Measuring the Moisture Content of Green Wood Using Time Domain Reflectometry

Laurence Schimleck Kim Love-Myers Joe Sanders
Heath Raybon Richard Daniels Jerry Mahon
Edward Andrews Erik Schilling

Abstract

The responsible usage of water by facilities that rely on wet log storage in the southern United States has become an issue of great importance as restrictions on water usage have grown in recent years. In order to learn about the dynamics of moisture content in wet-stored logs over time, it is necessary to conduct continuous monitoring of log piles. Time domain reflectometry (TDR) is a method that current research has shown to have potential for use in this area. In this study, TDR probes of three lengths (75, 100, and 125 mm) were systematically inserted into 39 saturated bolts of *Pinus taeda* L., and both TDR and moisture content measurements were taken nine times over a period of 16 days as the bolts air dried. The samples were then oven dried, and measurements were taken three more times during that process. TDR readings from the 125-mm probes had the strongest relationship ($R^2 = 0.9426$) with moisture content measurements. This result indicates TDR readings are sufficiently correlated with moisture content to accurately predict moisture variation over time and can be used to learn how water application and other factors affect the moisture content of wet-stored logs.

In the wood products sector, timely management of available resources is an ongoing concern. Because of the seasonal nature of harvesting, in the southern United States it is common practice to place logs in wet storage during periods of increased wood supply. Wet storage helps to ensure that mill facilities will have adequate wood available to allow operation during times when weather and other seasonal difficulties slow or prevent harvesting activities. As opposed to dry storage, wet storage maintains the wood under a system of sprinklers, allowing it to be stored for long periods of time without experiencing high levels of decay and damage by insects.

Wet storage of wood requires large amounts of water to maintain high moisture content in the logs. At present, most facilities operate under the assumption that more water is better, with high levels of water being continuously applied to wet-stored logs. While this has been shown to be an effective method of maintaining wood quality (Syme and Saucier 1995), increasing concerns in the southern United States regarding high levels of water consumption due to increasing urbanization and recent drought make reduced water use desirable. Elowsson and Liukko (1995) have shown that alternative regimes of water delivery may also be effective.

In order to learn about the effectiveness of different rates of water application to wet-stored logs, it would be advantageous to study the moisture content of the logs throughout the period of storage. Because of problems of accessibility (piles can be from 6 to 8 m high) and the high moisture content of stored logs, resistance-type and capacitance/power-loss moisture meters are unsuitable, as they cannot measure moisture content above 30 percent (Haygreen and Bowyer 1996), and at present there are no rapid assessment techniques available for this application.

The authors are, respectively, Professor and Codirector, Wood Quality Consortium, Warnell School of Forestry and Natural Resources, Univ. of Georgia, Athens (lschimleck@warnell.uga.edu [corresponding author]); Associate Director, Univ. of Georgia Statistical Consulting Center, Univ. of Georgia, Athens (krlove@uga.edu); Research Coordinator (sanders@warnell.uga.edu), Graduate Student (raybonm@warnell.uga.edu), and Professor and Codirector, Wood Quality Consortium (ddaniels@warnell.uga.edu), Warnell School of Forestry and Natural Resources, Univ. of Georgia, Athens; Division Forester, Molpus Timberlands Management, LLC, Monroe, Louisiana (jmahon@molpus.com); Forester, USDA Forest Serv., Southern Research Sta., Athens, Georgia (eandrews@fs.fed.us); and Senior Research Scientist, National Council for Air and Stream Improvement, Inc., Southern Regional Center, Newberry, Florida (eschilling@src-ncasi.org). This paper was received for publication in May 2011. Article no. 11-00060.

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However, a literature review suggested two methods that could possibly be adapted for this purpose: near infrared (NIR) spectroscopy and time domain reflectometry (TDR).

NIR spectroscopy has proven useful for measuring moisture content of trees using core and disk samples. Of the two, it was determined that NIR spectroscopy was not a viable method to use on a standing log pile. Typically, NIR spectroscopy could be used to measure the moisture content of a core, or a probe could be inserted in a log for continuous measurements. It is not possible to obtain core samples from or insert probes into logs while they are in wet storage, as most logs cannot be accessed. Additionally, the fiber-optic probes that could be inserted into a log are unable to withstand the hostile environment inside a standing log pile for long periods of time and cannot be reliably left inserted in the logs from one measurement to the next.

TDR is a standard method for determining soil moisture content. TDR can be used for this purpose because the dielectric constant of porous materials for frequencies between 1 MHz and 1 GHz is strongly dependent on volumetric water content and largely independent of bulk density (Constantz and Murphy 1990). For measurement of soil moisture, probes of known length are inserted into the soil, and a pulse is transmitted through the probes. As the dielectric constant of the soil is strongly influenced by its moisture content, the apparent length of the probe rods differs depending on the moisture content of the soil (Topp et al. 1980, Nadler et al. 2003).

The same principal can be applied to wood, and several studies have provided encouraging evidence indicating that TDR may be a reliable method of measuring the moisture content of wet-stored logs over time. Constantz and Murphy (1990) demonstrated that TDR could reasonably measure changes in moisture content in several species of living trees over time, though they showed that the calibration curve for determining moisture content of trees was different from the general calibration curve used for determining moisture content of soil. The study additionally demonstrated that individual tree species would likely need individual calibration curves to ensure accuracy, though no further studies were done to confirm this. Later, Wullschleger et al. (1996) applied similar techniques to several hardwood species and concluded that TDR was a sufficient method for determining seasonal variations in the moisture content of standing trees and confirmed that the calibration curve for standing trees was different from that for measuring the moisture content of soils. Their experiment, however, indicated that it may be possible to have one universal calibration curve for various tree species. One further study (Nadler et al. 2003) of 5-year-old lemon (*Citrus limon* (L.) Burman f.) trees used TDR to simultaneously measure differences in soil and stem moisture content under various irrigation regimes and concluded that TDR could be used successfully to measure changes in tree water status as they respond to water stress. While each of these studies showed potential for TDR as a means of measuring moisture content in trees, it should be noted that in each study, only one probe length was used (probe length varied from study to study, however), two of them (Constantz and Murphy 1990, Nadler et al. 2003) did not attempt unique calibrations for the species involved in the studies, and all of these studies assumed that the same part of the waveform reading that results from TDR measurement used in measuring soil moisture (the dielectric constant) would be most appropriate for measuring tree moisture content.

Therefore, in order to implement TDR as a basis for monitoring moisture content of wet-stored logs, it was first necessary to carry out a calibration study. The main goal of this study was to determine if TDR is a reasonable method for monitoring moisture content in logs. To accomplish this, several secondary goals were identified, including the following:

- determination of which part of the waveform reading is most highly correlated to moisture content of wood;
- determination of what probe rod length is the most conducive for predicting moisture content;
- determination of the nature of the statistical relationship between the apparent length of the probes and moisture content; and
- development of a mathematical model for use in further studies should a reasonable relationship be found.

Materials and Methods

TDR measurements

In order to adapt TDR technology to measure the moisture content of logs, probes were designed and built. Each probe consisted of two 3-mm-diameter stainless steel rods brazed to a length of copper coaxial cable. The brazed ends of the probes and the cable were cast inside a 30 by 30 by 60-mm plastic block so that the probe rods were spaced 25 mm apart, enabling them to be systematically inserted into logs or bolts. Once inserted, a pulse of energy was sent down the cable into the probes and then reflected back to the TDR instrument, where the apparent length of the probe rods was read as a waveform trace on an oscilloscope display. A Tektronix TDR cable tester was used to determine the apparent length of the probe rods inserted in short wood bolts.

Calibration samples

The main set of calibration wood samples was initially made up of 30 bolts, each 152.5 mm long, cut transversely from logs of *Pinus taeda* L. The diameter of the test bolts ranged from 124 to 229 mm with the bark removed. Because of a malfunctioning probe, one of the bolts was excluded from the experiment, and a total of 39 bolts were used. The main calibration set (29 bolts) had 75-mm probes inserted. Two additional sets of bolts, with five samples in each set, were tested with 100- and 125-mm probe rods inserted, respectively. These wood samples ranged from 124 to 220 mm in diameter for both sets of five.

Data collection

Wood samples were hydrated in a saturation tank for 2 weeks prior to the start of the experiment. Following saturation, probe weight, wood sample weight, and gravimetric weight were measured. Two 3-mm holes, 25 mm apart, were then drilled in the samples using a guide. The depth of holes was consistent with the length of the probe rods (i.e., 75, 100, or 125 mm) to avoid problems with inserting longer probes, and probe orientation was parallel to the grain. Once the holes were drilled, the probes were inserted and the first waveform readings taken.

Samples were air dried during the next 16 days and measured nine more times during this period. At each measurement, the samples were weighed without removing the probes (probe weights were later subtracted to obtain sample weights) and TDR waveform readings collected. After these initial 10 measurements, the wood samples were oven dried for 1 day at 50°C without removing the probes, and then weights and waveforms were recorded. For the 12th and final measurement interval, the probes were removed, and the wood samples were oven dried for 3 days at 103°C, and then ovendry weights were recorded. This final weighing provided a reference weight and percent moisture content on an ovendry basis for all previous readings.

The primary purpose of this calibration study was to use the apparent length of the probe rods as measured on the TDR display to predict wood moisture content. Note that apparent length is not the actual length of the rods but rather the point at which wave reflection signals appear. This apparent length is a function of the conductivity of the medium; wood with higher moisture content has higher conductivity and carries the signal farther before reflection occurs.

Figure 1 shows the waveform. In this figure, the starting point for measurement of the waveform is point X; this corresponds to the point where the probe rods emerge from the plastic block. The position of X is determined for each probe by short-circuiting the rods at the probe base while the probe is connected to the TDR.

Initially, lengths from point X to points A, B, C, and D (Fig. 1) were recorded. Ideally, we would have saved each waveform for later analysis but this was not possible using the Tektronix TDR cable tester. Previous TDR studies of soil moisture content measurement over the past 20 years have used points B, C, and D. Point D was abandoned during the second measurement interval because of difficulties in consistently determining the location of this point on the waveform. Point E, referred to also as the dropoff point of the signal, showed a more stable response and was recorded during the next 10 measurement intervals in place of point D. Point C, also referred to as the inflection point of the rising curve, was seemingly the most consistent feature on the waveform, as it was not difficult to locate and measurements were unambiguous. On visual assessment at the end of the experiment period, both point C and point E showed a steady shortening of the apparent length of the waveform over time as the samples dried; points A and B had considerable instability. Only points C and E were used in subsequent analyses.

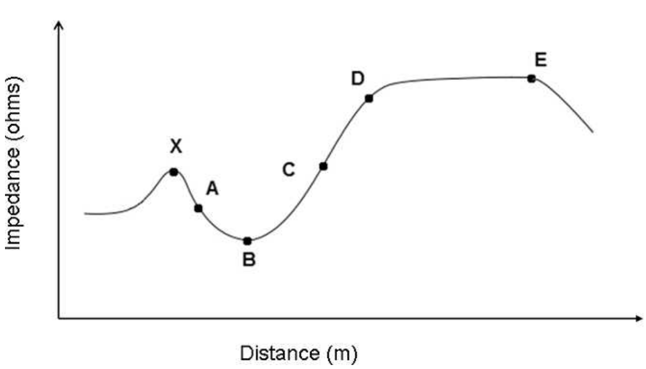

Figure 1.—Appearance of the time domain reflectometry waveform. X = starting point for measurement of the waveform; A = inflection point of the falling curve; B = first minimum; C = inflection point of the rising curve; D = apparent distance to the dropoff point of the signal; E = dropoff point of the signal.

Statistical analysis

The form of the relationship between apparent distances of the waveform and the moisture content of the wood samples was unknown at the start of the analysis. However, soil moisture content is often related to the waveform reading through the Topp equation (Topp et al. 1980). This equation is a third-order polynomial regression model, suggesting that a polynomial regression may also be appropriate for relating the TDR waveform to wood moisture content. The analysis therefore began with a visual assessment of plots of apparent distances against moisture content for each probe length to determine the validity of this conjecture. Following this, further analyses were conducted to determine the values of model parameters and evaluate the validity of these models.

Note that probe and sample effects were not accounted for, even though repeated measurements were taken on each wood sample over time. Because the ultimate goal of this study was to create a prediction equation that would work with other probes and wood samples rather than an equation descriptive of this particular data set, removing variance through the inclusion of random effects would be ineffectual. Additionally, autocorrelation within wood samples due to repeated measures was ignored. Note that repeated measures also have the potential to lead to an inflated R^2 estimate. This was because future application of these methods cannot take autocorrelation into account since actual moisture content will not be measured.

Results

The analysis of the TDR calibration data began with an examination of separate plots of the data for each probe length and apparent distance since the form of the relationship between apparent distance and percent moisture content was unknown. From this visual examination, a linear or curvilinear relationship between the apparent distance to the inflection point of the rising curve (point C) and the percent moisture content in the wood sample appeared reasonable. The relationship between the apparent distance to the dropoff point of the signal (point D) and the percent moisture content in the wood sample was clearly not linear but could possibly be modeled with a higher-order polynomial.

The analysis then continued with further examination of linear and second-order relationships between apparent distance to the inflection point of the rising curve and percent moisture content. Regression statistics indicated that apparent distance to the inflection point and the square of that distance were highly significant in prediction of percent moisture content for each probe length ($P < 0.0001$ in all cases for distance to inflection point, and $P = 0.0006$, 0.0018, and 0.0102 for square of distance to inflection point for 75-, 100-, and 125-mm probe lengths, respectively). The degree to which apparent distance was able to predict moisture content varied among probe lengths; the 125- and 100-mm probes were the most effective, and the 75-mm probes were the least effective ($R^2 = 0.7920$ for 75-mm probes, $R^2 = 0.9031$ for 100-mm probes, and $R^2 = 0.9281$ for 125-mm probes). Figure 2 shows plots of the apparent distance to the inflection point and percent moisture content

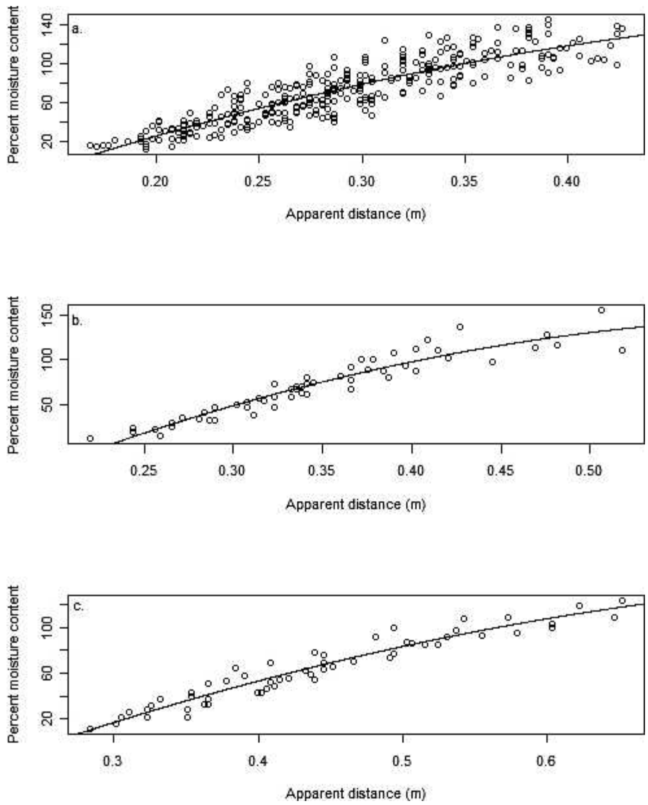

Figure 2.—Second-order polynomial regressions of apparent distance to inflection point predicting percent moisture content: (a) 75-mm probes, (b) 100-mm probes, and (c) 125-mm probes.

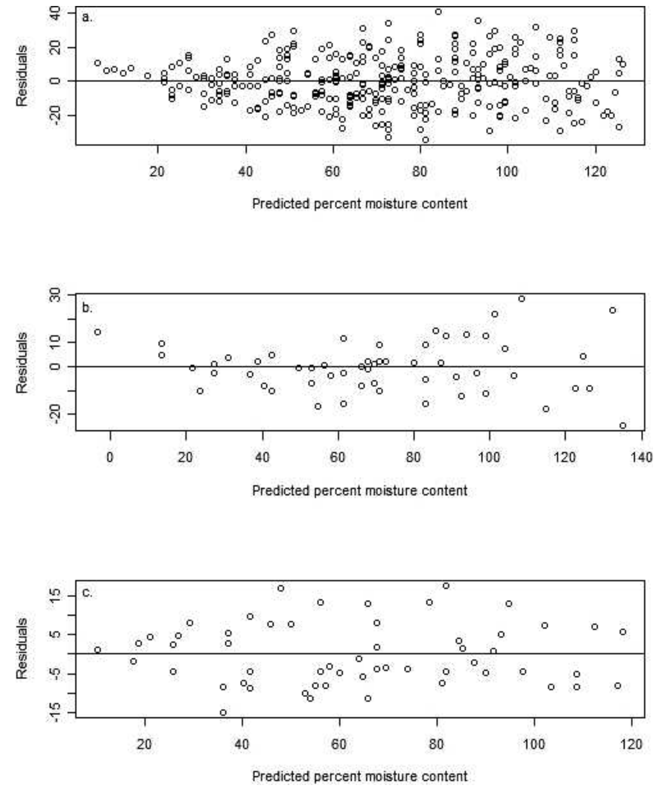

Figure 3.—Residual plots for second-order polynomial regressions of apparent distance to inflection point predicting percent moisture content: (a) 75-mm probes, (b) 100-mm probes, and (c) 125-mm probes.

of each sample at each measurement time, separated by probe length; the line resulting from the second-order regression is shown in each case. Figure 3 shows the residual plots associated with each of these regressions. The regression plots in Figures 2 and 3 indicate that a second-order regression was appropriate in each case. Analysis of a third-order model verified this, as the cube of the apparent distance proved insignificant in each case. However, the residual plots from Figure 3 indicate a problem with the variance of the residuals. This issue is most obvious in the data from the 75-mm probes, where the variance of the residuals was clearly larger for high predicted moisture content than low predicted moisture content. There could be several reasons for this, including influence on the apparent distance to the inflection point from a source other than moisture, differences between individual probes, or naturally occurring larger variance in the apparent distances at high moisture content. The effect was less noticeable in the 100-mm probe data and not noticeable in the 125-mm probe data.

To determine whether the diameter of the wood samples influenced this variance, the data from the 75-mm probes were broken into three diameter classes. The wood bolts with the 10 smallest diameters were classified as ''small diameter'' (124 to 175 mm), the 10 next smallest were classified as ''medium diameter'' (175 to 191 mm), and the 9 remaining wood bolts were classified as ''large diameter'' (191 to 229 mm). Figure 4 demonstrates that diameter was influential; in the regression for the 75-mm probes, small-diameter bolts tended to have positive residuals, and large-diameter bolts tended to have negative residuals. This indicated a need to include diameter as a covariate in the analysis. Figure 5 shows the residual plot for the 75-mm probes after diameter was included as a covariate. Diameter was extremely statistically significant in the model ($P < 0.0001$). This somewhat alleviated the problem, although some variance problems remained. Including diameter as a covariate also increased the R^2 from 0.7986 to 0.8496. Regression results for all three probe lengths with diameter included as a covariate can be found in Table 1. Diameter of the wood bolt was significant in the regressions for both the 75- and the 125-mm probes.

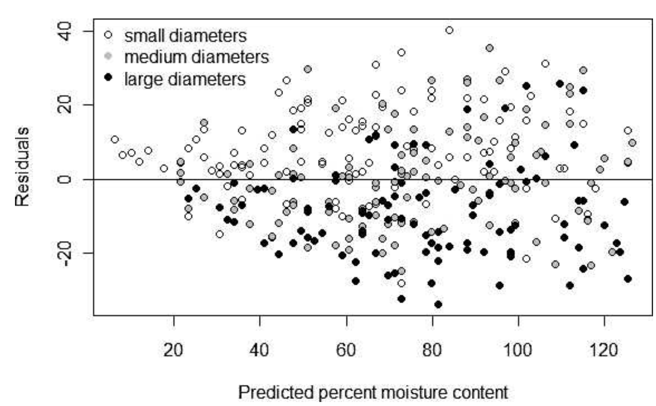

Figure 4.—Residual plot for linear regression of apparent distance to inflection point predicting percent moisture content for 75-mm probes, classified by diameter.

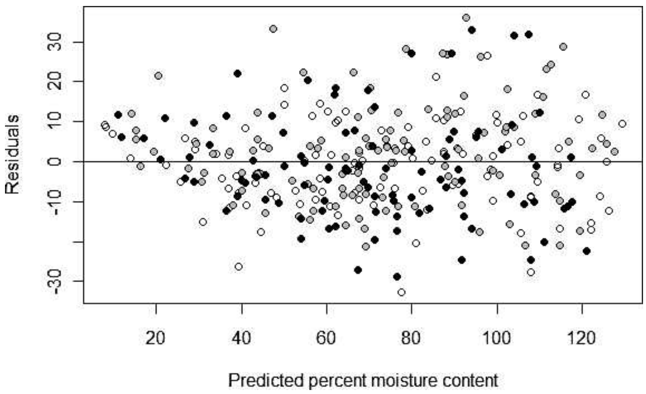

Figure 5.—Residual plot for second-order polynomial regression of apparent distance to inflection point predicting percent moisture content with diameter as a covariate for 75-mm probes, classified by diameter.

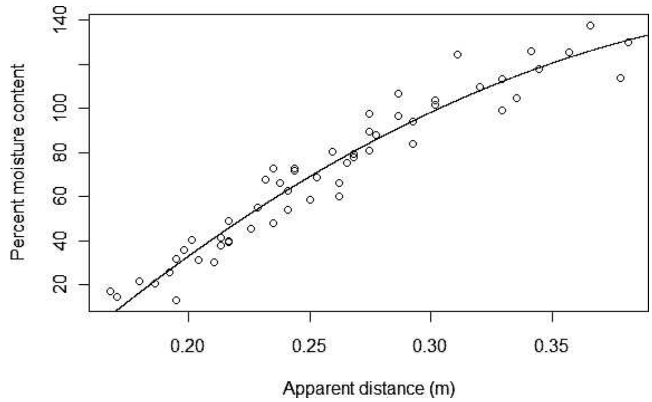

Figure 6.—Linear regression of apparent distance to inflection point predicting percent moisture content for 75-mm probes, for wood bolts with <75-mm radius.

Given these results, 125-mm probes were the most reliable for predicting percent moisture content from the apparent distance to the inflection point of the rising curve (R^2 with diameter as a covariate = 0.9426). However, wood sections with a diameter smaller than 125 mm cannot accommodate a 125-mm probe. To determine the effectiveness of shorter probes in these situations, a linear regression was performed after removing all wood bolts with a radius larger than 75 mm from the 75-mm probe data set. This ensured that the probes at least reached the center of the bolt. The results were excellent; in this data set containing 5 of the original 29 logs, diameter was no longer significant as a covariate (P = 0.7807 when included), the apparent distance to the inflection point and the square of the distance were still extremely significant ($P < 0.0001$ and =0.0003, respectively), and the R^2 of the model without diameter increased to 0.9384. Figure 6 is a plot of the data included in this analysis with the second-order regression line, indicating that the regression was appropriate. The residual plot is given in Figure 7, showing that the variance problem observed when all diameters were included was no longer apparent.

In addition to the apparent distance to the inflection point of the rising curve, the apparent distance to the dropoff point of the signal showed potential to predict percent moisture content. A linear regression on the 75-mm probe data proved inappropriate, as the relationship appeared to be curvilinear; the R^2 achieved was 0.5481. When a second-order model was applied, it became evident that outliers were present that had a large influence on the model. Given the success of prediction with the inflection point, it was determined that further analysis of the dropoff point was unnecessary.

Table 1.—Regression results for three probe lengths with diameter of wood bolt included as a covariate.

Probe length (mm)	R^2	Variable	P value of variable
75	0.8496	Inflection point	<0.0001
		Square of inflection point	<0.0001
		Diameter	<0.0001
100	0.9049	Inflection point	<0.0001
		Square of inflection point	0.0017
		Diameter	0.3335
125	0.9426	Inflection point	<0.0001
		Square of inflection point	0.0003
		Diameter	0.0008

To summarize the results, recommendations for TDR studies of wood moisture content include using 125-mm probes when the diameter of the wood sample allows and 75-mm probes for samples with a radius of no more than 75 mm. The most advantageous apparent distance (AD; measured in meters) to measure along the waveform is the distance from the base of the probes to the inflection point of the rising curve. The regression equations for relating this distance to the percent moisture content (%MC) of the sample follow:

$$\%MC = -180.65 + 1,344.77AD - 1,382.39AD^2 (75\text{-mm probes}) \quad (1)$$

and

$$\%MC = -132.14 + 676.99AD - 407.50AD^2 - 0.111\,\text{diam.}\,(125\text{-mm probes}) \quad (2)$$

Statistics summarizing the fit properties of these models can be found in Table 2. The statistics PRESS (predicted error sum of squares), PRESS RMSE (root mean square

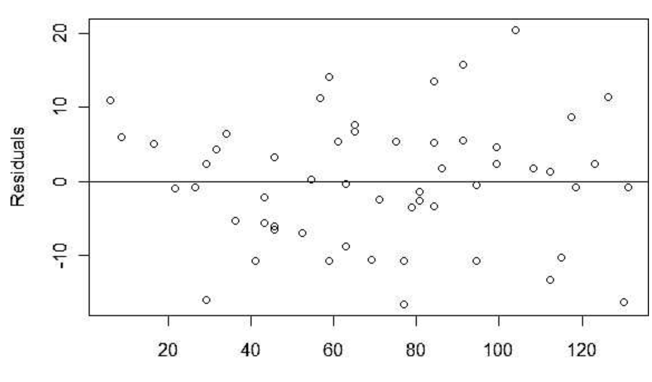

Figure 7.—Residual plot for linear regression of apparent distance to inflection point predicting percent moisture content for 75-mm probes, for wood bolts with <75-mm radius.

Table 2.—Model fit statistics for final recommended Models 1 and 2.[a]

Model	R^2	Q^2	RMSE	PRESS RMSE	PRESS
1	0.9383	0.9319	8.609	8.955	4,410.79
2	0.9426	0.9371	7.235	7.426	3,033.37

[a] RMSE = root mean square error; PRESS = predicted error sum of squares.

error; comparable to RMSE), and Q^2 (comparable to R^2; see Quan 1988) are related to predictive abilities of the models. The prediction-related statistics demonstrate good predictive abilities of the models.

To further confirm the predictive fit of the model, a cross validation was performed. The training data set retained 80 percent of the observations, and the remaining randomly selected 20 percent of observations became the validation data set. The training data resulted in the following models:

$$\%\text{MC} = -197.24 + 1,471.94\text{AD} - 1,609.35\text{AD}^2 \text{(75-mm probes)} \qquad (3)$$

and

$$\%\text{MC} = -131.60 + 659.95\text{AD} - 393.09\text{AD}^2 - 0.092 \text{ diam. (125-mm probes)} \qquad (4)$$

Model 3 has an R^2 of 0.9431 and an RMSE of 8.132, and Model 4 has an R^2 of 0.9410 and an RMSE of 7.324. These statistics are similar to those of the full model, as shown in Table 2, and should provide a reliable means of evaluation for the validation data set. The RMSE of the validation data for Model 3 was 10.387; the RMSE of the validation data for Model 4 was 7.235. These are similar to the RMSEs of the training data. A plot indicating the training data, the validation data, and both complete and training models is shown in Figure 8 for the 75-mm probes. These results provide further evidence of the predictive validity of Models 1 and 2.

Discussion

This study examined several issues related to the use of TDR as a means of measuring moisture content in logs. These issues included the differences in the results obtained by using probes of different lengths, the part of the waveform reading most correlated to moisture content,

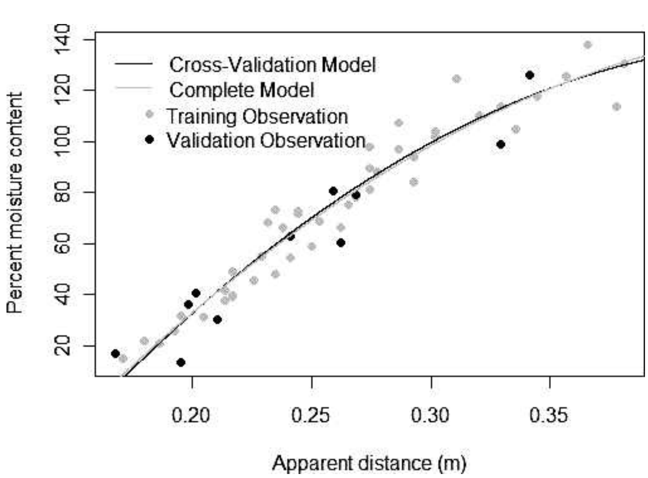

Figure 8.—Cross-validation examination of 75-mm model.

and the nature of the relationship between the TDR measurement and moisture content.

Previous research has not studied the impact of different probe lengths on the moisture content measurements of trees or logs. This study showed that 125-mm probes performed better for predicting moisture content than the shorter probe lengths included in the study. This is possibly due to the longer probes contacting a larger cross section of the log when inserted. As the estimated moisture content is an average along the length of the probe, a longer probe provides a more representative and accurate estimate of the moisture content over the complete cross section. This also allows the longer probes to perform more accurately with logs of large diameter.

An interesting finding of this study was that the most desirable method for predicting moisture content of logs was different than the method generally used for soil moisture content prediction. The Topp equation (Topp et al. 1980) is a third-order polynomial equation based on the apparent length to a particular point of the TDR waveform reading, which relates that distance to moisture content. Previous TDR tree moisture content studies considered only the Topp calibration curve to relate the measurements; this study determined that by using the inflection point of the rising curve of the TDR waveform, a statistically better result is obtained with a second-order model. Recent research based on four hardwood species (two ring porous and two diffuse porous species) has indicated that a logistic model better fits the hardwood species data. For each hardwood data set, an upper asymptote was observed that differed by species and represented a maximum moisture content. It is possible that our hydration period was insufficient for our samples to achieve a maximum moisture content, explaining the success of the linear models.

TDR was shown to be a reliable method for measuring the moisture content of *P. taeda,* with a high correlation between the inflection point of the rising curve of the TDR waveform and the moisture content of the log bolts. Combined with the durability of the constructed probes, this makes TDR an ideal method for measuring the moisture content of wet-stored logs. At present, studies using these probes to monitor the moisture content of wet-stored pine have been installed at the wet storage facilities of several southern US paper mills. These studies will monitor moisture content variation over time, both within the logs and within the pile, using multiple water regimes. Additional studies are planned, including studies of hardwood species, that will be based on a separate calibration study since it is unknown whether the specific equation or the general form of the calibration curve calculated here is universal. The results of these studies will provide information useful for controlling water application; understanding how water application rates affect log moisture under various conditions will allow wet storage facilities to maintain log quality and preserve water by applying it appropriately.

Conclusions

Of the several methods considered for monitoring moisture content over time in wet-stored logs, TDR was found to be the best suited because it has the ability to reliably measure high moisture content, measurement probes can be designed to withstand the conditions of a wet-stored log pile over time, and several studies have demonstrated its potential for measuring moisture content in wood. This study showed that the moisture content of wood can be accurately predicted with TDR with a very high correlation. Additionally, it indicated that longer probes may result in more reliable predictions and that the part of the waveform measurement most useful in predicting wood moisture content differs from the part traditionally used in soil moisture content measurements, as does the form of the calibration curve. This study also resulted in the calculation of a calibration curve specific to *P. taeda* that will be employed in future studies of the moisture content of wet-stored logs over time based on varying water regimes and wood pile dynamics. This will allow for future decisions regarding appropriate water use while maintaining moisture content high enough to preserve wood quality while in storage.

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