

Soil Water Retention Measurements Using a Combined Tensiometer-Coiled Time Domain Reflectometry Probe

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ABSTRACT

The objective of the presented study was to develop a single probe that can be used to determine soil water retention curves in both laboratory and field conditions, by including a coiled time domain reflectometry (TDR) probe around the porous cup of a standard tensiometer. The combined tensiometer-coiled TDR probe was constructed by wrapping two copper wires (0.8 mm diam. and 35.5 cm long) along a 5-cm long porous cup of a standard tensiometer. The dielectric constant of five different soils (Oso Flaco [coarse-loamy, mixed Typic Cryorthod-fine-loamy, mixed, mesic Ustollic Haplargid], Ottawa sand [F-50-silica sand], Columbia [Coarse-loamy, mixed, superactive, nonacid, thermic Oxyaquic Xerofluvents], Lincoln sandy loam (sandy, mixed, thermic Typic Ustifluvents), and a washed sand - SRI30) was measured with the combined tensiometer-coiled TDR probe (coil) as a function of the soil water content (θ) and soil water matric potential (h). The measured dielectric constant (ϵ_{coil}) as a function of water content was empirically fitted with a third-order polynomial equation, allowing estimation of $\theta(h)$ -curves from the combined tensiometer-coiled TDR probe measurements, with R^2 values larger than 0.98. In addition, the mixing model approach, adapted for the tensiometer-coiled TDR probe, was successful in explaining the functional form of the coiled TDR data with about 30% of the coiled-TDR probe measurement explained by the bulk soil dielectric constant. This new TDR development provides in situ soil water retention data from simultaneous soil water matric potential and water content measurements within approximately the same small soil volume around the combined probe, but requires soil specific calibration because of slight desaturation of the porous cup of the tensiometer.

MEASUREMENT OF soil water content θ as a function of soil water matric potential h in unsaturated soils yields the soil water retention curve. A priori knowledge of this curve is essential in both fundamental and applied soil's research. Several methods are used to determine the soil water retention curve from laboratory measurements on undisturbed or disturbed soil samples (Dane and Hopmans, 2002; Klute, 1986). Favorable measurement methods are the hanging water column, the suction table method, and the multistep outflow method using a glass porous plate and funnel, tension table, or pressure cells, respectively.

In the field, a combination of several methods is generally applied as well. In most experiments though, h is measured with a tensiometer, connected to a mercury manometer, vacuum gauge, or pressure transducer, whereas neutron moderation, gamma-ray attenuation,

TDR, or gravimetric methods are used to determine the volumetric water content (Scholl and Hibbert, 1973; Watson et al., 1975; Cheng et al., 1975; Arya et al., 1975; Royer and Vachaud, 1975; Simmons et al., 1979; Gardner et al., 2001). Disadvantages of field estimation of soil water retention curves are related to the considerable time effort involved and instrumentation required, and the relatively small range of soil water matric potentials that can be measured with a tensiometer (Bruce and Luxmoore, 1986). In addition, h and θ measurements generally pertain to different soil volumes, making their interpretation difficult and uncertain.

More recently, TDR has been used in combination with tensiometer and electrical resistance techniques to determine in situ soil water retention curves. Baumgartner et al. (1994) and Whalley et al. (1994) combined shallow stainless steel electrodes with a porous stainless steel material in a standard two parallel probe configuration for simultaneous in situ measurement of θ and h . Preliminary results showed its functionality and effectiveness, but limitations were related to the difference in measured soil volume between θ and h measurements of this probe. Simultaneous measurement of θ and h was also suggested by Noborio et al. (1999) using a TDR probe partially embedded in a porous gypsum block. Assuming hydraulic equilibrium between the porous block and the surrounding soil, bulk soil dielectric-water content relationships could be determined after laboratory calibration of the porous blocks. Results were promising, but further research is needed to select the ideal porous material with a water content sensitivity over a wide range of h , whereas the response time, temperature, and hysteresis effects of the porous material remain to be further investigated. Moreover, the presented development required measurements of θ and h in nearby but separate soil volumes.

A new soil water matric potential sensor was presented by Or and Wraith (1999) that combines porous ceramic and plastic ring materials stacked within a stainless steel coaxial cage of 17.5 cm long. The probe consisted of several porous disks with different pore-size distributions, allowing water content sensitivity over a wide range of h . Similar to existing porous heat dissipation and electrical resistance sensors, the h of the surrounding soil can be determined after laboratory calibration of the porous composite sensor. The authors suggested that pairing of standard TDR probes with this new sensor makes possible the in situ determination of soil retention curves using conventional TDR instrumentation.

The development of new probe designs (Selker et al.,

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Abbreviations: h , soil water matric potential; PVC, polyvinyl chloride; TDR, time domain reflectometry.

1993; Nissen et al., 1998; Nissen et al., 1999a) has allowed exciting new applications of the TDR technique in soil studies because of their miniaturization and combination of TDR with other probes and equipment. For instance, Selker et al. (1993) with their serpentine type probe were able to determine the θ at the soil surface and Nissen et al. (1999b) studied fingered flow and instable flow phenomena using small coiled TDR probes (1.5 cm in length and a 0.36-cm diam.). Vaz and Hopmans (2001) and Vaz et al. (2001) combined a coiled-TDR probe with a cone penetrometer to measure the soil penetration resistance and water content simultaneously in a soil profile.

The objective of the presented study was to develop a single probe that can be used to determine soil water retention curves in both laboratory and field conditions, by including a coiled TDR probe around the porous cup of a standard tensiometer. The main advantage of the presented combined probe design is the simultaneous measurement of θ and h at the same spatial location within approximately the same bulk soil volume around the porous cup. In addition to a direct calibration of the combined probe, an additional objective of this study was to test the mixing model approach of Roth et al. (1990), using the dielectric data of the combined tensiometer-coiled TDR probe data.

MATERIALS AND METHODS

Probe Design

Details of the combined tensiometer-coiled TDR probe are shown in Fig. 1. A 50 Ω coaxial cable was guided along and

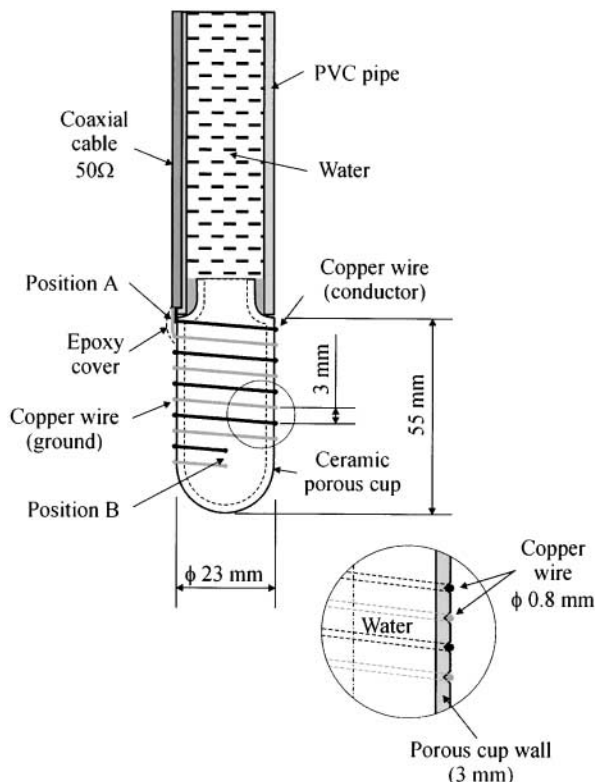


Fig. 1. Detailed diagram of the tensiometer-coiled TDR probe.

partially embedded in the outside wall of the polyvinyl chloride (PVC) pipe of the tensiometer, and was soldered at Location A to two copper wires (0.8 mm in diam. and 35.5 cm long). A pair of parallel copper wires (ground and conductor) was coiled using a 3-mm spacing along a standard 5-cm long porous cup (porosity about 34%, Soil Moisture Equipment, Santa Barbara, CA) of the tensiometer and was glued in the cup wall at Position B with epoxy. Copper wires were wrapped in small grooves machined into the porous cup to prevent their movement during tensiometer installation. Porous cup wall thickness was around 3 mm.

Time Domain Reflectometry Theory

Time domain reflectometry is a soil moisture measurement technique (Topp et al. 1980) that is based on the velocity measurement or travel time of electromagnetic (EM) waves along a wave guide of known length inserted into the soil. The travel time of TDR (T) is proportional to the square root of the apparent bulk dielectric constant of the transmitted medium (ϵ), as determined by the following expression:

$$T = \frac{2L\sqrt{\epsilon}}{c} \quad [1]$$

where L (cm) is the length of the coiled wave guide between Positions A and B, and c (3×10^8 m s $^{-1}$) is the speed of light in vacuum. Since the dielectric constant is highly dependent on moisture content, travel time measurements can be directly related to bulk soil volumetric water content. Using a coiled wave guide design has a distinct advantage as compared with the traditional straight wave guide of the TDR. When using a narrow spacing between the coiled parallel wires, the length of the wave guide per unit soil depth is increased thereby improving the relative precision of the water content measurement, whereas the increased length of the transmission lines improves the accuracy of the travel time measurement from the wave forms. Typical waveforms of the tensiometer-coiled TDR in water, and dry and saturated glass beads (Potters Industrial Ltda, Rio de Janeiro, Brazil) are presented in Fig. 2. These were obtained with the tensiometer-TDR probe positioned in the center of a 500-mL beaker filled with distilled water or glass beads of particle size between 150 and 300 μ m and a bulk density of 1.55 g cm $^{-3}$. The dielectric constants calculated from the travel time measurements, were 46.6 for wa-

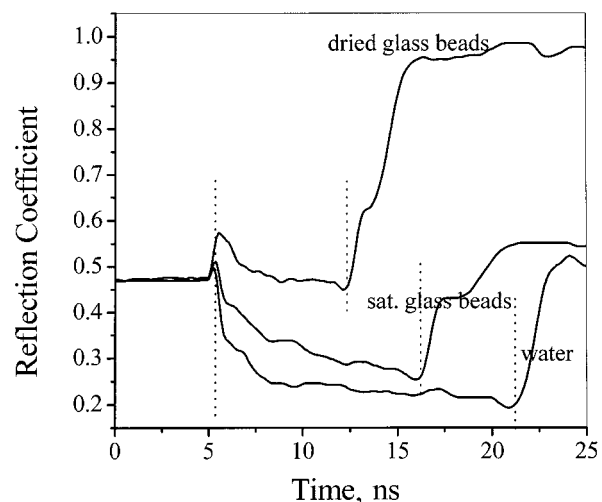


Fig. 2. Waveforms of the tensiometer-coiled TDR probe in water, saturated and dry glass beads (particle size = 150–300 μ m, bulk density [ρ] = 1.55 g cm $^{-3}$).

ter, 9.3 for dry beads, and 22.4 for the saturated glass beads. As is evident from the example traces, the wave forms of the coiled-TDR probe are clear, allowing precise estimations of travel times (T). The increased travel distance using the 35.5-cm transmission lines is achieved while maintaining excellent depth resolution of the TDR measurement because of the 3-mm spacing between the coiled transmission wires. The high precision and depth resolution of the coiled-TDR design, however, comes at the expense of a decreased sensitivity of the bulk soil dielectric constant, as caused by contribution of the porous cup to the composite dielectric constant, decreasing the range of bulk dielectric values from soil dryness to saturation. Moreover, the longer transmission lines may attenuate the signal in saline soil environments, necessitating shorter lengths under such conditions.

Direct Calibration

Direct calibration of the tensiometer-coiled TDR probe (ϵ_{coil} versus soil water content) was carried out in a funnel apparatus (Fig. 3) containing a glass porous plate (pyrex, 10- to 15- μm pore size, Corning, NY), which was in hydraulic contact with a hanging water column. While increasing this water column length, water from the soil sample drained freely into a burette, with the distance between the center of the ceramic of the tensiometer and the drain outlet equal to the imposed h . After saturation of the porous plate by adjusting the drain end of the tubing just above the plate, the soil was carefully packed in the funnel with the combined tensiometer-coiled

TDR probe positioned in the center of the soil sample. Subsequent soil saturation was achieved by further elevation of the water-filled tubing to slightly above the surface of the soil sample. Using the combined tensiometer-TDR probe, the soil water retention data of five soils were determined. These investigated soils were a Oso-Flaco fine sand, reported by Heeraman et al. (1997) and Eching and Hopmans (1993), a Ottawa sand (natural quartz sand, 0.1- to 0.4-mm particle diam., F-50 silica sand, U.S. Silica Co., Berkeley Springs, WV), a Columbia fine sandy loam (Coarse-loamy, mixed, superactive, nonacid, thermic Oxyaquic Xerofluvents), a Lincoln sandy loam (obtained from the EPA R.S. Kerr Environmental Research Laboratory, Ada, OK), both reported by Liu et al. (1998), and a washed sand (SRI30 supreme sand-30, Silica Resources Inc., Marysville, CA).

Starting from saturation, the h was decreased in steps by increasing the length of the hanging water column. After hydraulic equilibrium was established for each step, as indicated by zero drainage rate, the required TDR, tensiometer, and water volume measurements were completed. Initial suction increments were 5 cm, but after the soil-air entry value was exceeded, suction steps were increased to 10 cm. The maximum applied suctions were about 80 cm for the Oso Flaco, Ottawa, and washed SRI, 170 cm for the Lincoln soil, and 325 cm for the Columbia fine sandy loam. The funnel was covered with perforated PVC film to prevent evaporation.

Dielectric measurements were conducted with a 1502C Tektronix cable tester (Tektronix, Inc., Irvine, CA) connected to

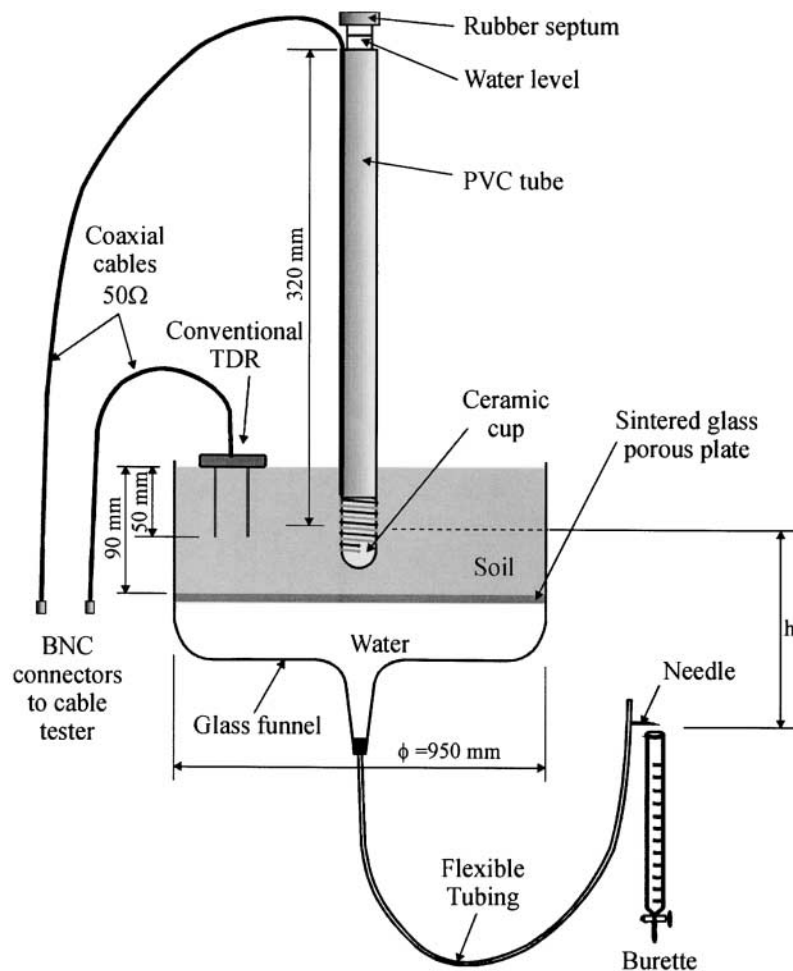


Fig. 3. Experimental design for determining soil water retention curves with the combined tensiometer-coiled TDR probe.

the serial port of a laptop computer. The winTDR98 software (<http://psb.usu.edu/wintdr98> [verified 29 May 2002]) was used to identify the first and second reflection points of the wave-form and to calculate the dielectric constant (Vaz and Hopmans, 2001a). Water content at each step was determined from measured drain water volumes in the burette. The h was determined by adding the height of the water column of the tensiometer (320 mm) to the tensiometer pressure transducer (Soil Measurement Systems Inc., Tucson, AZ) readings, immediately below the rubber septum of the tensiometer (Fig. 3). At selected times, the bulk soil dielectric coefficient (ϵ_{soil}) was measured with a two-rod 5-cm long conventional-TDR probe as tested in Vaz and Hopmans (2001a), simultaneously with the combined tensiometer-coiled TDR, h and drainage outflow readings (Fig. 3). At the end of each experiment, the soil material was oven-dried to determine the saturated water content and bulk density (Table 1). Calibration curves were obtained by fitting the experimental ϵ_{coil} data versus water content with a third-order polynomial equation.

Testing of Mixing Model

In addition to the direct calibration, the mixing model approach (Birchak et al., 1974; Dobson et al., 1985; Roth et al., 1990), adapted to the tensiometer-coiled TDR probe, was tested. However, rather than application of the mixing model to include all three soil phases directly, the dielectric constant measured with the tensiometer-coiled TDR probe (ϵ_{coil}) was related to the soil dielectric constant of the surrounding soil, determined by the conventional probe (ϵ_{soil}) and to the dielectric constant of the water-filled ceramic cup of the tensiometer (ϵ_{cup}), according to:

$$\epsilon_{\text{coil}}^n(\theta[h]) = w\epsilon_{\text{cup}}^n(h) + (1 - w)\epsilon_{\text{soil}}^n(\theta[h]) \quad [2]$$

where w is a weighting factor ($0 \leq w \leq 1$) that partitions the measured dielectric constant as determined by the coiled-TDR probe between contributions from the water-filled porous cup (ϵ_{cup}) and the bulk soil (ϵ_{soil}). Hence, the dielectric constant measured by the tensiometer-coiled TDR probe is a weighted average dielectric constant of the soil (solid particles, water, and air) and the water-filled ceramic porous cup. Since the mixing model includes the unknown θ -dependency of ϵ_{soil} , it cannot generally be used as a substitute for the empirical calibration curve, unless the relationship between water content and the soil's dielectric such as Topp et al.'s (1980) equation is known.

An optimal design of the coiled probe would minimize the contribution of the cup to the dielectric measurement (or minimize the value of w), thereby maximizing the sensitivity of the coiled probe measurement to bulk θ . The exponent n is a shape factor whose value depends on the soil particle's orientation with respect to the applied electric field and must be $-1 \leq n \leq +1$ (Roth et al., 1990). However, its physical significance was criticized by Hilhorst et al. (2000). Dielectric constants ϵ_{coil} and ϵ_{soil} vary with θ and corresponding h , whereas the value of ϵ_{cup} depends on the water content of the porous

cup that is controlled by the soil h . The standard porous cups are manufactured such that the air-entry value (or bubbling pressure) of the porous ceramic cup is larger than 700 cm, to prevent entry of air into the tensiometer for h larger (less negative) than -700 cm. Hence, in principle, the pores of the porous cup should remain completely water-filled during the drainage experiment. However, some pores of the ceramic cup may partially drain as suction is applied to the soil (Or and Wraith, 1999), without exceeding its air-entry value. In addition, some drainage of the porous cup is facilitated if trapped air is present in the porous cup. This may occur even though no appreciable amounts of air can enter into the tensiometer. Consequently, the ceramic cup is characterized by a retention curve. In the conducted drainage experiments, ϵ_{coil} was measured with the combined tensiometer-coiled TDR probe, whereas ϵ_{soil} was determined from dielectric measurements with the conventional-TDR probe (two-rod, 5-cm long).

To test the validity of Eq. [2] for the coiled-TDR probe, we must first determine values for ϵ_{soil} and ϵ_{cup} . The dielectric constant of the bulk soil (ϵ_{soil}), as measured with the conventional straight TDR probe, can be written in terms of the fractional bulk volume of each three soil phases (solid, gas, and water), according to Dobson et al. (1985):

$$\epsilon_{\text{soil}} = [(1 - \phi)\epsilon_s^\alpha + (\phi - \theta)\epsilon_a^\alpha + \theta\epsilon_w^\alpha]^{1/\alpha} \quad [3]$$

where ϕ ($\text{cm}^3 \text{cm}^{-3}$) and θ ($\text{cm}^3 \text{cm}^{-3}$) denote the soil porosity and volumetric water content, respectively, and ϵ_a , ϵ_w are the dielectric constant of the air and water, respectively, with assumed values of $\epsilon_a = 1.0$ and $\epsilon_w = 80$. The dielectric constant of the soil solid material ϵ_s varies from 3 to 5, depending on its texture, mineralogy, and organic matter content and will be fitted accordingly. As in the mixing model of Eq. [2], the exponent α depends on the geometry of the soil solid phase and the soil's orientation with respect to the applied electric field between the two straight wave guides of the conventional TDR probe (Roth et al., 1990).

To account for the influence of water potential on the dielectric of the porous cup (ϵ_{cup}), its relation must be determined separately. An additional experiment was conducted to determine ϵ_{cup} of the water-filled tensiometer-coiled TDR probe, with the porous cup exposed to the dry air of the laboratory. As a result of the evaporation of water on the ceramic porous cup surface, water in the tensiometer will experience suction, which will increase as the cup is continuously exposed to evaporation. From simultaneous dielectric measurement of the coiled cup in air ($\epsilon_{\text{coil-air}}$) and tensiometer readings, the following two-phase mixing model can be formulated:

$$\epsilon_{\text{coil-air}}^m(h) = w\epsilon_{\text{cup}}^m(h) + (1 - w)\epsilon_a^m \quad [4]$$

where ϵ_a is the dielectric constant of air (equal 1), w is the weighting factor, and m is the shape factor with a value likely to be different than in Eq. [2], but equally constrained to ranges of $-1 \leq m \leq +1$. The weighting factor (w) was assumed equal to the value used in Eq. [2], since the electrical field configuration can be considered approximately independent of the type of dielectric material surrounding the probe (water, air, or wet soil), and is a property of the probe design (Knight, 1992; Ferre et al. 1998) only.

Dependence of $\epsilon_{\text{coil-air}}$ with h was fitted with an equation similar to that of van Genuchten (1980):

$$\epsilon_{\text{coil-air}} = \epsilon_{\text{res}} + (\epsilon_{\text{sat}} - \epsilon_{\text{res}}) \left(\frac{1}{1 + (\gamma h)^p} \right)^{p-1} \quad [5]$$

where ϵ_{res} and ϵ_{sat} are the dielectric constants of the tensiometer-coiled TDR probe measured at residual and saturation conditions and γ and p are empirical parameters. Hence, after

Table 1. Soil bulk density (ρ), saturated water content (θ_{sat}), and porosity (ϕ) and fitted parameters α and ϵ_s (Fig. 6).

Soil	ρ g cm^{-3}	$\theta_{\text{sat}}^\dagger$ $\text{cm}^3 \text{cm}^{-3}$	ϕ^\ddagger	α	ϵ_s
Oso Flaco	1.53	0.400	0.423	0.46	4.99
Ottawa	1.65	0.348	0.377	0.49	5.00
SRI	1.60	0.373	0.396	0.49	5.00
Columbia	1.35	0.485	0.491	0.76	3.63
Lincoln	1.72	0.292	0.351	0.76	4.72

† Estimated from outflow data.

‡ Estimated from soil bulk density: $\phi = 1 - \rho/\rho_s$, where $\rho_s = 2.65 \text{ g cm}^{-3}$.

fitting of ϵ_{res} , ϵ_{sat} , γ , and p to the experimental cup-in-air data and subsequent substitution of Eq. [5] into Eq. [4], ϵ_{cup} can be written in terms of the h , and weighting and shape factor parameters w and m , assuming that $\epsilon_a = 1.0$ (Eq. [A1]). Subsequently, after fitting Eq. [3] to each soil type, yielding soil-specific values of ϵ_s and α , Eq. [2] was fitted to all soils combined, yielding parameter values for w , n , and m . The final form of the resulting mixing model is Eq. [A2] in the Appendix.

RESULTS AND DISCUSSION

Direct Calibration

Dielectric constant values as measured with the tensiometer-coiled TDR (ϵ_{coil}) for all five tested soil materials are presented in Fig. 4. Notably at high water content values, ϵ_{coil} is smaller than the bulk soil dielectric constant at equal water content values, because of the contribution of the lower dielectric of the saturated porous cup to the composite or bulk dielectric measurement of the coiled TDR probe. However, the opposite is true at low θ values when ϵ_{coil} is larger than ϵ_{soil} . Unexpectedly, the results in Fig. 4 show that the ϵ_{coil} is variable for the same water content among five different soils. As is demonstrated later, this soil dependency was caused by the slight desaturation of the porous cup by increasing soil water suction of the surrounding soil, thereby affecting the composite dielectric of the coiled TDR probe measurement volume that includes the porous cup. Since increasingly finer-textured soils will require increasing suction to achieve identical θ values, the finer-textured Columbia soil (solid triangles in Fig. 4) had the lowest ϵ_{coil} value for a given θ among all five soils. This largest suction causes maximum desaturation of the porous cup, thereby decreasing ϵ_{cup} and ϵ_{coil} as compared with the other soils with the same volumetric water content value.

Variation of ϵ_{coil} with θ for all soils analyzed suggests that the combined tensiometer-coiled TDR probe can

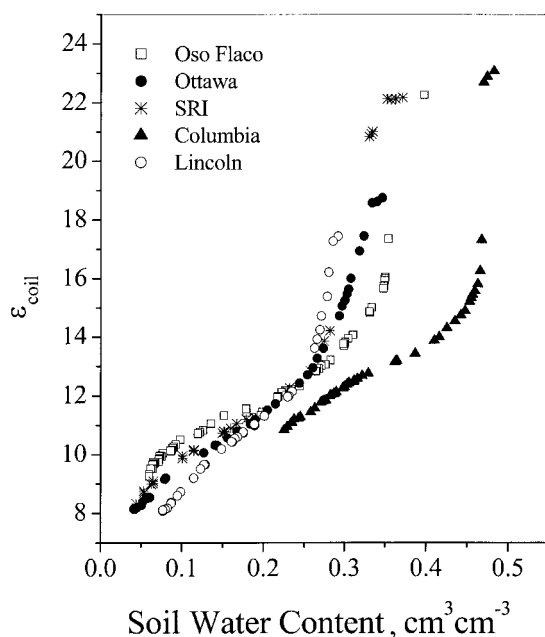


Fig. 4. Dielectric constant measured with the tensiometer-coiled TDR probe (ϵ_{coil}) as a function of the soil water content.

be used to determine θ of the soil after soil-specific calibration. This was done by fitting the ϵ_{coil} and θ data with a third-order polynomial equation, using the independently measured water content data from outflow measurements. Fitted parameters and correlation coefficients for all soils are presented in Table 2. We conclude that the third-order polynomial equation provides excellent fitting of the experimental data with correlation coefficients (R^2) between 0.986 and 0.995.

Using the polynomial calibration curves for each soil, water content was estimated from the measured ϵ_{coil} data, thereby providing soil water retention information when combined with the independently measured h data. Agreeably, all predicted retention data were determined by polynomial fitting to the measured data, and were not independently obtained. Figure 5 shows the resulting $\theta(h)$ relationships comparing data with water content determined by the tensiometer-coiled TDR probe (solid symbols) and by drainage outflow measurements (open symbols). Measured and estimated retention values are close, but some deviations are apparent for the Oso Flaco sand in the low water content range, and for the Columbia soil near saturation. Measured saturated water content values (either by outflow (Table 1) or from coiled TDR measurements) in Fig. 4 were lower than predicted from porosity calculations ($\phi = 1 - \rho_b/\rho_s$, where ρ_b denotes the dry soil bulk density and $\rho_s = 2.65 \text{ g cm}^{-3}$), likely because of air entrapment.

Mixing Model Validation

Dielectric constant data measured with the conventional-TDR probe as a function of the water content measured by outflow are presented in Fig. 6. The dielectric behavior of most soils was similar to the Topp equation (Topp et al., 1980), as indicated by the dashed line, indicating that the 5-cm long transmission lines were sufficiently long to yield reliable θ data. However, the dielectric values for the Columbia and Lincoln soils were higher than for the other soils and the Topp equation for reasons that are not clear. Fitting Eq. [3] to these data provides soil dependent ϵ_s and α values, which are presented in Table 1. Fitted values of ϵ_s , which depend on soil texture, mineralogy, and organic matter, are in the range found for most mineral soils (3–5). The α -values for Oso Flaco, Ottawa, and SRI (sandy soils) are close to reported values (approximately 0.5) for various soils (Dobson et al., 1985; Dasberg and Hopmans, 1992; Roth et al., 1992; Panizovsky et al., 1999; Vaz and Hopmans, 2001a,b), but α values for the Columbia and Lincoln loamy soils were much higher than values normally found ($\alpha = 0.76$). Hilhorst et al. (2000) attributed these large deviations in α values to assumptions of Birchak's mix-

Table 2. Third-order polynomial equation coefficients obtained with the coiled TDR-probe dielectric data (ϵ_{coil}) for each soil.

Soil	Coefficients: $\theta = A + B\epsilon_{\text{coil}} + C\epsilon_{\text{coil}}^2 + D\epsilon_{\text{coil}}^3$				R^2
	A	B	C	D	
Oso Flaco	-1.4162	0.4282	-0.0333	0.000852	0.988
Ottawa	-0.7182	0.2285	-0.0151	0.000274	0.995
SRI	-0.8827	0.2868	-0.0226	0.000605	0.998
Columbia	-1.3665	0.3992	-0.0257	0.000450	0.986
Lincoln	-0.1484	0.0044	0.0150	-0.001120	0.993

ing model, neglecting dielectric depolarization as caused by electric field refractions at phase interfaces.

The variation of $\epsilon_{coil-air}$, measured by the tensiometer-coiled TDR probe in air, as a function of the h (Fig. 7)

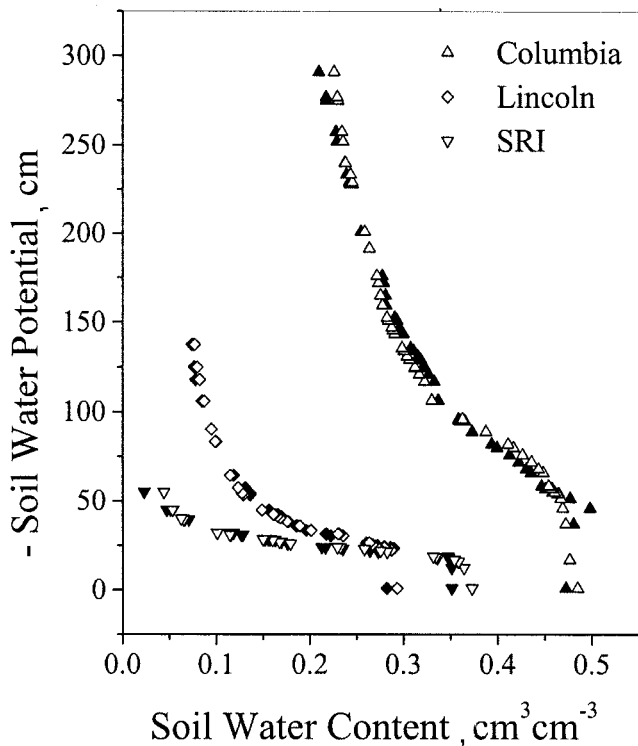
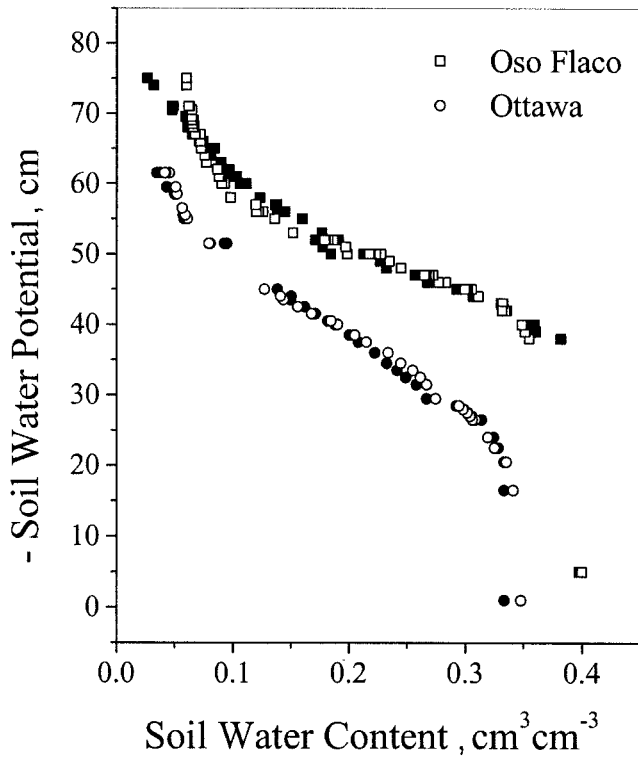


Fig. 5. Comparison of soil water retention curves for Oso Flaco and Ottawa (a) and SRI, Columbia and Lincoln (b) with water content measured by drainage outflow (open symbols) and after calibration of the combined tensiometer-coiled TDR probe (solid symbols).

resulted in fitted values for the parameters ϵ_{res} , ϵ_{sat} , γ , and p (Eq. [5]) equal to 5.716, 8.911, 0.045, and 2.092 respectively. As hypothesized earlier, the decrease of the measured dielectric of the porous cup ($\epsilon_{coil-air}$) was caused by draining pores in the ceramic. Hence, the resulting drainage curve in Fig. 7 may be characteristic for the pore-size distribution and entrapped air volume of the cup.

Tensiometer-coiled TDR data (ϵ_{coil}) were fitted to Eq. [A2], yielding parameter values of $w = 0.687$, $n = -0.48$, and $m = 0.34$. The weighting factor w indicates the large influence of the probe material (water-saturated ceramic porous cup) on the dielectric measurement of the tensiometer-coiled TDR probe. Possibly, the influence of the geometry of the coiled probe (wire thickness and spacing) may be further investigated to reduce this w value, thereby increasing the sensitivity of the tensiometer-coiled TDR probe. Different values for the shape factor, n (wet soil) and m (air) are expected because its value describes the position of the applied electrical field relative to the geometry of the surrounding medium (Roth et al., 1990). Hilhorst et al. (2000) proposed that the shape factor is merely an empirical constant, to account for electric field refractions in the bulk soil that are not considered in Birchak's mixing model. Validation of the mixing model theory applied to the tensiometer-coiled TDR probe was conducted by comparing ϵ_{coil} predicted with measured ϵ_{coil} data (Fig. 8). The linear fit of these data, when combining all soils, resulted in a correlation coefficient $R^2 = 0.83$ and a root mean squared error RMSE = 0.4. Although the mixing model results were relatively poor for the Columbia soil near soil saturation, the general results of Fig. 8 validate the applied mixing model concept for the coiled-TDR probe. Possible errors may be caused by model complexity resulting in a large number of fitted parameters and inadequate soil-probe contact. Further investigations are proposed

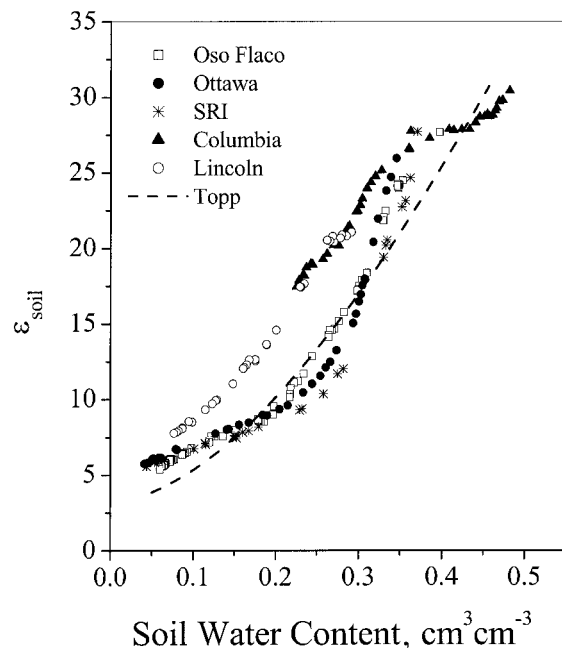


Fig. 6. Bulk soil dielectric constant (ϵ_{soil}) as measured with a conventional TRD probe (two-rod 5-cm long) as a function of water content as measured by drainage outflow measurements.

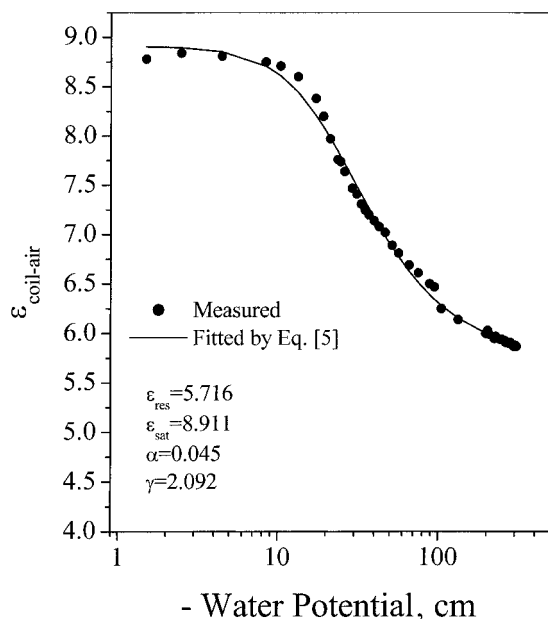


Fig. 7. Dielectric constant of the tensiometer-coiled TDR probe in air, as a function of the porous cup water potential (or drainage curve).

to improve on the physically based mixing model results for the combined tensiometer-coiled TDR probe.

We agree that soil-specific calibration of the combined tensiometer-coiled TDR probe as caused by desaturation of the tensiometer cup restricts its wide application. Therefore, we are recommending to include a low-conductive, water-impermeable epoxy resin in the groove between the transmission lines and the porous cup or to lacquer-coat the wires, thereby largely eliminating local desaturation and reducing the contribution of the por-

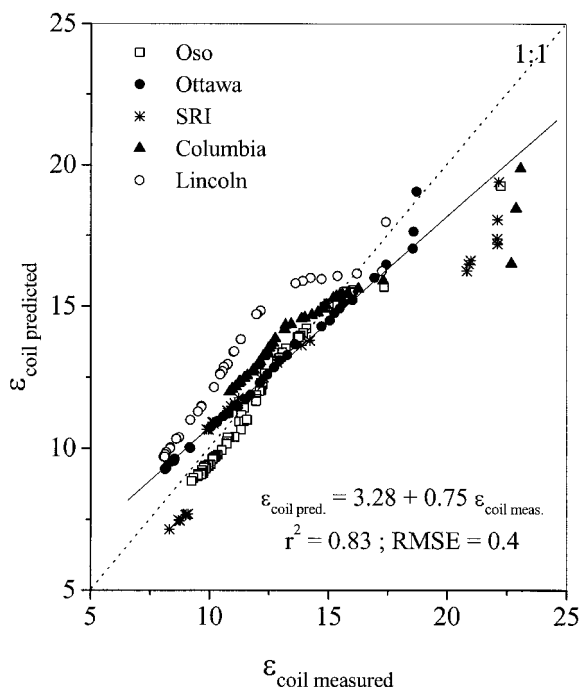


Fig. 8. Comparison of measured soil dielectric constant measured using the combined tensiometer-coiled TDR probe with estimated values using the mixing model approach of Eq. [2].

ous cup to the composite dielectric constant of the coiled TDR. One may also question the appropriateness of placement of the TDR wires in the porous cup. For example, it means that TDR readings are most sensitive to soil disturbance in the bottom of the excavation hole, where adequate soil-TDR probe contact may be questionable. However, it was our goal to develop a combined sensor that provides for the coupled measurement of both θ and h within approximately identical soil volumes. Moreover, soil contact and soil disturbance problems can make all invasive soil measurements questionable. Improved alternative designs may provide for fitting the coaxial cable inside the PVC pipe of the tensiometer.

Although we have shown that the mixing model is valid, we do not propose adapting the mixing model as a procedure to estimate the coiled probe dielectric constant and consequently the water content. Instead, we suggest using the empirical polynomial fitting approach to estimate water content and soil retention curves because of its direct application, simplicity and accuracy. Application of the mixing model theory to the tensiometer-coiled TDR, however, allows a better understanding of the influence of each specific dielectric (ceramic porous cup, water, air, soil) to the bulk dielectric constant measured with the tensiometer-coiled TDR probe, thereby providing information on ways to improve probe sensitivity.

CONCLUSIONS

A combined tensiometer-coiled TDR probe was developed by wrapping two parallel wires around the porous cup of an existing tensiometer. By simply measuring the dielectric constant of the soil surrounding the porous cup with a cable tester simultaneously with the tensiometer readings, both h and θ are measured for the same soil volume around the porous cup at the same time. Directly fitting the coiled-TDR data (ϵ_{coil}) to independently measured water content measurements using a third-order polynomial equation provided accurate water content measurements that allowed in situ determination of soil water retention data for all tested soils after calibration, when combined with tensiometer measurements. Moreover, the mixing theory was tested for the combined probe. Although the presented concept and development was tested for laboratory conditions only, we believe that a similar combined probe design can be equally applicable for estimation of field soil water retention.

APPENDIX A

Substitution of Eq. [5] in [4] yields:

$$\epsilon_{cup}(h) = \left[\frac{\left(\epsilon_{res} + (\epsilon_{sat} - \epsilon_{res}) \left(\frac{1}{1 + (\gamma h)^p} \right)^{\frac{p-1}{p}} \right)^n + (w - 1)}{w} \right]^{\frac{1}{m}} \tag{A1}$$

Subsequent substitution of [A1] into Eq. [2], while using Eq. [3] gives the general form of the mixing model:

$$\epsilon_{\text{coil}}(\theta, h) = \left[w \left[\frac{\left[\epsilon_{\text{res}} + (\epsilon_{\text{sat}} - \epsilon_{\text{res}}) \left(\frac{1}{1 + (\gamma h)^p} \right)^{p-1} + (w-1) \right]^m}{w} \right]^{\frac{n}{m}} + (1-w) \left[(1-\phi) \epsilon_s^\alpha + (\phi-\theta) \epsilon_a^\alpha + \theta \epsilon_w^\alpha \right]^{\frac{n}{\alpha}} \right] \quad [\text{A2}]$$

Equation [A2] was fitted to the $\epsilon_{\text{coil}}(\theta, h)$ data, after a priori fitting of parameters ϵ_{res} , ϵ_{sat} , γ , p , ϵ_s and α , to yield optimized parameter values for w (weighting factor), m and n (shape factor parameters).

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REFERENCES

- Arya, L.M., D.A. Farrell, and G.R. Blake. 1975. A field study of soil water depletion patterns in presence of growing soybeans roots: I. Determination of hydraulic properties of soil. *Soil Sci. Soc. Am. Proc.* 39:424-430.
- Baumgartner, N., G.W. Parkin, and D.E. Elrick. 1994. Soil water content and potential measured by hollow time domain reflectometry probe. *Soil Sci. Soc. Am. J.* 58:315-318.
- Birchak, J.R., C.Z.G. Gardner, J.E. Hipp, and J.M. Victor. 1974. High dielectric constant microwave probes for sensing soil moisture. *Proc. IEEE* 62:93-98.
- Bruce, R.R., and R.J. Luxmoore. 1986. Water retention: Field methods. p. 663-686. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Cheng, J.D., T.A. Black, and R.P. Willington. 1975. A technique for the field determination of the hydraulic conductivity of forest soils. *Can. J. Soil Sci.* 55:79-82.
- Dane, J.H., and J.W. Hopmans. 2002. Water retention and storage. p. 671-720. *In* J.H. Dane and G.C. Topp (ed.) *Methods of soil analysis: Part 4—Physical methods*. SSSA Book Ser. 5. SSSA, Madison, WI.
- Dasberg, S., and J.W. Hopmans. 1992. Time domain reflectometry calibration for uniformly and nonuniformly wetted sandy and clayey loam soils. *Soil Sci. Soc. Am. J.* 56:1341-1345.
- Dobson, M.C., F.T. Ulaby, M.T. Hallikainen, and M.A. El-Rayes. 1985. Microwave dielectric behavior of wet soil: II Dielectric mixing models. *IEEE Trans. Geosci. Remote Sensing* GE-23:35-46.
- Eching, S.O., and J.W. Hopmans. 1993. Optimization of hydraulic function from transient outflow and soil water pressure data. *Soil Sci. Soc. Am. J.* 57:1167-1175.
- Ferre, P.A., J.H. Knight, D.L. Rudolph, and R.G. Kachansoki. 1998. The sample areas of conventional and alternative time domain reflectometry probes. *Water Resour. Res.* 34:2971-2979.
- Gardner, C.M.K., D. Robinson, K. Blyth, and J.D. Cooper. 2001. Soil water content. p. 1-64. *In* K.A. Smith and C.E. Mullins (ed.) *Soil and environmental analysis: Physical methods*, 2nd ed. Marcel Dekker, New York.
- Heeraman, D.A., J.W. Hopmans, and V. Clausnitzer. 1997. Three dimensional imaging of plant roots in situ with X-ray Computed Tomography. *Plant Soil* 189:167-179.
- Hilhorst, M.A., C. Dirksen, F.W.H. Kampers, and R.A. Feddes. 2000. New dielectric mixture equation for porous materials based on depolarization factors. *Soil Sci. Soc. Am. J.* 64:1581-1587.
- Klute, A. 1986. Water retention: Laboratory methods. p. 635-662. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Knight, J.H. 1992. Sensitivity of time domain reflectometry measurements to lateral variations in soil water content. *Water Resour. Res.* 28:2345-2352.
- Liu, Y.P., J.W. Hopmans, M.E. Grismer, and J.Y. Chen. 1998. Direct estimation of air-oil and oil-water capillary pressure and permeability relations from multi-step outflow experiments. *J. Contam. Hydrol.* 32:223-245.
- Nissen, H.H., P. Moldrup, and K. Henriksen. 1998. High-resolution time domain reflectometry coil probe for measuring soil water content. *Soil Sci. Soc. Am. J.* 62:1203-1211.
- Nissen, H.H., P. Moldrup, T. Olesen, and P. Raskmark. 1999a. Printed circuit board time domain reflectometry probe: measurements of soil water content. *Soil Sci.* 164:454-466.
- Nissen, H.H., P. Moldrup, L.W. Jonge, and O.H. Jacobsen. 1999b. Time domain reflectometry coil probe measurements of water content during fingered flow. *Soil Sci. Soc. Am. J.* 63:493-500.
- Noborio, K., R. Horton, and C.S. Tan. 1999. Time domain reflectometry probe for simultaneous measurement of soil matric potential and water content. *Soil Sci. Soc. Am. J.* 63:1500-1505.
- Or, D., and J.M. Wraith. 1999. A new soil matric potential sensor based on time domain reflectometry. *Soil Sci. Soc. Am. Proc.* 39:221-223.
- Panizovsky, A.A., S.M. Chudinova, and Y.A. Pachepsky. 1999. Performance of TDR calibration models as affected by soil texture. *J. Hydrol.* 218:35-43.
- Roth, K., R. Schulin, H. Fluehler, and W. Attinger. 1990. Calibration of TDR for water content measurement using a composite dielectric approach. *Water Resour. Res.* 26:2267-2273.
- Royer, J.M., and G. Vachaud. 1975. Field determination of hysteresis in soil-water characteristics. *Soil Sci. Soc. Am. Proc.* 39:221-223.
- Scholl, D.G., and A.R. Hibbert. 1973. Unsaturated flow properties used to predict outflow and evapotranspiration from a sloping lysimeter. *Water Resour. Res.* 9:1645-1655.
- Selker, J.S., L. Graff, and T. Steenhuis. 1993. Noninvasive time domain reflectometry moisture measurement probe. *Soil Sci. Soc. Am. J.* 57:934-936.
- Simmons, C.S., D.R. Nielsen, and J.W. Biggar. 1979. Scaling of field-measured soil water properties. *Hilgardia* 47:77-173.
- Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resour. Res.* 16:574-582.
- Van Genuchten, M.T. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892-898.
- Vaz, C.M.P., and J.W. Hopmans. 2001. Simultaneous measurement of soil penetration resistance and water content with a combined penetrometer-TDR moisture probe. *Soil Sci. Soc. Am. J.* 65:4-12.
- Vaz, C.M.P., L.H. Bassoi, and J.W. Hopmans. 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer-TDR probe. *Soil Tillage Res.* 60:35-42.
- Whalley, W.R., P.B. Leeds-Harrison, P. Joy, and P. Hoefsloot. 1994. Time domain reflectometry combined in an integrated soil water monitoring system. *J. Agric. Eng. Res.* 59:141-144.
- Watson, K.K., R.J. Reginato, and R.D. Jackson. 1975. Soil water hysteresis in a field soil. *Soil Sci. Soc. Am. Proc.* 39:242-246.