Examination of the potential to reduce water application rates for hardwood pulp logs stored in wet decks

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ABSTRACT: Wet storage of logs under sprinklers is often used to maintain log quality and to provide consistent fiber supply to wood production facilities. Concerns about water use in the southeastern United States have increased interest in refining water application strategies in woodyards. By understanding how the moisture content of stored logs varies over time in response to varying rates of water application, an optimum moisture regime for stored logs could be identified. In this study, experimental trials with nominal water application (100 mm/day) and a 30% reduction in water application were established at two hardwood woodyards in Georgia (Offerman, with sweetgum and yellow poplar, and McBean, with red oak and sweetgum). Variations in log moisture were monitored using time domain reflectometry for 12 months at Offerman and 15 months at McBean. Significant differences between treatments were observed initially, likely resulting from pre-existing differences in the wood before the start of the experiment, but differences in log moisture soon disappeared. Pulping trials conducted using McBean woodyard logs stored for 9, 12, and 15 months found that treatment had no effect on pulp yield, indicating that a 30% reduction in the amount of water applied results in little change in log quality.

Application: The amount of water applied to hardwood wet decks can be reduced by at least 30% with little change in log moisture or quality.

Wet storage of logs under sprinklers is a common method for maintaining a consistent supply of quality fiber to wood production facilities. Water is applied continuously while the logs are stored (which can be up to 1 year). The aim is to achieve a very high moisture content, thereby reducing the risk of fungal decay or damage by insects [1,2]. Moisture contents exceeding 100% (on a dry weight basis) are typical, and it is assumed that at such high moisture levels fungi are unable to degrade wood.

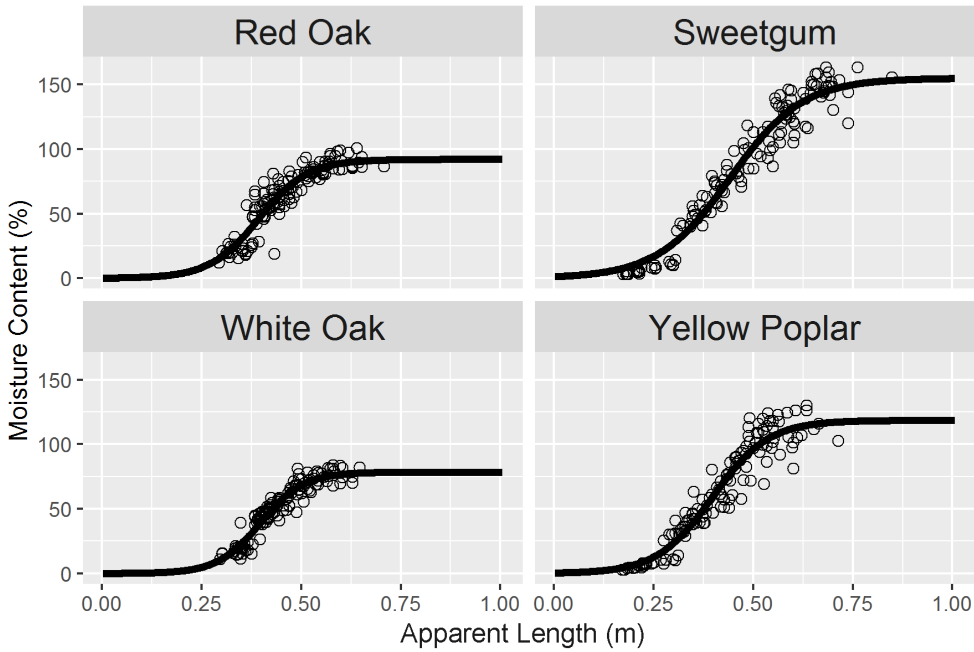
Recent droughts and increasing urbanization have raised concerns in the southeastern United States regarding water use and increased interest in refining water application strategies. To do so, it is necessary to examine how log moisture varies with time and in response to multiple water application rates. Monitoring the moisture content of stored logs is difficult and dangerous once a wet deck has been built, but recent studies have demonstrated that time domain reflectometry (TDR) can monitor log moisture over an extended period [3-5].

In the most recent of these studies, TDR was used over a 15-month period at woodyards in South Carolina and Alabama to examine moisture variation in southern pine logs in response to a nominal water application rate of 100 mm/day and a 30% reduction [5]. Significant differences between treatments were observed initially, but differences were short-lived. Pulping trials using logs from the two treatments at 9 and 15 months found no differences in pulp yield, indicating that a 30% reduction in the amount of water applied resulted in little change in log moisture or quality.

Schimleck et al. noted that TDR offers several benefits in monitoring the moisture condition of wet-stored logs [4]. It can be used to estimate moisture content above the fiber saturation point, and probes can be inserted in logs before building a 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 possible to remotely monitor moisture variation within the wet deck.

In the southern United States, most woodyards store hardwood species, alone or in addition to softwoods, and as for pine, they are interested in refining watering application strategies. More than 10 species of wood might be in storage at any one time, with sweetgum (*Liquidambar styraciflua L.*), red and white oak (*Quercus sp.*), and yellow poplar (*Liriodendron tulipifera L.*) among the most common.

Although TDR can be used to measure stem moisture in standing trees, the technique has not been applied to hardwood logs stored in wet decks [6-8]. To apply TDR to hardwood logs in wet decks, calibrations must be developed in a similar way to the pine calibration described in Schimleck et al. [3]. Hence, the objectives of this study were to:



1. Three-parameter logistic models for each species.

- Develop individual species models to predict the moisture content of the four most common hardwood types identified using TDR.
- Explore the possibility of developing a model (or models) that would apply across multiple species of hardwoods.
- Use TDR to monitor moisture variation in logs of three hardwood species (red oak, sweetgum, and yellow poplar) over an extended period (up to 15 months).
- Determine if water application rates can be reduced from current practice.

MATERIALS AND METHODS

Calibration development

Through consultation with several mill managers in the southeastern United States, the most common hardwoods stored in woodyards were identified as red oak, white oak, yellow poplar, and sweetgum. For the development of TDR-based calibrations for these hardwood types, red oak, white oak, sweetgum, and yellow poplar samples were collected (four per type) from an upland hardwood stand in Athens, GA, USA, with an approximate age of 30 years. Three bolts (150 mm to 300 mm in length) were taken from the butt and at 1.5 m and 3 m from the butt from each tree, giving a total of 12 bolts per species.

Data collection for calibration development

Bolts were debarked and soaked for 60 days to achieve full saturation. After soaking, two 4 mm diameter guide holes, 25 mm apart, were drilled into each bolt for insertion of custom-made TDR probes (with known weights). Probes were manufactured from high density, low dielectric constant resin that enclosed two 3.18 mm diameter stainless steel rods spaced 25 mm from center to center (Schimleck et al. [3] provides more information on probe manufacture). After drilling, samples were hydrated for an additional 2 days to avoid possible errors arising from wood drying when drilled. Bolts were then air dried at ambient laboratory conditions. Bolt weights (without removing probes) and TDR waveform readings of apparent length were collected using a Tektronix TDR cable tester every day for the first 4 days, and then every 2-3 days thereafter for 30 days. After 30 days, water loss was less than 3 g over 48 h, indicating equilibrium with laboratory conditions. Bolts were then dried in a forced-air convection oven (103°C–105°C) for 7 days (weight loss was less than 3 g/day), after which the bolts were considered oven dry and were weighed. Ovendry weight of each bolt was used to determine bolt moisture content on a dry weight basis on each measurement day:

Moisture content (%) = ([Wet weight – Ovendry weight] / Ovendry weight) × 100.

Hardwood calibrations

Using the empirical relationships between apparent length readings from TDR and measured moisture contents, calibrations were developed for each of the hardwoods. A sigmoidal relationship was observed between measured apparent length and moisture content (**Fig. 1**), and hence several proposed nonlinear models to describe the relationship (three-parameter logistic, Gompertz, and Chapman-Richards) were explored.

The three-parameter logistic regression model was selected based on fit statistics and ease of interpretation and was fitted separately for each species. The three parameter logistic regression model is written as

$$\text{Moisture content} = \alpha/(1 + \exp[\,-K(\text{apparent length} - \gamma)])$$

The parameter α represents the model's upper asymptote (average maximum bolt moisture content), K determines the curvature of the model, and γ the apparent length at the inflection point (where half the maximum moisture content is obtained) [9]. The selected model was fitted to the data as a non-linear mixed-effects model with both α and γ allowed to vary randomly based on the bolt from which the measurements came. This accounts for random bolt-to-bolt variability in the curve that predicts moisture content from apparent length as measured by TDR. Additionally, we used models combining various hardwood species to determine whether the models could be combined (whether the same parameter values could suffice for multiple species). In all cases, multiple parameter estimates were statistically significant, and separate models for each species were therefore estimated for ease of use.

The final models fitted for each species (based on best fit) were then used to predict moisture content of logs stored in wet decks in the manipulative study.

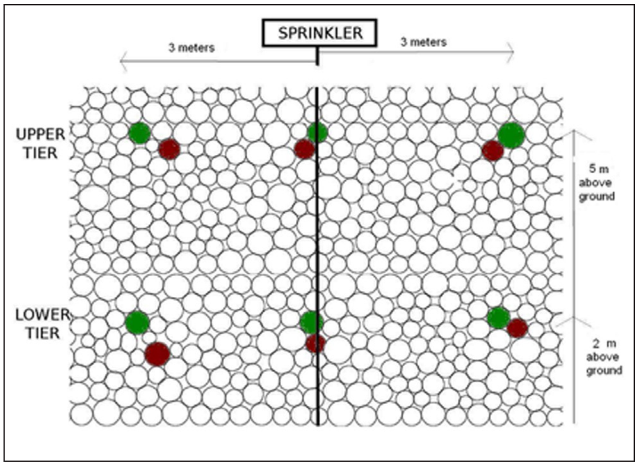
Manipulative studies

Studies were established at two sites in Georgia — a Rayonier wet storage facility in Offerman ("Offerman woodyard") and an International Paper wet storage facility in Augusta ("McBean woodyard") — to examine if the rate of water application could be reduced for hardwood wet decks in the southeastern United States.

Offerman woodyard

The trial at the Offerman woodyard was installed in August 2010, using yellow poplar and sweetgum. Study logs were relatively straight, had no forks, and a diameter greater than 150 mm at 4.6 m from the butt (to accommodate the 125 mm long probe rods). Twenty-four logs of each species were fitted with probes at 1.6 m and 4.6 m from the butt of each log. Initial log moisture readings were taken immediately after probe installation, but before piling the logs. **Figure 2** shows the position of logs. Note that logs of both species were arranged in two tiers and were directly below, and to the left and right, of the sprinkler.

Owing to space limitations, only two water level treatments were used with two replications of each. Each of the four treatment/replication combinations was located in a separate compartment or "stall" that was sprayed with water from a single sprinkler head located at the center of the stall. Sprinklers were 18 m apart to avoid overlap between adjacent sprinklers and ensure target application rates were achieved. A control treatment consisted of the nominal water application rate for the woodyard (estimated at 100 mm/day). The experimental treatment consisted of an approximate 30% reduction of the nominal rate, which was achieved by turning off sprinklers 2 days each week (the weekend, with water shut off to the same two stalls Friday afternoon, and resuming the following Monday).



2. Diagram of the layout of an experimental stall.

Data collection occurred at 2-3 week intervals, with some deviation, for a period of 9 months (considered by staff at both facilities to be the maximum time for storing hardwood logs). Several logs were then pulled from the pile and their wood quality examined. Logs showed little sign of decay and the study continued for an additional 6 months, for a total of 15 months. During this period measurements were collected monthly. The wet deck was dismantled in August 2011.

McBean woodyard

The second manipulative study was at the McBean woodyard. The design of this study differed in two ways, compared to Offerman. First, red oak (a more common species at McBean) replaced yellow poplar. Second, installation occurred in two stages: late September 2010 (lower tier) and mid-October 2010 (upper tier).

TDR measurements were taken as close to bi-weekly as possible for the initial 8 months, and monthly thereafter, for a period of 15 months. Final measurements were taken in January 2012.

To examine the effect of storage time on wood quality, 20 logs (10 representative of "soft" and 10 representative of "hard" hardwood species) were removed from the nominal and reduced water treatments for the determination of pulp yield. For comparison, 10 logs from an operational wet deck and freshly delivered (green) logs were also pulped using the conditions shown in **Table I**. Because of concerns about storing logs for more than 9 months, logs from each category were again pulped at 12 months. After 15 months, the wet deck was

White liquor sulfidity, % active alkali	31
Presteaming: Time, min Temperature, °C	10 105
Impregnation: Effective alkali charge, % Na_2O Liquid/Wood ratio, L/kg Temperature, °C Time to temperature, min Time at temperature, min	15.8 4 110 15 30
Cooking: Temperature, °C Time to temperature, min Time at temperature, min Residual EA, g/L Na_2O	170 30 110 6.2
H-factor	1845

I. Pulping conditions.

Effect	Num DF	Den DF	F Value	P Value
Tier	1	18.9	1.07	0.3135
Day	13	363	42.52	<0.0001
Tier*Day	13	363	4.9	<0.0001

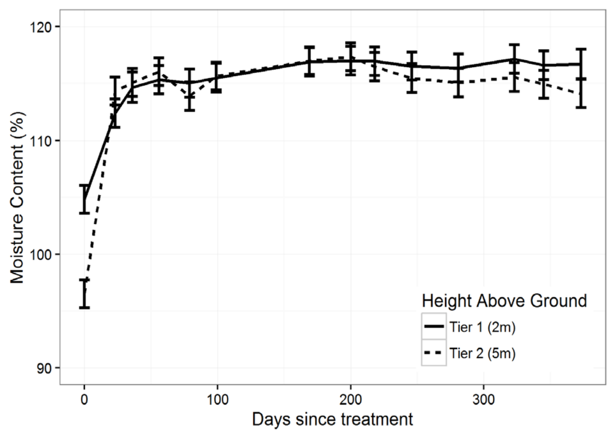
II. Type 3 tests of fixed effects for the yellow poplar logs at Offerman woodyard. (Num DF = numerator degrees of freedom; Den DF = denominator degrees of freedom.)

dismantled and logs from each category were again collected for pulping. Whole logs were then chipped and bulked, and a representative chip sample (approximately 30 kg) was removed for pulping.

Data analysis

Using the red oak, sweetgum, and yellow poplar calibrations and the TDR measurements, moisture contents (on a dry weight basis) were predicted for both woodyards. The predicted moisture contents for each probe were examined, and outliers were removed from the data before analysis. On rare occasions, probes appeared to malfunction, often resulting in extreme moisture predictions.

Mixed effects analysis of variance (AVOVA) models were used to analyze data from the two woodyards. The main effects in the model were treatment (nominal or 30% reduced water application), tier, position (placement of log with respect to sprinkler head), location (distance of probe from the butt of tree), and the day of measurement. The replication was considered as random effect in the model. All possible interaction effects (up to third order) were considered as part of the model building process. Because the measurements from each probe were taken over time, we expected to see a correlation between measurements collected at two consecutive time points within probes. The week of measurement was therefore analyzed as a repeated factor with an AR(1) covariance structure in the model.



3. Interaction of tier and day in yellow poplar at the Offerman woodyard. Standard error bars for estimated log moisture on each of the days' data were collected and are also shown.

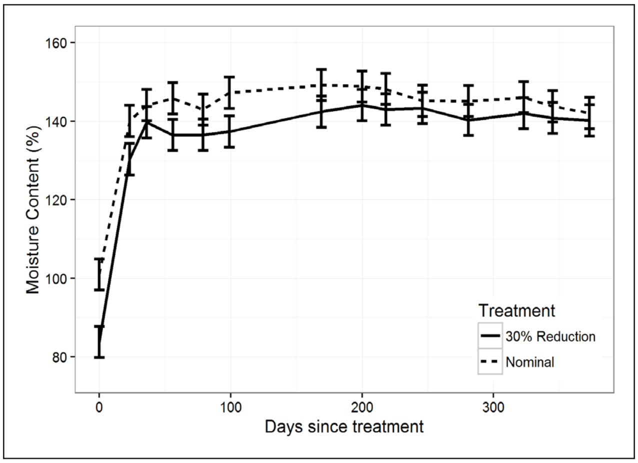
Effect	Num DF	Den DF	F Value	P Value
Treatment	1	1.95	2.95	0.2312
Tier	1	13.3	6.39	0.0249
Treatment*Tier	13	13.3	12.27	0.0038
Day	13	362	122.14	<0.0001
Treatment*Day	13	362	2.57	0.0021

III. Type 3 tests of fixed effects for the sweetgum logs at Offerman woodyard. (Num DF = numerator degrees of freedom; Den DF = denominator degrees of freedom.)

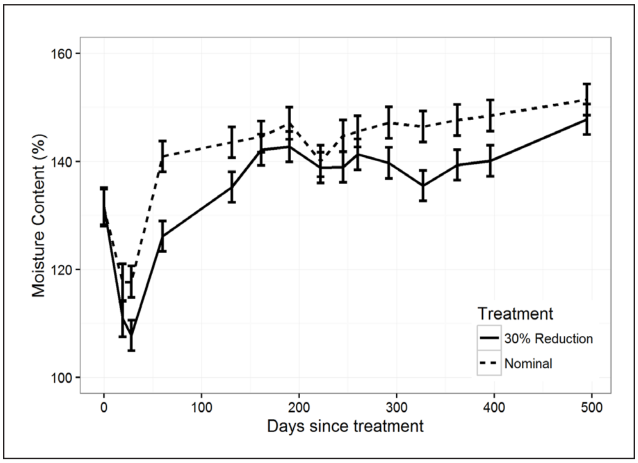
RESULTS

Offerman woodyard

Moisture content of yellow poplar logs in the control group averaged 117.0% on a dry weight basis; logs receiving 30% less water averaged 116.5%. We saw no significant relationship between treatment and log moisture (**Table II**). The only significant interaction was between tier and day: statistical differences existed between logs located in tier one and tier two during the study over time. Further tests revealed a significant difference (at the $\alpha = 0.05$ level) only during the initial days of study. **Figure 3** shows adjusted average moisture contents of all logs from the model, separated by tier. We do not know why the initial difference occurred, but by day 50, both tiers had nearly identical moisture contents. Figure 3 suggests that a difference was forming near the end of the study period, but it was not enough to produce significance differences between the tiers on any occasion. We saw no



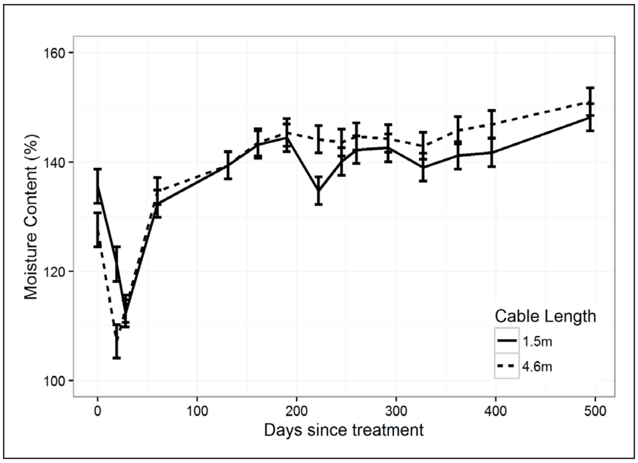
4. Interaction of treatment and day in sweetgum logs at the Offerman woodyard. Standard error bars for estimated log moisture on each of the days' data were collected and are also shown.



5. Interaction of treatment and day in sweetgum logs at the McBean woodyard. Standard error bars for estimated log moisture on each of the days' data were collected and are also shown.

Effect	Num DF	Den DF	F Value	P Value
Treatment	1	2.03	4.12	0.1775
Cable length	1	22.5	0.5	0.4879
Day	14	470	41.94	<0.0001
Treatment*Day	14	470	1.84	0.0308
Cable length*Day	14	472	2.71	0.0007

IV. Type 3 tests of fixed effects for the sweetgum logs at McBean woodyard. (Num DF = numerator degrees of freedom; Den DF = denominator degrees of freedom.)



6. Interaction of cable length and day in sweetgum logs at the McBean woodyard. Standard error bars for estimated log moisture on each of the days' data were collected and are also shown.

significant difference overall between average moisture content owing to tier. At day zero, when there was a difference, the moisture content was 96.5% for tier two (lower moisture content) and 104.8% for tier one.

For sweetgum, there was a significant interaction of treatment and day, but the difference in the treatments was only significant on day zero, indicating again that log moisture content was different when the study began (**Table III**). Within 50 days of the start of the study, the average log moisture for treatment two was slightly lower than for treatment one, but at no time did it fall below 135% (**Fig. 4**).

At the end of the study, logs with probes were removed from the wet deck and samples collected for the gravimetric determination of average log moisture content. The average for sweetgum was 140% and for yellow poplar it was 109.5%. Both compare well with TDR estimates for the two species (139.6% and 115.2%, respectively).

McBean woodyard

At McBean, average sweetgum log moisture content was significantly different between the two treatments on 2 days that readings were collected (day 60 and 327) (**Table IV**). We cannot explain why the variation in moisture was significant on these days only. The logs stored under treatment one (nominal water application rate) had a slightly higher average moisture content than logs stored under treatment two (**Fig. 5**).

A second effect on moisture was related to the position of the probe (1.6 or 4.6 m from the butt) within the log (**Fig. 6**). Post hoc tests reveal that only on day 222 was the average moisture content at 1.6 m lower than the moisture content at 4.5 m. On days 0 and 19 (the first two measurement periods), the opposite was observed, with the moisture content for probes at 1.6 m higher than for probes at 4.5 m.

Red oak at McBean demonstrated a three-way interaction between treatment, day, and position (i.e., the significance of treatment and position changed by day) (**Table V**). **Figure 7** shows the three-way interaction, with positions 1 and 3 being probes to the left and right of the sprinkler head,

Effect	Num DF	Den DF	F Value	P Value
Treatment	1	2.03	0.01	0.9852
Position	2	15.8	5.33	0.0170
Day	14	409	20.33	<0.0001
Treatment*Day	14	409	3.49	<0.0001
Position*Day	28	435	3.17	<0.0001
Treatment*Position	2	15.8	3.30	0.0635
Treatment*Position*Day	28	435	1.99	0.0023

V. Type 3 tests of fixed effects for the red oak logs at McBean woodyard. (Num DF = numerator degrees of freedom; Den DF = denominator degrees of freedom.)

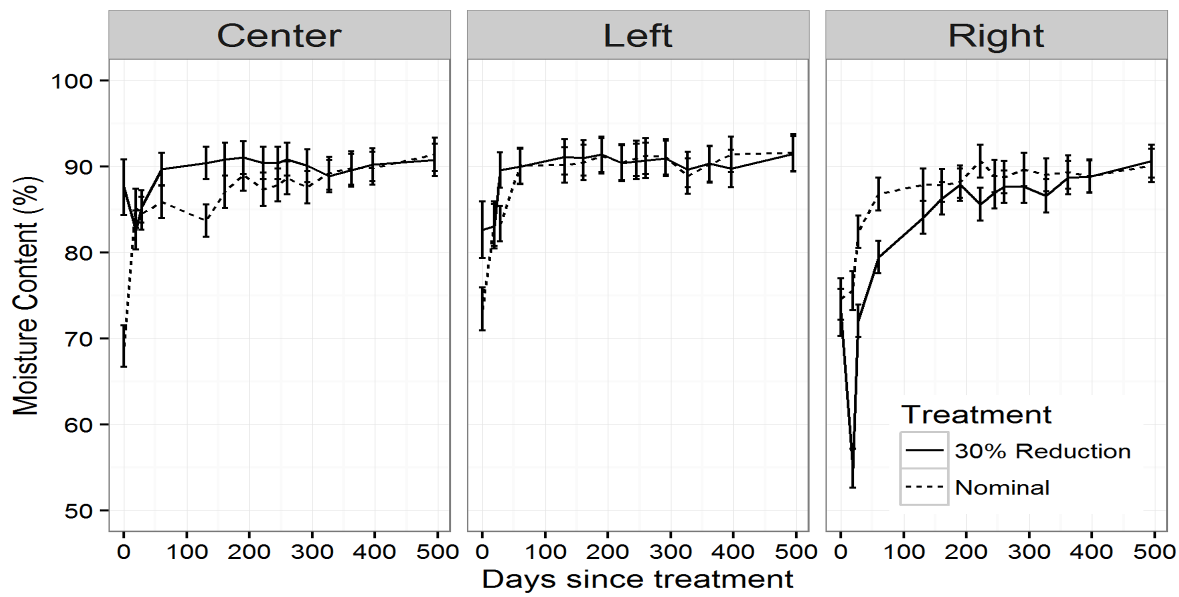
respectively, and position 2 being probes directly beneath the sprinkler. Treatment 1 is the nominal treatment and treatment 2 is the reduced treatment. The largest variability occurred on day 19 (the second reading period) when there was a large drop in moisture for logs in position 3 for the experimental treatment.

Table VI shows pulp yield data for hard and soft hardwood logs collected from the two treatments, an operational deck at the time of sample collection and green at 9, 12, and 15 months for the McBean woodyard. For comparative purposes the pulping results are reported as a percentage of the baseline green material. Table VI shows that over the duration of the study there was little change in screened pulp yield for the soft hardwoods, even when water application rates were reduced by 30%. The same conclusion can be reached for hard hardwoods, where pulp yields compared well with the baseline green material at 9, 12, and 15 months. For some samples (operational at 9 and 15 months) a marked increase in yield was observed, suggesting that

	Screened Yield, %	
	Hard Hardwoods	Soft Hardwoods
Green (woods run)	100.0	100.0
Nominal (9 months)	*	98.7
Nominal (12 months)	100.8	101.4
Nominal (15 months)	101.2	96.5
30% reduction (9 months)	99.7	100.7
30% reduction (12 months)	104.3	98.9
30% reduction (15 months)	102.7	98.7
Operational (9 months)	107.9	101.4
Operational (12 months)	101.0	100.1
Operational (15 months)	107.9	102.6

* The nominal (9 month) sample had a very low pulp yield at an elevated kappa number suggesting that either the wood chips used for pulping were atypical or there was a problem with the cook.

VI. Screened pulp yield for green and operational logs and logs from the nominal and reduced water treatments at 9, 12, and 15 months.



7. Interaction of treatment and position with respect to day in red oak logs at the McBean woodyard. Standard error bars for estimated log moisture on each of the days' data were collected and are also shown.

either the baseline green material or operational samples were not representative.

At the end of the McBean study, samples were taken from study logs for the gravimetric determination of moisture content. Based on these samples, average moisture contents of 145.9% (sweetgum) and 90.9% (red oak) were determined, which compare well with those determined using TDR: 143.9% for sweetgum and 89.0% for red oak.

DISCUSSION

Environmental awareness has raised concern over the volume of water used at woodyards in the southeastern United States. Because of these concerns, interest exists in understanding how different watering strategies can affect log moisture and log quality, with the ultimate aim of reducing water application rates. One barrier to the continuous monitoring of log moisture in wet decks is the difficulty (and danger) of accessing stored logs. Studies of southern pines demonstrate that TDR can be used for this purpose [4,5]. Similar interest exists in refining watering application strategies for hardwoods, which, on a wood volume basis, exceed that of softwoods, with most woodyards storing hardwood species alone or in addition to softwoods.

For the hardwoods identified as being most common in southeast woodyards (red and white oak, yellow poplar, and sweetgum) individual species models were successfully developed. The general form of the relationship of moisture content to TDR apparent length was similar for all species. However, considerable variation in maximum moisture contents was observed. Diffuse porous hardwoods (sweetgum and yellow poplar) had higher moisture contents than the ring porous oaks, but even within these groups, maximum moisture content varied.

Ideally, a multiple species calibration could be used. Models combining various hardwood species were developed to examine the possibility of using the same parameter values for multiple species. Multiple parameter estimates were statistically significant in all cases, supporting the use of separate models for each species. In contrast, Wullschelger et al. reported a calibration based on pooled data for four hardwood species that included red maple (*Acer rubrum L.*), white oak (*Quercus alba L.*), chestnut oak (*Q. prinus L.*), and black gum (*Nyssa sylvatica Marsh.*) [7].

In this study, the region of the TDR waveform identified as most suitable for calibration development in our earlier work on Pinus species [3] was utilized. Although the general shape of the waveform for the hardwoods examined was similar to pine, species differences were observed. Frequently, the point used for pine (point C, the inflection point of the rising curve) was more difficult to identify in the hardwood species [3]. A method proposed recently might resolve this issue by using an automated approach to signal analysis [10].

For the species examined at both sites (sweetgum and yellow poplar [Offerman] and red oak and sweetgum [McBean]), significant differences between treatments were initially observed. In-house pulping trials conducted by International Paper using McBean woodyard logs stored for 9, 12, and 15 months found that treatment had no effect on pulp yield, indicating that a 30% reduction in applied water is feasible. Although we showed that a 30% reduction in water application is feasible, realistically, the reduction in overall water consumption for a woodyard would be less owing to collection and recycling of water. These findings agree with research based on southern pine logs stored at woodyards in South Carolina and Alabama that were exposed to the same water reduction treatment for the same period [5]. In both studies, log moisture stabilized with time, with the time required to approach maximum moisture content being shorter for the hardwood species. Considering that vessels in hardwoods provide a far more effective water transport mechanism than do tracheids, this finding would be expected [11]. As noted in an earlier study based on pine, the two treatments might take different amounts of time to reach a maintenance moisture level, but once reached, are equally effective [5].

The moisture data collected at McBean showed greater variation than did the data from Offerman and the two softwood sites, particularly for red oak. The variation was related to a drying event for logs in treatment two positioned to the right side of the sprinkler (position 3). The low maximum moisture content of red oak, coupled with its ability to dry quickly (ring porous with large early wood vessels free of tyloses), suggests that it is particularly sensitive to changes in the volume of water applied, possibly limiting what is possible for hardwood wet decks. These should be carefully monitored if further efforts to reduce water application rates are undertaken.

CONCLUSIONS

TDR was successfully used to monitor log moisture variation at two hardwood woodyards over an extended period (12 months at Offerman and 15 months at McBean). At both, when water application rates were decreased by 30%, average log moisture content was found to be similar to that obtained through current practices. Further reductions might be possible, and additional research is required to determine the level to which water application rates can be reduced. However, species such as red oak appear to be particularly sensitive to changes in watering regimes. As a consequence, the potential to reduce application rates in hardwoods might not be as great as for softwoods. **TJ**

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ABOUT THE AUTHORS

We chose this topic to research because lack of knowledge regarding wet deck watering strategies has been identified by industry as an important question. This study compliments an earlier study published in *TAPPI Journal* [5]. This study examines hardwoods, and the duration of data collection was much longer. We also reduced the amount of water applied during the investigation.

The most difficult aspect of the study was setting logs in place and building the pile without damaging the time domain reflectometry (TDR) probes. I think that the most interesting finding was how stable log moisture content was once the logs were fully saturated.

Mills will benefit from this information because it will help them develop strategies for reducing water use on wet decks. The next steps include honing water application strategies and improving the accuracy of TDR readings.

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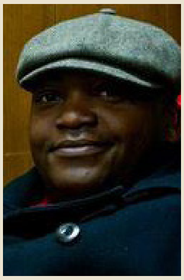

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