1791

Water content measurement in forest soils and decayed wood using time domain reflectometry

Andrew N. Gray and Thomas A. Spies

Abstract: The use of time domain reflectometry to measure moisture content in forest soils and woody debris was evaluated. Calibrations were developed on undisturbed soil cores from four forest stands and on point samples from decayed logs. An algorithm for interpreting irregularly shaped traces generated by the reflectometer was also developed. Two different calibration equations were needed to estimate volumetric moisture content at the four sites, but commonly implicated soil characteristics (organic matter content, bulk density, and soil texture) could not fully account for the differences between calibrations. The calibrations differed from previously published calibrations for mineral and organic soils. Estimation of moisture content in decayed wood was possible with a single significant regression. The standard errors of estimate for volumetric water content were less than 0.02 $m^3 \cdot m^{-3}$ for the soil calibrations and just over 0.05 $m^3 \cdot m^{-3}$ for the decayed wood calibration. We found we could reliably interpret most traces from field samples using an automated algorithm, but had to use a modified algorithm for one of the sites. This study suggests a need to calibrate time domain reflectometry measurements for individual forest sites and advises caution when using systems that have preprogrammed calibration and trace analysis routines.

Résumé : Les possibilités de la réflectométrie dans le domaine temporel pour mesurer la teneur en eau dans les sols forestiers et les gros débris ligneux ont été évaluées. Les calibrations ont été obtenues à partir d'échantillons de sols non perturbés dans quatre peuplements forestiers et de points-échantillons sur des débris ligneux en décomposition. Un algorithme a également été développé pour analyser les traces irrégulières du réflectomètre. Deux équations de calibration différentes ont été nécessaires pour évaluer la teneur en eau du sol aux quatre sites. Les différences entre ces équations n'étaient pas complètement expliquées par les caractéristiques du sol normalement utilisées (contenu en matière organique, densité apparente et texture du sol). Les calibrations différent de celles publiées antérieurement pour les sols minéraux et organiques. Une seule régression significative a suffi pour estimer la teneur en eau des débris ligneux en décomposition. Les calibrations ont donné des erreurs standard de la valeur estimée de la teneur en eau volumétrique inférieures à 0,02 $m^3 \cdot m^{-3}$ pour le sol et légèrement au-dessus de 0,05 $m^3 \cdot m^{-3}$ pour les débris ligneux. L'utilisation automatique d'un algorithme a permis une interprétation adéquate des traces obtenues des mesures au champ à l'exception d'un site pour lequel l'algorithme a dû être modifié. Cette étude suggère qu'il est nécessaire de calibrer les mesures de réflectométrie dans le domaine temporel pour chaque site et que l'utilisation des systèmes précalibrés et des algorithmes d'interprétation des traces doit se faire avec prudence.

[Traduit par la Rédaction]

Introduction

…domain reflectometers (TDR) is gaining popularity …ed researchers as a method for sampling soil moisture …ese samplings is rapid, nondestructive, and applicable …variety of problems ranging from stand dynamics to hydrology to plant water relations. Measurements made with TDR are relatively insensitive to variation in mineral composition, temperature, and salinity for a wide range of soils (Topp et al. 1980; Topp and Davis 1985; Roth et al. 1992). Examples are accumulating, however, of soils that do require individual calibrations to TDR measurements (Herkelrath et al. 1991; Dirksen and Dasberg 1993; Roth et al. 1992; Whalley 1993). While different soil properties have been implicated (e.g., organic matter content, bulk density, texture), it is not yet clear what causes the variation in TDR behavior. Most of the calibration work has been done with relatively homogeneous soils in agricultural fields or sieved samples in laboratories and some have compared intact forest soils from different sites. There is

…ived April 1994. Accepted December 4, 1994.

A.N. Gray.[1] Forest Science Department, Oregon State University, Corvallis, OR 97331, U.S.A.
T.A. Spies. USDA Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331, U.S.A.

…Author to whom all correspondence should be addressed.

Water content measurement in forest soils and decayed wood using time domain reflectometry

Andrew N. Gray and Thomas A. Spies

Abstract: The use of time domain reflectometry to measure moisture content in forest soils and woody debris was evaluated. Calibrations were developed on undisturbed soil cores from four forest stands and on point samples from decayed logs. An algorithm for interpreting irregularly shaped traces generated by the reflectometer was also developed. Two different calibration equations were needed to estimate volumetric moisture content at the four sites, but commonly implicated soil characteristics (organic matter content, bulk density, and soil texture) could not fully account for the differences between calibrations. The calibrations differed from previously published calibrations for mineral and organic soils. Estimation of moisture content in decayed wood was possible with a single significant regression. The standard errors of estimate for volumetric water content were less than 0.02 $m^3 \cdot m^{-3}$ for the soil calibrations and just over 0.06 $m^3 \cdot m^{-3}$ for the decayed wood calibration. We found we could reliably interpret most traces from field samples using an automated algorithm, but had to use a modified algorithm for one of the sites. This study suggests a need to calibrate time domain reflectometry measurements for individual forest sites and advises caution when using systems that have preprogrammed calibration and trace analysis routines.

Résumé : Les possibilités de la réflectométrie dans le domaine temporel pour mesurer la teneur en eau dans les sols forestiers et les gros débris ligneux ont été évaluées. Les calibrations ont été obtenues à partir d'échantillons de sols non perturbés dans quatre peuplements forestiers et de points-échantillons sur des débris ligneux en décomposition. Un algorithme a également été développé pour analyser les traces irrégulières du réflectomètre. Deux équations de calibration différentes ont été nécessaires pour évaluer la teneur en eau du sol aux quatre sites. Les différences entre ces équations n'étaient pas complètement expliquées par les caractéristiques du sol normalement utilisées (contenu en matière organique, densité apparente et texture du sol). Les calibrations diffèrent de celles publiées antérieurement pour les sols minéraux et organiques. Une seule régression significative a suffi pour estimer la teneur en eau des débris ligneux en décomposition. Les calibrations ont donné des erreurs standard de la valeur estimée de la teneur en eau volumétrique inférieures à 0,02 $m^3 \cdot m^{-3}$ pour le sol et légèrement au-dessus de 0,06 $m^3 \cdot m^{-3}$ pour les débris ligneux. L'utilisation automatique d'un algorithme a permis une interprétation adéquate des traces obtenues des mesures au champ à l'exception d'un site pour lequel l'algorithme a dû être modifié. Cette étude suggère qu'il est nécessaire de calibrer les mesures de réflectométrie dans le domaine temporel pour chaque site et que l'utilisation des systèmes pré-calibrés et des algorithmes d'interprétation des traces doit se faire avec prudence.

[Traduit par la Rédaction]

Introduction

Time domain reflectometry (TDR) is gaining popularity in forest research as a method for sampling soil moisture because sampling is rapid, nondestructive, and applicable to a wide variety of problems, ranging from stand dynamics to hydrology to plant water relations. Measurements made with TDR are relatively insensitive to variation in mineral composition, temperature, and salinity for a wide range of soils (Topp et al. 1980; Topp and Davis 1985; Roth et al. 1992). Examples are accumulating, however, of soils that do require individual calibrations to TDR measurements (Herkelrath et al. 1991; Dirksen and Dasberg 1993; Pepin et al. 1992; Whalley 1993). While different soil properties have been implicated (e.g., organic matter content, bulk density, texture), it is not yet clear what causes the variation in TDR behavior. Most of the calibration work has been done with relatively homogeneous soils in agricultural fields or sifted samples in laboratories; none have compared intact forest soils from different sites. Thus it is

Received April 5, 1994. Accepted December 4, 1994.

A.N. Gray.[1] Forest Science Department, Oregon State University, Corvallis, OR 97331, U.S.A.
T.A. Spies. UDSA Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331, U.S.A.

[1] Author to whom all correspondence should be addressed.

not known whether it is necessary to calibrate the TDR for different forest sites or if it is possible to account for soil composition in a standard equation. Given the importance of coarse woody debris in many forest systems (Harmon et al. 1986), it would also be useful to know whether the TDR method can be used reliably with decayed wood.

The trace shapes generated from TDR measurements can be difficult to interpret (Yanuka et al. 1988; Hook et al. 1992). Even though Topp et al. (1980) acknowledged TDR trace interpretation to be the major source of uncertainty in their study, little has been published on the details of analyzing the variety of trace shapes encountered in the field (Stein and Kane 1983; Heimovaara and Bouten 1990). The objectives of this paper are (1) to present a method for trace interpretation that handles irregularly shaped traces, (2) to determine whether multiple calibrations are necessary to use TDR on forest soils with different physical properties, and (3) to determine whether TDR can be used to reliably measure moisture content in decayed wood.

The theory and application of TDR have been covered in depth by Topp et al. (1980, 1982) and Gardner et al. (1991). Briefly, the TDR method determines volumetric water content (Θ) by measuring the elapsed time required for an electromagnetic wave (EMW) to travel the length of a pair of metal rods embedded in the soil (Fig. 1). A change in impedance as the EMW passes from cable to soil at the top of the rods causes a partial reflection of the EMW to travel back to the reflectometer. A second measurable reflection occurs when the EMW reaches the open circuit at the bottoms of the rods. The rod-end reflections and the travel time between them are displayed as a trace on the reflectometer's screen. The travel time of an EMW through a substance is determined by the apparent dielectric constant (K_a) of the substance. Water (with a relatively high K_a (80) compared with that of dry soil (K_a = 3–5) or air (K_a = 1)) slows the EMW, increasing both the EMW's travel time and the distance between the rod-end reflections on the trace. The volume sampled by the EMW is roughly cylindrical, with most of the EMW energy sampling within a diameter twice the distance between the rods and a height equal to the length of the rods (Davis and Chudobiak 1975). While the method effectively averages moisture content along the length of the rods (Topp et al. 1982), it is more sensitive to water content close to the rods (Baker and Lascano 1989).

Site descriptions

The study was conducted during the summers of 1991 and 1992 in four forest stands that are being used in a long-term study of forest canopy gap dynamics (Spies et al. 1990). One stand (hja) is in the H.J. Andrews Experimental Forest in the central Oregon Cascades (44°15′N, 122°15′W) on a colluvial slope at an elevation of 900 m. The vegetation is dominated by 350- to 525-year-old western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western red cedar (*Thuja plicata* Donn), and the understory is sparse. The other three stands are in the Wind River Experimental Forest in the southern Washington Cascades. Stand tco (45°49′N, 122°00′W) is on an old floodplain terrace at an elevation of 550 m. The vegetation is dominated by 350- to 500-year-old western hemlock, Douglas-fir, and Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) in the overstory and Oregongrape (*Berberis nervosa* Pursh), Alaska huckleberry (*Vaccinium alaskaense* How.), and deerfoot vanillaleaf (*Achlys triphylla* (Smith) DC.) in the understory. Stand mcy (45°47′N, 121°57′W) is on an upland slope at an elevation of 550 m. It is dominated by 90-year-old Douglas-fir and vine maple (*Acer circinatum* Pursh), with a dense understory of Oregongrape and salal (*Gaultheria shallon* Pursh). Stand pcm is on an upland slope at an elevation of 850 m. It is dominated by 145-year-old Douglas-fir and vine maple and has a dense understory, with deerfoot vanillaleaf and Oregongrape being most abundant. All stands established naturally following wildfire.

Soil textures and bulk densities for the four stands are shown in Table 1. The soil in stand hja is a deep (depth to C horizon 1 m), well-drained, dark brown gravelly loam over a cobbly silt loam C horizon. It was formed in colluvium from basic igneous rock and volcanic ash, and is classified as a loamy–skeletal, mixed, frigid Fluventic Dystrochrept (Brown 1975). The soil for stand tco is a deep (typically 2 m to bedrock), well-drained, dark-brown, sandy loam. It was formed in relatively young deposits of volcanic tephra over basaltic lava flows and is classified as an Andic Haplumbrept belonging to the Stabler series (Franklin and DeBell 1988). Soil classifications are unavailable for the other two stands. The mull forest floors are typically 2 to 5 cm deep in stands hja and tco and 1 to 3 cm deep in stands mcy and pcm.

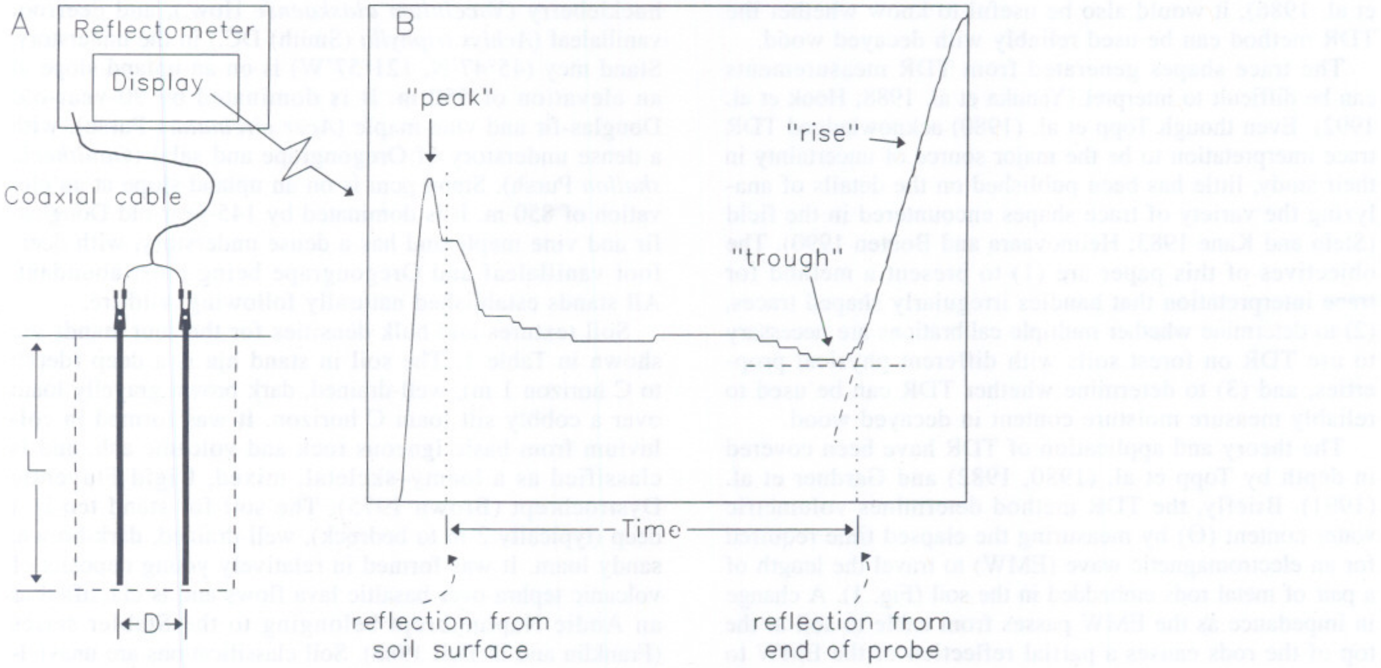
Methods

Calibration

We developed a TDR measurement system to facilitate repeated sampling of an extensive network of permanently installed probes. A probe consisted of two 3.06 mm diameter stainless steel welding rods driven into the soil 5 cm apart (stainless steel welding rod is rust resistant and relatively cheap). Rod ends were cut square, except for those used in wood, which had slightly rounded tips. A Tektronix 1502C reflectometer (Tektronix Inc., Beaverton, Oregon, U.S.A.) was attached to a high-quality coaxial cable (RG-58A/U, Belden 8259, Belden Wire and Cable, Richmond, Indiana, U.S.A.) with the inner and outer conductors each attached to an alligator clip. Clips could be rapidly attached to the ends of the rods comprising the probe. It is common to convert the TDR pulse to a balanced signal by attaching the coaxial cable to an impedance-matching balun, which is connected directly to the rods with balanced television wire. We found a slight reduction in the noise of some of the sampled traces with use of the balun, but felt that the additional components and fragile television wire (Herkelrath et al. 1991) would be poorly suited to the rigors of field use. A lap-top computer connected to the reflectometer saved the trace from each probe for later analysis.

We calibrated the TDR using seven relatively undisturbed soil cores with a method very similar to that used by Herkelrath et al. (1991). Two soil cores were taken from each forest stand. Sections of 10 cm diameter PVC pipe,

Fig. 1. (A) Schematic of TDR probes in soil illustrating cable and alligator clip connection to steel rods. Most of the volume sampled is equal to $\pi D^2 L$. (B) Trace resulting from signal reflections to the reflectometer, illustrating use of tangent lines to define probe end reflection.



50 cm long, were pounded into the ground and then excavated with a 46 cm long soil column intact. After the core samples had air dried at room temperature for 2–3 months, the bottom ends were sealed with a flat PVC plate with a spout attached. Stainless-steel rods 45 cm in length were inserted with 0.5 cm remaining above the surface (leaving 1.5 cm of soil below the ends of the rods). Water was uniformly added to the top of each core in increments of 60 or 80 mL (1.5 and 2% volumetric water content, respectively), and the TDR trace shapes were allowed to stabilize (about 1 min) before the trace was saved in the computer. It was assumed that there was no systematic nonuniformity in water content with distance from the rods (nonuniformities in the vertical dimension would be averaged by the EMW travel time). When the water level reached the surface of the core, the water was drained for about 20 min and measured. Cores were weighed at the beginning and end of the procedure. The soil was then removed from each core, weighed, oven-dried at 105°C for 2 days, and reweighed. Sample water contents were calculated using initial and ovendry soil mass and the volume of water that had been added. Values of Θ were then computed as the ratio of sample water content (as volume) to the volume of soil in the column. Bulk density was calculated from the ovendry mass and soil volume. Two additional soil samples were collected from each forest stand for particle size and organic matter content analyses (hydrometer and mass loss on ignition methods, respectively).

Our initial concern in using the calibration cores was to fully sample the volume of soil in the cores with the EMW from the TDR rods. Empirical work on the spatial sensitivity of TDR by Baker and Lascano (1989) suggested that our calibration design met this goal. Subsequent theoretical work by Knight (1992), however, indicated that the spatial sensitivity of TDR depends on rod diameter and spacing, such that 92.6% of the EMW energy around our rods would be distributed within the edges of our soil cores (the rest of the energy would be sampling air, which has a lower K_a than wet soil). To test the impact of our initial spacing and correct our original calibration measurements, we conducted an experiment where soil at uniformly distributed water contents was sampled first with rods at 2-cm spacing and rod ends 3 cm from the bottom of the core (soil sampled by 98.5% of the EMW using Knight's (1992) eq. 49), and then resampled at the same configuration used for the original calibrations. (Most published TDR calibrations had configurations where the soil was sampled by 97.4 to 98.9% of the EMW by Knight's (1992) equation.) We also compared TDR samples in a water-filled core with samples in a large container of water. Although comparing traces with slight differences strained the limits of precision capable with TDR, our test data suggest a response similar to, though slightly smaller than, Knight's (1992) equation would predict. Thus it appears that applying Knight's equation represents a conservative correction for our original data. We corrected our original TDR measurements using Knight's (1992) equation to calculate the proportion of the EMW that sampled soil in our cores (92.6%) and solving for K_a(soil) in the equation

$$K_a m = 0.926 K_a s + 0.074 K_a a$$

where $K_a m$, $K_a s$, and $K_a a$ refer to the dielectric constants of our original measurements, the soil in the cores, and the air around the cores, respectively (K_a of air = 1). All subsequent calculations of soil core data used the corrected K_a values ($K_a s$) for the soil in the cores.

Table 1. Characterization of soils from forest stands used in calibration of TDR.

Stand	Organic content (% mass)[a]	Bulk density (g/cm^3)	Coarse, >2 mm (% mass)[b]	Sand, 2 mm – 50 μm (% mass)[a]	Silt: Coarse 50–20 μm (% mass)[a]	Silt: Fine + med. 20–2 μm (% mass)[a]	Clay, <2 μm (% mass)[a]	USDA textural classification
hja	5.70	0.81	22.6	43.0	12.8	25.3	18.9	Loam
tco	3.95	0.96	24.5	39.9	13.8	21.7	24.7	Loam
mcy	3.50	0.85	4.1	33.0	9.4	29.2	28.4	Clay loam
pcm	3.15	1.01	34.8	62.0	10.3	16.1	11.5	Sandy loam

[a]Expressed as mass fraction of material with grain size less than 2 mm.
[b]Expressed as mass fraction of entire sample.

The calibration for water content of decayed wood was derived using point samples from 11 Douglas-fir logs from the field. Logs were decay class IV (Maser et al. 1979) and 60–100 cm in diameter. Probes 30 cm long were inserted into decayed logs in 5-cm increments, and TDR traces were recorded at each increment in order to account for the variability in moisture content with depth in logs. A 10 × 10 × 30 cm section of wood around the probes was removed with a chain saw. The resulting block of wood was cut into measured sections corresponding to sample depths, weighed, oven-dried at 105°C for 2 days, and weighed again. Θ was derived from the water mass lost by drying and the volume of each wood section.

Statistical analysis

The traces from each sample were analyzed to determine the EMW travel time using the algorithm described in the next section. Travel times were converted to velocities by dividing into probe length. The refractive index (n, equal to the square root of K_a) was calculated by dividing the speed of light by the TDR signal velocities. A linear regression was then calculated between Θ and n for each core. Data for the different cores were combined into two groups based on the clustering of the majority of data points, and best-fit lines were calculated on each group by least squares regression (the error estimates would be underestimated because of autocorrelation within cores and will not be reported). Data from the decayed logs did not appear to be autocorrelated, probably because wood decay and moisture content were highly variable within and between logs. A single linear regression was computed for the combined decayed wood data.

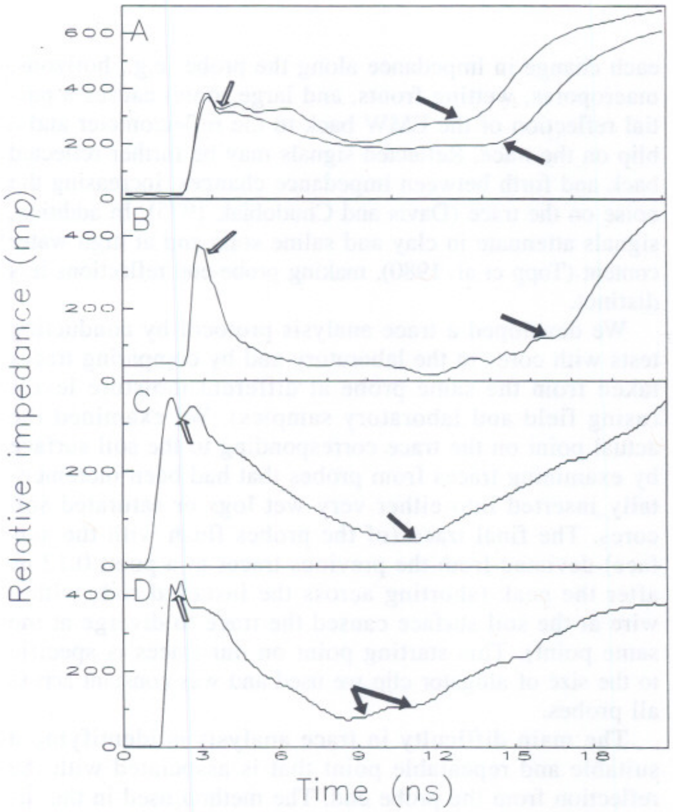
Trace interpretation

Many of the traces collected from our field studies did not have the sharp transitions and smooth lines seen in most published traces, and it was unclear exactly which parts of the traces corresponded to the ends of the probes. The basic shape of a TDR trace begins with a "peak" corresponding to the junction of the alligator clips with the start of the probe, a "trough" from the signal progressing down the probe, and ending in a "rise" corresponding to the open circuit at the end of the probe (Fig. 1B). In practice, TDR traces occur in a great variety of shapes, because each change in impedance along the probe (e.g., horizons, macropores, wetting fronts, and large roots) causes a partial reflection of the EMW back to the reflectometer and a blip on the trace. Reflected signals may be further reflected back and forth between impedance changes, increasing the noise on the trace (Davis and Chudobiak 1975). In addition, signals attenuate in clay and saline soils and at high water content (Topp et al. 1980), making probe-end reflections less distinct.

We developed a trace analysis protocol by conducting tests with cores in the laboratory and by comparing traces taken from the same probe at different moisture levels (using field and laboratory samples). We examined the actual point on the trace corresponding to the soil surface by examining traces from probes that had been incrementally inserted into either very wet logs or saturated soil cores. The final trace (of the probes flush with the surface) deviated from the previous traces at a point 0.12 ns after the peak (shorting across the installed rods with a wire at the soil surface caused the trace to diverge at the same point). This starting point on our traces is specific to the size of alligator clip we used and was constant across all probes.

The main difficulty in trace analysis is identifying a suitable and repeatable point that is associated with the reflection from the probe end. The method used in the literature (e.g., Topp et al. 1982) uses the intersection point of two lines to indicate the change of path of the reflected signal: one is a tangent line from the inflection point of the rise, and the other is a tangent line from the bottom of the trough. We used horizontal lines from the bottom of the trough rather than tangents (Fig. 1B) because most of the troughs in our traces were horizontal (this also simplified the automated algorithm). It was initially difficult to decide which rise and trough to use: many of our traces had a short rise after the main trough followed by a series of flat spots and one or more additional rises (Figs. 2A and 2B). By comparing multiple traces taken from the same probe, we noted that some portions of a trace were more stable with changing water content than others (Heimovaara and Bouten 1990). These trace portions were easily identified as probe ends at high moisture contents, but were surrounded by noise at low moisture contents. These end points always occurred at the beginning of the steepest rise on the trace (Figs. 2A and 2B). By examining multiple

Fig. 2. TDR traces illustrating different degrees of difficulty in interpretation. Open and filled arrows indicate reflection points from start and end of probes, respectively. Interval between *X*-axis ticks is 1 ns. (A) End points of traces from the same probe at different moisture contents illustrating similarity of curve before rise and slope of rise. (B) Trace with multiple steps before rise; trace analysis algorithm extends horizontal tangent line from long step under filled arrow. (C) Trace from probe in clay loam soil, illustrating attenuated rise and end point at end of trough. (D) Another trace from clay loam soil, but end point is unclear because of the lack of steep rise and transient step (comparison with previous, wetter trace from same probe suggested the left arrow as the end point).



traces from dozens of field probes as the soil dried during summer drought, we were able to develop an automated algorithm for trace analysis. (The general approach was reliable for our study, but the numerical limits depend on the resolution of the traces, which will vary with soil type, cable length, and attachment method.) The algorithm, with explanatory notes in parentheses, is as follows:

(1) Locate first peak, add 0.12 ns: this is the start point (as described above).

(2) Locate lowest point of trace (the trough).

(3) Locate the highest flat portion (step) ≥0.10 ns in length within 130 millirho (mρ) of the bottom of the trough and extend a horizontal line from it. (Shorter steps were found to be transitory for a given probe at different times (i.e., noise), and steps further than 130 mρ from the bottom of the trough always occurred after the steep rise portion of the trace.) For the clay loam site (mcy), use the last step within 40 mρ of the trough and output "check" message if another step exists within 130 mρ.

(4) Locate the 0.34-ns interval after the trough with the greatest slope and extend a tangent line from it. (Use of shorter intervals to compute slope occasionally led to slopes much steeper than the overall rise.)

(5) Find the intersection point of the horizontal and tangent lines and subtract the start point to arrive at the travel time.

This algorithm was modified for the attenuated traces acquired from the clay loam soil as noted in step 3. The check message was used to flag traces that had a series of steps connected in a gradual rise (Fig. 2C) and which needed to be interpreted manually. The rod-end reflection on these highly attenuated traces was found to correspond to the end of the trough. With a few traces, we were unable to determine which trough or large step was significant because no one rise portion was distinctly steeper or more consistent than the others (Fig. 2D). One of the only times traces from a probe were not useable was with one of the calibration cores from the clay loam site. Traces from this core had multiple steps throughout the rise and became deeper, but not apparently longer, as moisture content increased. These unusual traces may have been caused by the rods penetrating a section of root about 2 cm in diameter which was found in the core.

Results

The regression lines of Θ on the refractive index of TDR signal velocity (n) for each of the seven cores were combined into two groups (referred to as high C and low C to reflect relative differences in carbon content) based on the clustering of the majority of data points (Fig. 3). The slopes of the combined lines were not significantly different by Student's t-test ($p = 0.13$), but the intercepts were ($p = 0.01$) (Table 2). The standard errors of estimate for regressions of data from individual cores were all below ±1.3% Θ. Similar error estimates are unavailable for the combined regression lines because of autocorrelation; as a guide, 95% of the points from each combined data set fell within 3% Θ of the least-squares lines. The calibration for decayed wood was more variable than that for the soils (standard error of estimate of ±6.6% Θ), but the equation was similar to that for the high-C soils (Fig. 4).

The high-C soils tended to have higher organic matter contents than the low-C soils, although the organic matter content in high-C stand tco was closer to that of the low-C stands than to that of high-C stand hja (Table 1). Soil bulk density also varied between stands, with greater differences among high-C and low-C stands than between them. Soil texture differed substantially among stands, with low-C stand mcy having the lowest amount of coarse fragments and the highest clay content, and low-C stand pcm being the opposite. The mcy soils, which yielded the most problematic traces, also had the finest texture, with very few coarse fragments and large amounts of fine silt and clay (Table 1). One consistent difference between the two groups (most likely coincidental) is that the high-C stands were in old-growth forest condition, while the low-C

Fig. 3. The empirical relationship between volumetric water content (Θ) and the refractive index of TDR signal velocity (*n*) for seven soil cores, and the regression lines for the grouped (high-C and low-C) cores.

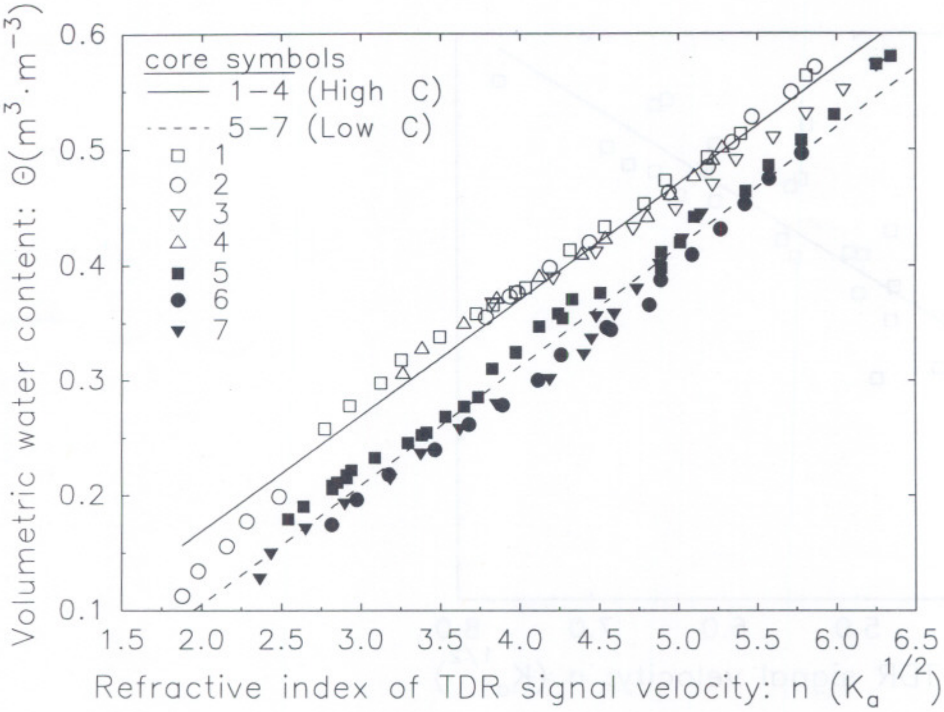


Table 2. Equations and errors of estimate (in parentheses) for regressions of volumetric water content (Θ) on the refractive index of TDR signal velocity (*n*) for individual soil cores, combined soil cores, and decayed wood.

		Calibration equation: $\Theta = \beta_0 + \beta_1 n$				
Core	Stand	β_0	β_1	*n*	SEE Θ	r^2
1	hja	−0.0040 (0.0051)	0.0965 (0.0012)	16	0.0042	0.998
2	hja	−0.0794 (0.0076)	0.1111 (0.0018)	16	0.0099	0.996
3	tco	0.0274 (0.0123)	0.0863 (0.0024)	11	0.0058	0.993
4	tco	0.0190 (0.0105)	0.0897 (0.0024)	12	0.0056	0.993
5	mcy	−0.0882 (0.0054)	0.1033 (0.0013)	33	0.0081	0.995
6	pcm	−0.1276 (0.0104)	0.1058 (0.0023)	17	0.0086	0.993
7	pcm	−0.1148 (0.0131)	0.1042 (0.0033)	17	0.0122	0.985
1–4	High C	−0.0320 —[a]	0.1005 —[a]	55	—[a]	—[a]
5–7	Low C	−0.1016 —[a]	0.1034 —[a]	67	—[a]	—[a]
Decayed wood		−0.0001 (0.0315)	0.1019 (0.0068)	48	0.0658	0.830

Note: SEE, standard error of the estimate.

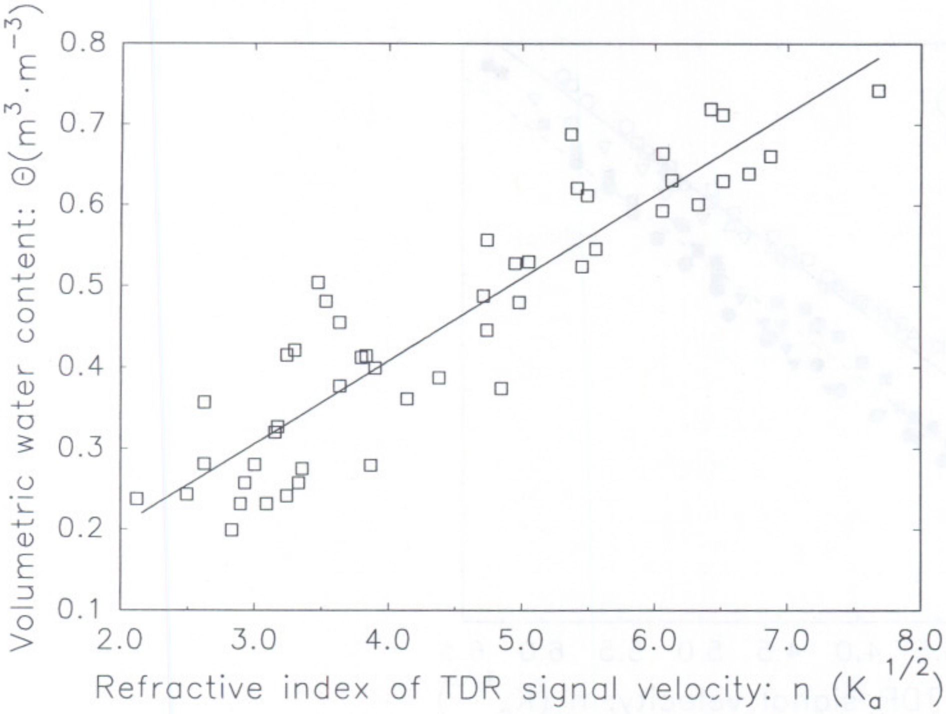
[a]Error estimates and regression statistics are inappropriate for autocorrelated data.

stands were in mature forest condition (dominant trees were 350–500 and 90–140 years old, respectively).

Discussion

We found that different calibrations were necessary to convert TDR travel times into soil moisture content for soils from four different forest stands. Both of our combined soil calibrations were significantly different from Topp et al.'s (1980) "universal" calibration equation. Application of their equation to our TDR measurements would have underestimated true Θ by 1.4 to 4.9% Θ for our low-C soils and by 7.0 to 11.4% Θ for our high-C soils (Fig. 5) (Topp et al.'s calculated error of estimate was 1.3% Θ). (Similarly, calibrations developed by Jacobsen and Schjønning (1993), Ledieu et al. (1986), and Nadler et al.

Fig. 4. The empirical relationship between volumetric water content (Θ) and the refractive index of TDR signal velocity (*n*) for decayed wood samples, and the regression line for combined data.



(1991) would fall along, or below, Topp et al.'s (1980) curve on Fig. 5 (not shown)). Application of the calibration developed by Roth et al. (1992) to our TDR measurements would have underestimated true volumetric water content (Θ) by 0 to 2.9% Θ for our low-C soils and by 4.0 to 9.6% Θ for our high-C soils (Fig. 5). Although the individual calibrations for some of our stands were very similar, there appeared to be no corresponding similarity in measured soil properties. Several soil properties have been implicated as affecting the TDR response to soil moisture, including organic matter content, texture, particle surface area, and bulk density.

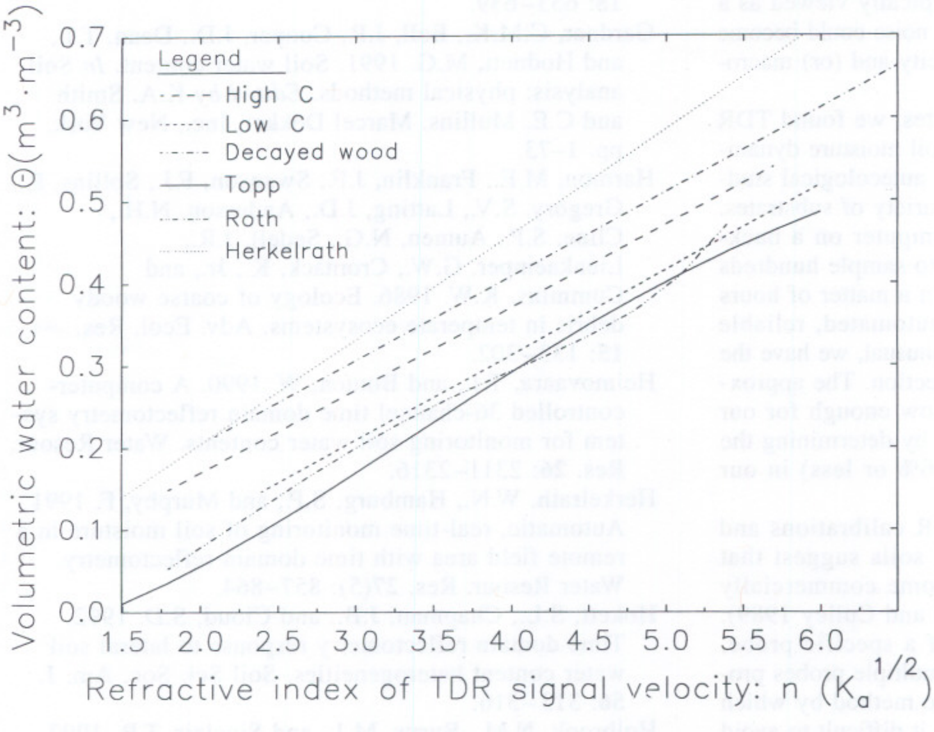
Fully organic soils require different calibrations than mineral soils, displaying higher Θ for a given TDR signal velocity (Topp et al. 1980; Pepin et al. 1992; Roth et al. 1992), yet soil organic matter content alone did not account for the differences among our soil cores. Although organic matter contents were in the same range for soils in Topp et al. (1980) (0–6%) and for soils in our study (3–6%), our calibration curves were different. On the other hand, Herkelrath et al.'s (1991) calibration line for a soil with 23.4% organic matter content was further from Topp et al.'s (1980) curve than our soil lines (Fig. 5). While soil organic matter content does appear to affect the relationship between Θ and *n*, it does not appear to be the only or most important factor affecting variability in the moisture calibration curves.

Differences in TDR calibrations have also been attributed to differences in soil bulk density and surface area, which are related to soil texture (Dirksen and Dasberg 1993; Topp and Davis 1985). Dirksen and Dasberg (1993) found that finer textured soils propagate the EMW at greater speed for a given Θ (i.e., higher curves on Fig. 5). Our data do not show consistent effects of texture; calibrations for the finest and coarsest soils (mcy and pcm) were similar, yet different from calibrations for the two loam soils (hja and tco). Similarly, there was no relationship between our calibration equations and soil bulk density. Thus it is not surprising that the application of calibration equations that incorporate commonly measured soil characteristics (Wang and Schmugge 1980; Whalley 1993; Jacobsen and Schjønning 1993) did not fit our data (not shown).

It may be that the differences between our calibrations and others for mineral soil and the greater variability of the TDR response in the field than in the laboratory (Topp and Davis 1985) were caused by differences in soil pore structure. Air-filled cracks speed up travel times (Hokett et al. 1992), so it is likely that small voids in the soil do the same. Many of the research results on the robustness of the TDR response came from sieved and packed soils in the laboratory (e.g., Topp et al. 1980; Roth et al. 1992) or tilled agricultural soils in the field (e.g., Topp and Davis 1985). In either case, the incidence of macropores, root channels, rocks, and cracks would have been eliminated or greatly reduced. Forest soils in our region appear to be quite heterogeneous, with burned-out root channels, buried charcoal, live and dead roots, and large volumes of buried or partially buried decayed logs (Spies et al. 1988). The differences in structural complexity between our intact forest soils and agricultural soils or sieved soil samples may have led to the differences in TDR calibrations.

We found that TDR was useful for moisture content measurement in decayed wood, although the calibration was more variable than that for soils. This variability could

Fig. 5. TDR calibration equations from Topp et al. (1980), Herkelrath et al. (1991), and Roth et al. (1992) are compared with low-C, High-C, and decayed wood equations from this study.



have been caused by the many stages and textures of decay that are often found in any section of log, although error due to the sampling design may have been a factor as well. Despite similarly high variance, TDR has been used to track moisture content in live tree stems (Holbrook et al. 1992; Constanz and Murphy 1990). We detected no differences in calibration among different logs, or due to extent of woody decay, suggesting that a single calibration equation may be adequate for decayed Douglas-fir wood. The accumulating evidence indicates that the TDR method may be useful for nondestructive monitoring of moisture content in many components of forest ecosystems, including soil, live trees, litter, and logs.

We found, similar to Herkelrath et al. (1991) and Whalley (1993), that a linear model was adequate for calibrating the TDR over the range of moisture contents found in the field. A nonlinear response can be expected at low moisture contents, where the electrical response of the first few molecular layers of water are controlled by the active surface area of the soil (Topp et al. 1980; Wang and Schmugge 1980); such a response was suggested for our data only at Θ less than 15% (cores 2 and 8, Fig. 3). The slopes of most of the calibration lines in Fig. 5 are very similar, suggesting that if only relative moisture differences within a site are desired, a site-specific calibration may not be necessary. For intersite comparisons, however, our results strongly indicate that separate calibrations should be made for each site.

TDR traces from probes installed in field settings can be quite noisy, especially when probes encounter discontinuities in the soil profile, or when soils are conductive (e.g., high clay content) (Topp et al. 1980; Herkelrath et al. 1991). Nevertheless, we found that by developing a consistent algorithm, almost all of our traces could be reliably interpreted (approximately 5% of the 7900 traces in our canopy-gap studies required manual inspection, and almost all were from the clay loam stand (mcy)). The need to develop a separate algorithm to interpret the attenuated traces from the clay loam soil indicates that a single trace analysis program may not be suitable for all soils, however. The design of automated analyses may be specific to instrument settings, waveguide configuration, and soil type, although methods that include initial manual parameterization for individual probes (e.g., Heimovaara and Bouten 1990) are probably quite robust. Perhaps the best way to avoid problems with trace interpretation, and with study results in general, is by avoiding air pockets, large roots, or buried wood when installing probes. These discontinuities can frequently be detected by paying attention to resistance and sound as probes are tapped into place. Horizontal placement of buried probes can circumvent noise problems caused by textural or water content changes in the soil profile (L.A. Morris, personal communication). The use of three parallel rods instead of two also reduces noise (Zegelin et al. 1989), but inserting three correctly spaced rods at some sites (e.g., with rocky soils) may prove difficult. Use of remote diode shorting to detect probe ends (Hook et al. 1992) is a promising technique that may permit TDR use in otherwise noisy conditions. We noticed few noise-reducing benefits from the widely used impedance matching balun; Zegelin et al. (1989) note that the balun itself can be a source of noise. It is also critical to avoid inadvertently moving probe ends after placement because that can create air pockets next to the rods, causing travel times to be reduced. Some loss of contact around permanently installed probes may be unavoidable, however, because of shrinkage during drying of some soils. Although noise is typically viewed as a measurement problem, it is possible that noise could become useful for characterizing soil heterogeneity and (or) macropore structure.

Once calibrated to our individual sites, we found TDR to be an invaluable tool for studies of soil moisture dynamics in forest canopy gaps as well as for autecological studies of plant survival and growth on a variety of substrates. By carrying the reflectometer and computer on a backpack into the field, one person is able to sample hundreds of scattered, permanent sample points in a matter of hours and then analyze the traces with an automated, reliable algorithm. When measurements appear unusual, we have the original traces available for visual inspection. The approximate calibration error of 3% Θ was low enough for our purposes, but may have been improved by determining the effect of the volume of forest floor (6% or less) in our samples.

Our results on the variation in TDR calibrations and trace shapes between different forest soils suggest that caution should be used in applying some commercially available TDR systems (see also Topp and Culley 1989). Most products also require the use of a specific probe, often making long-term installation of multiple probes prohibitively expensive. In some cases, the method by which the cable clamps onto the probes makes it difficult to avoid moving probes and breaking their contact with the soil. In addition to its many advantages, the TDR method has a number of limitations that must be considered before application to forest soils and substrates.

Acknowledgements

Mark Easter assisted with electrical theory and system configuration. Barbara Marks and Gody Spycher wrote the initial code for analyzing traces. Tom Sabin provided statistical advice. Thanks are extended to Mark Easter, Steve Wondzell, Mark Harmon, and Jim Boyle for their thoughtful comments. Funding was provided by National Science Foundation grants BSR 8909038 and BSR 9016633.

References

Baker, J.M., and Lascano, R.J. 1989. The spatial sensitivity of time-domain reflectometry. Soil Sci. **147**(5): 378–384.

Brown, R.B. 1975. Genesis of some soils in the central western Cascades of Oregon. M.S. thesis, Oregon State University, Corvallis.

Constantz, J., and Murphy, F. 1990. Monitoring moisture storage in trees using time domain reflectometry. J. Hydrol. **119**: 31–42.

Davis, J.L., and Chudobiak, W.J. 1975. In situ meter for measuring relative permittivity of soils. Geol. Surv. Can. Pap. 75-1. Part A. pp. 75–79.

Dirksen, D., and Dasberg, S. 1993. Improved calibration of time domain reflectometry soil water content measurements. Soil Sci. Soc. Am. J. **57**: 660–667.

Franklin, J.F., and DeBell, D.S. 1988. Thirty-six years of tree population change in an old-growth *Pseudotsuga–Tsuga* forest. Can. J. For. Res. **18**: 633–639.

Gardner, C.M.K., Bell, J.P., Cooper, J.D., Dean, T.J., and Hodnett, M.G. 1991. Soil water content. *In* Soil analysis: physical methods. *Edited by* K.A. Smith and C.E. Mullins. Marcel Dekker, Inc., New York. pp. 1–73.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Latting, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

Heimovaara, T.J., and Bouten, W. 1990. A computer-controlled 36-channel time domain reflectometry system for monitoring soil water contents. Water Resour. Res. **26**: 2311–2316.

Herkelrath, W.N., Hamburg, S.P., and Murphy, F. 1991. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resour. Res. **27**(5): 857–864.

Hokett, S.L., Chapman, J.B., and Cloud, S.D. 1992. Time domain reflectometry response to lateral soil water content heterogeneities. Soil Sci. Soc. Am. J. **56**: 313–316.

Holbrook, N.M., Burns, M.J., and Sinclair, T.R. 1992. Frequency and time-domain dielectric measurements of stem water content in the arborescent palm, *Sabal palmetto*. J. Exp. Bot. **43**: 111–119.

Hook, W.R., Livingston, N.J., Sun, Z.J., and Hook, P.B. 1992. Remote diode shorting improves measurement of soil water by time domain reflectometry. Soil Sci. Soc. Am. J. **56**: 1384–1391.

Jacobsen, O.H., and Schjønning, P. 1993. A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. J. Hydrol. **151**: 147–157.

Knight, J.H. 1992. Sensitivity of time domain reflectometry to lateral variations in soil water content. Water Resour. Res. **28**(9): 2345–2352.

Ledieu, J., de Ridder, P., de Clerck, P., and Dautrebande, S. 1986. A method of measuring soil moisture by time-domain reflectometry. J. Hydrol. **88**: 319–328.

Maser, C., Anderson, R.G., Cromack, K., Jr., Williams, J.T., and Martin, R.E. 1979. Dead and down woody material. *In* Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington. *Edited by* J.W. Thomas. U.S. Dep. Agric. Agric. Handb. 553. pp. 78–95.

Nadler, A., Dasberg, S., and Lapid, I. 1991. Time domain reflectometry measurements of water content and electrical conductivity of layered soil columns. Soil Sci. Soc. Am. J. **55**: 938–943.

Pepin, S., Plamondon, A.P., and Stein, J. 1992. Peat water content measurement using time domain reflectometry. Can. J. For. Res. **22**: 534–540.

Roth, C.H., Malicki, M.A., and Plagge, R. 1992. Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR. J. Soil Sci. **43**: 1–13.

Spies, T.A., Franklin, J.F., and Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology, **69**: 1689–1702.

Spies, T.A., Vogt, K.A., Franklin, J.F., and Van Pelt, R. 1990. Above- and below-ground response of coniferous ecosystems to tree-fall gaps. Northwest Environ. J. **6**(2): 435–436.

Stein, J., and Kane, D.L. 1983. Monitoring the unfrozen water content of soil and snow using time domain reflectometry. Water Resour. Res. **19**(6): 1573–1584.

Topp, G.C., and Culley, J.L.B. 1989. Correcting soil volumetric water contents from a direct-reading time domain reflectometry instrument (IRAMS). Can. J. Soil Sci. **69**: 701–704.

Topp, G.C., and Davis, J.L. 1985. Measurement of soil water content using time-domain reflectometry (TDR): a field evaluation. Soil Sci. Soc. Am. J. **49**: 19–24.

Topp, G.C., Davis, J.L., and Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. **16**(3): 574–582.

Topp, G.C., Davis, J.L., and Annan, A.P. 1982. Electromagnetic determination of soil water content using TDR: I. Applications to wetting fronts and steep gradients. Soil Sci. Soc. Am. J. **46**: 672–678.

Wang, J.R., and Schmugge, T.J. 1980. An empirical model for the complex dielectric permittivity of soils as a function of water content. IEEE Trans. Geosci. Remote Sens. **GE-18**: 288–295.

Whalley, W.R. 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. J. Soil Sci. **44**: 1–9.

Yanuka, M., Topp, G.C., Zegelin, S., and Zebchuk, W.D. 1988. Multiple reflection and attenuation of time domain reflectometry pulses: theoretical considerations for applications to soil and water. Water Resour. Res. **24**(7): 939–944.

Zegelin, S.J., White, I., and Jenkins, D.R. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. Water Resour. Res. **25**(11): 2367–2376.