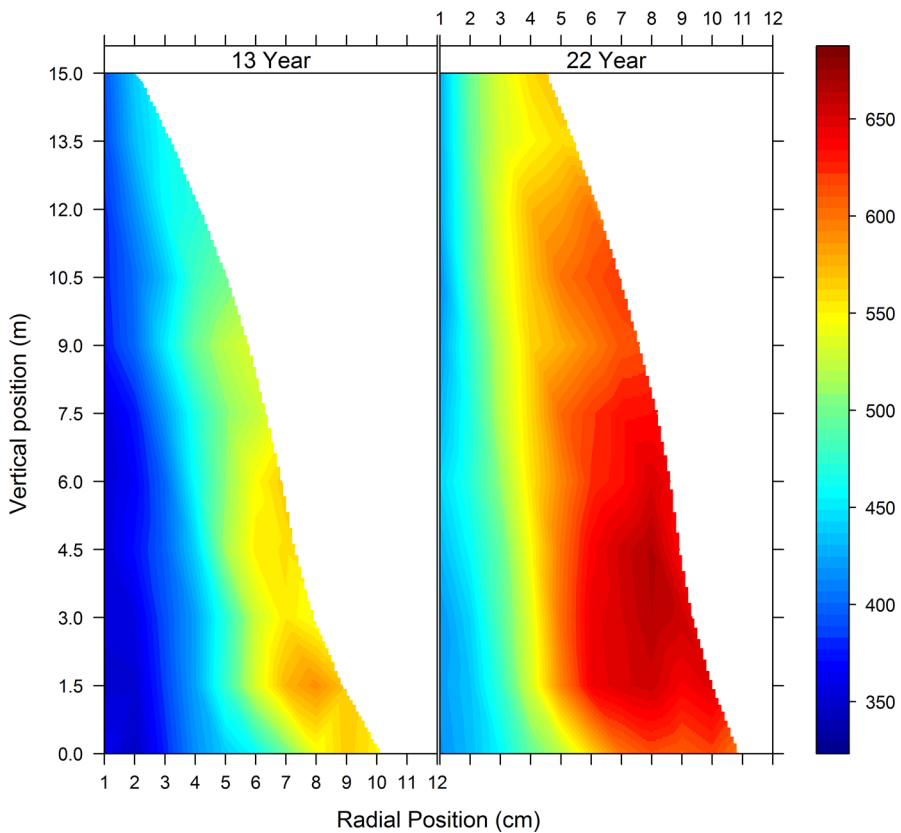


Fig. 2 Maps showing within-tree variation of coarseness ($\mu\text{g}/\text{m}$) for *P. taeda* trees aged 13 and 22 years. Maps represent the average of 18 trees and were developed using Akima's interpolation method

Tracheid property maps

Maps showing the within-tree variation of the five tracheid properties are shown in Figs. 2, 3, 4, 5 and 6. The maps represent the average of 18 *P. taeda* trees aged 13 and 22 years, respectively.

C , S , and w (Figs. 2, 3, 4) all have patterns of within-tree variation consistent with the air-dry density maps for *P. taeda* (Mora and Schimleck 2009; Schimleck et al. 2018). The maps are also very similar to those reported by Evans et al. (1995) for *P. radiata* and the C maps reported by Defo et al. (2009) for *P. menziesii*. As noted for density in *P. radiata* and *P. taeda* (Burdon et al. 2004), properties that demonstrate a radial increase at all heights have this pattern of variation. C , w and density are all strongly related at both ages (Table 6) with changes in density recognized as being directly related to w (in addition to percent latewood and lumen diameter) (Burdon et al. 2004), while S is determined from tracheid dimensions and C . Hence, the similarity in maps is to be expected.

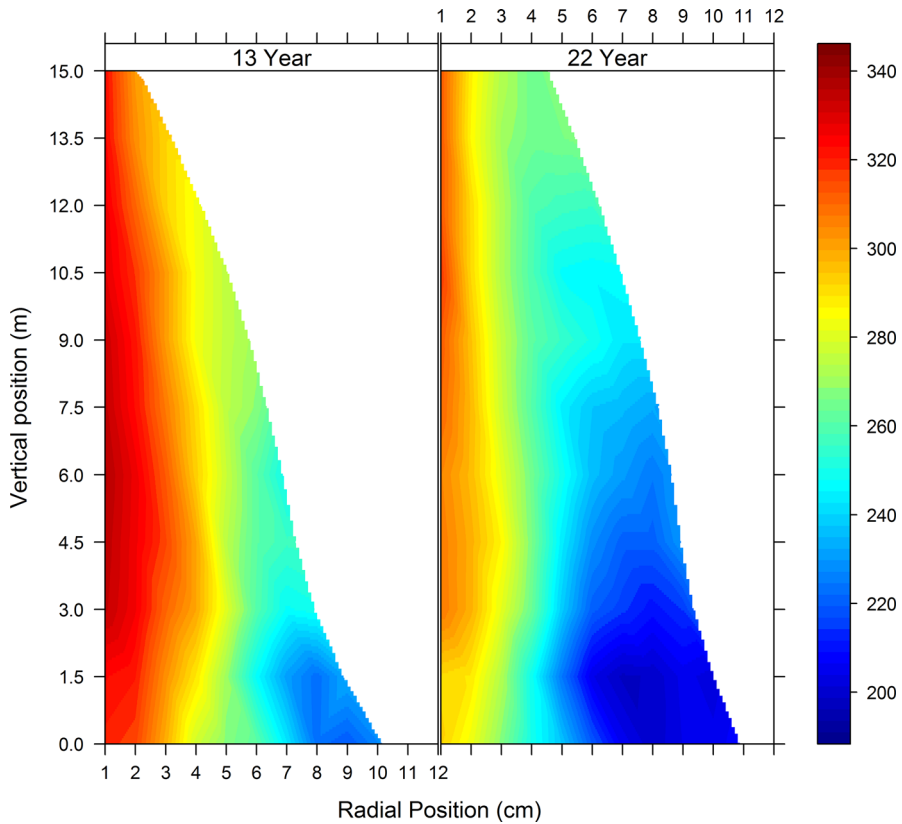


Fig. 3 Maps showing within-tree variation of specific surface (m^2/kg) for *P. taeda* trees aged 13 and 22 years. Maps represent the average of 18 trees and were developed using Akima's interpolation method

In their recent study, Schimleck et al. (2018) observed a lack of a vertical trend in their *P. taeda* density maps which disagreed with Megraw (1985) and Dahlen et al. (2018), who observed lower density values at the same ring number with increasing height. Schimleck et al. (2018) suggested reasons for the different observations (the lack of a vertical trend in density) including the relatively low resolution of the NIR data, and that variation is masked owing to distance from pith being used for the maps not annual ring properties. Considering the observations for density, it is likely that the maps for *C*, *S*, and *w* have the same limitations.

Comparison of the maps at 13 and 22 years for the three tracheid properties showed a trend of increasing *C* and *w* with age, while *S* decreased. The development of outer wood characteristics matches that observed for density in *P. taeda* (Schimleck et al. 2018). For density, Schimleck et al. (2018) determined the proportion of wood having density's above a given threshold. For a threshold of 650 kg/m^3 , the proportion above this value increased from 21 to 31% between the ages of 13 and 22, while for 550 kg/m^3 the proportion increased from 57 to 75%. Owing to the absence of information on accepted thresholds for tracheid properties,

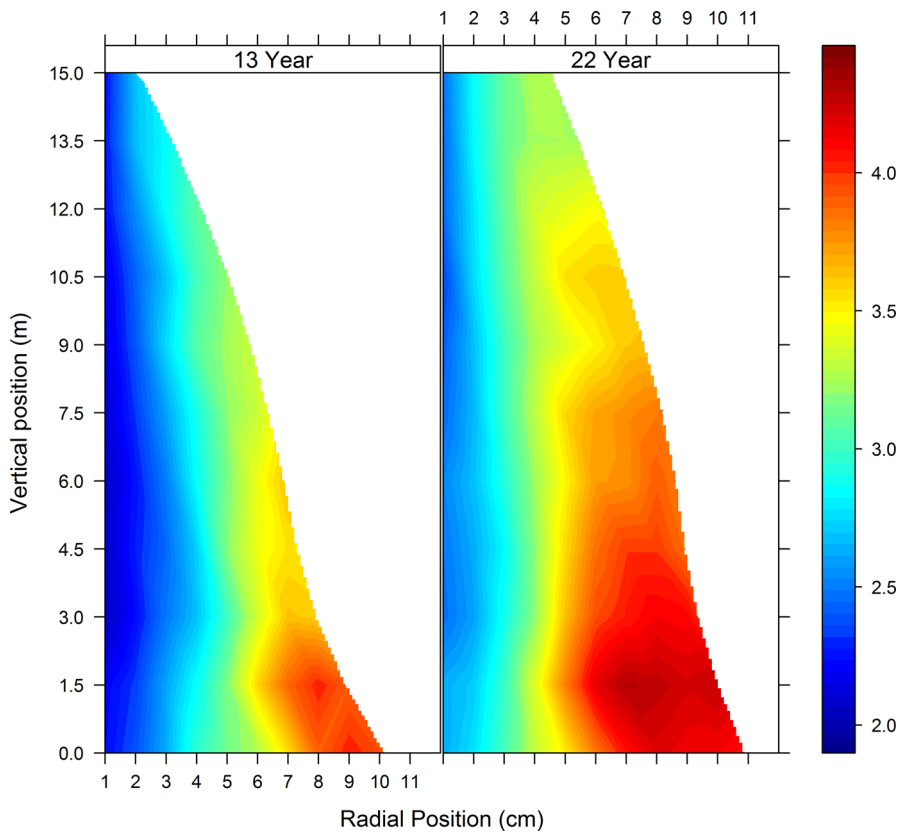


Fig. 4 Maps showing within-tree variation of wall thickness (μm) for *P. taeda* trees aged 13 and 22 years. Maps represent the average of 18 trees and were developed using Akima's interpolation method

it was not attempted to determine the proportion of wood exceeding a given value or questions related to age of maturation. Thresholds for solid wood properties are relatively easy to determine owing to the considerable amount of research that exists. For example, stiffness can be specified based on lumber grading targets specific to species, MFA can be specified based on longitudinal shrinkage values, which cause warp, density owing to its relationship with stiffness but for tracheid properties (and their influence on pulp properties) this information is not available.

The map for *T* diameter (Fig. 5) had variation very similar to the *P. taeda* maps reported for MFA and stiffness (Mora and Schimleck 2009; Schimleck et al. 2018) with both radial and longitudinal trends present. However, *T* diameter increased radially and with height, whereas MFA and stiffness decreased radially and with height. Small *T* diameters occur in the pith region within 0.5–1.0 m of the base of the tree, while the largest diameters occur toward the periphery. For 13-year-old trees, the largest values (approximately $31 \mu\text{m}$) were observed in a small region around 4.5 m, while for the older trees the zone of wood greater than $31 \mu\text{m}$ was much larger and had maximum predicted diameters around $35 \mu\text{m}$. While larger

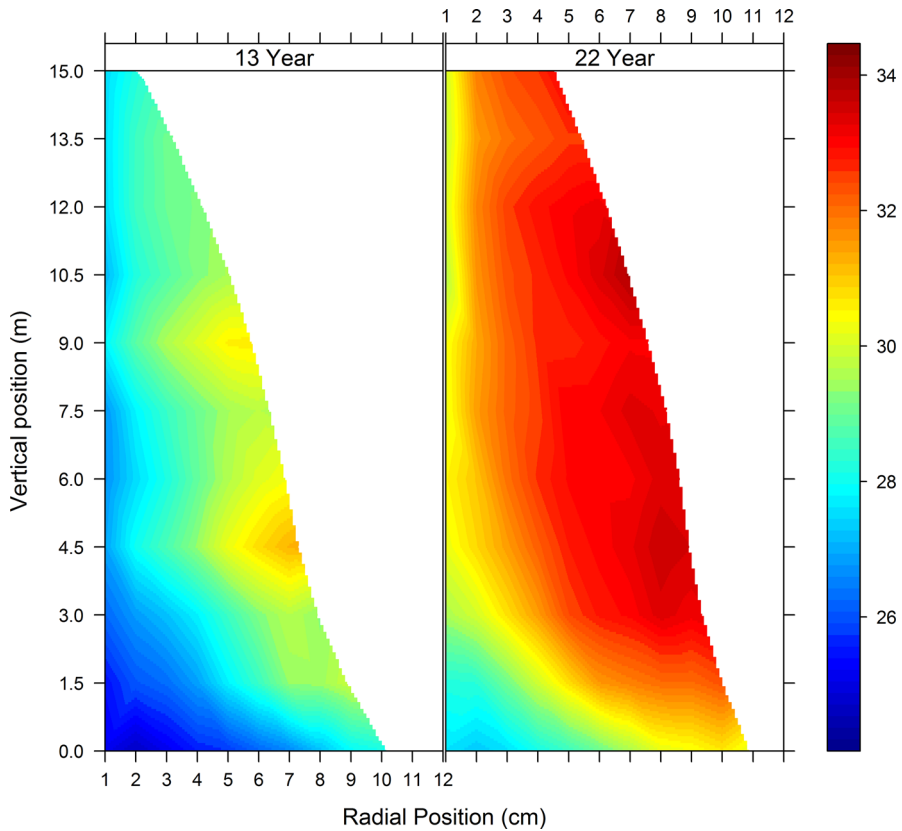


Fig. 5 Maps showing within-tree variation of tangential diameter (μm) for *P. taeda* trees aged 13 and 22 years. Maps represent the average of 18 trees and were developed using Akima's interpolation method

T diameters for older trees are expected, the size of the region greater than $31\ \mu\text{m}$ is unexpected considering that diameters of this size are largely absent for the younger trees. The weak prediction statistics reported for the phase 1 T diameter PLS model (Table 2) suggest that predictions of T diameter should be treated with less confidence than those of C , S , and w and perhaps this explains the large discrepancy in the two maps. Similar concerns were noted for the NIR predictions of R diameter, which had far weaker statistics than predicted T diameter (Table 2). The map showing R diameter within-tree variation (Fig. 6) was different to all other properties examined with minimum values at the base of the tree that increased with height. Largest R diameters for both maps occurred (approximately) in a zone from rings 2–6 from the pith and between 4.5 and 13 m in height. Owing to the weak statistics observed for the R diameter, NIR model caution is recommended regarding any interpretations based on the R diameter map.

While concern exists regarding the R diameter map, the accuracy of the NIR-predicted values may not be critical when the data are used to examine trends of wood properties within trees and when properties are averaged over many trees. The

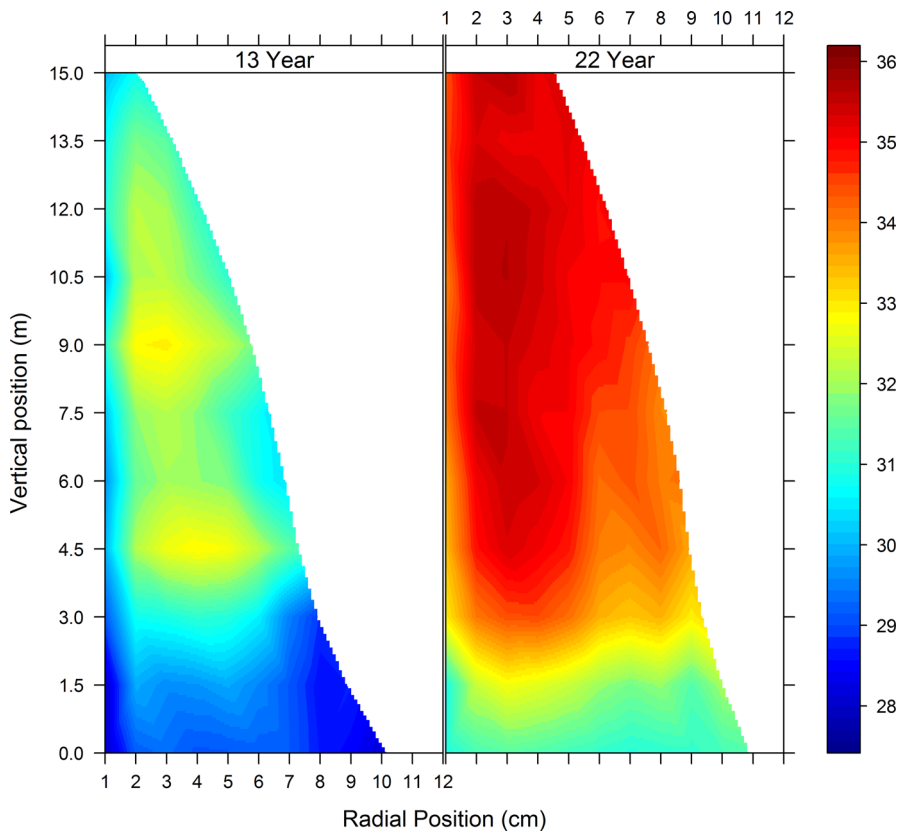


Fig. 6 Maps showing within-tree variation of radial diameter (μm) for *P. taeda* trees aged 13 and 22 years. Maps represent the average of 18 trees and were developed using Akima's interpolation method

trend of increasing diameter with height is consistent with the juvenile wood-mature wood, core wood-outer wood terminology proposed by Burdon et al. (2004). Few references exist that describe radial variation in tracheid dimensions. Evans et al. (1995), in reporting pith to bark trends in one *P. radiata* tree, noted that tracheid perimeter increased initially (120–145 μm) but after five years fell slightly (145–140 μm) toward the bark. While Mitchell and Denne (1997), in a research based on *Picea sitchensis* (Bong.) Carr (Sitka spruce) trees observed an increase in radial diameter for the first 8 rings from the pith followed by a slight decrease toward the bark at 3 heights (10–15, 30 and 60% of total tree height). Further research is required to improve our understanding of patterns of variation in radial diameter and many other properties. While a NIR spectrometer was utilized for this work, the recent emergence of hyperspectral scanning systems operational in the NIR range makes it possible to predict properties within rings (Fernandes et al. 2013; Ma et al. 2017). Ring-level data can also be obtained offering the potential for improving the resolution of wood property maps.

Table 6 Interrelationships between the various wood properties at 13 years and 22 years

	Density (kg/m ³)	MFA (deg.)	MOE (GPa)	Coarseness (μg/m)	Radial diameter (μm)	Specific surface (μm)	Tangential diameter (μm)	Wall thickness (μm)
<i>13-year-old trees</i>								
Density (kg/m ³)	1.0							
MFA (deg.)	0.01	1.0						
Stiffness (GPa)	0.58	− 0.75	1.0					
Coarseness (μg/m)	0.95	− 0.15	0.67	1.0				
Radial diameter (μm)	− 0.97	0.04	− 0.56	− 0.94	1.0			
Specific surface (m ² /kg)	0.06	0.08	− 0.22	0.12	− 0.04	1.0		
Tangential diameter (μm)	− 0.10	− 0.24	− 0.01	− 0.07	0.15	0.78	1.0	
Wall thickness (μm)	0.99	− 0.04	0.60	0.97	− 0.97	0.12	− 0.06	1.0
<i>22-year-old trees</i>								
Density (kg/m ³)	1.0							
MFA (deg.)	− 0.60	1.0						
Stiffness (GPa)	0.77	− 0.90	1.0					
Coarseness (μg/m)	0.92	− 0.62	0.73	1.0				
Radial diameter (μm)	− 0.87	0.34	− 0.59	− 0.86	1.0			
Specific surface (m ² /kg)	− 0.47	0.01	− 0.23	− 0.31	0.51	1.0		
Tangential diameter (μm)	0.02	− 0.48	0.37	0.20	− 0.06	0.64	1.0	
Wall thickness (μm)	0.98	− 0.68	0.81	0.90	− 0.79	− 0.40	− 0.06	1.0

Correlations between wood properties

Table 6 shows the interrelationships between the various wood properties at 13 years and 22 years. The 13-year-old stand shows no correlation between density and MFA, but the 22-year-old stand shows a moderate correlation ($R = -0.60$). MFA has no relationship with w in the younger stand but has a moderate correlation ($R = -0.68$) in the older stand. R diameter is well correlated with w for both the young ($R = -0.97$) and the older ($R = -0.79$) stand.

Conclusion

Multi-height coarseness (C), specific surface (S), radial (R) and tangential (T) diameter and wall thickness (w) calibrations based on NIR diffuse reflectance spectra collected from the radial-longitudinal surface of *P. taeda* wooden strips were successfully obtained. Calibration and prediction statistics were similar to those reported in previous studies using breast height cores with w providing the strongest results and R diameter the weakest. Maps were developed using data provided by the tracheid property multi-height NIR models and Akima's interpolation method. The maps, representing average data for 18 *P. taeda* trees, aged 13 and 22 years, respectively, were used to compare age-related change in patterns of within-tree variation. C , S , and w maps were similar to *P. taeda* density maps indicating these properties increase radially at all heights. The map for T diameter was similar to maps reported for microfibril angle, except that T diameter increased radially and with height whereas microfibril angle decreased radially and with height. The R diameter map was unlike the other properties examined with diameter increasing with height. Caution is recommended regarding interpretations based on the R diameter map owing to the weak statistics observed for the R diameter NIR model. Changes observed between the two ages are consistent with the asymptotic progression of properties associated with maturation.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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