

Real-time monitoring of deadwood moisture in forests: lessons learned from an intensive case study

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Abstract: Attributes of deadwood in forests, including quantity, landscape position, and state of decay, influence numerous ecosystem processes such as wildfire behavior, tree regeneration, and nutrient cycling. Attributes of deadwood that vary over subdiurnal time steps, including moisture, have not been routinely measured despite the profound effects they have on ecosystem processes. To improve our understanding of forest deadwood subdiurnal moisture dynamics, we installed an intensive time-domain reflectometry (TDR) sensor network in a log and surrounding soil within a northern hardwood forest in New England, United States. Intensive monitoring during a partial growing season indicated that deadwood moisture was dynamic but similar to that of surrounding soils at 15-min intervals, especially during wetting and drying events. Field results and bench analysis of the sample log revealed numerous challenges when attempting to monitor deadwood moisture with TDR such as heterogeneous and (or) advanced decay confounding TDR moisture measurements in logs. An efficient, high-frequency TDR sensor network was demonstrated to record deadwood and soil moisture fluctuations, which provides an opportunity to refine our understanding of deadwood dynamics in the context of global change such as changing precipitation regimes.

Key words: downed deadwood, soil moisture, TDR sensors, wildfire, wood decay.

Résumé : Les caractéristiques du bois mort en forêt, telles que la quantité, la position dans le paysage et l'état de décomposition, influencent plusieurs processus de l'écosystème, comme le comportement du feu, la régénération des arbres et le recyclage des nutriments. Les caractéristiques du bois mort qui varient en fonction d'échelles de temps sous-diurnes telles que l'humidité n'ont pas été mesurées de façon routinière malgré les effets importants qu'elles ont sur les processus de l'écosystème. Afin d'améliorer notre compréhension de la dynamique sous-diurne de l'humidité du bois mort en forêt, nous avons installé un réseau intensif de capteurs utilisant la réflectométrie à dimension temporelle (TDR) dans une bille et le sol environnant dans une forêt de feuillus nordiques en Nouvelle-Angleterre, aux États-Unis. Un suivi intensif durant une partie de la saison de croissance a montré que l'humidité du bois mort est dynamique mais semblable à celle du sol environnant à intervalles de 15 min, surtout durant les épisodes de mouillage et de séchage. Les résultats sur le terrain et l'analyse en laboratoire de la bille qui a servi d'échantillon ont fait ressortir de nombreux défis lorsqu'on tente de faire le suivi de l'humidité dans le bois mort avec la TDR, tels que l'état d'avancement et l'hétérogénéité de la carie qui réduisent la fiabilité des mesures d'humidité par TDR dans les billes. L'efficacité d'un réseau de capteurs qui utilisent la TDR à haute fréquence pour enregistrer les fluctuations de l'humidité dans le bois mort et le sol a été démontrée, ce qui fournit une opportunité de raffiner notre compréhension de la dynamique du bois mort dans le contexte du changement global dont le changement des régimes de précipitation. [Traduit par la Rédaction]

Mots-clés : bois mort au sol, humidité du sol, capteurs TDR, feu de forêt, décomposition du bois.

Introduction

Over the past decades, it has become increasingly evident that deadwood plays a critical role in numerous forest ecosystem functions, including wildfire behavior (Schoennagel et al. 2004), nutrient cycling (Harmon et al. 1986), tree regeneration (Bolton and D'Amato 2011), wildlife habitat, and fungal and insect community dynamics (Stokland et al. 2012). Despite such findings, a fundamental understanding of how deadwood interacts with weather, soil, and vegetation at diurnal and subdiurnal time scales is lacking. Such essential understanding will become increasingly important in a future of global change in which insect outbreaks and climate change may increase tree mortality (i.e., deadwood input) across the world's forests (McDowell and Allen 2015). Further,

such understanding could add to our current knowledge of the forest carbon cycle, given the influence of moisture and temperature on deadwood decomposition rates (Law et al. 2018). The underlying mechanisms that relate deadwood attributes to forest ecosystem functions such as the carbon cycle are poorly understood (Russell et al. 2015), especially over diurnal and subdiurnal time steps. Given the direct influence of deadwood moisture on carbon cycling, as well as deadwood's indirect influence on soil conditions and vegetation (Goldin and Hutchinson 2014), we propose that investigating and monitoring such deadwood attributes at high temporal resolution is imperative.

Deadwood can assume several forms in forest ecosystems, including standing dead trees, upturned roots, fine woody material

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(FWM), and coarse woody material (CWM) (Woodall et al. 2019). For the purposes of this study, we define CWM as aboveground dead and downed woody materials of at least 7.6 cm in diameter, following standard monitoring protocols (Woodall et al. 2019). Although deadwood other than CWM is clearly a major driver of various ecosystem processes such as wildfire (e.g., fine woody surface fuels; Rothermel 1983), here we initiate a study of real-time deadwood monitoring focusing on CWM, as there are fewer constraints on the installation of sensors with these larger materials. Sensor networks that collect relevant CWM moisture data underneath forest canopies at subdiurnal time steps (e.g., rainfall events) are absent, leaving a gap in our understanding of how CWM attributes change over short time scales. Furthermore, given that more episodic precipitation is projected as climate changes (Melillo et al. 2014), predicting how CWM moisture responds to new precipitation regimes will be essential for climate-adaptive forest management (e.g., Nagel et al. 2017). Hence, improved CWM moisture monitoring techniques would not only benefit forest ecosystem sciences, but also the management of wildfire and smoke in the context of global change.

Quantifying attributes of CWM such as moisture in near real time remains a major hurdle to wildfire and smoke management, resource conservation, and applied science efforts because of the very nature of deadwood. Although developments to ascertain CWM volumes via light detection and ranging (LiDAR) in open landscapes are promising (Joyce et al. 2019), CWM in the understory of intact forests remains elusive to remote sensing approaches, let alone the determination of its characteristics (e.g., state of decay and moisture level). An initial exploration of the variability of CWM moisture by destructively sampling individual CWM pieces indicated considerable variability in moisture (30%–195% moisture dry weight) within individuals, perhaps driven by sun exposure, ground contact, and wood condition (Reinhardt et al. 1991). Likewise, Pichler et al. (2012) found substantial ranges in CWM moisture by decay stage for European temperate species. Drivers of this variability have not been well quantified, nor have parsimonious approaches been suggested for monitoring the moisture content of CWM across populations of interest such as individual forest stands subjected to drought and (or) episodic precipitation. Despite the critical need to monitor CWM moisture and related attributes in real time, comprehensive advances in terms of technology and fundamental science have not occurred.

Given the demonstrated knowledge gaps involving the high-frequency monitoring (i.e., subdiurnal) of CWM attributes, the goal of this study was to investigate field-ready techniques for intensively monitoring CWM moisture in temperate forests. Our specific objectives were to (i) monitor the in situ, real-time moisture of a partially decayed CWM study specimen and associated soil underneath and in proximity to the CWM specimen during a growing season using time-domain reflectometry (TDR) sensors coupled with a data logger system; (ii) evaluate the variability in wood density throughout the study specimen in relation to high-frequency monitoring objectives; and (iii) combine the field and bench analyses to suggest optimal configurations for future CWM and soil field station sensor arrays.

Methods

The study design involved a field deployment of a TDR sensor array for one partially decayed sugar maple (*Acer saccharum* Marsh.) CWM piece (hereafter referred to simply as a log) and surrounding soil concomitant with laboratory evaluations of the CWM specimen's wood density. This design allowed for evaluation of field deployment realities in combination with assessment of sensor performance, which together should facilitate future development of optimal field station sensor configurations.

Study site

This work was conducted at the Hubbard Brook Experimental Forest (HBEF) in the United States Department of Agriculture (USDA) Forest Service's White Mountain National Forest, New Hampshire, United States (Fig. 1) (Holmes and Likens 2016). This experimental forest, which largely focuses on forest hydrology research, provided an ideal location for this study given the nearby long-term meteorological station (Bailey et al. 2003) and the compendium of published studies on HBEF forest dynamics (e.g., Holmes and Likens 2016) related to this study's objectives. Given that HBEF is a second-growth northern hardwood forest dominated by sugar maple, yellow birch (*Betula alleghaniensis* Britton), red spruce (*Picea rubens* Sarg.), and American beech (*Fagus grandifolia* Ehrh.) (Bailey et al. 2003; Holmes and Likens 2016), sugar maple was chosen as the study species, as it is an ecologically and economically important species in the region.

Moisture measurement

We used TDR sensors (Acclima 315L, Acclima, Meridian, Idaho, USA) in our study design. TDR utilizes measurements of the speed at which electromagnetic waves propagate through a medium, in this case, soil and wood. Because the velocity at which these waves travel is influenced by the medium's dielectric constant, and because this constant differs between water and a medium, estimates of velocity provide accurate estimates of volumetric moisture content (VMC) of a medium. A summary equation of this calculation can be expressed as

$$(1) \quad \theta_v = \frac{e}{2bL}(tt - tt_0)\left(1 + \frac{T - T_{ref}}{400}\right)$$

in which θ_v is soil VMC; e is the velocity of a wave in a vacuum; b is a validation coefficient; L is the length of the TDR sensor (in this case, 15 cm); tt and tt_0 are the times at which the wave leaves and returns to the sensor, respectively; and T and T_{ref} are soil temperature and a reference soil temperature (Ledieu et al. 1986), respectively. The selected TDR sensor measures percent VMC (0.1% resolution) and permittivity (0.1 unit resolution) and is capable of reporting data via the SDI-12 (serial digital interface at 1200 baud) digital protocol with a read time of 1.0 s.

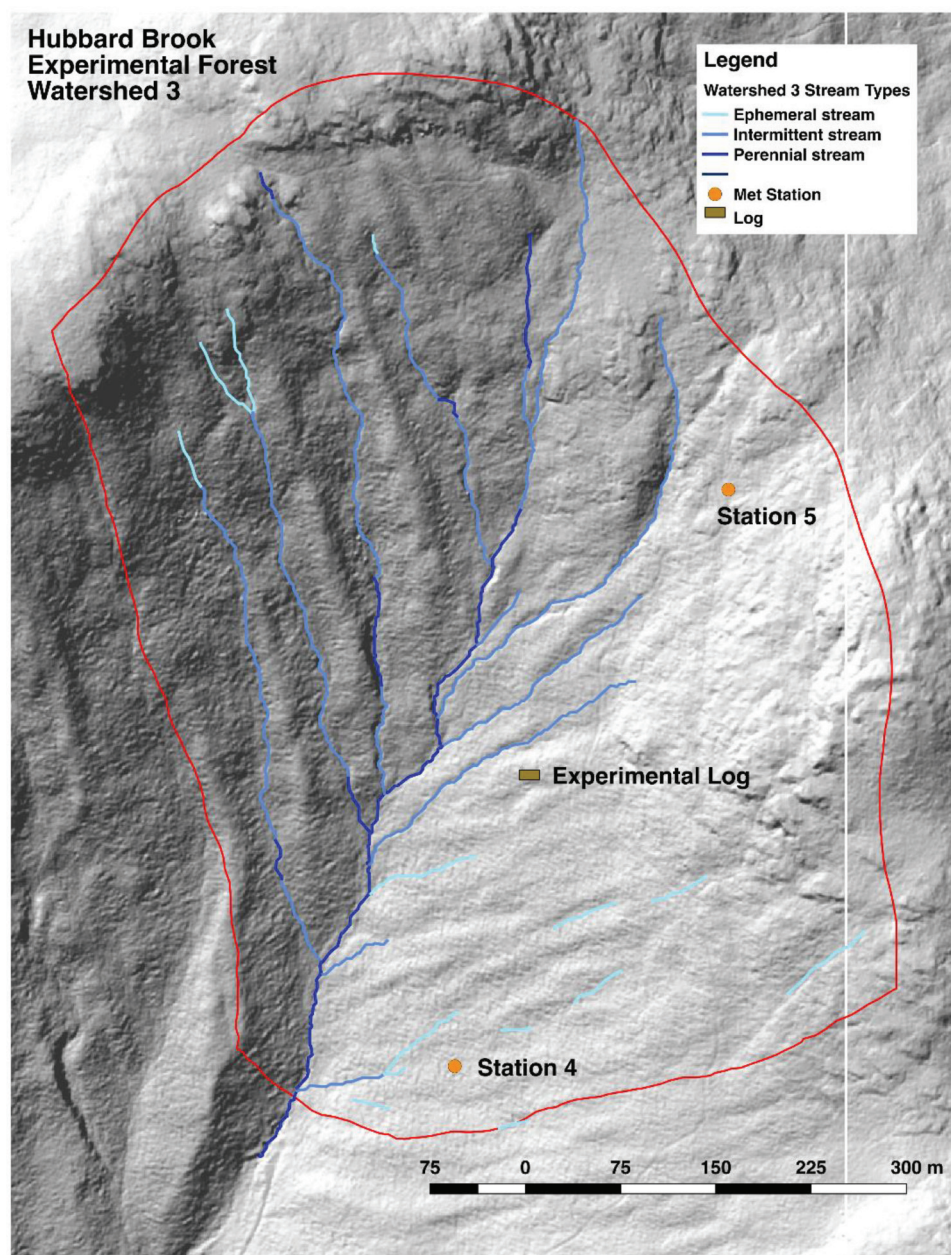
Study log description

To fully evaluate TDR across a sensor array in the field, we located a study log in HBEF's Watershed 3, which was established in 1958 as a hydrologic reference catchment and has an area of 42 ha, a south-facing aspect, a slope of 16°, and mean annual precipitation of 1324 mm (Bailey et al. 2003). The water budget, based on long-term measurements, indicates that 62% of the precipitation that enters the watershed leaves as streamflow and 37% leaves as evapotranspiration (Bailey et al. 2003). Soils are dominated by Spodosols of sandy loam to loamy sand texture derived from glacial drift parent materials (Holmes and Likens 2016). After a thorough search of the watershed, we selected the study log because of its moderate size (37 cm diameter at large end, 10.4 m length), moderate decay status (decay class 3 of a five-class system; Woodall et al. 2019), and importantly, its alignment perpendicular to slope (potentially intercepting downslope runoff), with only 50% of its length in contact with the ground (Fig. 2).

Sensor design and data retrieval

A total of 62 sensors were deployed across the entire sensor array. We placed 50 TDR sensors within the soil along five 5 m long transects arrayed perpendicular to the log and separated from each other by 2 m (Fig. 2). At each transect, we installed a TDR sensor at depths of 10 and 20 cm into the mineral soil horizon. We separated these sensors along each transect by 1 m. Thus, 10 soil TDR sensors were installed for each transect (Fig. 2). TDR sensors were also inserted into the log itself at 12 locations. To

Fig. 1. Location of sample log within Watershed 3 and proximity of meteorological stations at Hubbard Brook Experimental Forest (HBEF), New Hampshire, United States. Stream classification data and base map courtesy of Scott Bailey, USDA Forest Service.



install these sensors, we drilled three 15 cm guide holes (4.366 mm (11/64 inch) drill bit size) into the log at each point using a drill template with sensor tines installed directly into the log. Because of the partially decayed nature of the log, several TDR sensors could not be fully inserted into the log, with minimal lengths (majority <2.5 cm) of the sensor prong remaining outside of the log.

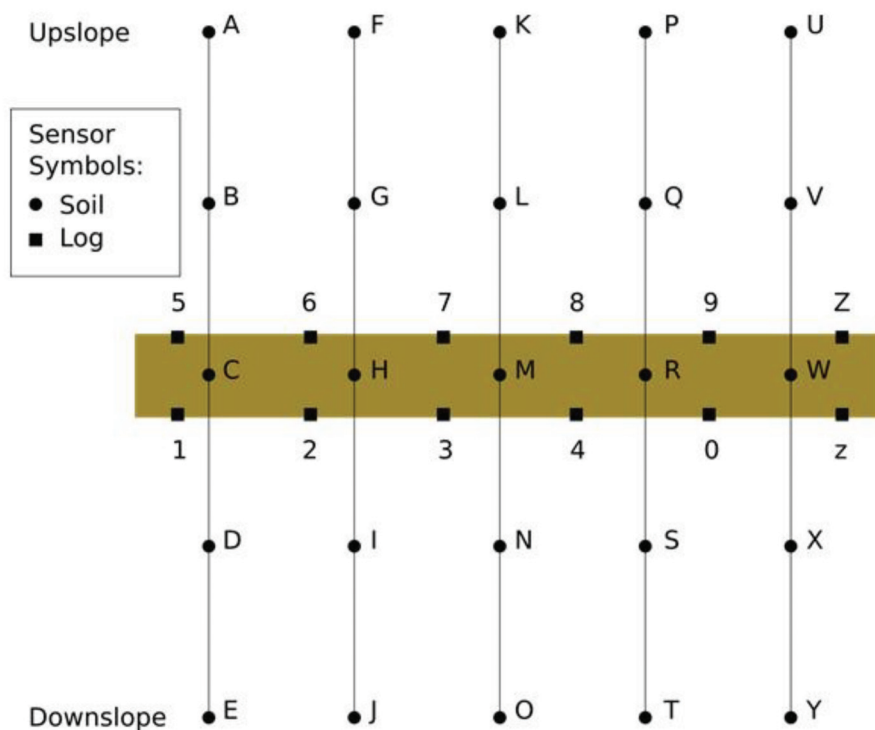
Measurements from each TDR sensor were taken every 15 min, beginning on 6 June and ending on 17 October 2018. Each TDR sensor was given a serial digital interface address (SDI-12) and connected to an Arduino-based data logger (Mayfly v0.5b, Stroud Water Research Center, Avondale, Pa., USA). We constructed three control boxes to house three data loggers, each of which could be connected to as many as 24 TDR sensors. Because the TDR sensors required between 6 and 15 V direct current (DC), we powered the sensor array using 12 V lead-acid rechargeable batteries. Alto-

gether, we collected over 2.4 million unique measurements during the field season.

Destructive sampling of sample log

On 17 October 2018, the sensors were removed, and 12 complete radial cross sections of the log (i.e., “cookies”) were collected for laboratory analyses of wood density and moisture content (for comparison with the last-recorded TDR measurements). Cookies were collected at the sensor locations, sealed in plastic wrap, and transported immediately to a laboratory, where they were weighed while moist. At the same time, cookie thickness was measured at 10 or more locations around the perimeter of each cookie, and outlines of each cookie (both surfaces) were traced onto poster board after removing bark. These tracings were scanned, and areas (in square centimetres) were determined using

Fig. 2. Schematic of field-installed sensor array with image of sample log relative to soil sampling transects. Soil transects were separated by 2 m, with soil sensors separated by 1 m along each transect, with two sensors installed at depths of 10 and 20 cm at each location. Deadwood sensors were installed at upslope and downslope locations as close as practical to each soil transect. [Color online.]



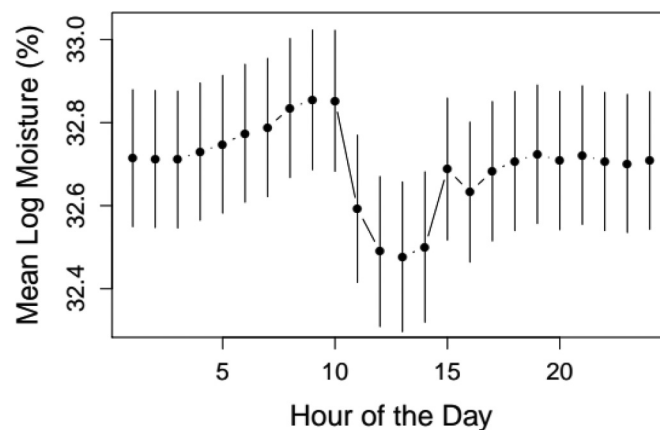
ImageJ software (Rueden et al. 2017). The field (moist) volume of each cookie was determined as the product of mean cookie-surface area and mean thickness. Cookies were then dried at 75 °C for 2 weeks and weighed to obtain dry mass. Given the state of decay, portions of the cookies became friable upon drying, which precluded the use of physical measurements to determine dry volume. We thus determined dry volume by assuming 9% shrinkage (Panshin and de Zeeuw 1980). From these volume and mass data, we determined mass moisture content, VMC, and wood density (dry mass/dry volume) for each cookie. Finally, to document the large range of variability in density that we observed within individual cookies, we cut cubes (mean ca. 35 cm³) of wood deemed to represent the lowest and highest densities from each cookie. Cubes were measured (using a micrometer), redried, and weighed to determine density of each.

Results

Sensor field results

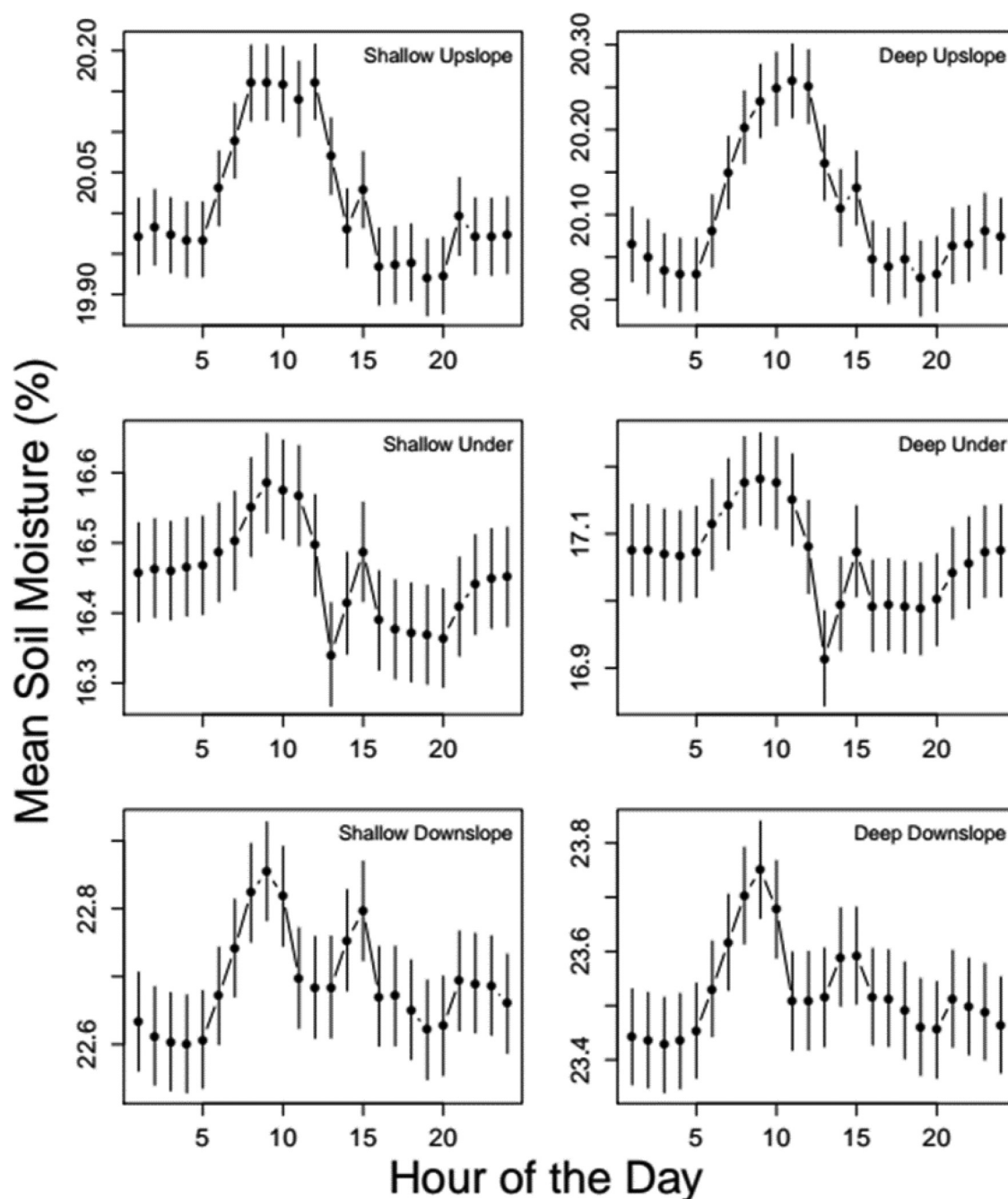
The TDR results across time in the field indicated successful tracking of deadwood moisture in response to meteorological events (i.e., wetting and drying). In terms of the log sensor network, diurnal trends in wood moisture followed a pattern of increasing VMC until 1000 hours, then a decline to a low VMC at approximately 1300 hours, followed by an erratic increase in VMC until 2400 hours (Fig. 3). The perturbations in the mean VMC

Fig. 3. Diurnal trends in mean volumetric moisture content (VMC) of sugar maple log (averaged across the growing season). Bars represent standard error.



trend line can be attributed to individual rain events during the sampling season. The soil sensors also demonstrated consistent diurnal patterns (averaged over the study period), with the highest VMC reached around 1000 hours before the day's warming

Fig. 4. Diurnal trends in mean soil VMC by location relative to a sugar maple log and sample depth (shallow = 10 cm, deep = 20 cm). Bars represent standard error.



started attenuating down into the soil (10 and 20 cm depths) (Fig. 4). It was also observed that the soil VMC was consistently lower underneath the log than at the upslope and downslope locations regardless of soil depth. In terms of subdiurnal patterns and response to individual precipitation events, the abundant data from both soil and log sensors resulted in a detailed array of VMC information (Figs. 5 and 6). For example, a ~35 mm precipitation event in the early hours of 22 August 2018 was reflected in almost all sensors with consistency in the soil VMC trend lines but with variation in absolute VMC estimates (Fig. 5). Given the variation in wood density (i.e., state of decay), log diameter, and log ground contact, there was considerable variation in the absolute VMC of the log-installed sensors but still with consistent reaction to the precipitation event. A minor precipitation event (~5 mm)

on 8 August 2018 during a longer dry spell indicated the responsiveness of the TDR sensors while suggesting that log moisture returned to pre-event levels within 24 h (Fig. 6).

Sample log attributes

Subsamples of the 12 cookies collected from the in situ sample log for density determination revealed substantial within-cookie variation. For example, for five of the 12 cookies, the subsample maximum density was at least five times greater than the subsample minimum (Table 1). Similarly, densities determined for entire cookies (Table 1, Total Density) varied considerably within the log, ranging from 0.163 to 0.477 g·cm⁻³. We note that the published density for a sugar maple in decay class 3 is 0.324 g·cm⁻³, with an uncertainty of ±0.043 g·cm⁻³ (Harmon et al. 2008); the median cookie

Fig. 5. Sample log and soil volumetric moisture measurements during a ~35 mm precipitation event on 22 August 2018 at HBEF.

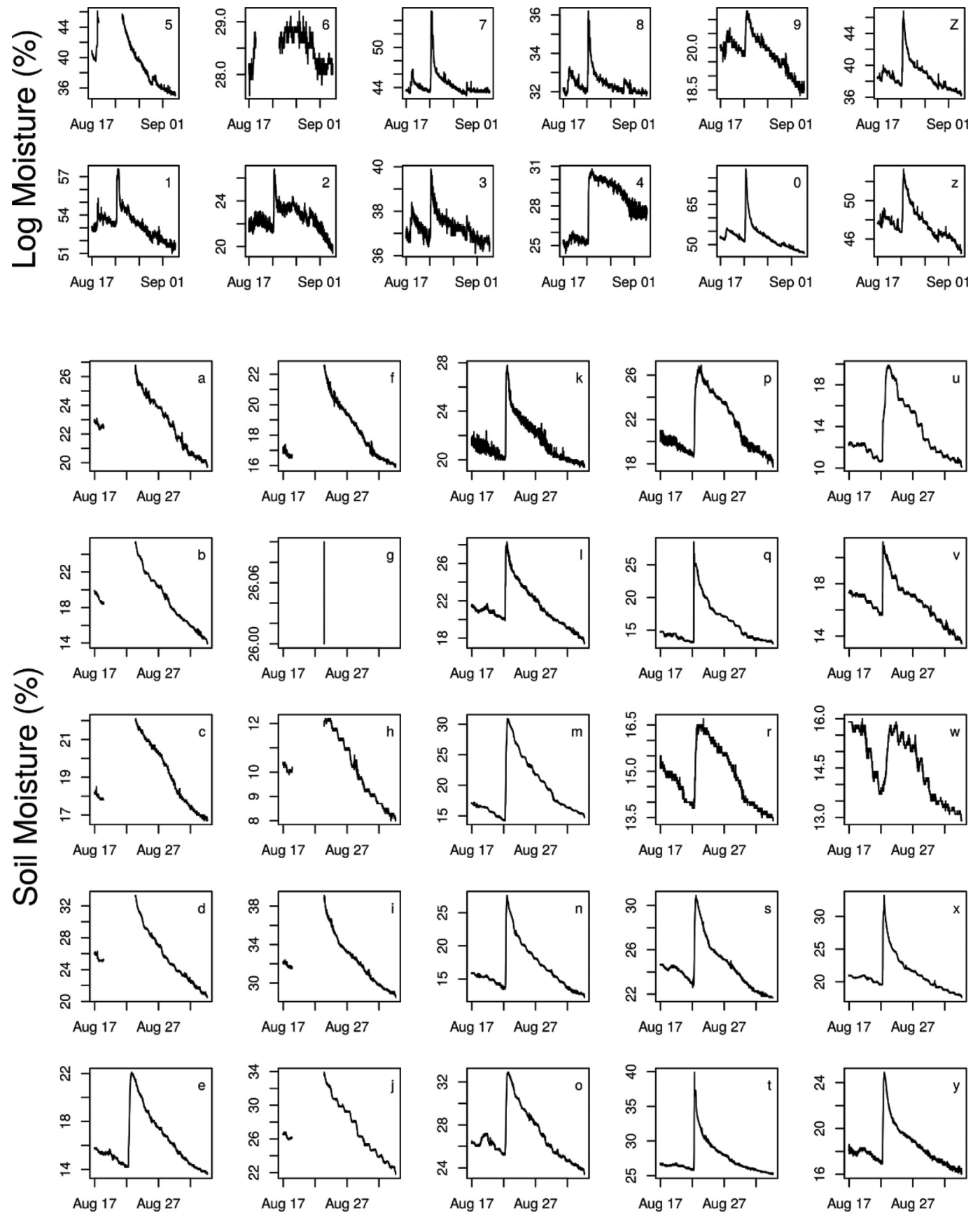


Fig. 6. Sample log volumetric moisture measurements during a ~5 mm precipitation event on 8 August 2018 at HBEF. All 12 sensor locations are shown (see Fig. 2).

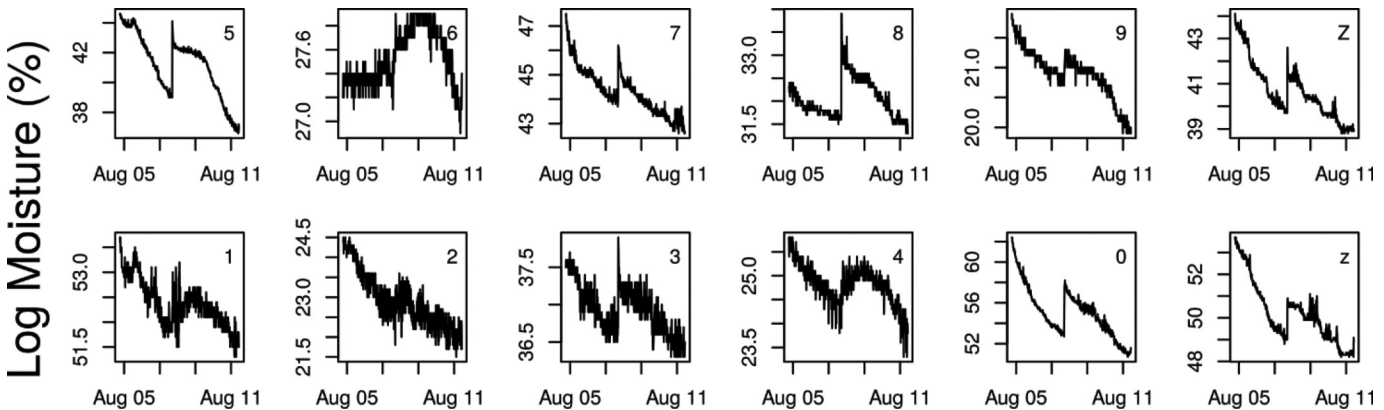


Table 1. Attributes of the 12 radial cross sections collected from the partially decayed *Acer saccharum* log.

Cross section	Volume (cm ³)	Density (g·cm ⁻³)			Volumetric moisture (%)	
		Total	Minimum	Maximum	Manual (lab)	TDR (field)
0	3317.1	0.342	0.134	0.591	47.4	55.2
1	2627.4	0.477	0.424	0.556	42.3	57.2
2	4851.6	0.189	0.088	0.568	59.7	21.5
3	5626.1	0.185	0.104	0.551	57.4	38.7
4	3622.0	0.438	0.100	0.600	35.8	31.9
5	1981.2	0.417	0.274	0.541	47.2	48.3
6	2887.8	0.354	0.173	0.517	30.5	31.4
7	5763.5	0.163	0.120	0.584	57.9	45.2
8	4714.3	0.327	0.121	0.454	34.1	33.2
9	3221.0	0.278	0.101	0.589	46.2	20.4
z	2962.2	0.200	0.114	0.557	54.0	47.0
Z	2695.7	0.198	0.081	0.553	51.6	40.4

Note: Density was calculated by the formula dry mass/dry volume. TDR, time-domain reflectometry.

density from our 12 samples was 0.303 g·cm⁻³. There was considerable variability between manual and TDR VMC estimates (Pearson’s correlation coefficient (r) = 0.10). A few sensors had a nearly identical VMC as manually determined (cross sections 5, 6, and 8), whereas others were substantially different (cross sections 2, 3, and 9). There was a strong positive correlation (r = 0.79) between total wood density of each cross section sample and the difference between the TDR VMC and manually derived VMC (i.e., greater moisture discrepancies with greater decay).

Discussion

The same hurdles that apply to the real-time monitoring of live tree attributes (e.g., diameter; [Drew and Downes 2009](#)) may be exacerbated in the case of downed dead trees. Whereas the architecture (i.e., wood density and form) of a live tree is governed by environmental and mechanical constraints (e.g., [Poorter et al. 2006](#)), the architecture of deadwood is one of breakdown by various fungal, microbial, and fragmentation pathways ([Harmon et al. 1986](#); [Stokland et al. 2012](#)), which presents challenges to monitoring via sensors. We examined the roles that wood density and density variation, in concert with wetting and drying events, played in high-frequency and low-cost TDR measurement of deadwood VMC. Although such technology is only just emerging, it may be seen as a complementary technique to forest inventory and (or) laser scanning technologies in which the volume (i.e., structure) of downed deadwood can be efficiently measured via laser scanning ([Klockow et al. 2020](#)) while low-cost sensor networks provide complementary information on deadwood conditions (e.g., moisture).

Variation in wood density in particular confounded our VMC estimates. The wood subsamples collected to examine density

variation with individual cookies revealed considerable variation, often with a fivefold difference between minima and maxima. The most decayed portions represented three-dimensional decay columns clearly delineated by interaction zone lines. Several of the least decayed portions may not have been colonized or decayed at all, as their densities fall within the published ranges for nondecayed wood of this species ([Harmon et al. 2008](#)). Similarly, whole-cookie density varied markedly among the 12 cookies, ranging from 0.163 to 0.477 g·cm⁻³. Taken together, these results highlight the sizeable small-scale (i.e., within cookie) and medium-scale (within log) variation that we feel is typical for in situ partially decayed logs (qualitative observations) that has implications for high-frequency moisture monitoring. That is, given the relationship between wood decay stage (i.e., density) and water holding capacity (greater moisture with greater decay; [Fraver et al. 2002](#)), the density variation evident in our samples suggests that the exact placement of the tines (decayed versus nondecayed portions) strongly influences sensor readings.

This study’s sensor array provided a relatively efficient technique for VMC measurement at short time steps (15 min) over a duration of ~5 months. As highlighted in the bench tests and sample log dissection, highly variable patterns of decay and concomitant variations in wood density and structure resulted in variations in absolute VMC. Although accurate measurements of VMC are needed for numerous applications, relative trends in VMC were similar across nearly all sample log sensors. Relative trends in VMC across the log-to-soil continuum ([Goldin and Hutchinson 2015](#)) may be valuable for assessing relationships between these forest ecosystem components in the context of meteorological events. During a relatively heavy rainfall event, there was consistent response by almost all TDR sensors in terms of a

nearly immediate response in log and soil VMC. As the log VMC exhibited faster wetting and drying than soil VMC, we propose that the advanced decay of the log enabled more rapid saturation of wood. Using TDR in logs with moderate to advanced decay may not provide accurate absolute measurements of VMC without extensive calibration (e.g., Pichler et al. 2012) while affording perhaps accurate relative trends in VMC with implications regarding deadwood ecosystem functioning. Freshly fallen logs and (or) logs in decay class 1 are most likely optimal for the application of TDR in monitoring deadwood VMC dynamics where accurate trends in absolute VMC estimates are needed. Setting aside applications for which accurate VMC is needed (e.g., wildfire behavior modeling; Schoennagel et al. 2004), the times at which TDR measurements become erratic (because of decay pockets filling or draining of water) may serve as indicators of ecosystem processes (e.g., log saturation inhibiting decay). Although deadwood may present additional hurdles to sensor usage when compared with live trees, such hurdles may be recast as research opportunities to refine our understanding of fundamental forest ecosystem processes (e.g., seasonal trends in deadwood carbon flux).

The diurnal results for both VMC across all sensors demonstrated their ability to track general trends in deadwood and soils across daily warming and cooling. Goldin and Hutchinson (2015) identified such diurnal trends in soils with respect to proximity to CWM pieces in Australia. In terms of subdiurnal trends in VMC, the sensor array was able to track the immediate response of deadwood and nearby soil response to precipitation events. We propose that far fewer TDR sensors are needed for monitoring applications given the consistency in the relative trends in VMC observed across all the log and soil sensors. The number of sensors depends not only on the application and accuracy requirements, but also on the condition of the samples themselves. Measurement of VMC in highly decayed logs and (or) heterogeneous soils will necessitate the use of more TDR sensors, whereas applications in fresh logs and homogenous soils might require fewer than half a dozen TDR sensors. Given the occasional failure of a TDR sensor or improper installation, we suggest a minimum of two TDR sensors per each log or associated soil profile. Given the lag of deeper soils responding to precipitation events, if one were interested in soil response, then shallower (<10 cm) deployment of TDR sensors in the soil profile is recommended.

This study has demonstrated the application of efficient and emerging TDR technology and an associated data logging system that can monitor subdiurnal VMC dynamics. An application of such technology would be quantifying the effect of projected changes in precipitation regimes (i.e., climate change; Melillo et al. 2014) on soil and deadwood moisture. Before such questions can be explored using TDR technology, as used in this study, additional research should be conducted. First, the effect of deadwood piece size on TDR performance should be evaluated. Although the length of the TDR tines (15 cm) restricts application in smaller CWM pieces and more notably in FWM, perhaps relationships can be established to allow extrapolation of VMC of moderately sized CWM to the full range of deadwood piece sizes. Second, if freshly fallen deadwood is optimal for accurate TDR measurements of VMC, the effect of drying in terms of checking should be evaluated. Third, if TDR sensors are deployed beyond a growing season, the effect of freezing events or snowpacks on TDR sensor arrays should be evaluated. Even if TDR sensors become nonfunctional at the point of freezing (Gasvoda 1998), this might be an important indicator of ecosystem function analogous to ice-in and ice-out measurements of lakes (e.g., Holmes and Likens 2016). Fourth, the effect of incomplete TDR sensor insertion on VMC measurement should be more fully evaluated. Fifth, although a drill template was used for inserting TDR tines into deadwood, perhaps alternative methods should be evaluated that enhance TDR performance and (or) integrity (i.e., avoiding damage upon insertion and removal). Sixth, given the challenges in-

volved with manually downloading data from data loggers in remote locations, wireless data transmission technology should be evaluated as a means to increase the efficiency of data retrieval from TDR sensor arrays.

Conclusions

As it has been suggested that global rates of tree mortality may increase and there is increased interest regarding the fate of deadwood (i.e., carbon balances), we expect increased focus on monitoring the real-time attributes of deadwood fundamental to ecosystem processes (e.g., decay and (or) fire risk). Despite the increased need for deadwood assessments, the very nature of deadwood presents additional hurdles for its monitoring. We found that sensor measurements of deadwood VMC were highly variable across one intensively studied field sample because of variations in log density and structure. Despite this variability in absolute sensor measurements, results suggest that diurnal and subdiurnal trends in deadwood VMC can be monitored relatively inexpensively using TDR sensors coupled with widely available data loggers. Although logs with moderate to advanced stages of decay will confound the use of TDR sensors for absolute assessment of VMC, they may still provide valuable trend data in terms of log VMC response to meteorological events. It is recommended that if accuracy in log moisture is needed for fire risk assessments, then freshly fallen, nondecayed logs should be used as samples. Additionally, given the consistency in sensor readings across the various permutations of soil and log conditions, we suggest that a greatly reduced number of sensors (compared with that used in this study) may adequately characterize the moisture dynamics of individual logs and the surrounding soil (e.g., fewer than six sensors). Finally, although this study demonstrated the ability of TDR sensors to appropriately track log and soil VMC over subdiurnal time steps for forest monitoring and scientific purposes, additional research is needed to examine their application across a wide array of deadwood or soil situations coupled with field limitations.

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