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Use of near infrared spectroscopy to predict the mechanical properties of six softwoods

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Abstract

The visible and near infrared (NIR) (500–2400 nm) spectra and mechanical properties of almost 1000 small clear-wood samples from six softwood species: *Pinus taeda* L. (loblolly pine), *Pinus palustris*, Mill. (longleaf pine), *Pinus elliottii* Engelm. (slash pine), *Pinus echinata* Mill. (shortleaf pine), *Pinus ponderosa* Dougl. ex Laws (ponderosa pine), and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) were measured. Projection to Latent Structures (PLS) modeling showed that the NIR spectra of these softwoods could be used to predict the mechanical properties of the clear-wood samples. The correlation coefficients for most of these models were greater than 0.80. All six softwood species were combined into one data set and a PLS model was constructed that effectively predicted the strength properties of any of the individual softwoods. Reducing the spectral range to between 650 and 1050 nm only causes a slight decrease in the quality of the models. Using this narrow spectral range enables the use of smaller, faster, lighter, less expensive spectrometers that could be used either in the field or for process control applications.

Keywords: mechanical properties; near infrared; NIR; softwoods.

Introduction

A wide variety of wood and paper properties, including chemical composition and physical properties, have been measured using near infrared (NIR) spectroscopy. Some of the earliest work focused on measuring the chemical composition of wood, pulp, and paper (Birkett and Gambino 1988; Wright et al. 1990; Michell 1995; Wallbacks et al. 1995; Schimleck et al. 1996, 1997; Schimleck and Michell 1998; Malkavaara and Alen 1998). Later work addressed changes in the chemical composition of cellulose and the physical properties of paper (Svensson et al. 1997; Berthold et al. 1998; Svedas 2000; Ali et al. 2001).

Although most of the work with NIR spectroscopy has focused on the chemical composition of wood or the properties of paper, some work has also been done on wood properties. For example, Hoffmeyer and Pedersen (1995) showed that NIR spectra could be used to predict the density, and compression and bending strength of dry wood; Thygesen (1994) and Schimleck et al. (1999) showed that NIR spectroscopy could be used to measure the density of wood; and Tsuchikawa and coworkers (1992) showed that NIR spectroscopy could be used to measure the grain angle of wood. More recently we have demonstrated the use of NIR spectra taken from solid wood to predict the chemical composition, mechanical properties and microfibril angle (MFA) of *Pinus taeda* L. (loblolly pine) (Kelley et al. 2002). Very recently, NIR spectroscopy has been used to predict the mechanical properties of *Pinus radiata* (radiata pine) (Thumm and Meder 2001; Schimleck et al. 2002), *Larix deciduas* Mill. (European larch) (Gindl et al. 2001) and *Picea abies* (Norway spruce) (Hauksson et al. 2001).

The goal of this work is to demonstrate the usefulness of NIR for predicting the mechanical properties of a number of different softwood species and to demonstrate the generality of the models between species. The impact of reducing the spectral range from 500–2400 nm to 650–1050 nm, which could enable the use of low-cost hand-held NIR systems, is also investigated. The ability to predict the strength and stiffness properties of wood could be useful for selective breeding and silvicultural studies.

Materials and methods

Collection of wood samples

The trees were gathered for several different studies and thus the sampling protocol was not identical for all the samples. The three *Pinus taeda* were harvested from a 48-year-old stand grown under a conventional plantation regime in the Crossett Experimental Forest in Southern Arkansas. The *P. taeda* had an average diameter at breast height (dbh) of 42 cm and an average height of 30 m. The five *Pinus elliottii* Engelm. (slash pine) were harvested from a natural stand in the DeSoto National Forest south of Hattiesburg, Mississippi. Two of the five *P. elliottii* were taken from a wet site approximately 26 years of age and had an average dbh and height, respectively, of 20 cm and 17 m. Three other *P. elliottii* were taken from a dry site and were 60 years of age and had average dbh and height of 35 cm and 25 m, respectively. The *Pinus palustris*, Mill. (longleaf pine) and *Pinus echinata* Engelm (shortleaf pine) were harvested from the Palustris Experimental Forest in central Louisiana. The *P. palustris* were taken from a conventional plantation regime and had an average dbh and height of 20 cm and 27 m. The *P. echinata* had an average

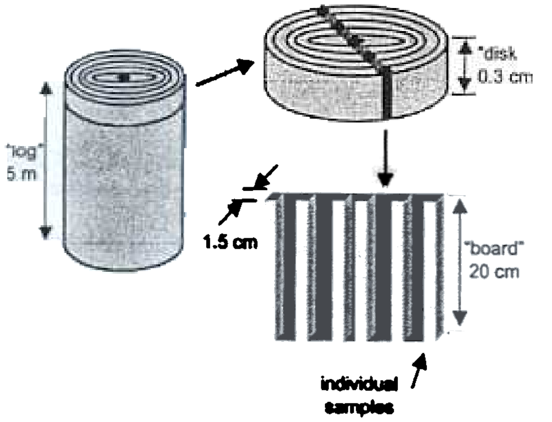

Figure 1 Schematic of the process used to obtain the bending samples.

dbh and height of 25 cm and 20 m, respectively. Ten *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) and nine *Pinus ponderosa* Dougl. ex Laws (ponderosa pine) were cut from over-stocked stands at several different sites in the Cascade Mountains of southern Oregon. All of the trees were at least 40 years old from naturally regenerated, unmanaged stands. The *P. menziesii* averaged 25 cm dbh while the *P. ponderosa* averaged 30 cm dbh.

Measuring mechanical properties

The sample preparation method is outlined in Figure 1. In the case of all the southern pines, a 0.3 m long "disk" was cut every 5 m along the trees producing four or five disks from every tree. "Boards" approximately 2.5 cm wide and 0.3 m long, were cut from the "disk" centered on the pith. The boards were then planed to a final thickness of about 1.5 cm. Bending samples containing three growth rings were then cut from these slices. The southern pine bending samples were centered on growth rings 2, 5, 9, 16, 25, and 48. For these samples the width in the radial direction depended on the width of the growth rings. The final dimensions of the bending samples were 20 cm in the longitudinal direction, 1.5 cm in the tangential direction, and 2–3.5 cm in the radial direction. Care was taken to minimize any slope of grain in the samples.

In the case of the *P. ponderosa* and *P. menziesii*, the 0.3 m sample "disks" were cut from ground level and at 5 or 10 m. The boards were cut from the disk and planed to 1.5 cm thickness. The boards were cut through the pith and then 2 cm samples were taken at evenly spaced intervals from the pith to the bark to produce 8 bending samples from each disk. The bending samples were 20 cm in the longitudinal direction, 1.5 cm in the tangential direction, and 2 cm in the radial direction. These were slow growing trees and the bending samples contained between 4 and 7 growth rings.

The *P. taeda*, *P. palustris*, and *P. echinata* samples were oven dried at 105°C, while the *P. menziesii*, *P. ponderosa*, and *P. elliottii* samples were air-dried. All of the samples were reconditioned to 12% moisture content prior to testing.

Stiffness, or modulus of elasticity (MOE), and ultimate strength, or modulus of rupture (MOR), of clear wood samples were measured in three-point bending according to ASTM standards (ASTM 1999). All of the samples were broken with the load applied against their radial face. All tests were conducted with an Instron 5500, and the MOR and MOE were calculated with Instron's Merlin software. Samples that broke at a visual defect were excluded from the analyses.

NIR measurements

The NIR analysis is described in detail elsewhere and is only briefly reviewed here (Kelley et al. 2002). The NIR measurements were all made with an Analytical Spectral Devices (ASD) Field Spectrometer at wavelengths between 500–2400 nm using the default parameters. A fiber optic probe oriented at a right angle to the sample surface was used to collect the reflectance spectra. A piece of commercial microporous Teflon was used as the white reference material. The samples were illuminated with a DC lamp oriented at 30° above the samples and aligned in parallel with the longitudinal axis of the sample. For each sample, 30 scans were collected and averaged into a single spectrum and four spectra were collected for each sample. The 4 averaged spectra collected were averaged to provide a single spectrum that was used to predict the mechanical strength of the individual sample. The NIR spectra of the different softwoods were measured at different times over a one-year period, but all of the samples from one species were measured at one time.

Projection to latent structures (PLS) modeling

In this study, no spectral preprocessing techniques were used. A complete description of multivariate analysis can be found elsewhere (Martens and Naes 1991; Vandeginste et al. 1998). Multivariate analysis was performed using Unscrambler® version 7.6 (CAMO, Corvallis, OR) software. All of the results presented here are based on PLS-2 analysis, which simultaneously predicts both MOR and MOE. A PLS-2 type of analysis was used since the MOR and MOE of small clear samples are highly correlated (Tsehaye et al. 1998). To compensate for the large differences in the absolute value of the MOE and MOR, they were weighted by the inverse of their standard deviations. The models were constructed with an X-matrix of either 190 points (500–2400 nm) or 40 points (650–1050 nm). All of the PLS models were based on 4 to 6 factors. The correlations for most of the models could have been improved by adding more latent variables, but the number of latent variables was limited to minimize concerns with overfitting.

Since the sample sets have different sizes, the calibration models (CALB) were constructed based on one-half to two-thirds randomly selected samples. For the larger sample sets, e.g., all softwoods, all southern pines, *P. elliottii*, and *P. taeda*, one half of the samples were used to construct the CALB models. In the case of the smaller data sets, *P. palustris*, *P. echinata*, *P. ponderosa*, and *P. menziesii* two thirds of the samples were used to construct the CALB models. All of the CALB models were constructed using full cross-validation. (Martens and Naes 1991; Vandeginste et al. 1998).

The quality of a correlation model can be measured in several ways; two common measures, r-value and RMSEP (Martens and Naes 1991; Vandeginste et al. 1998), are used in this work. The r-value is a measure of the strength of the correlation of the measured and predicted data. For a heterogeneous material such as wood, r-values of 0.85 and above are generally considered good. The RMSEP is a measure of the prediction error, expressed in the units of the original measurement.

Results and discussion

NIR spectra

Representative spectra data collected from *P. menziesii*, *P. palustris* and *P. elliottii* heartwoods are shown in Figure 2. The spectra all have similar spectral features with small differences in intensity. Many of the NIR peaks have been

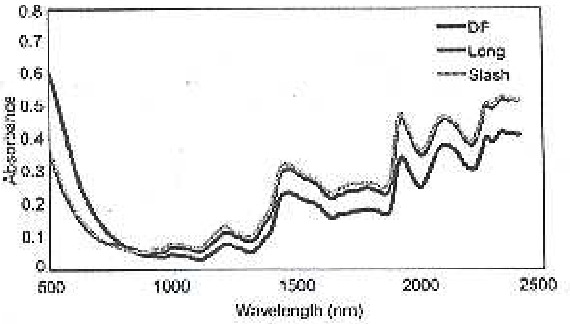

Figure 2 NIR spectra of *P. menziesii* (Douglas fir), *P. palustris* (longleaf pine) and *P. elliottii* (slash pine) heartwood.

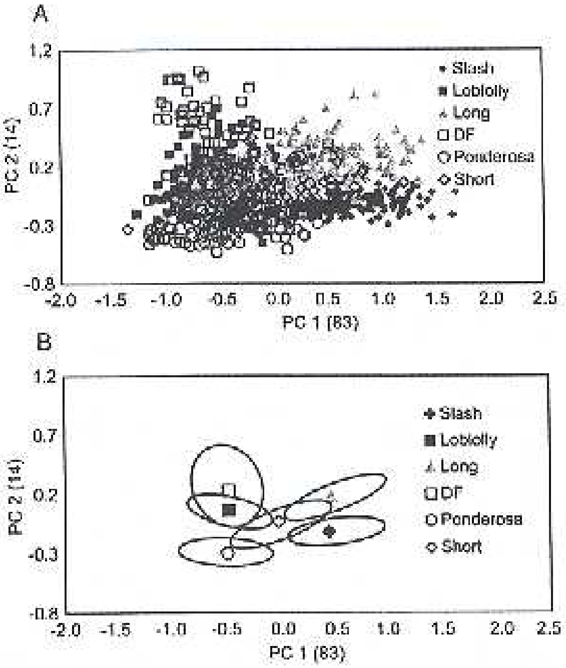

Figure 3 Results from Principal Component Analysis (PCA) of the (A) all the individual NIR spectra of the six softwoods and (B) the average and 95 percentile of the PCA of the six softwoods.

previously assigned (Marten et al. 1985; Curran et al. 1992; Fourty et al. 1996; Svedas 2000; Ali et al. 2001). The major vibrations include the yellow-brown color of the wood at 400–700 nm, which is primarily due to the presence of lignin and extractives, and the relatively high intensity of the *P. menziesii* wood spectrum, which is indicative of its red-brown color. The major peak between 1400 nm and 1660 nm has been assigned to the first overtone of cellulose and hemicellulose hydroxyls. The peak between 1890 nm and 2020 nm has been assigned to interactions between hydroxyls and water in the wood. There is an additional strong vibration centered on 2020 nm that has been assigned to the combination vibrations of the carbohydrate hydroxyls. Lignin hydroxyl vibrations overlap the carbohydrate hydroxyl vibrations; *e.g.*, the first overtone of the lignin hydroxyl vibrations occur between 1400 nm and 1520 nm. The first overtone of the lignin C-H stretching vibrations is seen at 1700 nm. These assignments provide some insight into the chemical structure of the wood.

Spectral differences between all of the wood samples are highlighted by PCA. The results of a PCA of all of the wood samples are shown in Figure 3. The PCA highlights the greatest spectral differences between all of the wood samples. In this case, the two principal components (PC) shown in Figure 3a account for 97% of the variation present in the spectra. The results shown in Figure 3a show that in spite of some overlap, there are clear differences between several of the different wood species. These differences are clarified in Figure 3b, which shows the same result on the same scale, but with a single point at its average value now representing each softwood species for PC1 and PC2. The ellipse around each species average (Figure 3b) represents the standard deviation of PC1 and PC2 for the different softwoods. This presentation clearly shows the difference between the six softwoods. While there is some overlap between the four southern pines, the *P. menziesii* and *P. ponderosa* are clearly different from the southern pines. Examination of additional PCs (not shown) did not enhance the separation of the different southern pines.

Mechanical properties

In this study we measured the mechanical properties of almost 1000 small, clear softwood samples. The summary data for MOE and MOR, or stiffness and strength, of the samples are shown in Table 1. The average MOE of the *P. taeda* and *P. elliottii* are similar, while the *P. palustris* and *P. menziesii* are slightly stiffer, and the *P. echinata* and *P. ponderosa* are less stiff. In the case of the average MOR, the *P. taeda*, *P. echinata*, and *P. ponderosa* are all weaker, and the *P. menziesii* is stronger. All of the

Table 1 Summary of properties for the different wood species. The number of samples for each group or species is shown in parentheses.

Sample Set	MOE (MPa)			MOR (MPa)		
	Min	Max	Ave	Min	Max	Ave
All softwoods (989)	2200	22 600	9900	14	199	101
All southern pines (784)	2200	22 600	10 190	14	199	102
P. elliottii (353)	2200	22 600	9910	14	199	101
P. taeda (225)	2500	16 700	9190	21	138	86
P. palustris (144)	2200	20 200	11 140	14	186	108
P. menziesii (104)	6300	16 300	11 580	35	168	115
P. ponderosa (101)	2200	14 000	5620	25	149	71
P. echinata (62)	3000	22 600	7700	33	199	85

Table 2 Summary of PLS-2 model parameters. The correlation coefficient for the calibration model (r CALB) and the prediction model (r TEST), and the normalized RMSEP (RMSEP divided by the average MOE or MOR for that group or species).

	MOE (MPa)				MOR (MPa)			
All SFWD	PC=3	PC=4	PC=5	PC=6	PC=3	PC=4	PC=5	PC=6
r (CALB)			0.81	0.83			0.86	0.87
r (TEST)			0.81	0.84			0.86	0.87
Norm. RMSEP			23	22			18	17
All SP	PC=3	PC=4	PC=5	PC=6	PC=3	PC=4	PC=5	PC=6
r (CALB)		0.82	0.84	0.86		0.85	0.88	0.89
r (TEST)		0.83	0.85	0.87		0.85	0.88	0.88
Norm. RMSEP		22	20	19		19	17	17
P. elliottii	PC=3	PC=4	PC=5	PC=6	PC=3	PC=4	PC=5	PC=6
r (CALB)	0.84	0.89	0.89		0.85	0.90	0.90	
r (TEST)	0.85	0.89	0.90		0.86	0.89	0.90	
Norm. RMSEP	20	17	17		18	16	16	
P. ponderosa	PC=3	PC=4	PC=5	PC=6	PC=3	PC=4	PC=5	PC=6
r (CALB)		0.85	0.87	0.87		0.86	0.90	0.90
r (TEST)		0.82	0.84	0.84		0.84	0.89	0.89
Norm. RMSEP		35	30	32		21	17	18

mechanical properties of the samples used in this study are 10% to 20% below the published values (Green et al. 1999); however, the rank order of the different softwoods corresponds to data published in the Wood Handbook (Green et al. 1999). The differences in the average values for MOE and MOR are likely due to the inclusion of a large proportion of juvenile wood in the samples used for this study. As expected, *P. echinata* and *P. ponderosa* are generally weaker than the other softwoods studied. The average values for the *P. elliottii* samples used in this study are slightly lower than expected.

Table 2 shows the r-values and RMSEP for the CALB and TEST sets for the models based on groups of species and several of the individual species. Table 2 also shows the effects of varying the number of latent variables on the quality of the models. The latent variables contain chemical or physical information that is used to predict the mechanical properties of the samples. Increasing the number of latent variables improves the model but will also increase the risk of overfitting the data. The results in Table 2 show that for the single species models, e.g., *P. elliottii* and *P. ponderosa*, there is little benefit to using more than 4–5 latent variables. In the case of the models that are based on groups of species, e.g., all softwoods and all southern pines, more latent variables may be needed to obtain a good model. The model for all the softwoods must measure the chemical and physical information that is related to mechanical properties but it must also "account" for a more heterogeneous set of samples. Thus, the model for all the softwoods requires 6 latent variables to effectively predict mechanical properties. The model for the group of southern pines only requires 5 latent variables, which indicates that these samples are relatively homogeneous. The large number of samples and relatively wide range of physical properties contained in the all southern pine group also tends to reduce the number of latent variables needed for a good model.

A summary of the r-values and normalized RMSEP for both MOE and MOR of all the sample sets are shown in Table 3. With the exception of the MOE predictions for *P. taeda* and *P. echinata* the r-values are all above 0.80. These r-values are comparable to those reported by Hoffmeyer and Pedersen (1995), Thumm and Meder (2001) but lower than those reported by Gindl et al. (2001) and Schimleck et al. (2002), although these other studies

Table 3 Summary of correlation coefficients (r) and normalized RMSEP for the within groups or within species predictions of MOE and MOR. The number of latent variables used in the CALB models are shown in parentheses.

	MOE (MPa)		MOR (MPa)	
	r	Normalized RMSEP	r	Normalized RMSEP
ALL SFWD (6)	0.84	22	0.87	17
ALL SP (5)	0.87	20	0.88	17
P. elliottii (4)	0.89	17	0.89	16
P. taeda (5)	0.78	20	0.84	13
P. palustris (5)	0.91	19	0.85	22
P. menziesii (4)	0.83	10	0.80	13
P. ponderosa (5)	0.84	30	0.89	17
P. echinata (5)	0.69	31	0.92	14

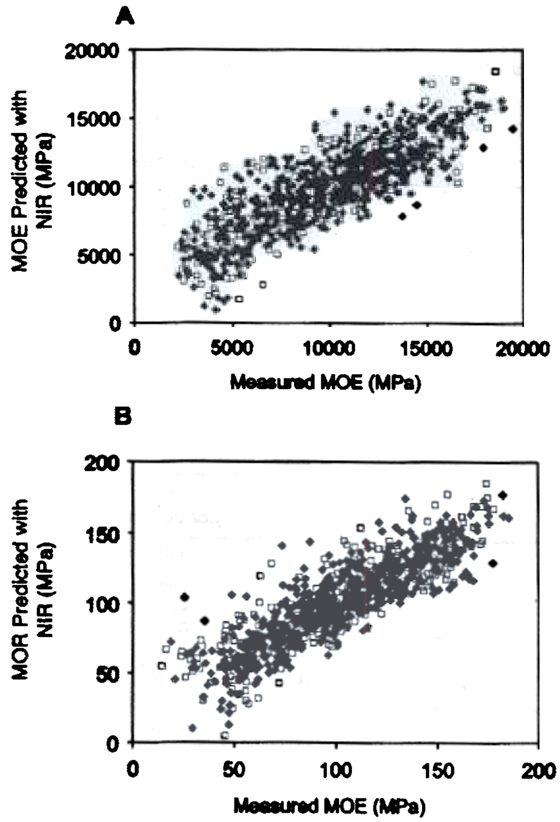

Figure 4 Measured and predicted (A) MOE and (B) MOR for all six softwoods (ALL SFWD). The solid symbols indicate the CALB set and the open symbols indicate the TEST set.

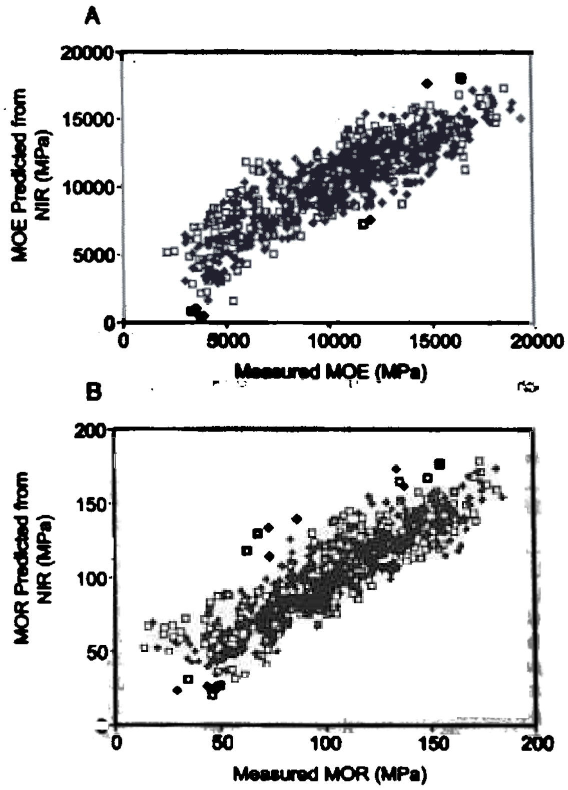

Figure 5 Measured and predicted (A) MOE and (B) MOR for the four southern pines (ALL SP). The solid symbols indicate the CALB set and the open symbols indicate the TEST set.

used PLS-1 models and more latent variables in their predictions. Both of these considerations will increase the quality of the correlations. The low r-value for the *P. echinata* is likely due to the relatively small sample size that results in a lower quality model. The relatively poor correlation between the measured and predicted MOR for the *P. taeda* set is surprising since this is a relatively large set of samples, and the correlation coefficient for MOR is in line with the other species. Table 3 also shows that based on either r-value or the normalized RMSEP, NIR spectra can be used to predict MOR better than MOE. This is surprising since MOE is generally thought to be strongly linked to MFA, density, fiber orientation, and wood composition (Tsehaye et al. 1998), while even in small clear samples MOR is strongly influenced by small undetectable defects. NIR is sensitive to MFA (Kelley et al. 2002), density (Hoffmeyer and Pedersen 1995; Gindl et al. 2001; Schimleck et al. 2002), fiber orientation (Tsuchikawa et al. 1992), and the chemical composition of wood (Schimleck et al. 1997; Kelley et al. 2002), however it is not obvious that NIR should be sensitive to very small defects.

Figure 4a shows a plot of the measured MOE versus the MOE predicted from the NIR spectra using the PLS-2 models for all of the six softwoods treated as a group. Figure 4b shows a similar plot for MOR. While there is some scatter in the data, it is clear that there is strong correlation between the measured mechanical properties and the mechanical properties predicted with NIR spectroscopy. It is important to note that although the PCA results highlighted the fact that there are chemical differences between the six different softwoods, the results of this PLS-2 show that these chemical differences do not prevent data from all six softwoods from being used to produce one model for predicting mechanical strength. The r-values for both the CALB and TEST sets are very similar (Table 2). The spectra and mechanical properties data in the TEST set were not used in constructing the original PLS-2 model and thus the results from the TEST set can be viewed as a prediction of the mechanical properties of unknown samples of the six different softwoods from their NIR spectra.

Figure 5a and b show the results for MOE and MOR from similar PLS-2 models for all the southern pines treated as a group. Again, the r-values for both the CALB and TEST sets are very similar (Table 2). The mechanical strength values of the TEST set predicted from the NIR spectra are highly correlated with the measured strength values. Compared to the set of all six softwoods, the southern pines are viewed as a relatively homogenous group. In addition, the quality of the predictive models based on the southern pines alone (ALL SP) is similar to those based on the entire set of softwoods, indicating that the models for all softwoods (ALL SFWD) are quite robust.

Both sets of MOE/MOR data show a slight decrease in the quality of the correlations for the individual bending

Table 4 Summary of correlation coefficients for the within groups or species (numbers in bold), and between groups or species predictions of MOE (MPa) (4a) and MOR (MPa) (4b). The number of latent variable used in the CALB models are shown in parentheses.

A. MOE — TEST set

CALB set	ALL SFWD	ALL SP	*P. elliottii*	*P. taeda*	*P. palustris*	*P. menziesii*	*P. ponderosa*	*P. echinata*
ALL SFWD (6)	**0.84**	0.84	0.90	0.73	0.90	0.69	0.84	0.75
ALL SP (5)	0.75	**0.87**	0.88	0.79	0.93	0.81	0.79	0.80
P. elliottii (4)	0.94	0.78	**0.89**	0.74	0.90	0.83	0.82	0.75
P. taeda (5)	0.72	0.73	0.83	**0.78**	0.89	0.86	0.76	0.63
P. palustris (5)	0.66	0.77	0.82	0.74	**0.91**	0.80	0.75	0.82
P. menziesii (4)	0.53	0.59	0.85	0.54	0.75	**0.83**	0.72	0.78
P. ponderosa (5)	0.71	0.73	0.86	0.62	0.90	0.81	**0.84**	0.86
P. echinata (5)	0.71	0.74	0.85	0.35	0.84	0.77	0.68	**0.69**

B. MOR — TEST set

CALB set	ALL SFWD	ALL SP	*P. elliottii*	*P. taeda*	*P. palustris*	*P. menziesii*	*P. ponderosa*	*P. echinata*
ALL SFWD (6)	**0.87**	0.88	0.88	0.82	0.88	0.72	0.86	0.93
ALL SP (5)	0.85	**0.88**	0.88	0.84	0.89	0.81	0.88	0.91
P. elliottii (4)	0.80	0.84	**0.89**	0.81	0.87	0.74	0.72	0.87
P. taeda (5)	0.79	0.79	0.85	**0.84**	0.84	0.71	0.79	0.95
P. palustris (5)	0.75	0.82	0.85	0.80	**0.85**	0.70	0.76	0.93
P. menziesii (4)	0.67	0.76	0.84	0.64	0.76	**0.80**	0.72	0.70
P. ponderosa (5)	0.75	0.77	0.83	0.72	0.86	0.69	**0.89**	0.91
P. echinata (5)	0.77	0.79	0.84	0.61	0.84	0.54	0.71	**0.92**

samples with lower values. The samples with lower stiffness and strength came primarily from juvenile wood and many of them included a portion of the pith. The NIR spectra were collected from both sides of the samples, and the dark color and substantial chemical differences of the pith would result in NIR spectra that are very different from "normal" weak wood. Thus, poorer correlations for the weaker samples that included a portion of the pith is not unexpected. Plots that are very similar to those shown in Figures 4 and 5 can be obtained from all of the individual wood species (not shown).

Predictions within and between species

The results for predictions of all the models are shown in Tables 4 and 5. Table 4 shows the r-values for all of the intra- group or species and inter- group or species models for MOE (Table 4a) and MOR (Table 4b). Table 5 shows the corresponding RMSEP for the predictions of MOE (Table 5a) and MOR (Table 5b). For both tables the intra-group or species value is shown on the diagonal in bold. The other cells show the r-values or RMSEP for the inter-group or species models. For example, the first row in Table 4a, e.g., ALL SFWD, shows the r-values for MOE predicted using a CALB model constructed with samples from all six softwood species. This "six species" CALB model was then used to predict the MOE values of TEST sets made up of all six species combined, four southern pines combined, and each of the individual species. These values are shown in each cell for the first row. In the second row of Table 4a the values are based on a CALB model constructed for the four southern pines. This ALL SP model is then used to predict the MOE values of TEST sets made up of all six species combined, four southern pines combined, and each of the individual species. The first column in Table 4a shows the r-values for the ALL SFWD TEST set predicted with different CALB models. The first r-value is based on a CALB model constructed with all six softwoods. The last cell in column one shows the r-value for the prediction of the MOE of the TEST set that includes all six softwoods based on a CALB model constructed from only the *P. echinata*. This same format is used to calculate the values in Tables 4b, 5a, and 5b.

Close examination of Table 4 shows that, in general, the r-values for predictions using the same group or species for both the CALB and TEST sets, shown on the diagonal, are the highest. The same trends are seen in Table 5 where the lowest normalized RMSEP, or the best predictions, are seen on the diagonal. This is not too surprising since one would expect that the CALB models constructed from one group or species would have all of the spectral features seen in the TEST set for that group or species, and thus be most effective for predicting the properties of that group or species. While this general trend is seen for the values in Table 4 and Table 5, there are several notable exceptions in Table 4a. In the case of the TEST sets of *P. elliottii* and *P. palustris* the r-values are relatively high regardless of the CALB model. This may be because these two species have the largest range of MOE values. With a few exceptions, the normalized RMSEP (Tables 5 and 6) show that the CALB models constructed from one group or species do the best job of predicting the properties of that group or species. The results in Table 5 also highlight the difficulty of using CALB models based on samples that are dissimilar from those in the TEST set. The CALB models based on *P. menziesii* and *P. ponderosa* do a poor job of predicting the properties of any of the other TEST sets, and the properties of the *P. menziesii* and *P. ponderosa* TEST sets are best predicted by the respective *P. menziesii* and *P.*

Table 5 Summary of the percentage normalized RMSEP (RMSEP/Average Property) within groups or species (numbers in bold), and between groups or species predictions of MOE (MPa) (5a) and MOR (MPa) (5b). The number of latent variable used in the CALB models are shown in parentheses

A. MOE — TEST set

CALB set	ALL SFWD	ALL SP	*P. elliottii*	*P. taeda*	*P. palustris*	*P. menziesii*	*P. ponderosa*	*P. echinata*
ALL SFWD (6)	**22**	21	17	23	21	16	40	26
ALL SP (5)	26	**20**	20	20	18	24	94	25
P. elliottii (4)	30	30	**17**	40	37	27	52	27
P. taeda (5)	35	37	50	**20**	24	27	67	29
P. palustris (5)	35	29	33	32	**19**	54	70	22
P. menziesii (4)	52	56	66	52	38	**10**	122	103
P. ponderosa (5)	41	45	28	50	61	35	**30**	18
P. echinata (5)	50	49	41	55	56	47	81	**31**

B. MOR — TEST set

CALB set	ALL SFWD	ALL SP	*P. elliottii*	*P. taeda*	*P. palustris*	*P. menziesii*	*P. ponderosa*	*P. echinata*
ALL SFWD (6)	**17**	19	24	22	31	56	34	26
ALL SP (5)	19	**17**	17	14	20	21	35	28
P. elliottii (4)	24	24	**16**	31	31	26	33	18
P. taeda (5)	22	29	36	**13**	25	24	32	13
P. palustris (5)	31	27	23	40	**22**	54	30	13
P. menziesii (4)	56	56	64	45	57	**13**	83	80
P. ponderosa (5)	34	37	24	40	54	30	**17**	18
P. echinata (5)	26	26	29	26	22	28	30	**14**

ponderosa CALB models. This is not too surprising given the lack of similarity between *P. menziesii* and *P. ponderosa* compared to the southern pines.

These results highlight the potential for using a single CALB model, constructed with a large number of samples from different species, to predict the mechanical properties of a wide variety of different softwoods. While other species of commercial interest, e.g., noble fir, grand fir, white fir, or spruce species, were not included in this study, it appears likely that a single CALB model can be constructed for all of these different softwoods. Schimleck et al. (2002) showed that a single high quality model could be constructed from one softwood (*Pinus radiata*) and one hardwood (*Eucalyptus delegatensis*), however our preliminary analysis of a data set that included these six softwoods and two hardwoods (*Populus deltoids* and *Alnua rubra*) (not shown) suggests that it is unlikely that high quality models can be constructed from this particular combination of softwoods and hardwoods.

Effects of reduced spectral range

The use of NIR spectra to predict the mechanical strength of wood has been previously reported by several groups (Hoffmeyer and Pedersen 1995; Hauksson et al. 2001; Thumm and Meder 2001; Kelley et al. 2002). We have also reported on the use of a reduced spectra range (650–1050 nm) to predict the mechanical properties of *P. taeda* (Kelley et al. 2002), while Thumm and Meder (2001) have reported the use of a similar range for predicting the strength properties *P. radiata*. The use of this reduced spectral range to produce high quality models is a critical advance, since it enables the use of small, very lightweight, inexpensive, handheld spectrometers with very rapid acquisition times. These handheld spectrometers could be used for predicting mechanical properties under practical field conditions or for in-line process monitoring. Reducing the spectral range to 800–1100 nm still allows for the construction of high quality models for the chemical composition of wood (Axrup et al. 2000).

Table 5 highlights the impact of reducing the spectral range from 500–2400 nm to 650–1050 nm. Reducing the spectral range to 650–1050 nm, coupled with averaging the original data prior to PLS modeling, means that only 40 data points are used for constructing the CALB models and predicting the properties of the TEST set. The results in Table 5 generally show a slight decrease in the r-value for both the CALB and TEST set. For the sample sets of greatest interest, i.e., all softwoods and all southern pines, this decrease in the r-value is between 0.03 and 0.05. This is a very slight decrease given the significant advantages of moving to a reduced spectral range. Similar results are seen for the PLS models of *P. elliottii*, *P. taeda*, and *P. palustris*. The decrease in the quality of the models is generally greater for *P. menziesii*, *P. ponderosa*, and *P. echinata*. As mentioned previously, these models are based on smaller data sets that include a narrower range of mechanical property values. This is probably the cause of the greater decrease in model quality, rather than some inherent limitation of these species.

Conclusions

The mechanical properties of almost 1000 small clearwood samples from six softwood species were measured in three-point bending. The NIR reflectance spectra of these solid samples were also collected. The results of PCA of these spectra showed clear differences between

Table 6 Summary of correlation coefficients for models using a reduced spectral range. The number of latent variable used in the CALB models are shown in parentheses.

Sample	MOE (MPa) 500–2400 nm	MOE (MPa) 650–1050 nm	MOR (MPa) 500–2400 nm	MOR (MPa) 650–1050 nm
All SFWD (6)	0.84	0.76	0.87	0.82
All SP (5)	0.87	0.81	0.88	0.85
P. elliottii (4)	0.89	0.88	0.89	0.89
P. taeda (5)	0.78	0.76	0.84	0.78
P. palustris(5)	0.91	0.90	0.85	0.86
P. menziesii (4)	0.83	0.78	0.80	0.69
P. ponderosa (5)	0.84	0.74	0.89	0.74
P. echinata (5)	0.69	0.66	0.92	0.73

the six different species. Using PLS modeling, the NIR spectra of these softwoods could be used to predict the mechanical properties of the clear-wood samples. The r-values for most of these models were greater than 0.85. The RMSEP for most of the models was about 20% of the full range of mechanical values for the samples.

Even though there were subtle spectral differences between the six species, all of the samples could be combined into one PLS model that could effectively predict the strength properties of any of the individual softwoods. The r-values for most of these predictions were above 0.80.

The CALB model containing all six softwoods performed least well for predicting the properties of *P. menziesii*, which is least similar to the other five pines used in the CALB model.

The original CALB models were constructed using a full spectral range between 500 nm and 2400 nm. Reducing the spectral range to between 500 nm and 1050 nm caused a slight decrease in the quality of the models, however, this decrease of the r-values by 0.05 was minor considering the advantages of using a reduced spectral range. These advantages include the ability to use a much smaller, faster, lighter, less expensive spectrometer that could be used either in the field or for process control.

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