Pinus taeda L. wood property calibrations based on variable numbers of near infrared spectra per core and cores per plantation

Laurence R. Schimleck,[a,*] Justin A. Tyson,[a] P. David Jones,[b] Gary F. Peter,[c] Richard F. Daniels[a] and Alexander Clark III[d]

[a]*Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA, USA. E-mail: lschimleck@warnell.uga.edu*

[b]*Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA*

[c]*School of Forest Resources and Conservation, University of Florida, Gainesville, FL, USA*

[d]*USDA Forest Service, Southern Research Station, Athens, GA, USA*

Near infrared (NIR) spectroscopy provides a rapid, non-destructive method for the estimation of several wood properties of increment cores. NIR spectra are collected from adjacent sections of the same core; however, not all spectra are required for calibration purposes as spectra from the same core are autocorrelated. Previously, we showed that wood property calibrations that included a single spectrum per core were almost as successful when used to predict the wood properties of sections of new cores, as calibrations based on multiple, consecutive spectra per core. However, it is not known, for calibration purposes, how many NIR spectra should be collected per core, nor how many cores are required to represent a plantation. In this study, we demonstrate that it is unnecessary to use NIR spectra from every section of a core for calibration development. One spectrum per core adequately represents it, provided that sections from other cores representing juvenile, mature and the juvenile/mature wood transition are included in the calibration set. Calibration and prediction statistics can be slightly improved by increasing the number of spectra per core from one to between three and five, with the addition of further spectra unnecessary. For the plantations examined in this study, a minimum of seven cores per plantation is recommended. Increasing the number of cores per plantation to ten (the maximum) is unnecessary and the small improvement is not worth the cost.

Keywords: air-dry density, increment cores, microfibril angle, near infrared spectroscopy, NIR, stiffness, *Pinus taeda*, SilviScan

Introduction

Near infrared (NIR) spectroscopy provides a rapid, non-destructive method for the estimation of several wood properties of increment cores, including air-dry density, cellulose and lignin content, microfibril angle (MFA), stiffness and tracheid coarseness and wall thickness.[1–10] In some of these studies,[1–4,7,8] calibrations for estimating the wood properties of cores in 10 mm sections, have been based on NIR spectra collected in consecutive 10 mm sections from the radial–longitudinal surface of strips cut from increment cores and wood property data provided by SilviScan,[11–13] an instrument designed for the rapid measurement of wood properties of cores. Because the NIR spectra were collected from adjacent sections of the same core, the success of these calibrations could be explained by an autocorrelation that exists in wood cores. The exact nature of this autocorrelation is unknown, but comes from genetic and/or genetic by environmental relationships that are present across all cambial ages.

Recently,[14] we investigated if it was possible to obtain strong calibration statistics for SilviScan measured wood properties using NIR spectra collected from independent cores. A single NIR spectrum, representing an individual 10 mm section, was selected from each core examined by Jones *et al.*[7,8] and used to form new wood property calibrations that were applied to a separate prediction set. Spectra were selected to represent juvenile wood (close to pith), transition wood (zone between juvenile and mature wood) and mature wood (close to bark). Selection of a single spectrum per core ensured that samples used in the calibration and prediction sets were unrelated. The new calibrations (based

DOI: 10.1255/jnirs.738 ISSN 0967-0335

on unrelated 10 mm sections) were compared with those obtained using spectra collected from consecutive 10 mm sections and similar statistics were obtained for both sets demonstrating that calibration success was not due to an autocorrelation.

While it was demonstrated that the success of our wood property calibrations was not due to an autocorrelation[14] two important questions remain, and both must be resolved if NIR spectroscopy is going to be routinely used to estimate the wood properties of cores. The first question relates to the number of spectra utilised per core. Wood property calibrations based on a single spectrum per core had weaker statistics[14] than those reported for consecutive spectra[7,8] and thus, one of the objectives of this study was to investigate the extent to which calibration and prediction statistics can be improved by using more than one spectrum per core. For example, do calibrations based on four spectra per core provide improved statistics compared to calibrations based on a single spectrum per core? The second question relates to the number of trees from a plantation that must be represented in the calibration set. Jones *et al.*[7,8] utilised cores obtained from ten different trees per plantation but it is presently unknown if NIR spectra from all ten strips were necessary and thus, our second objective was to determine the optimum number of cores required to adequately represent a plantation. If a small number of NIR spectra are required to represent a core for calibration purposes, then the time required to collect spectra from a given core will be greatly reduced as will the cost of SilviScan analysis. In addition, if cores from fewer than 10 trees are required to represent a plantation, then sampling time per location, as well as the subsequent NIR analysis, can be reduced. Therefore, successful resolution of both questions will have important practical implications for the use of NIR in estimating wood properties.

Materials and methods

Sample origin

Cores were collected from *P. taeda* plantations located in Georgia, USA. For three physiographic regions in Georgia (Lower and Upper Atlantic Costal Plain, and Piedmont) five plantations, ranging in age from 21 to 26 years, with a range of site indices, were sampled (where site index is equal to the average height of dominant and co-dominant trees at age 25). The calibration set was comprised of 90 breast height (1.37 m) increment cores sampled from three plantations within each region. At each plantation, ten trees with a range of breast height diameters were sampled. One increment core developed blue stain and was unavailable for analysis because of discoloration, leaving 89 cores for analysis. The prediction set was comprised of thirty breast height increment cores (five cores per plantation, two plantations per region). Further information about the plantations sampled was reported previously.[7]

Measurement of wood properties using SilviScan

One hundred and nineteen radial wooden strips (cut from the increment cores using a twin-blade saw) were available for SilviScan analysis. The radial strips were extracted in warm acetone for 24 hours prior to SilviScan analysis. The measurement of wood properties has been previously described.[11–13] All measurements were made in a controlled environment of 40% relative humidity and 20°C.

Near infrared spectroscopy

NIR diffuse reflectance spectra were obtained in consecutive 5 mm sections along the radial–longitudinal face of each *P. taeda* strip using an NIRSystems Inc. Model 5000 scanning spectrophotometer (Silver Spring, Maryland, USA). For each strip, the first spectrum was collected from the bark end. The strips were held in a custom-made holder[15] and a 5 mm × 5 mm mask was used to ensure that a constant area was tested. It is important to note our research based on a single, unrelated NIR spectrum per radial strip[14] was based on NIR spectra collected using a 5 mm × 10 mm mask. The higher resolution data was used in this study to provide a larger number of spectra for calibration purposes. Fifty scans were accumulated for each 5 mm section; these scans were averaged to give a single spectrum per section. The spectra were collected at 2 nm intervals over the wavelength range 1100–2500 nm. The instrument reference was a ceramic standard. All measurements were made in a conditioned atmosphere maintained at 40% RH and 20°C.

Sample selection for calibration—variable number of spectra per core

In our previous study,[14] a single average NIR spectrum representing a 5 mm × 10 mm random section of wood was selected per radial strip in the calibration (89) and prediction sets (30). Spectra were selected to represent juvenile wood (close to pith), transition wood (zone between juvenile and mature wood) and mature wood (close to bark). In this study the same approach was used; however, the number of spectra per radial strip [referred to as core(s) in the remaining text] was increased from one to eight, to give calibration sets where the number of spectra ranged from 89 to 712, respectively. For comparative purposes, the full set of spectra (1637) was also used to obtain wood property calibrations. The calibrations were used to estimate the wood properties of all prediction set samples that had been scanned in the same way as the calibration set, i.e. core properties were predicted in 5 mm sections. Table 1 gives a statistical summary of the calibration and prediction sets for all available spectra.

Sample selection for calibration—variable number of trees per plantation

To investigate if the number of cores per plantation was important, the number of cores represented in the calibration set was reduced, in increments of one, from a maximum of ten to a minimum of one. For the selected cores, all

Table 1. Range of each wood property for the calibration and prediction sets when all available samples were used.

Wood	Calibration set (1637 spectra)					Prediction set (521 spectra)			
Property	Minimum	Maximum	Av.	Std dev.		Minimum	Maximum	Av.	Std dev.
Air-dry density (kg m^{-3})	304.7	903.1	575.2	118.6		316.1	885.4	575.5	121.3
Microfibril angle (deg)	9.6	51.0	26.3	7.8		8.7	42.5	24.0	7.7
Stiffness (GPa)	1.6	27.8	9.7	5.3		1.9	26.4	10.4	5.9

NIR spectra collected from it were used for calibration, the number of spectra per core ranged from a low of six to a high of 34. The wood property calibrations were used to estimate the wood properties of all prediction set samples.

Calibration development

Calibrations for air-dry density, MFA and stiffness were developed using the Unscrambler (version 8.0) software package (Camo Ås, Norway). Partial least squares (PLS) regression with four cross-validation segments and a maximum of ten factors. Calibrations were developed using second derivative spectra, left and right gap widths of 8 nm were used for the conversion and, as a consequence, the wavelength range available for calibration development was limited to 1108–2492 nm. For nearly all calibrations, the number of factors recommended by the Unscrambler software was consistent, regardless of the number of spectra used. On the rare occasion when the number of factors recommended differed, the final number used was changed to agree with that recommended for the majority.

The standard error of calibration (*SEC*) (determined from the residuals of the final calibration), the standard error of cross-validation (*SECV*) (determined from the residuals of each cross-validation phase) and the coefficient of determination for both the calibration (R^2) and predictions (r^2) were used to assess calibration performance. This predictive performance of the calibrations was assessed using the standard error of performance (*SEP*).

Results and discussion

Wood property calibrations—variable number of NIR spectra per core

Table 2 summarises the wood property calibrations (for air-dry density, MFA and stiffness) developed using an incrementally increasing number of spectra per core.

Calibrations for the three wood properties were very similar regardless of the number of spectra utilised per core. R^2 ranged from 0.66 to 0.68 for density, 0.82 to 0.89 for MFA (a single spectrum per core provided the highest R^2) and 0.84 to 0.89 for stiffness (a single spectrum or seven spectra per core provided the highest R^2). *SECV*s ranged from 67.7 to 72.3 kg m^{-3} for density, 3.2 to 3.8 deg. for MFA and 2.1 to 2.6 GPa for stiffness. The lowest *SECV* for MFA and stiffness were obtained using the calibrations based on five spec-

Table 2. Summary of calibrations for air-dry density, microfibril angle (MFA) and stiffness obtained using a variable number of NIR spectra per core. The number of factors used for each calibration for the respective properties are shown in parenthesis.

Number of spectra/core	Air-dry density (kg m^{-3}) (three factors)			MFA (deg.) (six factors)			Stiffness (GPa) (five factors)		
	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*
1	0.68	63.58	70.48	0.89	2.39	3.79	0.89[a]	1.62	2.21
2	0.66	67.08	72.28	0.84	2.81	3.52	0.85	1.87	2.30
3	0.67	67.64	70.10	0.83	2.88	3.25	0.84[a]	1.98	2.23
4	0.67	68.69	71.91	0.82	3.05	3.29	0.85[a]	1.98	2.22
5	0.68	66.21	68.37	0.86	2.86	3.16	0.86	1.94	2.06
6	0.67	66.56	67.85	0.85	2.96	3.25	0.85	2.03	2.16
7	0.68	66.78	68.31	0.85	3.02	3.22	0.89[a]	1.85	2.59
8	0.68	66.82	67.68	0.84[a]	3.09	3.28	0.85	2.08	2.18
Full set	0.64	71.05	71.93	0.84	3.14	3.20	0.84	2.09	2.14

[a]Note: seven factors were recommended for the MFA calibration based on eight spectra per core, six factors were recommended for the stiffness calibrations based on one and three spectra per core, while four and three factors, respectively, were recommended for the MOE calibrations based on four and seven spectra per core.

tra per core, while for density the lowest *SECV* was obtained using eight spectra per core. The calibrations obtained using a single spectrum per core showed the greatest difference between *SEC* and *SECV* values, indicating that the calibrations obtained using more spectra per core benefited from the inclusion of additional spectra. MFA calibrations based on a single spectrum per core and all available spectra (full set) are shown in Figure 1.

When compared to the calibrations obtained using the full set (all the spectra available per core) the calibrations based on one to eight spectra per core generally gave improved statistics. It is probable that the wood property calibrations based on all available spectra suffered owing to the large number of spectra in the calibration set and that they added little new variation, i.e. as the number of spectra present in the calibration set increased, the variation hardly changed and, consequently, calibration statistics were decreased slightly.

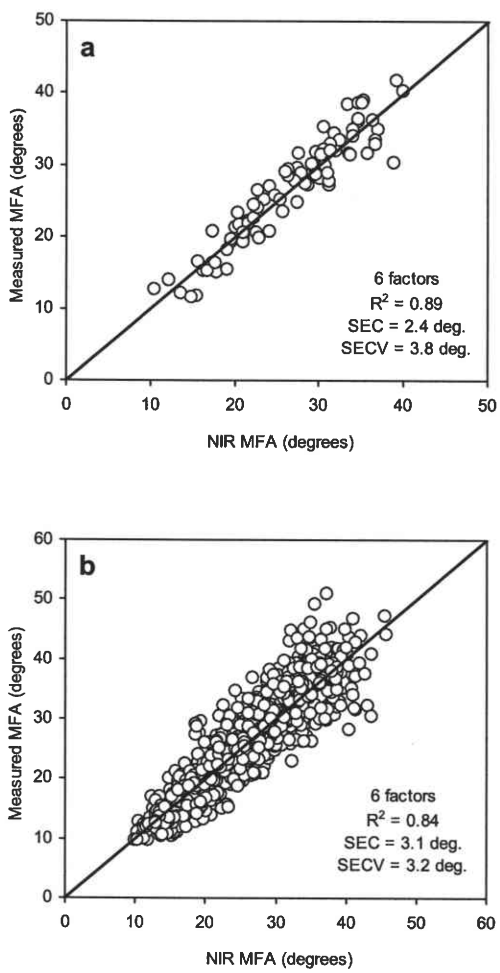

Figure 1. MFA calibrations based on (a) a single spectrum per core and (b) all available spectra.

The calibrations reported here all have weaker statistics compared to those reported by Jones *et al.*[7] The most noticeable reduction was for density, while MFA was the least affected. Jones *et al.*[7] based their calibrations on spectra collected in 10 mm increments while calibrations in this study were based on spectra collected in 5 mm increments. A decrease from 10 mm to 5 mm reduces the area of the sample exposed to NIR energy ($25\,mm^2$ for a $5\,mm \times 5\,mm$ window, compared to $50\,mm^2$ for a $10\,mm \times 5\,mm$ window) which reduces the quality of the NIR spectrum and, as noted here, the quality of the subsequent calibrations based on the spectra. Of the three properties, density showed the greatest variation from pith to bark and was the most influenced as the quality of the spectra declined, while MFA, the least variable of the three properties, only showed a small reduction in calibration statistics.

When used to predict the wood properties of the test set, i.e. the properties of cores in consecutive 5 mm sections, the respective calibrations performed consistently (Table 3). Prediction (r^2) ranged from 0.67 to 0.69 for density, 0.79 to 0.82 for MFA and 0.81 to 0.84 for stiffness. *SEP*'s ranged from 67.7 to 70.1 $kg\,m^{-3}$ for density, 3.5 to 3.9 deg. for MFA and 2.4 to 2.6 GPa for stiffness, with the predictions of stiffness showing the least variation in terms of *SEP*. Prediction errors for calibrations based on a single spectrum per core were among the highest obtained, regardless of the property. The best performing calibrations, in terms of their predictive errors, were obtained using two to four spectra per core.

Our results indicate that it is not necessary to collect NIR spectra from every section of a core for calibration purposes. In addition, one spectrum was sufficient to represent an individual core, provided that sections from other cores representing juvenile, mature and the juvenile/mature wood transition were included in the calibration set.[14] Calibration and prediction statistics can be slightly improved by increasing the number of spectra per core to between three and five, with the addition of further spectra unnecessary.

Wood property calibrations—variable number of cores per plantation

The effects of reducing the number of cores per plantation represented in the calibration set, in increments of one, from a maximum of ten to a minimum of one, on the subsequent wood property calibrations are summarised in Table 4. For the calibrations presented in Table 4, all available spectra per core were used.

These data indicate that the number of cores per plantation represented in the calibration can be reduced; however, each property, particularly density, differed in the response to a reduction in the number of cores. For density, the calibrations based on seven to ten cores per plantation provided similar statistics, but if less than seven cores were used then the calibration statistics were noticeably weaker. Stiffness calibrations had similar statistics using seven to

Table 3. Summary of predictions made by the air-dry density, MFA and stiffness calibrations when applied to the separate test set.

Number of spectra/core	Air-dry density ($kg\,m^{-3}$)		MFA (deg.)		Stiffness (GPa)	
	r^2	*SEP*	r^2	*SEP*	r^2	*SEP*
1	0.67	70.14	0.79	3.80	0.81	2.61
2	0.69	67.67	0.81	3.54	0.83	2.43
3	0.69	68.25	0.82	3.55	0.84	2.38
4	0.68	69.07	0.81	3.63	0.84	2.40
5	0.68	69.22	0.82	3.75	0.83	2.44
6	0.68	69.19	0.82	3.79	0.83	2.43
7	0.68	69.35	0.81	3.79	0.83	2.47
8	0.68	69.41	0.82	3.94	0.82	2.51
Full set	0.67	70.12	0.81	3.71	0.83	2.46

ten cores per plantation, however, unlike the density calibrations, calibrations based on three to six cores per plantation gave *SECV*'s close to those obtained using seven to ten cores per plantation. Calibrations for MFA were consistent regardless of the number of cores used per plantation, with R^2 ranging from 0.83 to 0.85 and *SECV*'s ranging from 3.0 to 3.4 deg.

Table 5 shows the results of using these calibrations to predict the wood properties of the test set cores in 5 mm sections. For density, the calibration based on five cores per plantation provided the strongest statistics ($r^2=0.67$, $SEP=69.6\,kg\,m^{-3}$), though little difference was observed between the calibrations with five to ten cores per plantation. For MFA, the ten cores per plantation calibration provided the strongest statistics ($r^2=0.81$, $SEP=3.7$ deg.) but there was little difference between this calibration and the calibrations based on six to nine cores per plantation (for example, six cores per plantation, $r^2=0.80$, $SEP=3.9$ deg.). Calibrations for stiffness provided similar predictive statistics even if two cores per plantation were used, however, the best results were obtained using the calibration based on ten cores per plantation ($r^2=0.83$, $SEP=2.5$ GPa).

Based on the plantations examined in this study, a minimum of five cores per plantation could be used. Increasing the number of cores used per plantation to seven will marginally improve the performance of the calibrations and is recommended, while using ten cores per plantation is unnec-

Table 4. Summary of calibrations for air-dry density, MFA and stiffness obtained using NIR spectra collected from a variable number of cores per plantation. The number of factors used for each calibration for the respective properties are shown in parenthesis.

Number of cores/plantation	Air-dry density ($kg\,m^{-3}$) (three factors)			MFA (deg.) (six factors)			Stiffness (GPa) (five factors)		
	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*
1	0.54	78.92	85.56	0.85	2.73	3.39	0.78	2.20	2.53
2	0.54	79.92	83.99	0.84	2.72	2.98	0.78	2.20	2.43
3	0.58	76.45	78.56	0.83	2.94	3.11	0.81	2.17	2.29
4	0.61	74.98	77.01	0.85	2.88	3.06	0.82	2.20	2.33
5	0.63	73.47	74.94	0.84	3.09	3.22	0.83	2.21	2.30
6	0.63	72.88	73.91	0.84	3.13	3.24	0.84	2.17	2.23
7	0.64	71.48	72.34	0.84	3.11	3.18	0.84	2.12	2.18
8	0.64	70.82	71.64	0.84	3.12	3.19	0.85	2.10	2.15
9	0.65	70.36	70.90	0.84	3.10	3.17	0.85	2.09	2.14
10 (Full)	0.64	71.05	71.93	0.84	3.14	3.20	0.84	2.09	2.14

Table 5. Summary of predictions made by the air-dry density, MFA and stiffness calibrations when applied to the separate test set.

Number of cores/plantation	Air-dry density (kg m^{-3})		MFA (deg.)		Stiffness (GPa)	
	r^2	*SEP*	r^2	*SEP*	r^2	*SEP*
1	0.66	71.51	0.63	4.92	0.74	3.32
2	0.66	71.99	0.71	4.53	0.81	2.59
3	0.64	74.51	0.78	3.94	0.80	2.63
4	0.67	69.93	0.80	3.91	0.81	2.58
5	0.67	69.60	0.77	4.19	0.82	2.59
6	0.67	69.93	0.80	3.88	0.82	2.55
7	0.67	69.57	0.80	3.85	0.83	2.48
8	0.67	70.01	0.80	3.88	0.82	2.51
9	0.67	70.18	0.81	3.78	0.82	2.50
10 (Full)	0.67	70.12	0.81	3.71	0.83	2.46

essary and the marginal improvement in predictive statistics is not worth the additional cost of sampling and, particularly, SilviScan analysis.

Wood property calibrations based on the optimum number of NIR spectra per core and cores per plantation

Based on our recommendations regarding the number of spectra per core and number of cores per plantation, calibrations using seven cores per plantation with two to four NIR spectra per core were examined (Tables 6 and 7). Calibration statistics for density were similar to those reported in Table 2 and superior to those reported in Table 4, demonstrating that reducing the number of NIR spectra collected per core has had a positive influence on how well the data were fitted. The MFA calibrations had similar statistics to the calibrations reported in Tables 2 and 4; however, the *SECV* was much larger than the *SEC*. Calibrations for stiffness were similar to those reported in Tables 2 and 4, particularly when only two NIR spectra were used per core.

The predictive performance of the density and stiffness calibrations, based on a limited number of spectra per core and cores per plantation, were very similar to the results reported in Tables 3 and 5. The predictions of MFA were not as good as those reported in Tables 2 and 4, with lower r^2 and higher *SEP*, particularly for the MFA calibration based on two spectra per core.

When sampling plantations in the south-eastern United States of America (SE USA) to obtain an estimate of mean stand density, we have traditionally collected 30 cores per location.[16] For this study, we were unable to have all 30 cores analysed by SilviScan as the cost was prohibitive. The ten cores utilised were a sub-sample of the 30 collected at the 15 different sites used for this study and were subjected to further wood property analysis by the SilviScan system. In New Zealand and New South Wales, Australia, the strategy

Table 6. Summary of calibrations for air-dry density, MFA and stiffness obtained using seven cores per plantation and a variable number of NIR spectra per core (two to four, for example). The number of factors used for each calibration for the respective properties are shown in parenthesis.

Number of spectra/core	Air-dry density (kg m^{-3}) (three factors)			MFA (deg.) (six factors)			Stiffness (GPa) (five factors)		
	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*	R^2	*SEC*	*SECV*
2	0.67	71.54	79.54	0.86	2.94	4.20	0.87[a]	1.79	2.58
3	0.75	64.11	69.22	0.87[a]	2.98	3.81	0.91*	1.65	2.06
4	0.70	69.64	73.23	0.86[a]	3.07	3.84	0.87*	1.91	2.22
All	0.64	71.48	72.34	0.84	3.11	3.18	0.84	2.12	2.18

[a]Note: eight and five factors, respectively, were recommended for the MFA calibration based on three and four spectra per core, while six, four and four factors, respectively, were recommended for the MOE calibrations based on two, three and four spectra per core

Table 7. Summary of predictions made by the air-dry density, MFA and stiffness calibrations when applied to the separate test set.

Number of spectra/core	Air-dry density (kg m^{-3})		MFA (deg.)		Stiffness (GPa)	
	r^2	*SEP*	r^2	*SEP*	r^2	*SEP*
2	0.65	72.09	0.78	4.38	0.81	2.62
3	0.68	69.09	0.78	4.09	0.83	2.44
4	0.67	70.36	0.77	4.06	0.82	2.51
All	0.67	69.57	0.80	3.85	0.83	2.48

of collecting 30 cores per location has also been employed.[17] Recently, Raymond[17] examined the effect of reducing the number of cores per location (36 sites in the Macquarie region and 27 sites in the Hume region) when assessing the basic density of *Pinus radiata* D.Don (radiata pine). Mean density and its standard deviation were determined for each site using a random sample of 5, 10, 15, 20 and 30 cores and the correlations between means and standard deviations for the different number of samples examined. It was found that estimates of mean density for a location were similar when ten or more cores were used and it was concluded that reducing the number of trees sampled from 30 to 10 would not greatly reduce the quality of the density estimate.[17] In another recent study,[16] the same question was examined for *P. taeda*, from 130 locations (with 30 trees sampled per location) across the SE USA, using a cost-benefit approach. Estimated standard errors for specific gravity were relatively constant as the number of cores per location was reduced from 30 to 10. If less than eight cores per location were used estimated, standard errors were observed to increase. While we have not explored using more than ten cores per location in our NIR work, the findings of Jordan *et al.*[16] and Raymond[17] suggest that there would be little benefit, in terms of calibration performance, in increasing the number of cores per location to greater than ten. In addition, it is interesting that our estimate of seven cores per location agrees well with the lower estimate of Jordan *et al.*[16] Raymond[17] cautioned against the use of five cores per location as it was found that the correlation between site means showed a large decrease falling from 0.95 (30 trees per location) to 0.84, supporting our recommendation that a minimum of seven cores be used per location.

While we have examined the number of cores that should be included in a multi-site wood property calibration, we have not examined the number of cores required to obtain an estimate of a NIR predicted wood property with a given level of precision and this will be the subject of a future study. It is possible that the recommendations of Jordan *et al.*[16] and Raymond[17] will apply equally to the samples that form the prediction set. It is also possible that the number of cores required per property will differ by location and also by wood property. For example, locations with greater micro-site variation, whether it be caused by variation in elevation, soil etc, may require more samples per location when NIR is used to give an estimate of wood properties. In terms of the wood properties examined in this study, the results presented in Tables 6 and 7 suggest that MFA is most sensitive to a reduction in the number of spectra per core and cores per plantation. As a consequence, additional samples, possibly in terms of the number of spectra per core or even the number of cores per location, may be required to adequately predict it.

Jorden *et al.*[16] have noted for density that more variability exists among stands than among trees within stands and concludes that a reduction in the variability of an estimate of stand density can be achieved by sampling more locations and fewer trees within a location. It is presently unknown if this conclusion can be made where NIR spectroscopy is used to predict wood properties for a given location but it is possible that, as the number of stands represented in a calibration increases (note we utilised only nine stands), the number of cores required per stand will decrease.

Conclusions

It is unnecessary to collect or use NIR spectra from every section of a core for wood property calibrations. One spectrum per core (representing a 5 mm section) is sufficient to represent an individual core, provided that sections from other cores representing juvenile, mature and the juvenile/mature wood transition are included in the calibration set. However, calibration and prediction statistics can be slightly improved by increasing the number of spectra per core in the calibration to between three and five, with the addition of further spectra unnecessary.

For the plantations examined in this study, a minimum of seven cores per plantation is recommended. Increasing the number of cores per plantation to ten (the maximum) is unnecessary and the small improvement in calibration performance is not worth the cost.

Acknowledgements

The authors thank the UGA Wood Quality Consortium for sample collection and preparation and the Georgia TIP[3] programme for funding the SilviScan analysis necessary for this study. The authors thank the SilviScan team for the determination of wood properties.

References

1. L.R. Schimleck and R. Evans, "Estimation of wood stiffness of increment cores by near infrared spectroscopy: the development and application of calibrations based on selected cores", *IAWA J.* **23,** 217–224 (2002).
2. L.R. Schimleck and R. Evans, "Estimation of microfibril angle of increment cores by near infrared spectroscopy", *IAWA J.* **23,** 225–234 (2002).
3. L.R. Schimleck and R. Evans, "Estimation of air-dry density of increment cores by near infrared spectroscopy", *Appita J.* **56,** 312–317 (2003).
4. L.R. Schimleck and R. Evans, "Estimation of *P. radiata* D. Don tracheid morphological characteristics by near infrared spectroscopy", *Holzforschung* **58,** 66–73 (2004). doi: 10.1515/HF.2004.009
5. T.-F. Yeh, H.-M. Chang and J.F. Kadla, "Rapid prediction of solid wood lignin content using transmittance near-infrared spectroscopy", *J. Agric. Food Chem.* **52,** 1435–1439 (2004). doi: 10.1021/jf034874r
6. T.-F. Yeh, H.-M. Chang and J.F. Kadla, "Rapid prediction of wood chemical component variations using transmittance near-infrared spectroscopy", *J. Agric. Food Chem.* **53,** 3328–3332 (2005). doi: 10.1021/jf0480647
7. P.D. Jones, L.R. Schimleck, G.F. Peter, R.F. Daniels and A. Clark, "Nondestructive estimation of *Pinus taeda* L. wood properties for samples from a wide range of sites in Georgia", *Can. J. For. Res.* **35,** 85–92 (2005). doi: 10.1139/x04-160
8. P.D. Jones, L.R. Schimleck, G.F. Peter, R.F. Daniels and A. Clark, "Nondestructive estimation of *Pinus taeda* L. tracheid morphological characteristics for samples from a wide range of sites in Georgia", *Wood Sci. Technol.* **39,** 529–545 (2005). doi: 10.1007/s00226-005-0021-1
9. F.S. Poke and C.A. Raymond, "Predicting extractives, lignin, and cellulose contents using near infrared spectroscopy on solid wood in *Eucalyptus globulus*", *J. Wood Chem. Technol.* **26,** 187–199 (2006). doi: 10.1080/02773810600732708
10. P.D. Jones, L.R. Schimleck, G.F. Peter, R.F. Daniels and A. Clark, "Nondestructive estimation of wood chemical composition of sections of radial wood strips by near infrared spectroscopy", *Wood Sci. Technol.* **40,** 709-720 (2006). doi: 10.1007/s00226-006-0085-6
11. R. Evans, "Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*", *Holzforschung* **48,** 168–172 (1994).
12. R. Evans, "Rapid scanning of microfibril angle in increment cores by x-ray diffractometry", in *Microfibril Angle in Wood: Proceedings of the IAWA / IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality*, Ed by B.G. Butterfield. University of Canterbury Press, Christchurch, New Zealand, pp. 116–139 (1998).
13. R. Evans, "A variance approach to the x-ray diffractometric estimation of microfibril angle in wood", *Appita J.* **52,** 283–289, 294 (1999).
14. L.R. Schimleck, P.D. Jones, A. Clark, R.F. Daniels and G.F. Peter, "Success in using NIR spectroscopy to estimate wood properties of *Pinus taeda* radial strips not due to autocorrelation", *J. Near Infrared Spectrosc.* **13,** 47–52 (2005).
15. L.R. Schimleck, R. Evans and J. Ilic, "Estimation of *Eucalyptus delegatensis* clear wood properties by near infrared spectroscopy", *Can. J. For. Res.* **31,** 1671–1675 (2001). doi: 10.1139/cjfr-31-10-1671
16. L. Jordan, L.R. Schimleck, A. Clark, D.B. Hall and R.F. Daniels, "Estimating optimum sampling size to determine weighted core specific gravity of planted loblolly pine", *Can. J. For. Res.* (in press).
17. C. Raymond, "Density assessment of radiata pine: Sampling strategy revisited", *Holzforschung* **60,** 580–582 (2006). doi: 10.1515/HF.2006.096

Received: 20 November 2006
Revised: 2 May 2007
Accepted: 18 May 2007
Publication: 18 July 2007