Field Measurements of Moisture Content in Black Spruce Logs with Unilateral Magnetic Resonance

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Abstract

The development of portable unilateral magnetic resonance (UMR) devices permits nondestructive characterization of wood moisture content (MC) in the field. In this study, six *Picea mariana* Mill. logs were measured. UMR measurements of MC were taken in four different spots displaced 15 cm from the end of each log. UMR measurements were also taken at the midpoint longitudinally for three of the six logs.

The end goal of this study was to demonstrate a viable approach to estimating the whole-sample MC in the field. In the case of the species studied, there is a significant difference in MC between sapwood and heartwood regions. The sapwood MC is approximately three times greater than the heartwood MC. However, the volume of heartwood is greater than sapwood in wood logs. The sapwood region contains most of the water; therefore a measurement in the sapwood, coupled with sapwood-to-heartwood volume proportions and an estimate of heartwood MC, provide a viable estimate of bulk MC of logs.

Results indicate that both measurement spots (15 cm displaced from the end and at the midpoint longitudinally) give good predictions of log MC. The UMR measurement signal-to-noise ratio decreases and variability in the total sapwood signal of the four spots, displaced 15 cm from the end, increases as drying progresses. The increase in variability is because of the appearance of a drying front at some measurement spots. The UMR device and technique provide a good tool to measure MC of logs in the field.

The nondestructive monitoring of wood log properties, such as moisture content (MC), directly in the forest or in the mill yard is of great practical interest. In the field, such capabilities could lead to the improvement of industrial processes such as sorting, drying, and overall product quality. Better preprocess evaluation of wood properties could permit sorting of the raw material into more homogeneous categories (Trung and Leblon 2011). There are numerous nondestructive techniques available for measuring wood MC (Bucur 2003); however, nearly all face significant limitations. Many techniques use electromagnetic radiation, such as visible light, near-infrared (NIR), thermal infrared (TIR), microwave energy, and magnetic resonance (MR). NIR and TIR sensors have a limited penetration depth in solid wood, ranging from 1 to a few millimeters depending on surface roughness and the wavelength used (Tsuchikawa et al. 1996).

Microwave-based sensors such as handheld ground-penetrating radar (GPR) show good potential for nondestructive characterization of wood MC. They are portable, lightweight, and low-cost devices that do not present any health and safety issues, in contrast to X-ray–based sensors. However, measurements performed on logs can be challenging because of their curved surface, which can affect the GPR signal (Hans et al. 2015). The GPR measurement is also a line-integrating measurement through the cross section of the log.

Acoustic systems can be used for measuring log MC, but they were found to work only for liquid water, i.e., ambient temperatures above the freezing point (Nader 2007). Furthermore, the relationship between MC and acoustic measurement parameters was shown to vary between species and within the same species (Nader 2007). There are also resistance- and capacitance-type handheld moisture meters that are invasive, species dependent, and often

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limited in terms of MC working range (Forest Products Laboratory [FPL] 2010).

MR and magnetic resonance imaging (MRI) are well-known methodologies for molecular structure determination and clinical diagnostic imaging. MR-based methods measure the quantity of hydrogen-containing compound, in this instance water, within the sample of interest, and can provide secondary information on the molecular dynamics and molecular environment. In the context of wood materials, MR and MRI offer the possibility of noninvasively determining the nature of both free and bound water within the wood and in the case of MRI allowing water concentration spatially resolved (Araujo 1993; MacMillan et al. 2002, 2011; Casieri et al. 2004; Lamason et al. 2014, 2015). The water in the sample must not be frozen as shown in Lamason et al. (2014). The MR signal lifetimes of frozen water do not permit MRI.

A promising recent development in MR is the advancement of portable unilateral magnetic resonance (UMR). Numerous studies and designs have been presented in the literature. Blümich et al. (2005, 2008) presented a review on the advances of single-sided MR. UMR has been used in many different measurement problems. In food and agriculture research, Veliyulin et al. (2008) used UMR for rapid and nondestructive determination of fat content in dairy products. Other applications include biomedicine, polymers, cultural heritage, porous media, and building materials (Blümich et al. 2008).

There are relatively few studies in the literature that use portable UMR sensors for wood measurement. Casieri et al. (2004) used portable UMR as a nondestructive and noninvasive tool for water content analysis and moisture fraction determination in wood. Senni et al. (2009) used a portable UMR sensor for in situ noninvasive determination of MC of wooden works of art and painted wood. A portable UMR sensor was used by Dvinskikh et al. (2011) to study MC profiles and water uptake kinetics in wood materials. Pourmand et al. (2011) evaluated the moisture protective properties of a wood coating with a portable UMR sensor. Most sensors used have a maximum depth of penetration of 3 to 5 mm. Lamason et al. (2014) used a UMR sensor that has a penetration depth of 13 mm to observe freeze–thaw behavior of wood samples.

In the case of water in wood, there are three different water environments. (1) Water in the cell walls is motionally restricted and conventionally considered bound water. There are two different types of lumen water. One is the bulk lumen water (2), which is considerably more mobile, and the other is a small fraction that adheres to the lumen walls (3). The observed relaxation rate from the water in the lumen (conventionally called free water in wood science literature) is the weighted average rate of the surface water and bulk water, which rapidly exchange. Typically, there is more bulk water than surface water when the wood is green, but the surface relaxation rate is much larger than the bulk relaxation rate. The bulk and surface water in the lumen together are considered free water in the wood science literature (Wong 1999). Readers are referred to Lamason et al. (2015) for relevant discussions on MR relaxation rates in wood.

Lamason et al. (2015) also used UMR to study water states of black spruce (*Picea mariana* Mill.) and aspen (*Populus tremuloides* Michx.). They found a biexponential decay of the time-domain MR measurements, which was attributed to the cell wall (short lifetime signal) and lumen water (long lifetime signal).

In the current article, a portable UMR sensor is evaluated for application to log moisture measurement in the field. This device permits measurements of water content deeper than most bark layers and cambium in log samples. Wood is composed of sapwood and heartwood in a radial fashion from bark to pith. In the case of the species studied (*Picea mariana* Mill.), there is a significant difference in MC between sapwood and heartwood regions. The sapwood region has an MC approximately three times greater than the heartwood, whereas the volume of heartwood is greater than that of sapwood in the logs studied. The sapwood region contains most of the water; therefore, an MC measurement in the sapwood coupled with sapwood and heartwood volume proportions, and an estimate of the heartwood MC, will provide a viable estimate of bulk MC of logs.

This study is a field test of a UMR device with MC measurement in the sapwood to predict whole-log MC. The field test builds on our experience with a recent laboratory study of the UMR device (Lamason et al. 2015). The current work used more samples and more measurement spots than the laboratory study to explore the variability of sapwood MC for a particular drying duration. The objective of this work was to evaluate the practical viability of UMR as a reliable field measurement tool. This is necessary to provide the wood industry with a reliable, accurate, and nondestructive measurement tool for MC.

Materials and Methods

Six black spruce (*P. mariana* Mill.) logs were cut from six different trees with a diameter at breast height (DBH) of approximately 20 to 25 cm. The DBH was measured 1.4 m from the ground. A 10-m-long butt log was cut from each tree. The six 10-m logs were then moved to the yard for further processing. At the yard, fresh ends were prepared by removing 25 cm from both ends of each log. Two 2.5-cm-thick disks were cut from each end for gravimetric MC measurements. The heartwood MC was determined gravimetrically by separating the heartwood from one of the disks for each end of the log. Table 1 gives the log dimensions used in this study.

The general experimental scheme was to stack logs for air drying and monitor MC using a portable UMR device. The stack was covered with plywood to protect the logs from rain and direct sun exposure. The air drying was undertaken during the summer of 2015 for a 70-day period in Fredericton, New Brunswick, Canada. Ambient drying conditions were monitored using a data logger with temperature and relative humidity (RH) probes mounted near the drying stack. The data logger measured the temperature and RH every 10 minutes and stored the data with a time and date stamp. The temperature and RH data were averaged for each day to be used in data analysis.

The UMR measurements were performed with a three-magnet array designed and built at the University of New Brunswick MRI Centre. The device is lightweight, features open access, and is portable (Marble et. al. 2007). It produces a magnetic field of 0.1 Tesla along the central vertical line above the surface of the unilateral magnet that is shown in Figure 1. It shows that the unilateral magnet has a region of homogenous magnetic field, located approximately 1.3 cm from the top surface of the magnet. The radio frequency (RF) coil in combination with the static field

Table 1.—Black spruce log dimensions and moisture content (MC).

Log sample ID	Small-end diameter (cm)	Large-end diameter (cm)	Length (m)	MC (%)[a]	Heartwood MC (%)[b]
1	22.3	24.1	1.4	64.9	31.9
2	24.6	25.8	1.4	96.0	37.4
3	23.7	24.6	1.4	61.8	33.4
4	19.6	21.4	1.4	83.0	37.5
5	22.3	23.4	1.4	66.5	37.6
6	23.6	24.9	1.4	56.8	32.4

[a] End discrete gravimetric disks (sapwood and heartwood), average of two disks for each log.

[b] Heartwood sections measured gravimetrically, average of two heartwood disks for each log.

topology gives a sensitive spot for MR measurement of approximately 1 cm^3. This is significant because it allows measuring the MC within a finite volume inside the sample at a fixed depth within the log. In the current work, all measurements were taken in the sapwood region.

The unilateral magnet RF probe was connected to a quarter lambda circuit. A Tomco RF amplifier (BT00250-AlphaS, Tomco Technologies, Adelaide, Australia), Tecmag LapNMR console (Tecmag, Houston, Texas, USA), and acquisition laptop were used in the field measurements. The MR frequency in the sensitive spot was 4.46 MHz. The UMR measurements were performed using a Carr-Purcell-Meiboom-Gill (CPMG) measurement to determine the transverse relaxation time T_2 and signal amplitude. The initial MR signal amplitude was proportional to MC. CPMG measurement parameters were echo time = 160 μs, scans = 512, and number of echoes = 1,024. The 180° pulse length, 11 μs, and the 90° pulse length were the same but the 90° pulse power was 6 dB attenuated with respect to the 180° pulse. The overall acquisition time for each chosen spot was approximately 10 minutes. The UMR sensor was in direct contact with the log surface throughout the measurement.

For each spot measurement, a reference sample was first measured, followed by Logs 1, 2, and 3. The reference sample had 30 percent MC and was fabricated from a mix of H_2O, deuterium oxide (D_2O), and copper sulfate. The reference sample was then remeasured to ensure instrument and measurement stability. Measurements of Logs 4, 5, and 6 commenced after remeasuring the reference sample.

The UMR measurements were undertaken at four different spots in the sapwood, through the bark, for each log. The four spots were located 15 cm from the bottom of the log and were evenly spaced around the circumference at 90° intervals. Two perpendicular lines were inscribed at the end of each log to ensure consistent orientation during measurements. The measurement spots were carefully marked to maintain the same spot for succeeding UMR measurements. Data from the four spots provided information about the variability of MC in sapwood at this chosen distance from the end. Variability in sapwood MC was examined throughout the duration of drying in the field. Apart from the four measurement spots displaced 15 cm from the end, measurements at the midpoint longitudinally were undertaken for three of the six logs. In practice, it was sometimes difficult to access the midpoint of the log, especially in logs that are placed in the interior of the stack.

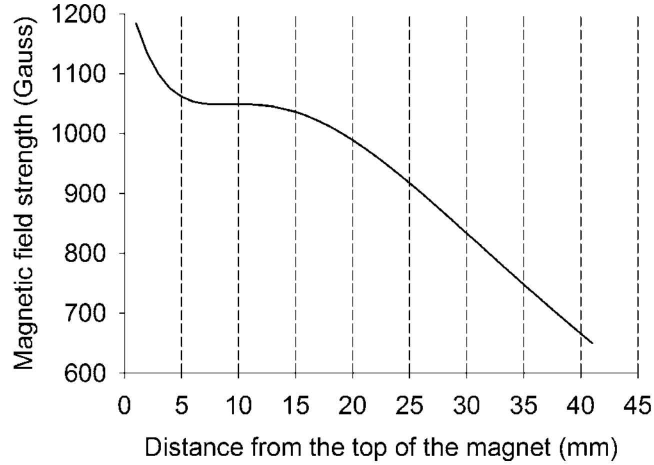

Figure 1.—Magnetic field along the central vertical line of the magnet array. The center of the homogeneous spot is 1.3 cm from the surface of the magnet. This permits measurement of signal within a finite volume inside the sample and not just on the surface. In the case of wood logs, measurements of magnetic resonance signal in the sapwood are therefore possible without first removing the bark.

The CPMG decays were analyzed using biexponential fitting, performed with a least-squares regression in SigmaPlot (Systat Software Inc., USA). The CPMG decay constant is the T_2 relaxation time. A biexponential fitting permits determination of the relative water content in different environments (cell wall and lumen), based on the lifetime of the MR signal. The short lifetime signal component is related to the cell wall water, whereas the long lifetime signal component is related to the lumen water (Riggin et al. 1979; Menon et al. 1987, 1989; Lamason et al. 2015). The sum of the two signal populations is converted into MC by using a reference sample of known MC.

Results and Discussion

Figure 2 shows photos taken during the field measurements. Logs were stacked outside and individual logs were moved and placed on a workbench under cover during UMR measurements. Figure 3 shows the average daily temperature and RH near the drying stack. The average daily air-drying temperature and RH ranged from 14.9°C to 24.8°C and 57.6 to 93.9 percent, respectively.

Typically, when wood is wet (green condition) the signal intensity measured with the UMR in a CPMG measurement decayed biexponentially (Lamason et al. 2015). The short lifetime signal component, for freshly cut black spruce sapwood, is associated with the water in the cell walls, whereas the long lifetime signal component is associated with the lumen water (Riggin et al. 1979; Menon et al. 1987, 1989; Araujo 1993; Lamason et al. 2015). The biexponential fitting used was sufficient to fit the experimental decay. Previous work on spin–spin relaxation rates in porous media, such as wood, suggests that MR measurement could differentiate water in different cell sizes. However, there was no experimental evidence of three discrete exponentials in the current work. Menon et al. (1987, 1989) assigned early-wood and late-wood lumen water (different cell cavity sizes) to the longer two of three observed time constants in their work. In the current work, the long lifetime T_2 reported

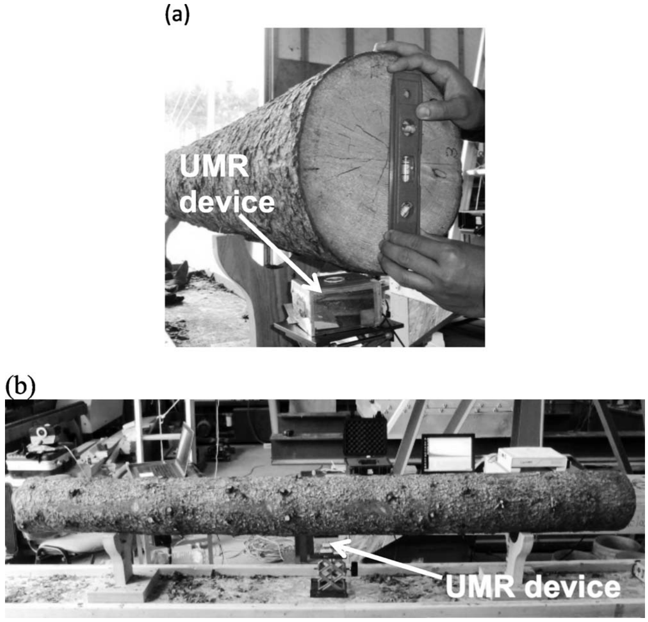

Figure 2.—Photos of the field measurements: (a) markings at the end of the log for consistent orientation; (b) unilateral magnetic resonance measurements at the midpoint longitudinally. UMR = unilateral magnetic resonance.

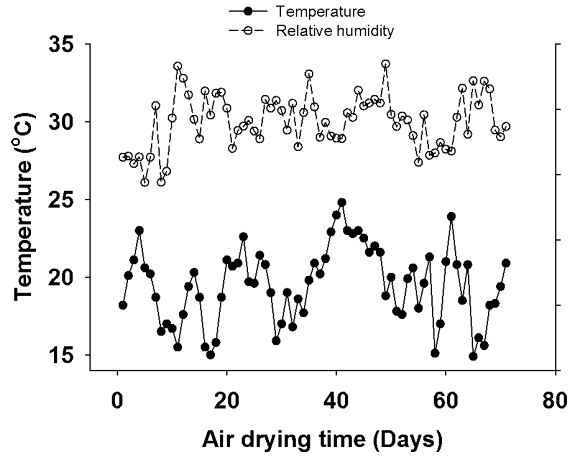

Figure 3.—Average daily temperature and relative humidity near the drying stack.

is likely an average of the cell lumen water in early wood and late wood. The initial MR signal intensity is proportional to the overall quantity of water. Total MC is equal to the sum of the signal from the two water environments. Initial signal intensity decreased as the sample dried.

Optimization of the UMR CPMG measurement allows quantification of both short and long lifetime signal components. The optimization involved using the shortest possible echo time. Because the UMR measurements allowed quantification of both short and long lifetime signal components, one can easily determine the fiber saturation point (FSP) for each species as the MC wherein the signal of the long lifetime component is no longer observable, while the short lifetime signal component remains at maximum amplitude (Lamason et al. 2015). Table 2 summarizes the different T_2 values of a freshly cut black spruce sample. The observed T_2 values of short (cell wall) and long (lumen) lifetime components ranged from 3.8 to 6.8 ms and 75.8 to 99.6 ms, respectively.

Figure 4 plots the total water as a function of drying time in sapwood in a measurement spot 15 cm from the end of the log, through the bark. Each data point was the average value of the four different spots for each individual log (Figs. 4a through 4f). Overall, the total signal decreases with air-drying duration. The total signal intensity in the sapwood did not significantly change in the early stages of drying. However, for all samples, there was a significant drop in the signal intensity at 70 days of drying. This was owing to the fact that the end drying front has reached the measurement spot during this stage of drying. Variability in the data among the four spots increased with drying time. Variability was also observed between samples. As the drying front progresses into the log, some measurement spots will be drier than others for a particular drying duration.

The signal-to-noise ratio (SNR) was calculated as the ratio of maximum signal amplitude and standard deviation in the noise level. It was found that the SNR decreased by a factor of 10 from Day 1 to Day 70. The typical SNR at the initial condition was approximately 100. The decrease in SNR as drying time progressed is attributed to the decrease of MR signal as MC of the sample decreases. The noise level remained constant.

Figure 5 plots the total water signal as a function of drying time in sapwood at the midpoint longitudinally in three logs. The total signal intensity in the sapwood decreases with air-drying duration. The signal intensity at 70 days of drying was less than that of the early stages of drying. The signal intensity at the midpoint longitudinally is higher than the signal intensity at 15 cm from the end of the log at the same drying duration. This suggests that the diffusive drying front, from the exposed end, has reached the 15-cm measurement spot during this time. The R^2 values of the best-fit line for Logs 3, 4, and 5 were 0.87, 0.94, and 0.79, respectively.

The total sapwood signal intensities were converted to MC using a standardized reference sample with known MC. Only data from one of the three logs are presented in Figure 5. This result is, however, representative of the findings for all three logs measured at the midpoint longitudinally. Figure 6 (data for Log 3 only) shows that the measured sapwood MC in a spot 15 cm from the end (Fig. 6a) and at the midpoint longitudinally (Fig. 6b) were linearly related to the gravimetric MC of the whole log sample. The

Table 2.—Spin–spin relaxation times of freshly cut black spruce sapwood.

	Spin–spin relaxation time (ms)			
	15 cm from end		Midpoint	
Log sample ID	Short	Long	Short	Long
1	4.5	89.9	—	—
2	3.8	83.6	—	—
3	4.0	97.7	4.2	97.3
4	4.5	75.8	4.1	80.2
5	5.6	84.0	6.8	99.6
6	5.3	81.0	—	—

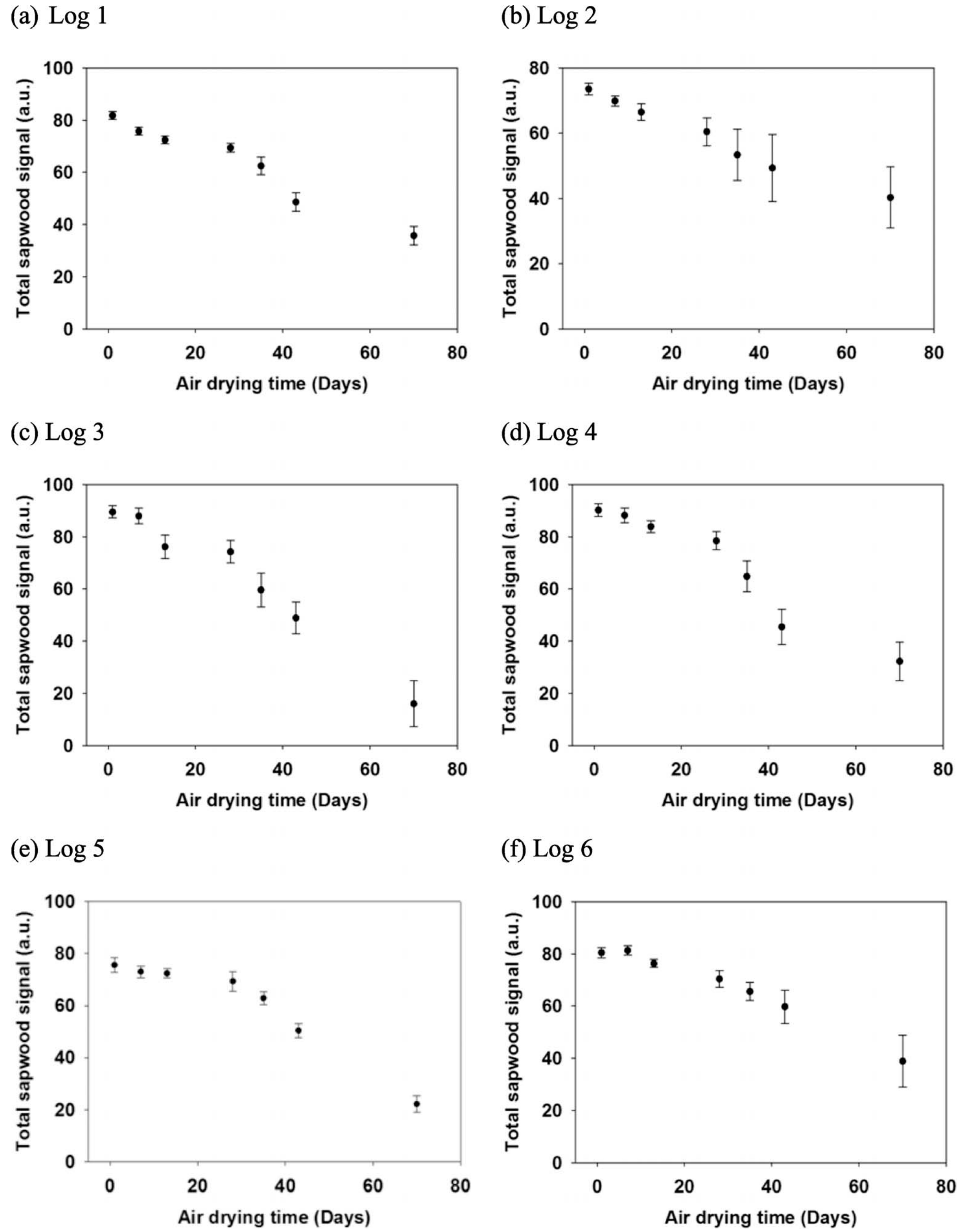

Figure 4.—Total water signal in black spruce sapwood in a measurement spot 15 cm from the end of the log, as determined by unilateral magnetic resonance: (a) Log 1, (b) Log 2, (c) Log 3, (d) Log 4, (e) Log 5, and (f) Log 6. The standard deviation of four measurements for each log is illustrated with the error bars.

relationship is clear, especially during early stages of air-drying. This is because most of the water loss occurred in the sapwood and because the observed diffusive drying at the end surfaces of the log does not significantly affect the overall MC during early stages of drying. The exact position of the measured spot does not matter as long as it is displaced from the ends. The UMR measurements in Figure 6 were undertaken at air-drying times that ranged from 1 to 70 days.

The relationship between the measured sapwood MC in a spot displaced from the ends and the gravimetric MC was linear, with an R^2 value of 0.92 (Fig. 6a). Likewise, the relationship between the measured sapwood MC in a spot at the midpoint longitudinally and the gravimetric MC was linear, with an R^2 value of 0.87 (Fig. 6b). This linear relationship was proven in a recent laboratory study (Lamason et al. 2015) and the relationship was again manifested in the current field study.

The boundary between sapwood and heartwood was visually determined by observing the difference in color and transparency at the cut end. There is a large visual disparity between heartwood and sapwood MC. The sapwood area was estimated by subtracting bark area and heartwood area from the total cross-sectional stem area. For these samples, the sapwood thickness was approximately 1.8 cm and the ratio of sapwood to heartwood was 25:75 with respect to the overall volume of the log. It was assumed that the log was cylindrical and that heartwood MC does not change

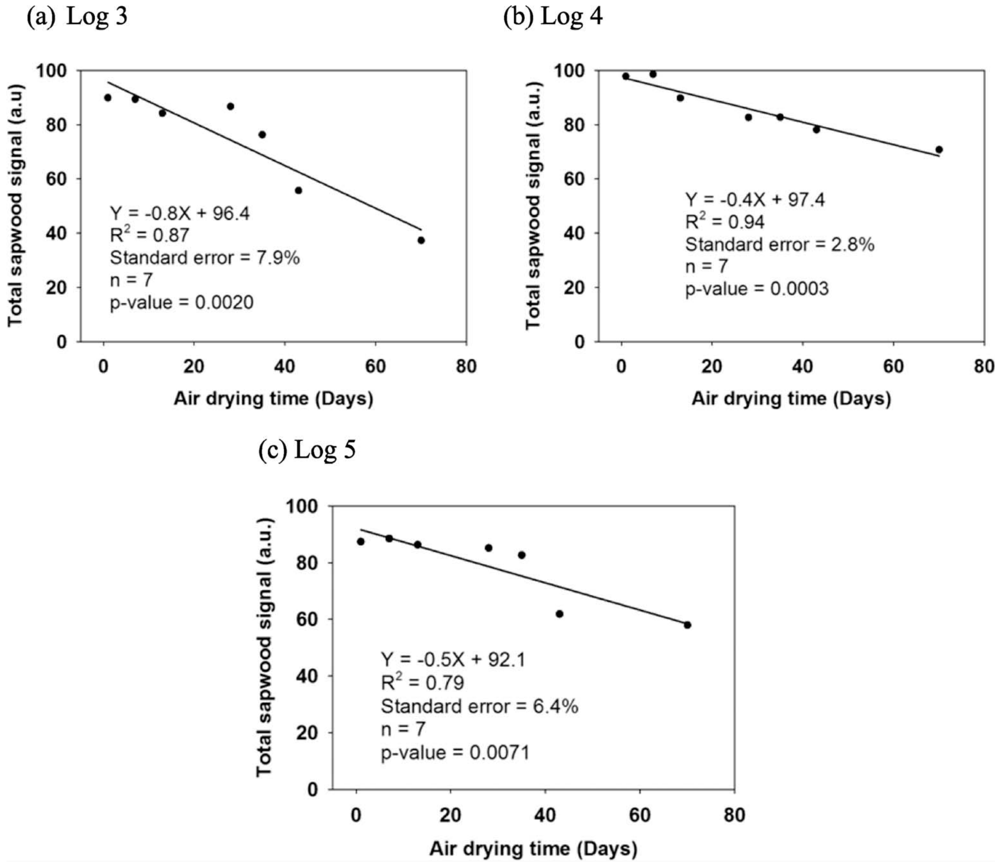

Figure 5.—Total water signal in black spruce sapwood at the midpoint longitudinally, as determined by unilateral magnetic resonance: (a) Log 3, (b) Log 4, and (c) Log 5.

significantly unless the MC of sapwood is at or near the FSP.

A reliable estimation of MC of logs includes a direct MC measurement of sapwood and takes into account the volume proportions of the heartwood and sapwood regions as well as an estimate of heartwood MC, assumed in the case of black spruce to be at the FSP. One difficulty with this approach is that not all species of wood have a distinct boundary between sapwood and heartwood. For species with a clear distinction between heartwood and sapwood, a simple measurement approach as described by Equation 1 may be used.

$$MC_{log} = (MC_{sapwood} \times \%Vol_{sapwood}) + (MC_{heartwood} \times \%Vol_{heartwood}) \quad (1)$$

where MC_{log} is the overall MC of the log; $MC_{sapwood}$ and $\%Vol_{sapwood}$ are MC and volume proportion of sapwood to the entire volume of the log, respectively; and $MC_{heartwood}$ and $\%Vol_{heartwood}$ correspond to the MC and volume proportion of heartwood to the entire volume of the log. The first term in Equation 1 was measured and the remaining terms were estimated assuming the heartwood is at fiber saturation (35% MC). Although a reasonable assumption for black spruce, it is important to note that the MC of heartwood is not always near the FSP and is species dependent (FPL 2010).

UMR measurement of heartwood MC at the end of the freshly cut log is possible, but this will not be reflective of the overall heartwood MC because of diffusive drying from the exposed end surface. The average gravimetric MC of heartwood presented in Table 1 was used in Equation 1 to estimate the whole-log MC. The average gravimetric MC of heartwood listed in Table 1 is 35 percent. This value is consistent with other published literature on heartwood MC for this species (Shottafer and Brackley 1982, FPL 2010). This is close to the literature FSP (FPL 2010). Table 1 also reports the initial log MC for each of the six logs, determined gravimetrically from wood disks. The initial MC ranged from 56.8 to 96.0 percent.

Table 3 summarizes the gravimetric MC and predicted MC of logs after 35 days of air-drying. The predicted values were remarkably close to the gravimetric MC despite the assumptions of Equation 1. The minimum and maximum absolute differences were 1.4 and 5.9 percent, respectively.

Figure 7 shows the relationship between the predicted black spruce log MC, determined with MR measurement, and the gravimetric measurement of one log (Log 3). This result was similar to the other logs with spot measurements at the midpoint longitudinally. The relationship was linear, with $R^2 = 0.92$ (Fig. 7a) and $R^2 = 0.91$ (Fig. 7b). Although the R^2 value in Figure 7a was high, it is important to note that the prediction that corresponded to lowest gravimetric MC was dramatically below the best-fit line. Again, this was owing to the emergence of the end diffusive drying fronts in some of the spots. The UMR data measured 15 cm from the end of the log predicted the log MC well, especially during early stages of drying. The challenge occurred when the diffusive end drying advanced sufficiently longitudinally so

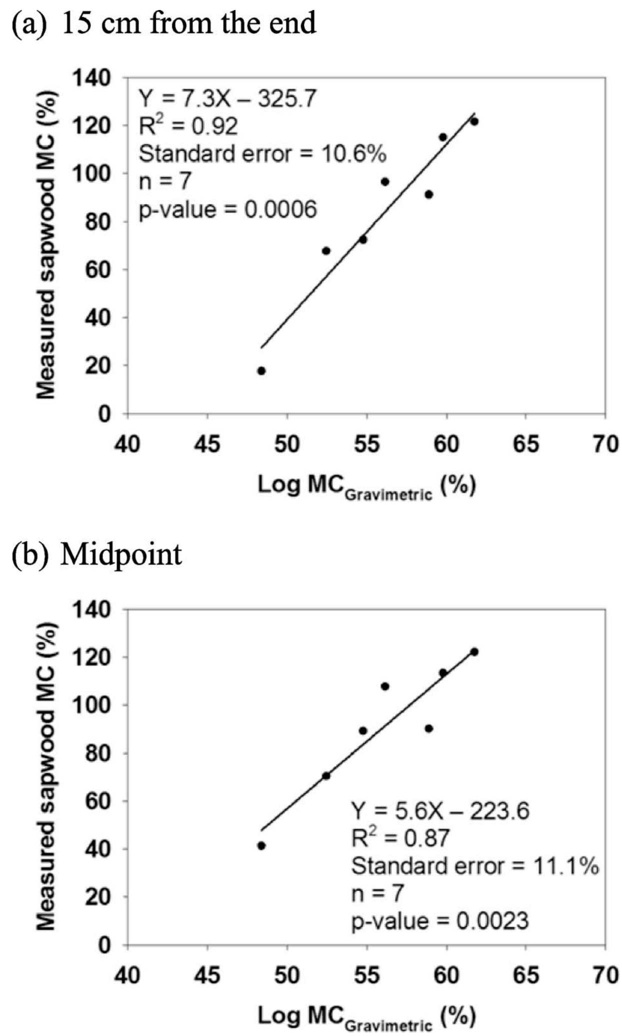

Figure 6.—Linear relationship between sapwood moisture content (MC) in a spot 15 cm from the end (a) and at the midpoint longitudinally (b) to that of the overall log gravimetric MC in the case of Log 3.

that the UMR signal at any of the end spots is not representative of the sapwood MC in the log. In this case the UMR signal amplitude is no longer predictive of the bulk (gravimetric) MC of the log as suggested in Equation 1.The relationship between the predicted black spruce log MC, determined with MR measurement, and the gravimetric measurement was linear. The UMR-derived MC has an

Table 3.—List of gravimetric and predicted moisture content (MC) of each log at 35 days of air-drying.

	MC (%)		
Log sample ID	Gravimetric	Predicted[a]	Absolute difference (%)
1	59.0	53.1	5.9
2	86.1	82.0	4.1
3	54.8	51.4	3.4
4	74.7	73.3	1.4
5	59.8	55.2	4.6
6	51.1	45.4	5.7

[a] The predicted MC involves estimation of sapwood and heartwood volume proportions.

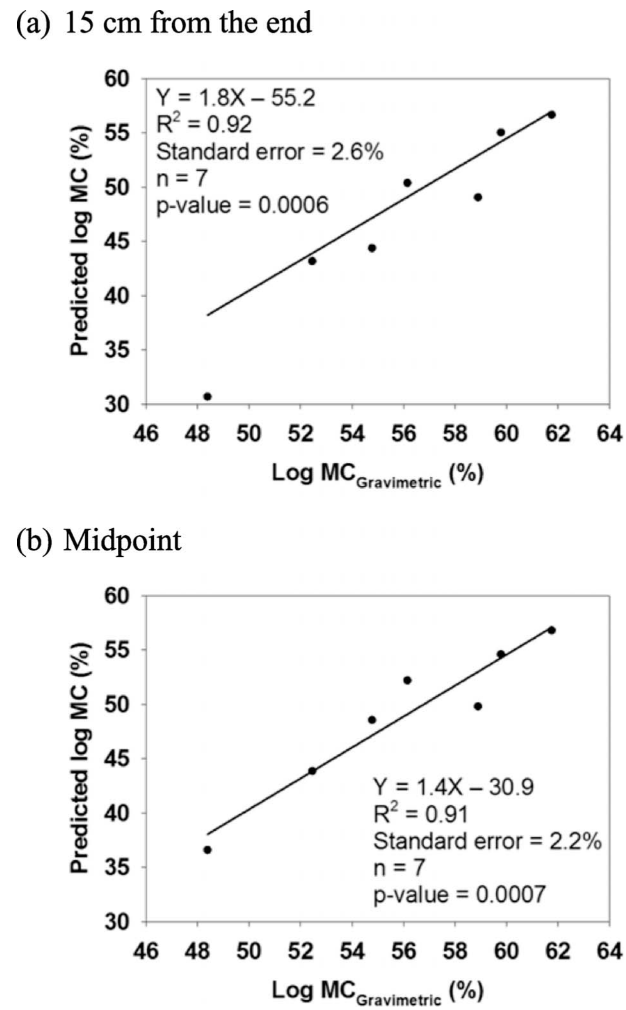

Figure 7.—Linear relationship between moisture content (MC) predicted by magnetic resonance (MR) measurement plotted versus MC determined gravimetrically in the case of Log 3. The unilateral MR measurement of sapwood MC was scaled through the heartwood and sapwood volume proportions to yield a whole-sample estimate. The different MCs correspond to different drying times, specifically 1, 7, 13, 28, 35, 43, and 70 days. The diffusive end drying reaches the spot 15 cm from the end (a) at the later stage of drying. The better location when accessible is at the midpoint longitudinally (b).

estimated uncertainty, in absolute MC, of 2.6 percent (Fig. 7a) and 2.2 percent (Fig. 7b). This measurement approach is a viable strategy in predicting MC of black spruce logs in the field.

Conclusions

The UMR spot estimates of bulk MC in the sapwood can be used to estimate the overall MC of a black spruce log in the field. The sapwood-measured MC coupled with sapwood-to-heartwood proportions is a viable approach to predicting log MC. The UMR method will allow measurement of water in samples that are not debarked, as it measures a volume located 1.3 cm below the surface, which is a significant operational advantage.

MC variability of the measurement spots displaced from the end increased as drying progressed. Despite this variability, both the spot at the midpoint longitudinally and the spot displaced from the ends gave predictions that were remarkably close to the gravimetric MC. A ''through the bark'' measurement is ideal, especially if the device is able to directly measure sapwood.

The use of a portable UMR instrument to measure MC in wood log samples was demonstrated. This instrument has the advantage of portability, permitting MC estimations of thawed logs in the field without oven drying. One may anticipate that further development will lead to a reduction in the acquisition time as measurement hardware and software improve.

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