Examination of moisture content variation within an operational wet deck

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ABSTRACT: Many forest products companies in the southeastern United States store large volumes of roundwood under wet storage. Log quality depends on maintaining a high and constant wood moisture content; however, limited knowledge exists regarding moisture variation within individual logs, and within wet decks as a whole, making it impossible to recommend appropriate water application strategies. To better understand moisture variation within a wet deck, time domain reflectometry (TDR) was used to monitor the moisture variation of 30 southern pine logs over an 11-week period for a wet deck at the International Paper McBean woodyard. Three 125 mm long TDR probes were inserted into each log (before the deck was built) at 3, 4.5, and 7.5 m from the butt. The position of each log within the stack was also recorded. Mixed-effects analysis of variance (ANOVA) was used to examine moisture variation over the study period. Moisture content varied within the log, while position within the stack was generally not significant. The performance of the TDR probes was consistent throughout the study, indicating that they would be suitable for long term (e.g., 12 months) monitoring.

Application: Moisture content variation of wet-stored logs with time can be monitored using TDR. Such information can be used to develop optimal watering strategies.

The storage of logs in wet decks plays an important role in maintaining a consistent fiber supply to wood products facilities in the southeastern United States, especially during times when weather and other seasonal difficulties slow or prevent harvesting. Wet storage involves storing logs under a system of sprinklers with the aim of achieving a very high moisture content, which allows the wood to be stored for extended periods without experiencing appreciable decay or damage by insects [1,2]. Water is applied to the logs continuously; however, there is a need to refine how and when water is applied owing to increased concerns in the southeastern U.S. regarding water use following recent drought and increasing urbanization.

To better understand the effectiveness of different rates of water application to wet stored logs, it is necessary to examine how log moisture content varies throughout the period of storage. However, few options are available for monitoring the moisture content of logs stored in wet decks and, practically, accessing logs once the deck has been built is difficult and dangerous. Hence, a moisture measurement system that can be installed as the wet deck is being built and can be used to monitor the high moisture contents that exist within logs is required.

Time domain reflectometry (TDR) is one technique that might be suitable for monitoring the moisture content of wet-stored logs over an extended period. Several studies have used TDR to monitor moisture variation in standing trees [3-5], and the basic measurement principle reported in these studies can be applied to wet stored logs. A probe, which in this study consists of two 3 mm-diameter stainless steel rods brazed to a copper coaxial cable of known length and cast inside a 30 mm × 30 mm × 60 mm plastic block, is connected to a TDR instrument. A pulse of energy is transmitted through the cable to the probe where it is reflected back to the instrument. The time the pulse takes to return is influenced by the moisture content of the wood; a higher moisture content slows the pulse, and this is reported by the instrument as a change in the apparent length of the cable. The longer the apparent length, the higher the moisture content of the wood. The apparent length is read from a waveform trace on an oscilloscope display [6].

Recently, Schimleck et al. [6] reported the development of a second-order linear regression model based on TDR measurements of apparent length for the estimation of moisture content. Calibrations were developed using rod lengths of 75 mm, 100 mm, and 125 mm; calibration accuracy improved as probe length increased. TDR readings from the 125 mm probes provided the strongest relationship ($R^2 = 0.94$) with moisture measurements. The authors concluded that their TDR readings were sufficiently correlated with moisture content to accurately monitor moisture variation with time. As our TDR moisture content studies continued, extrapolation beyond the range of the data used for the initial model made it clear that a different calibration model might be more generally appropriate. A three-parameter logistic regression, which limits moisture contents to a range between 0 and some maximum amount while maintaining a monotonic increasing relationship between TDR readings and moisture content, provided a more theoretically appropriate fit. A new calibration study was used to refine the calibration model.

TDR presents several benefits in monitoring the moisture condition of wet-stored logs. It can be used to estimate moisture content above the fiber saturation point, and probes can be inserted in logs before building the wet deck, which makes it possible to follow moisture variation within logs located at any position within the wet deck. In addition, the co-axial cable attached to the probe can be cut to any length, making it is possible to monitor moisture variation within the wetdeck from a distance.

An understanding of how moisture content varies within individual logs and how position within a wet deck influences log moisture content (i.e., according to height [total operational wet deck heights can range from 6 m to 8 m] and according to proximity to the sprinklers used to apply water to the logs) is needed before TDR can be used successfully to monitor moisture variation within a wet deck. In addition, the performance of the probes might or might not remain consistent over an extended period. This pilot study aims to answer these questions with the goal of developing a protocol that can be used in the future for monitoring moisture variation within wet decks.

MATERIALS AND METHODS

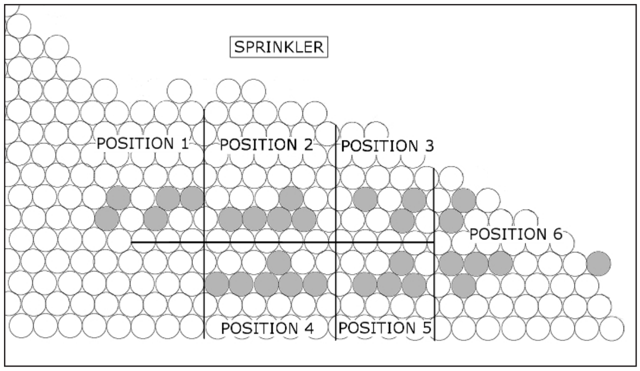
Materials

The study was conducted at the International Paper McBean wood storage yard near Augusta, GA, USA. The study used 30 southern pine logs selected at random and typical of logs stored at the yard. Once selected, a small section of bark was removed from each log at the following predetermined distances from the butt of the log: 3, 4.5, or 7.5 m. Probes with rod lengths of 125 mm were inserted into the logs at these positions. Probes were concentrated near the butt of the log, which represents the majority of log volume. After all probes were inserted, the log deck was built.

The study commenced on March 12, 2009. Data recorded for each probe included the distance to the probe from the butt of the log, the number assigned to the log in which the probe was inserted (from 1 to 30), and measurements of the apparent distance of the probe rods from the TDR waveform taken at 1-3 week intervals, from March 12, 2009 through May 28, 2009. Information about the position of each log within the wet deck also was recorded. The logs were deliberately placed in an upper tier and a lower tier, and horizontally from the left to the right of a sprinkler located at the top of the pile. Some logs were very close to the end of the pile and shared characteristics with both tiers; therefore, they were not easily classified as upper or lower tier. This resulted in six separate position classifications (**Fig. 1**).

Positions 1, 2, and 3 were all considered upper tier, while positions 4 and 5 were considered lower tier. Position 6 was considered an atypical position because the great majority of logs stored in wet decks will not be located at the end of the wet deck; these logs could be classified as neither upper tier nor lower tier.

Of the 90 probes originally included in the study, eight probes showed evidence of malfunctioning soon after the log deck was built. These probes were all found in different logs and no particular location-based pattern was observed. The probes themselves, rather than the logs, appeared to be responsible for any aberrant measurements, likely because of damage during the setup of the log deck. As a result, only 81 probes were used in the statistical modeling; two single-occasion observations were additionally removed, and one single-occasion observation was missing. The final analysis was performed on 653 observations involving 30 individual logs, three positions within logs, and eight observational occasions.



1. Position of logs within the wet deck. Study logs are shown in grey.

At the completion of the study, discs were removed from 15 logs at 3, 4.5, and 7.5 m (the positions of the three probes). The discs were used to determine the final moisture content of the logs in the vicinity of the probes.

Conversion of TDR readings to moisture contents

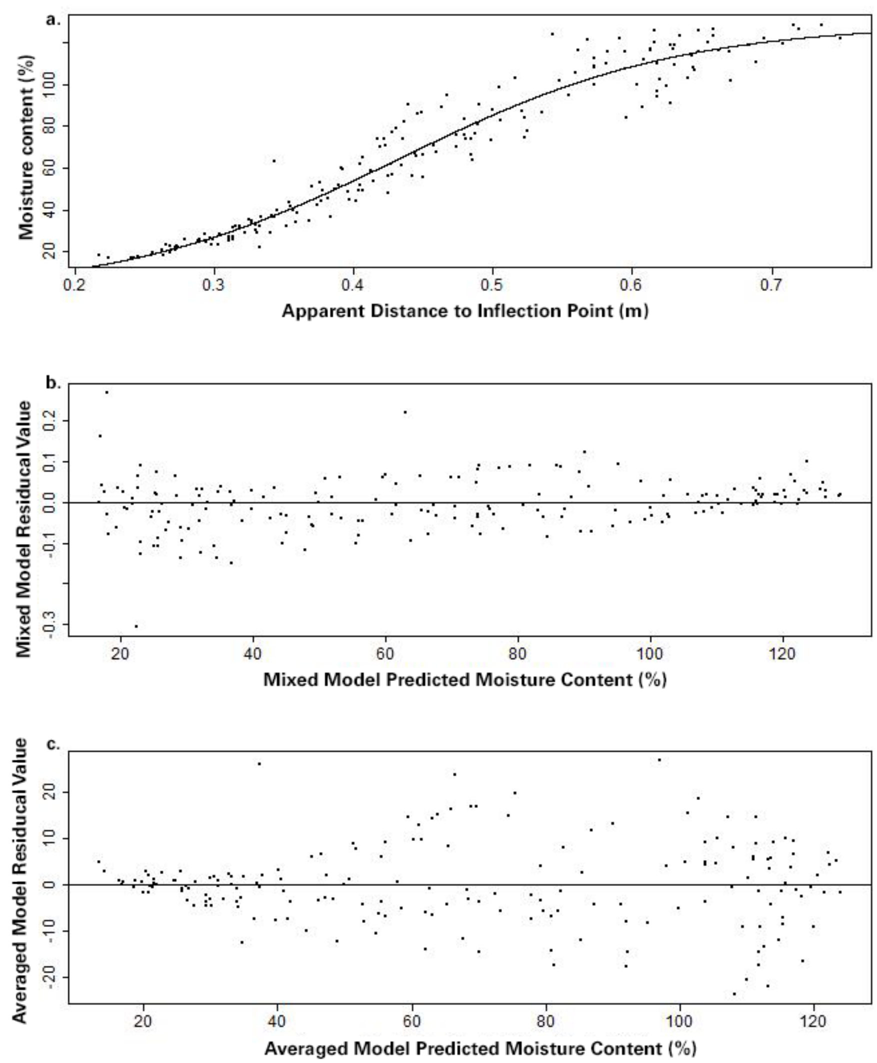
Schimleck et al. [6] demonstrated that TDR readings are reliably related to moisture content of *Pinus taeda* L. logs, and developed a successful predictive equation to determine moisture contents from TDR readings. As our studies using TDR-predicted moisture contents progressed, however, we needed to refine this initial calibration model. The primary reason for this was that when using a second-order linear regression model, once TDR readings became high enough, moisture contents were predicted to become negatively related to the TDR readings. In other words, the predicted moisture contents would begin to decrease with high TDR readings, whereas empirical evidence indicated that the higher the TDR reading, the higher the moisture content of the log. This problem may have been undetected during the initial calibration because of a failure to achieve maximum moisture content of the subject logs before drying, leading to poor model extrapolation abilities.

A new calibration study was undertaken with *P. taeda* bolts from the lower coastal plain. Calibration samples were collected in November 2010 from a wet yard that supplies logs to the International Paper pulp mill in Georgetown, SC, USA. Samples were collected from nine logs freshly delivered to the wet storage yard. This assured that the logs were typical of the raw material pulped at the mill. From each log, a bolt 150-300 mm in length was cut at approximately 15% to 20% of total log length (measured from the butt of the log). One log was cut to provide two bolts, giving 10 bolts in total. The procedure for soaking, drying, and collecting TDR data was similar to that described by Schimleck et al. [6], with the exceptions that only 125-mm probe rods were used and the bolts were initially allowed to saturate for 60 days before the start of the TDR measurement process. After all moisture content and TDR measurements had been collected, a three-parameter logistic regression model was used to model the relationship between TDR and moisture content measurements. This model was chosen because it met the theoretical considerations already mentioned, and fit statistics for this model were relatively better than or similar to those of alternative models meeting the same theoretical considerations (e.g., the Chapman-Richards or Gompertz models [7]).

The final model chosen to predict moisture contents from TDR readings was:

$$MC = \frac{129.14}{1+\exp(-10.0217*(x-0.4328))}$$

where x is the apparent distance (in meters) to the inflection point of the TDR curve. This model used a non-linear mixed model approach, as multiple readings were taken on the same bolts over time and the variability among the individual bolts could be accounted for by use of random factors. **Figure 2** displays the fit of the model through (a) the model imposed over the actual observations, (b) the mixed model predicted moisture content versus the mixed model residuals, and (c) the averaged model predicted moisture content versus the averaged model residuals. A fixed-effects model was fitted with the same function, and from this model a pseudo R-square of 0.9395 was calculated. The model fit was deemed acceptable.



2. Three-parameter logistic model fit: (a) plot of averaged model compared with data points, (b) plot of mixed model predicted moisture contents compared with mixed model residuals, and (c) plot of averaged model predicted moisture contents compared with averaged model residuals.

Statistical model for moisture content

The statistical model was a mixed-effects analysis of variance (ANOVA), relying on the following equation:

$$y_{ijkl} = \mu + p_i + e_{ij} + l_k + pl_{ik} + e^*_{ijk} + w_l + pw_{il} + lw_{kl} + plw_{ikl} + o_{ijkl}$$

where:
y_{ijkl} is the predicted moisture content
μ is the intercept of the model
p_i is the position of the log (i = 1 to 6, as indicated in Fig. 1)
e_{ij} is the error introduced by log j in position i
l_k is the location of the probe within the log (k = 3 m, 4.5 m, or 7.5 m)
pl_{ik} is the interaction of the position of the log and the location of the probe within the log
e^*_{ijk} is the error introduced by location of probe k in log j in position i
w_l is the week in which the measurement occurred (l = 1, 2, 3, 4, 5, 6, 8, or 11)
pw_{il} is the interaction of the position of the log and the week
lw_{kl} is the interaction of the location of probe k and the week l
plw_{ikl} is the three-way interaction of the position of the log, location of probe within the log, and week
o_{ijkl} is the error introduced in week l for probe location k in log j for log position i

Because the measurements from each probe were taken over time, it was appropriate to include an autocovariance structure to account for the similarities between measurements within a single probe. The week of measurement was therefore analyzed as a repeated factor with an AR(1) covariance structure (the p-value of the covariance test for this structure was <0.0001). This was the most appropriate covariance structure, based on the fit statistics of the resulting model.

RESULTS AND DISCUSSION

Several variables included in the model were significant at the α = 0.05 level (**Table I**). These variables included location within the log (L) (p = 0.0019), week of measurement (W) (p<0.0001), and the interaction of position in the pile with week of measurement (P*W) (p<0.0001).

Backward selection was performed to arrive at a parsimonious model for moisture content; variables were removed hierarchically, the least significant first, until all variables remaining in the model were significant or included in a significant interaction. These variables are indicated in **Table II**, and are the same as those found to be significant in Table I.

The significance of location within the log was attributable to a difference between moisture contents at 4.5 m and 7.5 m from the butt of the log (p = 0.0016, according to Tukey's "honestly significant difference" [HSD] pairwise comparisons); moisture content at 3 m from the butt of the log was not significantly different from either of the other two locations. **Table III** presents the modeled averages (least-square means) over all weeks at each location within the logs, along with their standard errors. Table III also shows average moisture contents based on the discs removed from 15 logs at each probe position. **Figure 3** shows data-averaged moisture contents at each location within the logs in each week, averaged over all available probes. Overall moisture contents changed weekly, but no significant interaction between location within log and week of study were noted. Therefore, the relationship of moisture contents among the various locations is considered to be consistent over time (i.e., in any given week, moisture contents will be approximately 5% higher at 7.5 m from the butt than at 4.5 m from the butt).

Tukey's HSD comparisons of the weeks of the study indicated that overall moisture contents through week 4 were significantly higher each week at the 0.05 level of significance. Weeks 4, 5, 6, 8, and 11, however, demonstrated statistically similar moisture contents. A larger difference existed between location 6 and other locations in week 6 than found in other weeks; however, even these larger differences were not significant within week 6, according to Tukey's HSD comparisons. **Figure 4** provides data-averaged weekly moisture contents by location, averaged over all available probes. A statistical contrast was used to determine whether those positions in the upper tier (1, 2, and 3) differed significantly overall from those in the lower tier (4 and 5), and the two tiers were not found to be statistically different (p = 0.7816).

Variable	NUM DF	DEN DF	F Value	P Value
P	5	21.2	1.17	0.3545
L	2	40.2	7.37	0.0019
P*L	10	40.1	1.53	0.1639
W	7	356	136.86	<0.0001
P*W	35	402	3.58	<0.0001
L*W	14	385	0.79	0.6838
P*L*W	70	394	1.23	0.1121

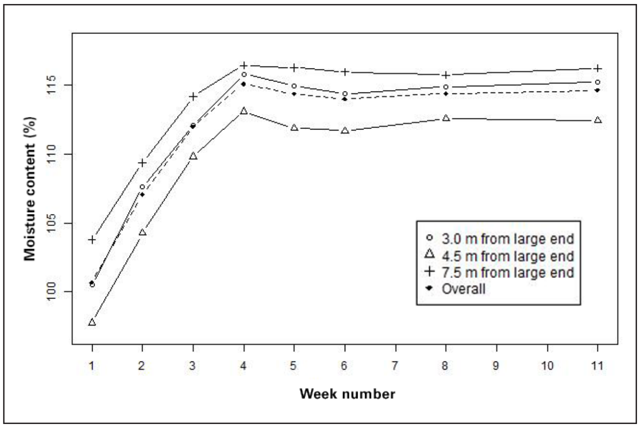
I. Analysis of variance results for the full model.

Variable	NUM DF	DEN DF	F Value	P Value
P	5	21.7	1.17	0.2657
L	2	50.8	7.37	0.0024
W	7	417	136.86	<0.0001
P*W	35	479	3.58	<0.0001

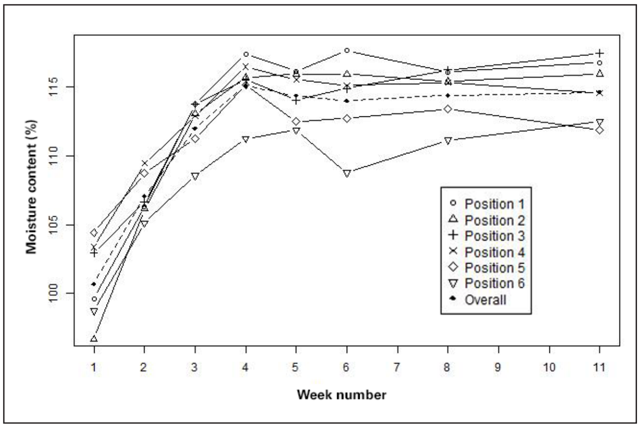
II. Analysis of variance results for the reduced model.

Distance from Large End (m)	Estimated Moisture Content	Standard Error	Laboratory Moisture Content
3	111.93%	1.031	137.0%
4.5	109.22%	1.064	149.9%
7.5	114.15%	1.092	147.4%

III. Modeled average moisture contents within logs over the study period.



3. Data-averaged weekly moisture contents by location within a log.



4. Data-averaged weekly moisture contents by log position in the wet deck and overall.

This study aimed to use TDR estimated moisture contents to develop an understanding of how moisture content varied both within individual logs located in a wet deck and across an operational wet deck with time. Our findings indicate that moisture contents may be somewhat variable within a log. In particular, moisture content was lowest in the most volume-central location within the log. We therefore recommend that at least two probes be used per log, one in a more volume-central location and one closer to an end of the log. Position within the deck did not significantly contribute to variation in moisture content. However, logs in an atypical location near the edge of the pile might be more sensitive to weekly changes in conditions. Because this part of the stack is not a primary concern for most log storage yards, this setup should be avoided in future experiments.

The average moisture contents of the discs removed at each probe position at the completion of the study were considerably higher than the corresponding average TDR moisture contents. Maximum predicted moisture contents are constrained by the upper asymptote (129.14 for our model), but there is no guarantee that it will be the upper limit for different wet decks. A possible solution is to allow the upper asymptote to vary among woodyards (or regions) and to subsample before the commencement of any new studies to determine what is a typical maximum moisture content at the new location. While the lower estimates of log moisture by TDR are of concern, we do not expect that the conclusions of this study would change greatly if a different upper asymptote was used.

This study also sought to examine if the TDR probes could survive the harsh environment of the wet deck. Over the duration of the study, the performance of the probes remained consistent, and after being removed from the logs at the completion of the study, the probes showed no signs of deterioration. The excellent performance of the probes can be attributed, in part, to care taken when selecting probes for the study. Any probes that had odd waveforms or prongs that appeared loose were rejected. Great care also was taken when inserting the probes into the logs. It is important that the predrilled probe holes are of sufficient size to provide a snug fit. The probe usually would have to be hammered into the log; this was done with a rubber mallet.

This study also demonstrated that it was possible to build a wet deck without damaging the probes or the cables, providing care was taken when lifting and positioning logs. In particular, it is of utmost importance to avoid pinching the cable between the arm of the loader and the log as the log is being lifted. In addition, care has to be taken when placing the log, with attention given to the orientation of the head of the probe. Ideally, the log will be oriented so that the probe is at 45° or 135° to the top of the log. The aim is to create a cavity for the probe, minimizing the chances of the probe touching another log. Maintaining tension on the cable while the log is being positioned also is important because it helps ensure that the cable is not pinched and that it is positioned with the same orientation as the probe. Another important aspect in maintaining good probe performance is to protect the end of the cable. Where the cable exited the wet deck, care was taken to ensure that it was kept off the ground at all times. Often the cable was overly long and had to be wrapped around an end of a log. When this was done, the end of the cable was left hanging downward. This kept the BNC connector as dry as possible and was usually sufficient to avoid the build-up of water minimizing shield corrosion.

Note that in this experiment, all logs received water from the same sprinkler, so there is no replication on the level of the water application. Replication was only included for analysis of location differences, and so the variability from sprinkler to sprinkler is unknown. In future experiments where varying levels of water application will be studied, it is vital that replications are set up for each level of water application. Failure to do so would ignore variation that occurs between sprinkler setups and various locations in the woodyard, and results would not be applicable beyond the immediate experiment. In this initial experiment, however, our focus was on the ability of TDR to measure variation in moisture content, and determining the basic sources of variation without varying levels of water application, so this experimental setup was appropriate.

SUMMARY AND CONCLUSIONS

TDR estimated moisture contents were used to develop an understanding of how moisture content varied within individual logs located in a wet deck and across an operational wet deck with time. Location within a log was found to be potentially important, because moisture content in this study varied by an average of 5% between locations within a log; we therefore recommend that two probes be used per log (one near a volume-central point and one closer to the large end). Position within the stack was not found to be important, with the possible exception that logs near the edge of a pile might be more susceptible to weekly changes in conditions. Another important aspect of the study was the performance of the TDR probes, which showed no deterioration over the duration of the study. **TJ**

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ABOUT THE AUTHORS

Several forest products companies in the southeastern United States that operate wet decks expressed an interest in improving their water application strategies, but they knew very little about moisture variation within individual logs and within wet decks, making this impossible to achieve on their own.

The research follows on from an earlier study showing that we could use time domain reflectometry to estimate the moisture content of wood, and that it had potential to be used for this purpose in wet decks.

Setting up the trial was the most difficult aspect of this research. The probes had to be inserted into the logs before placing them in the wet deck. We had coaxial cable attached to each probe and care had to be taken by the person building the pile to ensure that the probes and cables were not damaged.

The group working on the project discovered how moisture content varies within individual logs, how it varies with location (relative to height in the wet deck and relative to distance from a sprinkler), and how it varies with time. What was most interesting to us was how consistent water uptake was within a log. We expected to see the end of the log achieve a higher moisture content more quickly than points far from the end.

Wood quality depends on adequate water application. Our study indicates that an excess of water was being applied and that water application strategies can potentially be refined to reduce water use. As the next step, we want to conduct trials that monitor moisture variation within wet decks under reduced water application rates.

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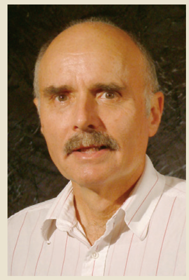

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