ELSEVIER

Soil Technology 9 (1996) 199–207

SOIL TECHNOLOGY

A two-probe method for measuring water content of thin forest floor litter layers using time domain reflectometry

Tino Börner [a], Mark G. Johnson [b,*], Paul T. Rygiewicz [c], David T. Tingey [c], Glenn D. Jarrell [b]

[a] *Fachbereich Wasserwirtschaft, Fachhochschule Magdeburg, 39104 Magdeburg, Sachsen Anhalt, Germany*
[b] *Dynamac Corp., National Health and Environmental Effects Research Laboratory, Western Ecology Division, 200 S.W. 35th Street, Corvallis, OR 97333, USA*
[c] *U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Western Ecology Division, 200 S.W. 35th Street, Corvallis, OR 97333, USA*

Received 20 November 1995; accepted 2 February 1996

Abstract

Few methods exist that allow non-destructive in situ measurement of the water content of forest floor litter layers (Oa, Oe, and Oi horizons). Continuous non-destructive measurement is needed in studies of ecosystem processes because of the relationship between physical structure of the litter and the biological and chemical processes that take place therein. We developed a method using time domain reflectometry (TDR) to monitor water content in a coniferous forest floor litter layer. Litter and mineral soil horizons were reconstructed in test beds in which TDR probes were placed and measurements taken using a range of litter and mineral soil water contents. Two probes are necessary when litter thickness is less than the spatial sensitivity (6 to 8 cm) of the TDR probes; one probe placed in the mineral soil and another one at the interface of the litter and mineral soil. Using this arrangement of TDR probes and simple mathematical relationships, the volumetric water content of forest litter can be estimated continuously. When the results of the two-probe method are compared to volumetric water content of forest litter obtained by gravimetric means there is a strong positive linear relationship between the two measured values of litter water content ($r^2 = 0.93$). The two-probe method, however, underestimates litter water at low water contents and overestimates it at high water contents. This error has at least three components: (1) TDR instrument error, (2) errors in estimating volumetric water content from gravimetric data, and (3) using a TDR calibration curve not specific for high organic matter

* Corresponding author. Tel.: + 1-541-7544696; fax: + 1-541-7544799; e-mail: mark@mail.cor.epa.gov.

00933-3630/96/$15.00 Published by Elsevier Science B.V.
PII S0933-3630(96)00019-0

litter layer material. Calibrating the instrument for this specific condition should improve the overall estimate of the litter layer water content.

Keywords: Time domain reflectometry; TDR probes; Litter layer; Forest floor; Volumetric water content; Water budget

1. Introduction

Water is an essential component of ecosystems. To understand water use and hydrology in ecosystems, data on the water held in soil and the movement of water from the soil through either evapotranspiration or percolation are needed. In many forested ecosystems, such as those in the Pacific Northwestern United States, the forest floor litter layer, the uppermost part of the soil, is an important but often overlooked component of the forest hydrology. However, the forest floor litter layer is thin (< 10 cm) which makes the continuous determination of water content in situ difficult.

We are conducting a study on the effects of elevated CO_2 and climate change (i.e., elevated temperature) on a Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) seedling–soil system (Tingey et al., 1996). In this study, Douglas fir seedlings are being grown in native forest soil that has been reconstructed by horizon in outdoor climate controlled exposure chambers called terracosms (Tingey et al., 1996). The soil compartment of each terracosm has a 1 m by 2 m footprint and is 1 m deep (the mineral soil is 90 cm deep and is overlain with a 6 cm thick litter layer). One goal of our research is to construct daily water budgets. To accomplish this goal we use 4 time domain reflectometry (TDR) probes to continuously measure the water content, in situ, of the mineral soil in each terracosm. We quantify evapotranspiration and we quantify the amount of water added to the terracosms during irrigation events and as water vapor (used to control vapor pressure deficit). When the experiment began, we did not, however, have a method for measuring the water content of the litter layer. The objective of this paper is to determine whether or not TDR could be used to continuously measure the water content of thin, forest floor needle litter layers.

2. Materials and methods

Time domain reflectometry has gained popularity as a way to measure volumetric soil water content in situ (Herkelrath et al., 1991; Topp, 1993; Cassel et al., 1994). The TDR technique relies on the apparent dielectric constant (K_a) of materials surrounding the TDR probe to measure water content. The time it takes a wave of electromagnetic energy to travel down parallel transmission lines and return to the source is proportional to the water content of the surrounding material. The higher the apparent dielectric constant of the medium (i.e., the higher the water content), the longer the delay in the return of the energy wave. This works well in soil because of the large differences in dielectric constants: air ($K_{air} = 1$), mineral particles ($K_{mineral} = 2$ to 4) and water ($K_{water} = 80$). The TDR method is also accurate (±1%) and precise (±0.5%, Topp, 1993), has excellent spatial (Baker and Lascano, 1989) and temporal (Wraith and Baker, 1991) resolution, and is amenable to automation and multiplexing (Baker and Allmaras, 1990).

There are at least two types of TDR probes (balanced and unbalanced) commercially available. We chose to use unbalanced TDR probes (TRASE, Model 600512, Soilmoisture Equipment, Santa Barbara) because the volume of soil sampled is reported to be smaller than the volume sampled with a balanced probe design (Zegelin et al., 1989; Campbell Scientific, 1991). The three stainless steel waveguides, in each probe, are approximately 3 mm in diameter and 20 cm long. The three parallel waveguides are coplanar and are approximately 25 mm apart. The spatial sensitivity of these waveguides is about 6 to 8 cm diameter around the central waveguide (Baker and Lascano, 1989). Water content measurements, in units of volumetric water content ($\Theta_V = cm^3$ water $* cm^{-3}$ soil), were recorded with a portable TDR unit (TRASE, Model 6050X1).

2.1. Substrate thickness and probe placement

A plastic tub (35 cm by 30 cm by 15 cm deep) was used to hold sieved (2.54 cm) forest floor litter at a bulk density (0.16 $g \cdot cm^{-3}$) similar to that found in the Douglas fir forest where the soil and litter collected for our CO_2 study. In the first experiment, one TDR probe was placed horizontally in forest floor litter of various depths and volumetric water contents (from 5 to 50%) to determine the minimum litter thickness required to make a water measurement. With the plane of the probe in the middle of the litter layer we determined that a minimum litter thickness of 6 cm (3 cm above and 3 cm below the plane of the probe) was necessary to obtain reliable estimates of litter water content (data not presented). With respect to our Douglas fir experiment the initial litter layer thickness is 6 cm but is allowed to decompose and settle to 3 cm before more litter is added. Consequently, using a TDR probe in the middle of the litter layer to measure litter water content would work best for the initial condition and not for the subsequent thinner layers. We decided to investigate an alternative probe arrangement to estimate the water content of litter layers less than 6 cm thick.

In another experiment the plastic tub was used to hold sieved (2.54 cm) mineral soil (coarse-loamy, mixed, mesic, Typic Hapludand) and litter at bulk densities similar to that found in the Douglas fir forest where the soil and litter were collected (0.79 and 0.16 $g \cdot cm^{-3}$, respectively). Three to four cm of litter (approximately one-half the spatial sensitivity of the TDR probe) were placed on top of the mineral soil (10 cm thick) and two unbalanced TDR probes were used (Fig. 1). Because TDR measurements of soil water are an average of the materials adjacent to the TDR probe we assumed that if we placed one TDR probe at the litter layer/mineral soil interface that it would measure a water content that is the average of the water contents of the litter layer and the mineral soil. The second probe was placed 3 to 4 cm deep in the mineral soil (Fig. 1) and would measure the water content of the mineral soil only. The objective of this experiment was to determine if we could measure the water content at each probe and, using their physical arrangement, calculate the litter layer water content. In this experiment we varied the litter volumetric water content from 5 to 50% and the mineral soil from 5 to 60% and measured the water content at each probe.

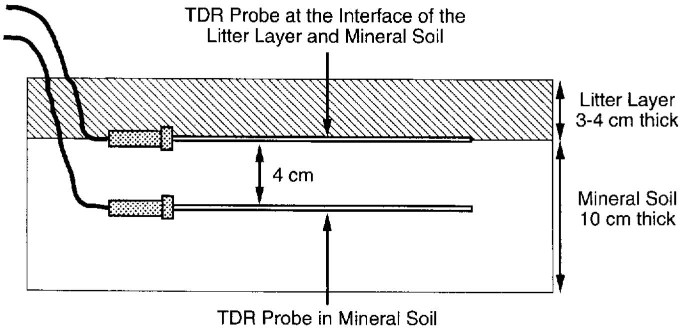

Fig. 1. Physical arrangement of TDR probes, litter layer, and mineral soil used in development of the two-probe method.

2.2. Mathematical relationships

The following set of relationships was used to calculate the volumetric water content of the litter (Θ_{VL}) using the two-probe configuration. Assuming that the water content measured at the interface of the litter and mineral soil is the average of the water content of the litter and mineral soil if measured separately; this relationship is described by Eq. (1).

$$\Theta_{VI\text{-}TDR} = (\Theta_{VL} + \Theta_{VS\text{-}TDR})/2, \qquad (1)$$

where:

$\Theta_{VI\text{-}TDR}$ = volumetric water content measured at the interface of the litter and mineral soil [(cm^3 water) · (cm^{-3} litter or soil)$^{-1}$] determined by TDR.

Θ_{VL} = volumetric water content of the litter [(cm^3 water) · (cm^{-3} litter or soil)$^{-1}$].

$\Theta_{VS\text{-}TDR}$ = volumetric water content of the mineral soil [(cm^3 water) · (cm^{-3} litter or soil)$^{-1}$] determined by TDR.

Eq. (1) is widely applicable due to the linear relationship between the delay in the time domain signal and volumetric water content (Θ_V). For example, when evaluating thin layers, this relationship holds when litter thickness is at least one-half the diameter of the spatial sensitivity of the probes and the probe orientation is normal to the thickness of the litter.

Eq. (1) is rearranged to isolate the term for litter layer water content (Θ_{VL}).

$$\Theta_{VL} = 2\Theta_{VI\text{-}TDR} - \Theta_{VS\text{-}TDR} \qquad (2)$$

Therefore, Θ_{VL} is inferred from direct TDR measurements of water in the mineral soil ($\Theta_{VS\text{-}TDR}$) and at the interface of the litter and mineral soil ($\Theta_{VI\text{-}TDR}$).

In conjunction with our TDR measurements we also measured litter water content gravimetrically (Gardner, 1986). To estimate the accuracy of the TDR method to measure the water content of litter ($\Theta_{VL\text{-}TDR}$) we compared Θ_{VL} measured with the TDR to the volumetric water content of the litter ($\Theta_{VL\text{-}GRAV}$) calculated by multiplying the litter water content, determined on a mass basis (Θ_{ML}), by the bulk density (ρ_b) of the litter. The relationship between Θ_{ML} and Θ_{VL} is:

$$\Theta_{VL} = \Theta_{ML} \cdot \rho_b, \tag{3}$$

where:

Θ_{VL} = litter volumetric water content [(cm^3 water) $\cdot$ (cm^{-3} litter or soil)$^{-1}$]

Θ_{ML} = litter gravimetric water content [(g water) $\cdot$ (g dry litter)$^{-1}$].

ρ_b = litter bulk density (g $\cdot$ cm^{-3}).

To relate litter volumetric water content measured with the two-probe TDR method ($\Theta_{VL\text{-}TDR}$) to volumetric litter water content calculated from gravimetric (mass) values ($\Theta_{VL\text{-}Grav}$), $\Theta_{VL\text{-}TDR}$ was regressed against $\Theta_{VL\text{-}Grav}$ using DeltaGraph® (DeltaPoint, 1991).

3. Results and discussion

We found a strong linear relationship between $\Theta_{VL\text{-}TDR}$ and $\Theta_{VL\text{-}Grav}$. Fig. 2 shows a plot of $\Theta_{VL\text{-}TDR}$ to $\Theta_{VL\text{-}Grav}$. Included is a plot of the regression line (solid line) and a plot of a 1:1 (dashed line) where the data would lay if there were perfect agreement between $\Theta_{VL\text{-}TDR}$ and $\Theta_{VL\text{-}Grav}$. Approximately 93% of the variability in the data can be

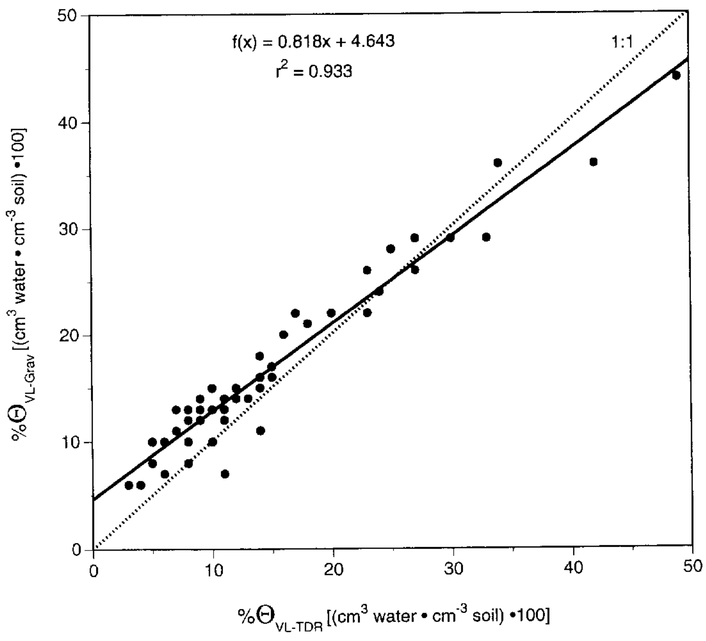

Fig. 2. Linear regression (solid line) of litter volumetric water content ($\Theta_{VL\text{-}Grav}$) against litter volumetric water content ($\Theta_{VL\text{-}TDR}$) obtained by the two-probe TDR method. The $\Theta_{VL\text{-}Grav}$ was determined by measuring litter water content on a mass basis (Θ_{ML}) and then multiplying the value by the bulk density (ρ_b) of the litter layer. The dashed line indicates 1:1 correspondence between $\Theta_{VL\text{-}Grav}$ and $\Theta_{VL\text{-}TDR}$.

explained by the resulting regression equation. This suggests that the two-probe method is effective at measuring litter water of thin litter layers (3 to 4 cm) over a wide range of water contents (5 to 50% Θ_V). The slope of the regression line is, however, less than 1 (0.8), indicating that the method underestimates litter water at low water contents and over estimates the value at high water contents (assuming that $\Theta_{VL\text{-}Grav}$ is correct).

To investigate the potential sources of error we calculated the absolute error between $\Theta_{VL\text{-}TDR}$ and $\Theta_{VL\text{-}Grav}$ (average difference between $\Theta_{VL\text{-}TDR}$ and $\Theta_{VL\text{-}Grav}$, at any value of $\Theta_{VL\text{-}Grav}$, and plotted it against $\Theta_{VL\text{-}Grav}$) which is shown in Fig. 3A. The extreme values of these average absolute error values are -4 and 5% Θ_{VL}. In general, we found that, for Θ_{VL} less than 30%, the two-probe TDR method gave litter water estimates slightly greater than $\Theta_{VL\text{-}Grav}$. All of the values differed by 4% Θ_{VL} or less and approximately half of the values were less than or equal to 2% Θ_{VL}. At higher litter water contents (greater than 30% Θ_{VL}) the two-probe method underestimates $\Theta_{VL\text{-}Grav}$ but the absolute differences were less than or equal to 5% Θ_{VL}.

In terms of relative error $[100*((\Theta_{VL\text{-}Grav} - \Theta_{VL\text{-}TDR})/\Theta_{VL\text{-}Grav})]$, the ability of the two-probe method to predict litter volumetric water content decreases as the litter becomes drier (Fig. 3B). In general, the average percent relative error between the two methods was -11 to -12% for litter water contents above 10% Θ_{VL}. As litter water decreased to 5% Θ_{VL} the percent relative error approached -40%. One component of this pattern of accuracy is the error of the TRASE TDR system (dashed lines in Fig. 3B). At the same 5% Θ_{VL} the instrument error can account for about half of the total error (approximately 20% Θ_{VL} out of a total of about 40% Θ_{VL}). Another component of the pattern of accuracy is the error of the gravimetric method to determine volumetric water which is dependent upon both the measurement of ρ_b and gravimetric water determination. The larger errors associated with the drier litter may not be important when considering biological processes in ecosystems; when there is little total water in the litter biological activity is likely to be negligible compared with activity at higher water contents.

For our water budget calculations relative errors of 40% Θ_{VL} in litter water estimates when the litter is at or near 5% Θ_{VL} is of little consequence. For example, the measured water content of a litter layer 100 cm by 200 cm by 6 cm deep at 5% Θ_{VL} would range between 3.6 and 8.4 l, a difference of 4.8 l. If all the mineral soil in the terracosm were at the permanent wilting point (-1.5 MPa) there are approximately 163 l of water in the soil (unpublished data). Of the total water (litter at 5% Θ_{VL} and mineral soil at the wilting point) the uncertainty in the estimate for litter water (4.8 l) would account for less than 3% of the total. Alternatively, if all the mineral soil were at 50% of field capacity (approximately 246 l held in the mineral soil, unpublished data), and the litter were at 5% Θ_{VL}, the uncertainty would only account for less than 2% of the total. As the soil and litter get wetter (up to 30% Θ_{VL}) the error in the litter water measurement decreases. Therefore, the contribution of the litter to the daily water budget can be estimated more precisely. However, for investigations concerning soil physics or chemistry these large errors at lower litter water contents may not be acceptable.

Another reason why there was not better agreement between $\Theta_{VL\text{-}TDR}$ and $\Theta_{VL\text{-}Grav}$ could be due to inaccuracies in TDR measurements of soils high in organic matter when the instrument calibration curves that relate K_a to Θ_V were developed for mineral soils.

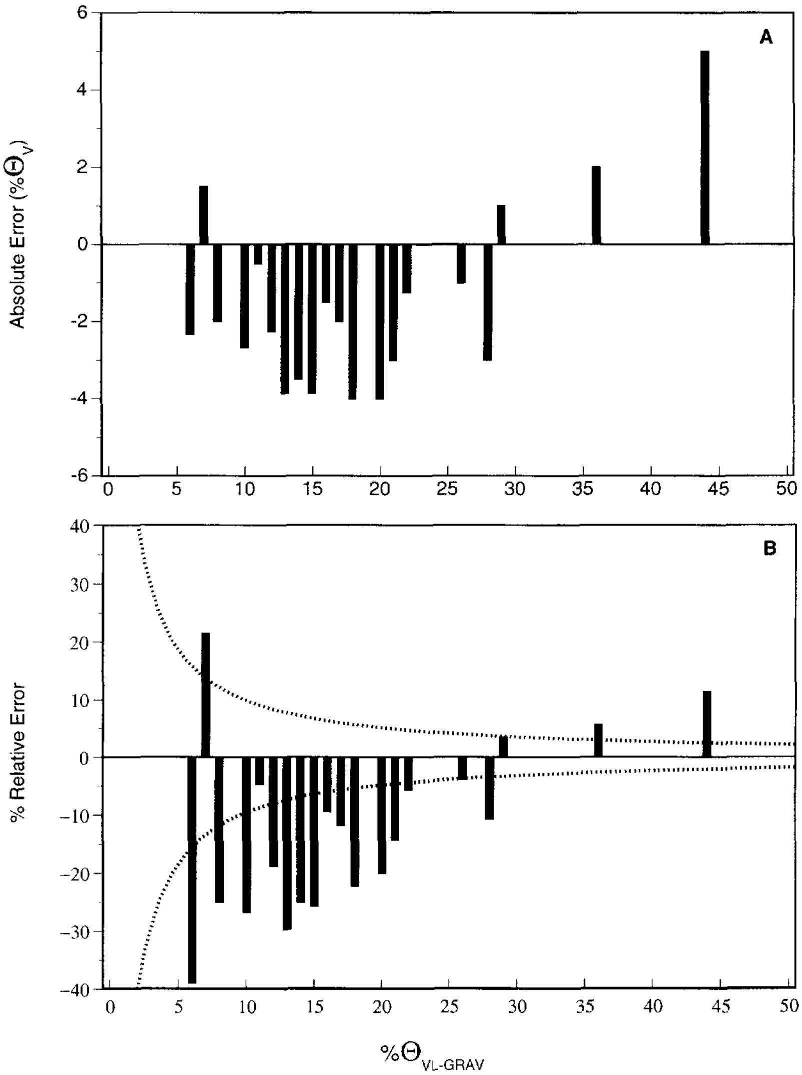

Fig. 3. Error analyses of differences between volumetric water content of litter determined by using two-probe time domain reflectometry (TDR) and gravimetric methods. (A) Absolute error (% $\Theta_{VL\text{-}TDR}$ − % $\Theta_{VL\text{-}Grav}$) between volumetric water contents measured by two-probe TDR ($\Theta_{VL\text{-}TDR}$) and gravimetric ($\Theta_{VL\text{-}Grav}$) methods, plotted against % $\Theta_{VL\text{-}Grav}$. (B) Percent relative error [(absolute error/% $\Theta_{VL\text{-}Grav}$)· 100] between the two methods described in (A). Dashed lines indicate the percent relative instrument error [±(% accuracy/% $\Theta_{VL\text{-}Grav}$)· 100] of TDR based on an instrument accuracy of ±1% reported by Topp (1993).

Herkelrath et al. (1991) plotted Θ_V versus K_a for soils high in organic matter across a range of water contents and found that the resulting curves for soils high in organic matter were offset (i.e., same slope but different intercept) from Θ_V versus K_a for mineral soils. This implies that a separate calibration curve relating K_a to $\Theta_{Vl\text{-}TDR}$

should be developed because of the high carbon content of the forest floor litter. In the current study we used the calibration equation that was programmed into the TRASE TDR instrument by the manufacturer. This equation is similar to the equation of Topp et al. (1980) for mineral soils and may account for some of the imprecision in our estimates of Θ_{VL}. Consequently, most of the measurement uncertainty associated with an improper calibration equation resides in the $\Theta_{VI\text{-}TDR}$. This uncertainty is multiplied by 2 in Eq. (2) when using $\Theta_{VI\text{-}TDR}$ to calculate Θ_{VL}. Using an instrument calibration that is specific for the litter layer/mineral soil interface would improve the accuracy of $\Theta_{VI\text{-}TDR}$ which in turn would reduce the overall error in the estimate of Θ_{VL}.

Litter decomposition results in changes in bulk density and organic matter content (Wood, 1989). For example, the bulk density of the Oi horizon (least decomposed) may be different than that of the lower Oa horizon (most decomposed). However, changes in bulk density are reported not to affect TDR measurements (Topp, 1993). Different organic matter contents in the horizons of the litter layer may necessitate calibrating the TDR system for each horizon (Herkelrath et al., 1991). Calibrations may be needed with probes having spatial sensitivities that can distinguish among the litter layer horizons (e.g., ThetaProbes, Delta-T Devices, Cambridge). However, calibrations for individual litter layer horizons may not be needed with probes having spatial sensitivities that cannot distinguish among the horizons.

4. Summary and conclusions

In our research on the effects of elevated CO_2 and climate change on a Douglas fir seedling–soil system we needed an automated, non-destructive method for measuring the water content of forest floor litter layers that are initially 6 cm thick but will become as thin as 3 cm as the litter decomposes and settles over time. Since the spatial sensitivity of unbalanced TDR probes is between 6 to 8 cm placing a probe horizontally within the litter layer of our system did not appear to be an adequate solution. We developed and tested a two-probe method in which one TDR probe was placed horizontally at the litter layer/mineral soil interface and a second probe was placed 3 to 4 cm deep in the mineral soil. Using the water contents measured by both probes we calculated the litter water content. The litter water content obtained this way is strongly related to volumetric litter water content estimated using the gravimetric water content and bulk density of the litter. The two-probe method underestimates litter water at low water contents and overestimates the value at high contents. There are a least three factors that contribute to the errors we observed. The first is due to the inherent error of the TDR instrument. The second is due to the inaccuracy of estimating Θ_{VL} from Θ_{ML} and ρ_b. Third, a portion of this error is due to our use of a TDR instrument that was not specifically calibrated for mineral soil in contact with high organic forest floor litter material. Calibrating the instrument for this specific condition should improve the overall estimate of the litter layer water content.

One advantage of the two-probe technique is that it provides a method to continuously estimate the water in litter layers 3 cm or thicker in situ. In our global climate change research, the two-probe TDR method, with the proper TDR instrument calibration, will provide the water content of the litter layer needed to construct daily water budgets. Since TDR technology is continually developing and TDR probes with smaller spatial sensitivities are being constructed (Kelly et al., 1995) advancements will likely lead to continuous in situ water content measurements in litter layers less than 3 cm thick with single probes.

Acknowledgements

The research described in the article has been funded by the U.S. Environmental Protection Agency. This document has been prepared at Western Ecology Division of the EPA National Health and Environmental Effects Research Laboratory, in part, through contracts 68-C4-0019 to ManTech Environmental Technology Inc., and 68-C6-0005 to Dynamac Corporation. It has been subjected to the Agency's peer and administrative review and approved for publication. We thank CDS International, Inc., New York, for financial assistance to the senior author.

References

Baker, J.M. and Allmaras, R.R., 1990. System for automating and multiplexing soil moisture measurement by time domain reflectometry. Soil Sci. Soc. Am. J., 54: 1–6.

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

Cassel, D.K., Kachanoski, R.G. and Topp, G.C., 1994. Practical considerations for using a TDR cable tester. Soil Tech., 7: 113–126.

DeltaPoint, Inc., 1991 DeltaGraph® Profession for Macintosh. DeltaPoint, Inc., Monterey, CA.

Gardner, W.H., 1986. Water content. In: ed. A. Klute, Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. 2nd Ed., Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, WI, USA, pp. 493–544.

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: 857–864.

Kelly, S.F., Selker, J.S. and Green, J.L., 1995. Using short soil moisture probe with high-bandwidth time domain reflectometry instruments. Soil Sci. Soc. Am. J., 59: 97–102.

Tingey, D.T., McVeety, B., Waschmann, R., Johnson, M.G., Phillips, D.L., Rygiewicz, P.T. and Olszyk, D., 1996. A versatile sun-lit controlled-environment facility for studying plant and soil processes. J. Environ. Qual., in press.

Topp, G.C., 1993. Soil water content. In: ed. M.R. Carter, Soil sampling and methods of analysis, Can. Soc. Soil Sci., Lewis Publishers, Boca Raton, LA, pp. 541–557.

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: 574–582.

Wood, M., 1989. Soil Biology. Blackie and Son Ltd., Glasgow.

Wraith, J.M. and Baker, J.M., 1991. High resolution measurement of root water uptake using automated TDR. Soil Sci. Soc. Am. J., 55: 928–932.

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: 2367–2376.