

Time-Domain Reflectometry for the Prediction of Loblolly Pine and Sweetgum Moisture Content

Joseph Dahlen,^{a,*} Finto Antony,^a Anzhi Li,^b Kim Love-Myers,^b Laurence Schimleck,^c and Erik B. Schilling^d

Time-domain reflectometry (TDR) can be used to predict the moisture content in porous materials, including soil, and is an exciting tool that could be used to measure the moisture content in wet-stored wood. Three-rod probes with 127 mm- or 152 mm-long rods were inserted into 62 loblolly pine and 34 sweetgum saturated bolts. The bolts were air dried over a span of five weeks. TDR waveforms and moisture content were periodically recorded. In total, 534 and 482 readings were taken for the loblolly pine and sweetgum bolts, respectively. An algorithm in R was written to automatically analyze the apparent length of the TDR rods. Calibration models were developed between moisture content and X (apparent length / actual rod length). A three-parameter logistic model was developed for loblolly pine ($R^2=0.64$) and sweetgum ($R^2=0.84$). The process was repeated using shorter bolts and 152 mm-long rods, resulting in improved models for loblolly pine ($R^2=0.99$) and sweetgum ($R^2=0.97$). Overall, TDR and the algorithm written to analyze the waveforms were accurate in predicting moisture content and could be used to monitor moisture in wet-decks.

Keywords: Fiber saturation point; Nondestructive testing; Pulp and paper; Southern pine; Wet-decks; Wet-storage; Wood physics

Contact information: a: Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green Street, Athens, GA 30602-2152, USA; b: University of Georgia Statistical Consulting Center, University of Georgia, 101 Cedar Street, Athens, GA 30602-2152, USA; c: Wood Science & Engineering, Oregon State University, 119 Richardson Hall, Corvallis, OR 97331, USA; d: NCASI Southern Regional Center, 402 SW 140th Terrace, Newberry, FL 32669, USA; *Corresponding author: jdahlen@uga.edu

INTRODUCTION

Forest industries in the Southeastern United States frequently store tree-length logs in wet-decks to ensure a year-round supply of wood. Water is continuously sprayed over the logs to maintain water saturation, providing the anaerobic conditions necessary to prevent fungal degradation of the wood (Zabel and Morrell 1992). Fungal growth is minimized when there is less than 20% air in the cell lumen (Zabel and Morrell 1992). Forest product industries are continuously working on developing and testing methods to improve the efficiency of water usage in wet-decks. Measuring log moisture content, and thus controlling water usage, is an area of interest towards this end. However, commercially available tools that measure free water as compared to bound water in wood are limited (Bergman 2010).

Time-domain reflectometry (TDR) has traditionally been used to detect faults in cables, but over the past 40 years it has been used to measure soil volumetric moisture content (Topp *et al.* 1980). Recently, TDR has been used to measure wood volumetric and gravimetric moisture content (Constantz and Murphy 1990; Nadler *et al.* 2003; Schimleck

et al. 2011). The sensitivity of TDR makes the technique suitable for measuring moisture content of porous materials such as soil and wood (Cerny 2009) because: 1) the electrical conductivity of materials increases with increasing moisture content, and 2) the dielectric constant of water at 20 °C ($\epsilon_{\text{water}}= 80$) is much higher than that of oven-dry wood ($\epsilon_{\text{wood}}= 2$) (Torgovnikov 1993). TDR units propagate signals through probes with stainless steel rods inserted into porous materials; the connection between the TDR and the probes is a coaxial cable. The time required for a signal to propagate through the probes and reflect back to the TDR is converted to distance (Eq. 1):

$$L = \frac{Vt}{2} \quad (1)$$

where L is a distance, V is the propagation velocity, and t is the time required to propagate to the end of the rods and back. The point at which the stainless steel rods enter the wood is the start distance of the signal (X_1) which can be found due to the differences in impedance between the coaxial cable, typically 50 or 75 Ω , and the probe head (Fatas *et al.* 2013). The end of the rods or the stop distance of the signal (X_2) can be found graphically through manual interpretation of the waveform (Schimleck *et al.* 2011), *via* waveform processing, *via* tangent lines, or *via* derivatives (Evelt 2000; Fatas *et al.* 2013). The apparent length L_a ($X_2 - X_1$) is compared to the actual rod length distance (L) in Eq. 2:

$$K_a = \left(\frac{L_a}{L}\right)^2, \quad X = \sqrt{K_a} \quad (2)$$

where K_a is the apparent dielectric constant, X is the square root of the apparent dielectric constant, L_a is the apparent length of the reflected TDR signal, and L is the actual rod length. As moisture content increases, the apparent length, and therefore the X distance, increases (Jones *et al.* 2002). A calibration model is needed to explain the relationship between X and the moisture content of the material of interest. The third-order polynomial model developed by Topp *et al.* (1980) is a universal model that has been applied to a wide range of soils. However, work on wood has shown that different species require different models (Hernandez-Santana and Martinez-Fernandez 2008; Schimleck *et al.* 2011).

Though previous works showed TDR as a potential method to measure wood moisture, some challenges still need to be addressed before fully implementing this technology in wet-decks. Schimleck *et al.* (2011) conducted research on TDR and concluded that the method could reliably predict moisture content. However, the apparent length was determined visually through interpretation of the waveform, and thus the method could have been subjected to personal measurement error, particularly if multiple users collected data. Digitizing this waveform is important for precise translation of TDR waveform readings to wood moisture content, as well as to enable the technology to be used by a wider variety of operators. Additionally, previous research used a Tektronix TDR cable tester that has not been manufactured since 2001. This research was conducted to automate the TDR waveform processing using a relatively low cost and portable E20/20 step TDR from AEA. The specific objectives were to automate analysis of TDR waveforms to calculate apparent rod length, and develop calibration equations to compare X (the apparent length divided by the actual rod length) to the moisture content for loblolly pine and sweetgum bolts.

EXPERIMENTAL

Materials

An E20/20N step TDR from AEA Technology, Inc. (Carlsband, CA) was used throughout the project. The system is a cable testing unit and not specifically designed for moisture content measurement. For each moisture content reading, a digitized waveform with 1920 data points was saved in a text based format, and exported onto a computer for analysis.

Studies conducted on wood have used two-rod probes (Hernandez-Santana and Martinez-Fernandez 2008; Shimleck *et al.* 2011). Three-rod probes were used throughout this study because the 2-rod probe configuration is a balanced signal design which does not mimic the unbalanced nature of coaxial cables where the positive signal is surrounded by ground. As a result, excessive noise could be introduced in the signal that leads to inaccurate readings (Zegelin *et al.* 1989; ASTM 2000). Some consideration was given to using a 2-rod probe with a custom built balun to minimize noise (Spaans and Baker 1993). However, this approach was abandoned because the 3-rod probes were constructed with greater consistency than what could be achieved in the laboratory using the balun approach. Probes were constructed using 3 mm stainless steel rods soldered to 75 Ω RG6 coaxial cable with the outer rods connected to the ground wire on the coaxial cable, and the middle rod connected to the coaxial cable lead and encased in a water-proof epoxy resin. The reader is referred to Evett and Ruthardt (2014) for a general primer on probe construction.

Sixty-two loblolly pine (*Pinus taeda* L.) bolts from 17 trees and 34 sweetgum (*Liquidambar styraciflua* L.) bolts from 5 trees were collected. The diameters for the loblolly pine bolts ranged from 150 mm to 460 mm, and sweetgum bolts ranged from 200 mm to 500 mm in diameter. Bolt heights were approximately 4600 mm. The bark from each bolt was peeled, and the bolt was soaked in water for a minimum of 2 weeks to achieve saturation. After soaking, a 127 mm rod length probe with 3 stainless steel rods was inserted into each loblolly pine bolt, and a 152 mm rod length probe with 3 rods was inserted into each sweetgum bolt. Three pilot-holes were drilled into each bolt to ensure rod straightness and a tight fit to minimize air gaps. The probes were installed on the tangential face. Cable length was approximately 1.5 m from the TDR to the probe head, and the TDR distance was set from 0 m to 6 m, and thus 1920 data points were recorded between 0 m and 6 m. The measuring setup is shown in Fig. 1. To better illustrate the setup, the probe is not fully inserted into the bolt.

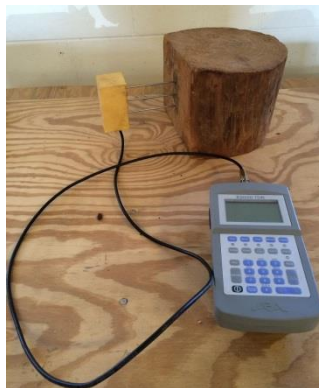


Fig. 1. Time-domain reflectometry measuring setup; the probe is not fully inserted into the bolt to better illustrate the setup.

The bolts were dried under ambient air conditions for up to 5 weeks. Periodically, the bolts were weighed, and a TDR waveform was recorded along with each weight measurement. More measurements were taken at the beginning of the drying cycle than at the end because of the initial high rate of water evaporating from the bolt surface after the soaking process. When the moisture content fell below the fiber saturation point on the ends and outer diameter of the bolts and the moisture stabilized, the probes were removed from each bolt and the bolts were oven-dried at 103 °C until a constant weight was achieved. After oven-drying, the moisture content of each reading was determined on an oven-dry and green basis; the oven-dry basis is used throughout, except where noted. A total of 482 and 534 readings were taken on the sweetgum and loblolly pine samples, respectively.

Methods

Waveform analysis

A typical TDR waveform is shown in Figure 2. The waveforms were analyzed using the statistical software R (R Core Team 2014). TDR instruments typically display the reflected waveform with x-axis units of distance, and the y-axis as measured impedance (Ω) or the reflection coefficient, ρ (rho); ρ (rho) is the “ratio of the reflected pulse amplitude to the incident pulse amplitude” (Tektronix 2008) and is calculated as (Eq. 3):

$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (3)$$

where $V_{reflected}$ is the voltage of the reflected signal, $V_{incident}$ is the voltage of the sent signal, Z_L is the measured impedance (output from AEA unit), and Z_0 is the cable impedance (typically 50 Ω or 75 Ω); ρ will range from -1 to 1 and is commonly used for soil moisture content measurement (Tektronix 2001). The AEA unit displayed the measured impedance and thus the y-axis was converted to ρ (rho) using the above formula.

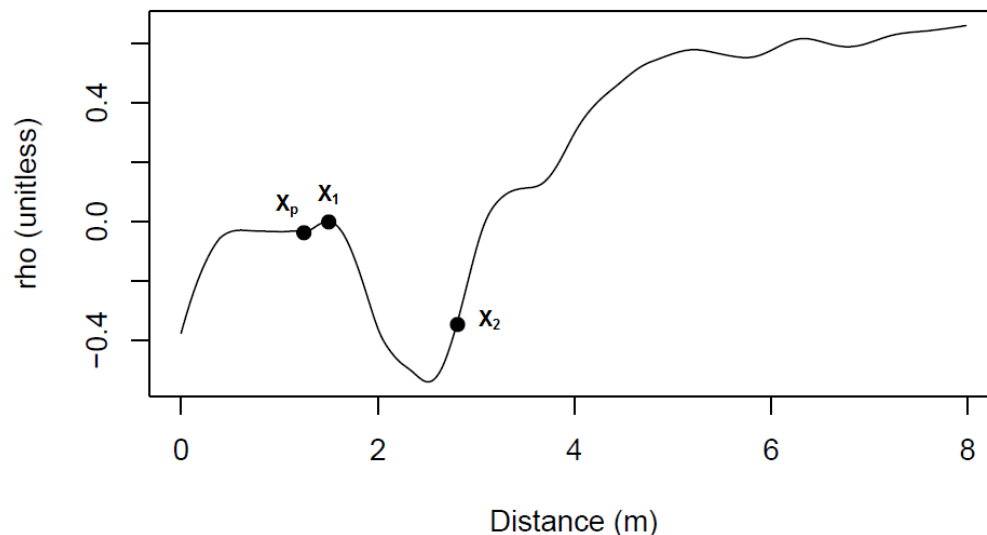


Fig. 2. Typical time-domain reflectometry waveform. X_p is the signal entering the probe head from the coaxial cable, X_1 is the signal leaving the probe head and the starting point for measurement of the waveform, X_2 is the signal at the end of the rods using the inflection point of the rising curve method, rho is unit-less.

The apparent length of each waveform was found by determining the inflection point distance of the reflected waveform (point X_2 on graph) and subtracting the starting distance (point X_1) (Eq. 4):

$$\text{Apparent Length} = X_2 - X_1 \quad (4)$$

Because the raw TDR data contained noise, the data was first smoothed using the Savitzky-Golay function (Savitzky and Golay 1964) in the signal package of R with a 2nd degree polynomial and a window size of 111 points (Signal Developers 2013). Each graph was truncated to aid in finding the start and stop distances for the apparent length calculation. The cable length between the TDR and the probe was approximately 1.5 m. The overall plots were truncated approximately 0.29 m (1.21 m) before the beginning of the probe (~1.5 m), and approximately 1.55 m (3.05 m) after the beginning of the probe. The stop distance to the end of the rod (X_2) was found by truncating the data between 1.21 m and 3.05 m and then finding the distance point (X_2) that corresponded to the maximum rho value of the smoothed 1st derivative plot, *i.e.*, the inflection point of the signal. The start distance of the rod (X_1) was found by truncating each plot from 1.21 m and the X_2 point of each individual waveform and then finding the distance point (X_1) that corresponded to the minimum rho value of the smoothed 2nd derivative plot, *i.e.*, the local maximum point of the signal prior to the inflection point of the rising waveform (Fig. 3).

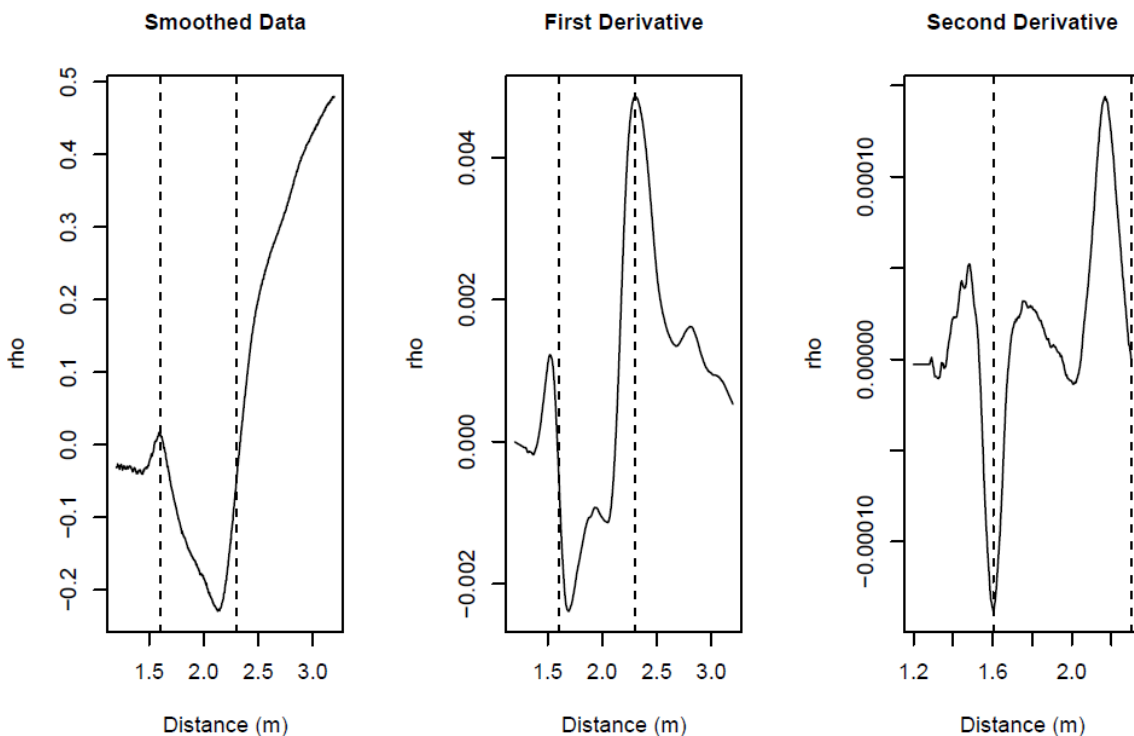


Fig. 3. Example of truncated plots with the smoothed data, the 1st derivative used to find the distance to the end of the rod (X_2), and the 2nd derivative plot used to find the starting distance (X_1)

Statistical analysis

Calibration models and plots were developed in R using the RStudio (2014) interface and SAS 9.4 (SAS Institute, USA). The effect of bolt diameter was compared to the initial moisture content with analysis of variance on both species and a significance value of $\alpha = 0.05$. The response variables of oven dry moisture content and green moisture content were modeled against the explanatory variable X (apparent length/actual rod length) using linear and non-linear approaches.

RESULTS AND DISCUSSION

Starting moisture content values ranged from 41% to 162% for the loblolly pine samples and 89% to 130% for the sweetgum samples. Starting moisture content varied significantly with bolt diameter for loblolly pine (p-value = 0.0002) but not for sweetgum (p-value = 0.371). A total of 480 and 526 moisture and TDR readings were taken on the sweetgum and loblolly pine samples, respectively. The plots of bolt diameter versus measured moisture content taken throughout the study are shown in Fig. 4. The minimum MC% for loblolly pine and sweetgum was 15% and 32%, respectively.

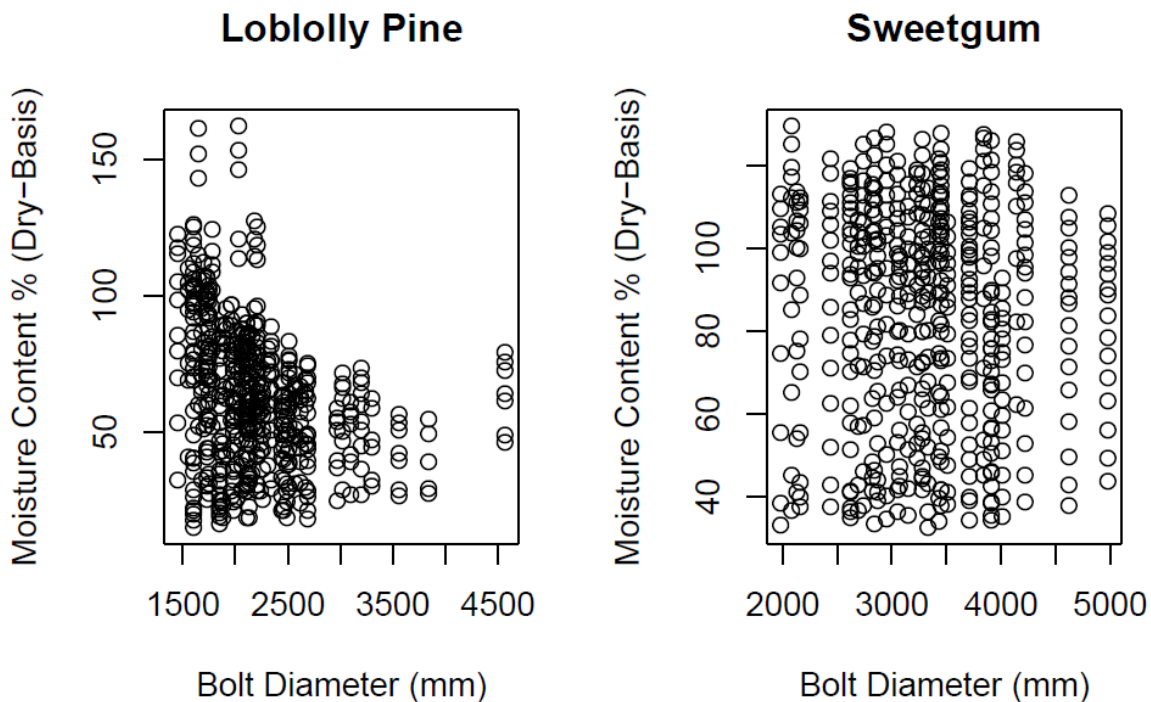


Fig. 4. Plot of moisture content (dry-basis) versus bolt diameter (mm) for loblolly pine and sweetgum samples

All of the TDR waveforms were visually checked to determine whether the algorithm was accurately finding the appropriate X_1 and X_2 distances. The algorithm worked properly for all samples collected in this study, but it may be preferable to use a greater distance setting on the TDR and thus collect fewer data points in the region of interest. This would reduce the level of smoothing that is required to obtain usable derivative information.

For both species, a non-linear model relationship was observed in plots of the data. Based on the shape of the plots, three non-linear models were explored using a mixed effects model. The models were the Gompertz growth model, the Chapman Richards model, and the three parameter logistic model. The final model was selected based on the Akaike Information Criterion (AIC) and the residual variance. An R^2 was calculated for the selected models but because the models were nonlinear the R^2 values were considered pseudo R^2 .

Loblolly Pine Moisture Content

For the oven-dry and green moisture content of loblolly pine, the best model was the three parameter logistic model. The residuals are approximately normally distributed for both models. The three parameter logistic model estimation coefficients and their p-values are shown in Table 1. The models for loblolly pine are (Eqs. 5 and 6):

$$\text{Loblolly Pine Moisture Content Oven Dry Basis} = \frac{140.21}{1+e^{-0.8736(X-3.9291)}} \quad (5)$$

$$\text{Loblolly Pine Moisture Content Green Basis} = \frac{55.2067}{1+e^{-0.8937(X-(2.7792))}} \quad (6)$$

The plots (Fig. 5) and the data show a general trend of decreasing X values as moisture content decreases. However, there was a relatively large amount of spread in the data points.

Table 1. Loblolly Pine and Sweetgum Three-Parameter Logistic Regression Model Parameters for Dry-Basis and Green-Basis Moisture Content, Modeled vs. X (Apparent Length / Actual Rod Length)

Species	Moisture Content	DF	AIC	R^2	Parameter	Estimate	Standard Error	p-value
Loblolly Pine	Dry-Basis	59	4299.3	0.64	alpha	140.21	19.6853	<0.0001
					kappa	0.8736	0.1206	<0.0001
					gamma	3.9291	0.3509	<0.0001
					Residual Variance	74.0708	8.4071	<0.0001
	Green-Basis		alpha	55.2067	2.0832	<0.0001		
			kappa	0.8937	0.08435	<0.0001		
			gamma	2.7792	0.08773	<0.0001		
			Residual Variance	20.2654	2.4849	<0.0001		
Sweetgum	Dry-Basis	31	3085.5	0.84	alpha	143.56	3.1951	<0.0001
					kappa	1.1656	0.03029	<0.0001
					gamma	3.8451	0.05344	<0.0001
					Residual Variance	23.7342	1.6764	<0.0001
	Green-Basis		alpha	61.2960	0.7868	<0.0001		
			kappa	1.0205	0.02824	<0.0001		
			gamma	3.1031	0.05274	<0.0001		
			Residual Variance	2.5324	0.1794	<0.0001		

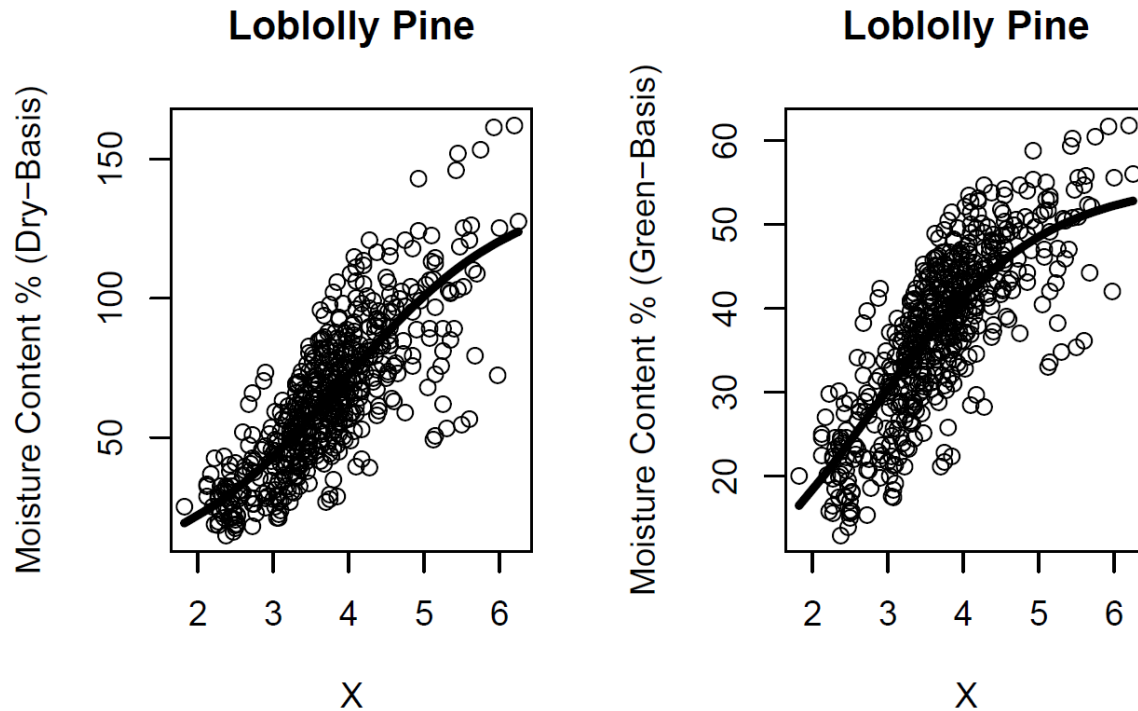


Fig. 5. Plots of moisture content vs. X (apparent length / rod length) for loblolly pine with oven-dry basis model on right, green-basis on left

Sweetgum Pine Moisture Content

For the oven-dry and green moisture content of sweetgum, the best model was the three parameter logistic model. The residuals were approximately normally distributed for both models. The three parameter logistic model estimation coefficients and their p-values are shown in Table 1. The models for sweetgum are (Eqs. 7 and 8):

$$\text{Sweetgum Moisture Content Oven Dry Basis} = \frac{143.56}{1 + e^{-1.1656(X - (3.8451))}} \quad (7)$$

$$\text{Sweetgum Moisture Content Green Basis} = \frac{61.296}{1 + e^{-1.0205(X - (3.1031))}} \quad (8)$$

The plots for oven-dry basis and green-basis moisture content are shown in Fig. 6. Overall, the plots (Fig. 6) and model results for sweetgum are much better than the loblolly pine results.

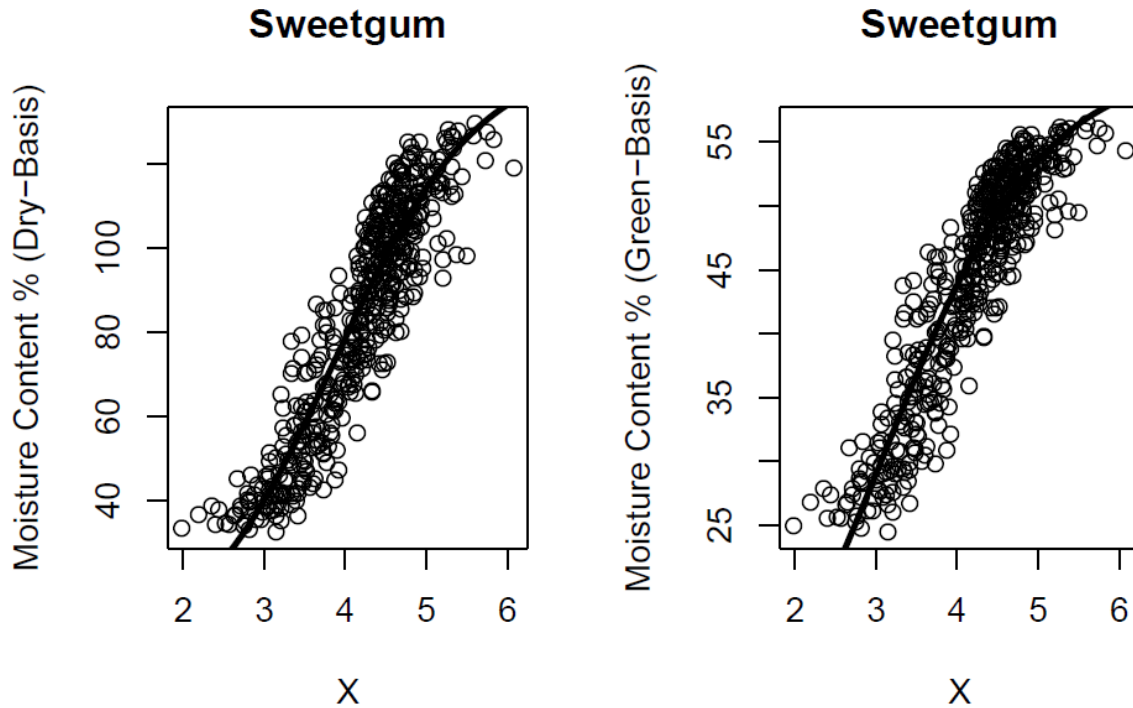


Fig. 6. Plots of moisture content vs. X (apparent length / rod length) for sweetgum; oven-dry basis model on the right and green-basis on the left

Further Test on Loblolly Pine and Sweetgum Pine Moisture Content

The relationship for loblolly pine ($R^2=0.62$) did not match the relationship for sweetgum ($R^2=0.84$). The authors hypothesize that the lack of accuracy in the model was primarily due to the height of the bolts (4600 mm) for both species, as well as the shorter rod length (127 mm) for loblolly pine compared to sweetgum (152 mm). Both cases would result in the TDR sampling a relatively small fraction of the actual wood, which could cause inaccuracy if the moisture content of the TDR reading was not representative of the whole bolt. Generally, soil moisture content literature recommends a minimum of 150 mm rods for most soil types, and work on models related to wood moisture content has shown that longer rods yield a lower error in determining the distance of the reflected signal (Schimleck *et al.* 2011). While a longer rod length is desired for accuracy purposes, it also limits the bolt diameter that can be used for TDR analysis. To determine if improvements could be made, a new set of loblolly pine bolts from 39 trees, and sweetgum bolts from 39 trees were collected. The height of the bolts was reduced from 4600 mm to 2500 mm, and the probe length for all bolts was 152 mm. A total of 194 and 192 waveforms were recorded for the pine and sweetgum bolts, respectively. The three parameter logistic model estimation coefficients and their p-values, are shown in Table 2.

Table 2. Updated Loblolly Pine and Sweetgum Three-Parameter Logistic Regression Model Parameters for Dry-Basis and Green-Basis Moisture Content, Modeled vs. X (Apparent Length / Actual Rod Length)

Species	Moisture Content	DF	AIC	R ²	Parameter	Estimate	Standard Error	p-value
Loblolly Pine	Dry-Basis	36	1402.3	0.98	alpha	168.42	4.9420	<.0001
					kappa	1.1585	0.05008	<.0001
					gamma	4.7869	0.06185	<.0001
					Residual Variance	29.5403	4.1029	<.0001
	Green-Basis		998.5	0.98	alpha	63.1934	1.1063	<.0001
					kappa	1.1280	0.05731	<.0001
					gamma	3.9318	0.04981	<.0001
					Residual Variance	4.3084	0.6222	<.0001
Sweetgum	Dry-Basis	36	1322.5	0.97	alpha	212.78	24.9367	<.0001
					kappa	0.7137	0.05001	<.0001
					gamma	5.9574	0.3208	<.0001
					Residual Variance	29.8811	3.5197	<.0001
	Green-Basis		905.8	0.97	alpha	67.9432	2.5765	<.0001
					kappa	0.7138	0.04484	<.0001
					gamma	4.3697	0.1177	<.0001
					Residual Variance	3.1952	0.398	<.0001

The updated models for loblolly pine oven-dry basis are (Eqs. 9 and 10):

$$\text{Loblolly Pine Moisture Content Oven Dry Basis} = \frac{168.42}{1 + e^{-(1.1585)(X - (4.7869))}} \quad (9)$$

$$\text{Loblolly Pine Moisture Content Green Basis} = \frac{63.1934}{1 + e^{-(1.1280)(X - (3.9318))}} \quad (10)$$

Overall, the reduction in bolt height and increase in rod length improved the accuracy of the model, as shown in Fig. 7 and Table 2. The results for loblolly pine are now similar to the models developed for sweetgum.

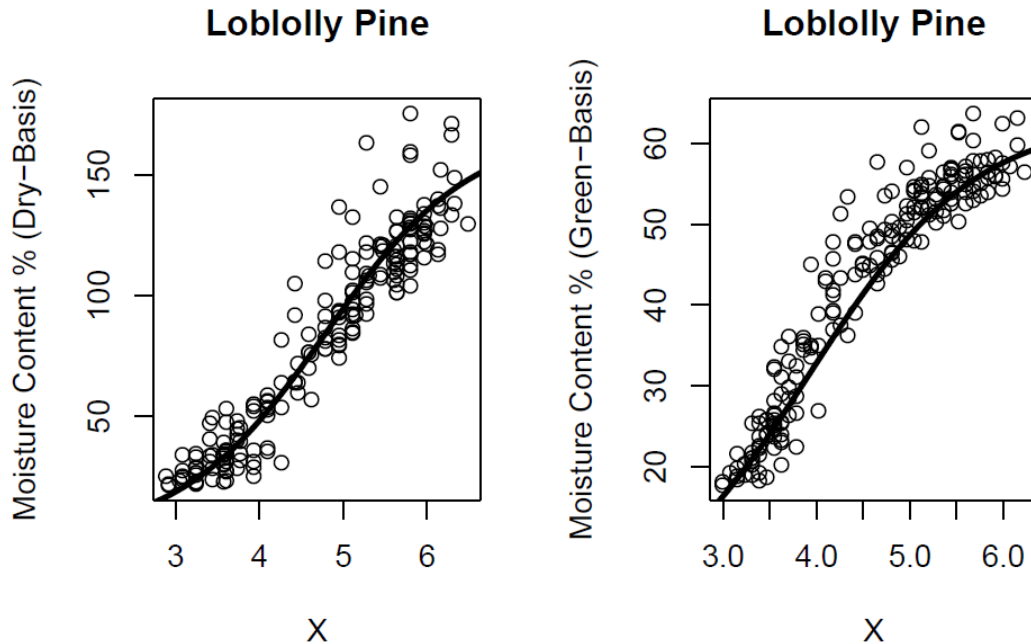


Fig. 7. Updated plots of moisture content vs. X (apparent length / rod length) for loblolly pine; oven-dry basis model on right, green-basis on left

The updated models for sweetgum oven-dry basis are (Eqs. 11 and 12):

$$\text{Sweetgum Moisture Content Oven Dry Basis} = \frac{212.78}{1+e^{-(0.7137)(X-(5.9574))}} \quad (11)$$

$$\text{Sweetgum Moisture Content Green Basis} = \frac{67.9432}{1+e^{-(0.7138)(X-(4.3697))}} \quad (12)$$

The updated models (Table 2) exhibited similar performance to the original sweetgum model (Fig. 8).

The increase in model performance during the second phase is likely due to the TDR sampling a higher volume of wood within the bolt. Soil TDR probes are frequently built with 30 cm rods, which would sample even greater volumes of wood. However, these types of probes would be difficult to install in wood, and would also require large diameter trees, unless the probes were installed in the cross-sectional face. The authors installed the probes in the tangential face, which allows for greater flexibility during installation. While different wood types will require different models, the three-parameter logistic model worked well for both loblolly pine and sweetgum and thus serves as a good starting point for future work.

The models developed for this work have improved performance over models developed by Schimleck *et al.* (2011). The improvement in performance is likely due to the algorithm written that calculates the apparent length, as well as using 3-rod probes that have reduced noise compared to 2-rod probes (Zegelin *et al.* 1989). The algorithm developed in this research will allow for adoption of TDR by the forest industry. While there are numerous handheld tools that are available to measure moisture content below the fiber saturation point, there is a lack of tools available for field use to measure above the fiber saturation point. TDR could be adopted for other uses, including monitoring the moisture content of bridge members and poles.

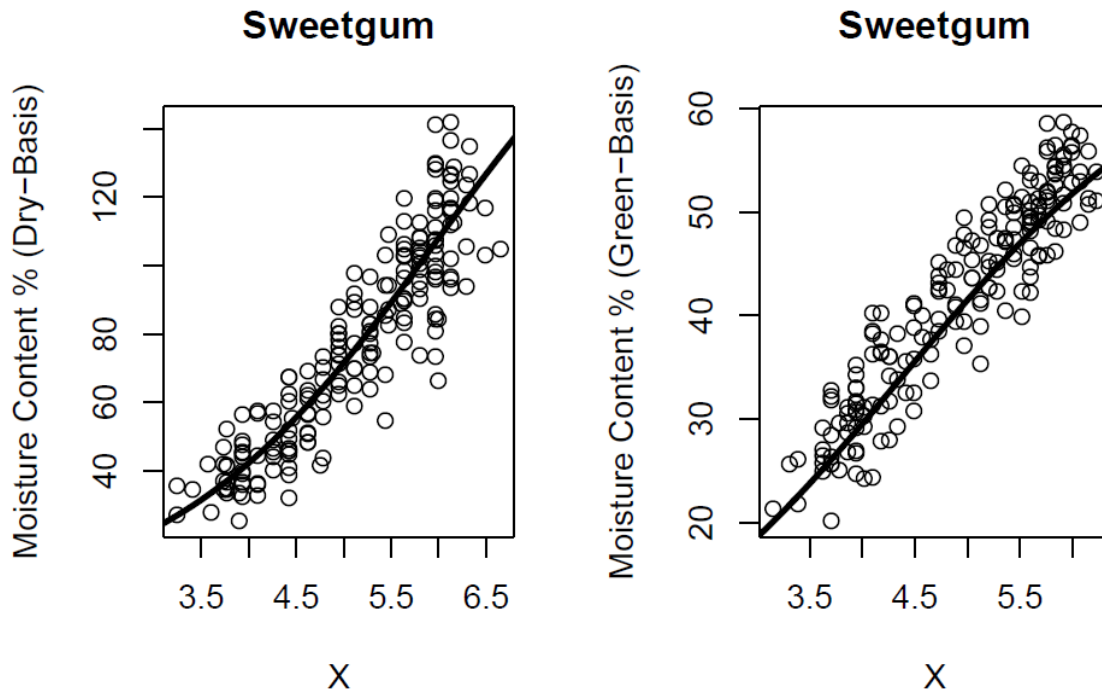


Fig. 8. Updated plots of moisture content vs. X (apparent length / rod length) for sweetgum; oven-dry basis model on right, green-basis on left

CONCLUSIONS

1. Time-domain reflectometry in combination with custom built probes was effective for measuring the moisture content in wood above the fiber-saturation point when using the derivatives algorithm developed for this project.
2. To develop accurate calibrations, it is critical that the TDR measure a representative portion of the wood. Longer rods and shorter bolt heights result in the TDR measuring a more representative portion of the wood, leading to strong calibration models.
3. The non-linear three-parameter logistic model shape worked well for both loblolly pine and sweetgum, and both species had models with an R^2 greater than 0.97.

ACKNOWLEDGMENTS

The authors are grateful to the National Council for Air and Stream Improvement, Inc. and its member companies for their financial support, as well as their donation of the bolts used in this study.

REFERENCES CITED

- ASTM International. (2000). "D6565-00: Standard test method for determination of water (moisture) content of soil by time-domain reflectometry (TDR) method," West Conshohocken, PA. 19428-2959.
- Bergman, R. (2010). "Drying and control of moisture content and dimensional changes," *Wood Handbook* (General Technical Report FPL-GTR-190), R.J. Ross (ed.), Forest Products Laboratory, USDA Forest Service, Madison, WI.
- Cerný, R. (2009). "Time-domain reflectometry method and its application for measuring moisture content in porous materials: A review," *Measurement* 42(3), 329-336. DOI: 10.1016/j.measurement.2008.08.011
- Constantz, J., and Murphy, F. (1990). "Monitoring storage moisture in tree using time domain reflectometry," *J. Hydrol.* 119, 31-42. DOI: 10.1016/0022-1694(90)90032-S
- Evet, S. R. (2000). "The TACQ computer program for automatic time domain reflectometry measurements: I. Design and operating characteristics," *Transactions of the ASAE: 2000 American Society of Agricultural Engineers* 43(6), 1939-1946.
- Evet, S. R., and Ruthardt, B. B. (2014). "A primer on TDR probe construction," Agricultural Research Service, United States Department of Agriculture, (http://www.cprl.ars.usda.gov/TDR/MAKE_PRB.PDF).
- Fatas, E., Vicente, J., Latorre, B., Lera, F., Vinals, V., Lopez, M. V., Blanco, N., Pena, C., Gonzalez-Cebollada, C., and Moret-Fernandez, D. (2013). "TDR-Lab 2.0 improvement TDR software for soil water content and electrical conductivity measurements," *Procedia Environmental Sciences* 19, 474-483. DOI: 10.1016/j.proenv.2013.06.054
- Hernandez-Santana, V., and Martinez-Fernandez, J. (2008). "TDR measurement of stem and soil water content in two Mediterranean oak species," *Hydrolog Sci. Journal* 53(4), 921-931. DOI: 10.1623/hysj.53.4.921
- Jones, S. B., Wraith, J. M., and Or, D. (2002). "Time domain reflectometry measurement principles and applications," *Hydrol. Process* 16, 141-153. DOI: 10.1002/hyp.513
- Nadler, A., Raveh, E., Yermiyahu, U., and Green, S. R. (2003). "Evaluation of TDR use to monitor water content in stem of lemon trees and soil and their response to water stress," *Soil Sci. Soc. Am. Journal* 67, 437-488. DOI: 10.2136/sssaj2003.4370
- R Core Team. (2014). "R: A language and environment for statistical computing," RFoundation for Statistical Computing, Vienna, Austria. (<http://www.R-project.org/>).
- RStudio. (2014). "RStudio: Integrated development environment for R (Version 0.98.201) [Software]," Boston, MA.
- Savitzky, A., and Golay, M. J. E. (1964). "Smoothing and differentiation of data by simplified least squares procedures," *Anal. Chem.* 1964(36), 1627-1639. DOI: 10.1021/ac60214a047
- Schimleck, L., Love-Myers, K., Sanders, J., Raybon, H., Daniels, R., Mahon, J., Andrews, E., and Schilling, E. (2011). "Measuring the moisture content of green wood using time domain reflectometry," *Forest Prod. Journal* 61(6), 428-434. DOI: 10.13073/0015-7473-61.6.428
- Signal Developers. (2013). Signal: Signal processing, (<http://r-forge-r-project.org/projects/signal/>).
- Spaans, E. J. A., and Baker, J. M. (1993). "Simple baluns in parallel probes for time-domain reflectometry," *Soil Sci. Soc. Am. Journal* 57, 668-673. DOI: 10.2136/sssaj1993.03615995005700030006x

- Tektronix. (2001). "User manual: 1502C metallic time-domain reflectometers," Tektronix, Inc. Beaverton, OR.
- Tektronix. (2008). "Application note: TDR impedance measurements: A foundation of signal integrity," Tektronix, Inc. Beaverton, OR.
- Topp, G. C., Davies, J. L., and Annan, A. P. (1980). "Electromagnetic determination of soil water content: Measurements in coaxial transmission line," *Water Resources Res.* 16, 574-582. DOI: 10.1029/WR016i003p00574
- Torgovnikov, G. I. (1993). *Dielectric Properties of Wood and Wood-Based Materials*, Springer Series in Wood Science, Berlin.
- Zabel, R. A., and Morrell, J. J. (1992). *Wood Microbiology: Decay and its Prevention* Academic Press, London.
- Zegelin, S. J., White, I., and Jenkins, D. R. (1989). "Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry," *Water Resources Res.* 25(11), 2367-2376. DOI: 10.1029/WR025i011p02367

Article submitted: February 13, 2015; Peer review completed: June 14, 2015;

Revisions accepted: June 19, 2015; Published: June 23, 2015.

DOI: 10.15376/biores.10.3.4947-4960