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Spatially characterizing apparent electrical conductivity and water content of surface soils with time domain reflectometry

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Abstract

Unlike other measurement methods discussed in this special issue, time domain reflectometry (TDR) has the ability to measure both water content (θ) and apparent electrical conductivity (EC_a) of soils. From simultaneous knowledge of θ and EC_a, the soil solution electrical conductivity (EC_s) and even the concentration of specific ionic constituents such as NO_3–nitrogen may be estimated through soil-specific calibration. This paper provides an introduction, some theoretical background, and a practical review of the TDR method for spatially characterizing θ, EC_a, and related attributes in soils. Time domain reflectometry measurement principles for determining θ, EC_a, and EC_s, along with suggestions for inferring matric potential from dielectric measurements, are addressed. We discuss point, handheld, and vehicle-based measurement methods. Applications of TDR to spatially characterize θ in a hilly agricultural field using TDR and gravimetric methods, and to monitor θ and nitrate concentrations at three depths under peppermint production, are presented. A pickup-mounted TDR measured θ at 100 m × 100 m grid spacing in two wheat fields in north-central Montana. Soil θ, as well as NO_3–N, grain yield, and grain protein increased from upper to lower slopes. Soil θ early in the growing seasons appeared critical to final yields in this rainfed system. An array of fixed

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TDR probes was monitored over two growing seasons under peppermint in northwest Montana, to estimate θ, EC_s, and NO_3–N every 6 h at 12 field locations. Although the field soils appeared uniform, measured spatial patterns of θ, EC_s, and NO_3–N were highly space- and time-variant. These results indicate that TDR is a potentially useful tool for precision agriculture, and that fixed TDR arrays could serve as real-time monitoring systems for water and fertilizer salts in soil profiles. The primary limitation of the TDR method for spatially characterizing θ and EC at soil management scales using fixed arrays is the cable length limitation of about 20–30 m. Mobile platforms are of high interest, and prototype designs have been reported in the literature. Truly ‘on-the-fly’ TDR measurements for large-scale applications may be feasible in the near future.

Keywords: TDR; Soil water; Electrical conductivity; Spatial measurement; Dielectric constant

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1. Introduction

The ability to provide reliable, spatially explicit information concerning field soil water, electrical conductivity, and ionic solute status is needed to advance the spatial resolution of soil and land management. Soil water status is critical to plant growth, chemical fate and transport, and microbial processes. Apparent soil electrical conductivity is related to salinity, wetness, clay content, and other attributes of interest in soil science and management. Efficient use of our soil and water resources mandates that knowledge of these and other land attributes be readily available to researchers and practitioners. Given the expected variations in soil properties in space and time (Mulla and McBratney, 1999), we must develop effective means to characterize them across representative field areas.

Time domain reflectometry (TDR) is a relatively new method for measurement of soil water content (θ) and apparent electrical conductivity (EC_a). Both θ and EC_a have substantial utility in studying a variety of soil and hydrologic processes. The first application of TDR to soil water measurements was reported by Topp et al. (1980) and Dalton et al. (1984) were the first to discuss its utility for EC. TDR has several advantages over many other soil water content measurement methods, which have been responsible for its rapid and extensive adoption during the past two decades.

A unique advantage of TDR is its ability to rapidly measure both EC_a and θ with the same probes and in the same sampling volume. Knowledge of surface soil θ presents inherent value in many land management endeavors. In addition to the added value (beyond EC_a) of θ measurements, the paired measurements allow estimation of the soil solution electrical conductivity (EC_s) (Risler et al., 1996; Mallants et al., 1996; Persson, 1997; Vogeler et al., 1997), and from EC_s the concentration of specific solutes such as nitrate nitrogen (NO_3–N), based on soil-specific calibrations (Nissen et al., 1998; Das et al., 1999). TDR is particularly well suited to near-surface measurements because it has well-defined spatial resolution, integrates along the entire probe length, often does not require soil-specific calibration, and the measurement itself is quite rapid. However, it is not well suited to very hard or stony soils because the (typically multi-rod) probes must be inserted into the soil. Stones or other obstructions may either prevent insertion entirely, or if they are pushed aside they may create air voids adjacent to the rods that will contribute to inaccurate measurements of the apparent soil θ.

This paper briefly examines the working principles of TDR. Recent and more comprehensive reviews of the TDR technique include those of Noborio (2001), Jones et al. (2002), Ferré and Topp (2002), Hendrickx et al. (2002), Wraith (2003), and Robinson et al. (2003). We consider measurements from the point or sample scale to transects and field scales, using static arrangement of sensors and mobile sensor platforms. Some applications of TDR to spatially characterize θ, EC_a, EC_s, and NO_3–N concentrations of surface soils are presented and discussed.

2. Review of spatial characterization of soil θ and EC using TDR

TDR began as a point source measurement technique used in the laboratory and for obtaining field soil water content profiles (Topp et al., 1980, 1982a,b). The technique offered high spatial and temporal resolution relative to other methods. The advent of automating and multiplexing capability (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Herkelrath et al., 1991) increased the ability to monitor the dynamics and spatial patterns of θ and EC_a. There has been a recent increase in the use of TDR to monitor spatial patterns, for example, in assessing the use of ground penetrating radar with TDR being used as a reference (Huisman et al., 2001). TDR has even been adapted to fit on mobile platforms such as pickups, tractors or spray rigs (Inoue et al., 2001; Long et al., 2002). This may still require insertion of the TDR probe but is a more efficient means to cover large areas. The system described by Long et al. (2002) incorporated a global positioning system to document the measurement locations for field-scale mapping. In the following sections we review the transitional steps between point source measurements and field spatial mapping.

2.1. *Point measurement*

TDR is ideally suited to point source monitoring at fixed locations. Electrodes can be either inserted vertically to obtain near-surface soil profile moisture, or horizontally to obtain better depth resolution; horizontal insertion usually requires that a small pit be excavated. Automated measurements at multiple locations can be made using a series of multiplexing devices that may allow up to 512 probes for a single TDR device. In the case of multiple locations monitored using multiplexed probes connected to a single cable tester, users should consider the transmission cable length limitations discussed below.

van Wesenbeeck and Kachanoski (1988) characterized the spatial distribution of soil water in the surface layer across a 20-m transect under a corn crop, using manual TDR measurements repeated every 1–2 days. They documented differential drying and wetting behaviors in the row versus inter-row positions. A similar approach was used by Zhai et al. (1990) to examine the effects of tillage practices on the spatial and temporal variability of near-surface θ under corn.

Wu et al. (2001) monitored soil profile θ and EC_a daily for 117 days at three locations. They used the measurements to evaluate a state space model to describe soil water and salinity dynamics in the presence of a shallow saline groundwater table. Time domain reflectometry probes were installed at five depths from 0.1 to 1.1 m under a cotton (*Gossypium hirsutum* L.) crop. They suggested that the method could be used to aid in irrigation management to alleviate salinity stress. Spatial and temporal dynamics of near-surface soil θ and temperature were investigated by Mohanty et al. (1998), who measured at three depths (2, 7, and 12 cm) at 49 locations spaced 1-m apart in two orthogonal transects. They collected measurements automatically every 20 min for a period of 45 days during different irrigation events. No specific spatial patterns in θ were found along the transects, nor were any clear diurnal temporal structures found, but a spatio-temporal hysteresis was identified in soil temperature.

2.2. Handheld monitoring

Anyone who has carried a cable tester and computer or datalogger around the field for a day will appreciate that the method is not ideally suited to large-scale human-powered mobile monitoring. However, it has been used in this manner, and some interesting and more mobile systems have been presented in the literature (e.g., Brisco et al., 1992). One of the difficulties associated with this sort of approach is that the probe head must be sufficiently robust to cope with multiple insertions into and extractions from the soil; the latter is particularly stressful with typical steel rods in epoxy head probe designs. Robust designs have been produced by some vendors, and may also be user-fabricated.

Time domain reflectometry has been applied to the study of θ for transects and areas by a number of authors with good success (Reeves and Smith, 1992; Urie, 1994; Huisman et al., 2001; Hupet and Vanclooster, 2002). In a study concerning environmental controls of trail erosion processes, Urie (1994) measured θ for the upper 20 cm of soils immediately adjacent to two trails in a mountainous region of southwest Montana. Measurements were obtained three times over 2 years, at 100-m intervals over a combined trail length of 13 km, using a packframe-mounted Tektronix TDR cable tester with datalogger. Hupet and Vanclooster (2002) obtained moisture content using TDR on a 28-point rectangular grid at 15-m spacings. Three-wire TDR probes were placed vertically at each point to monitor θ in the top 20 cm, with measurements taken on 60 dates over the summer. Transect and other measurements covering relatively small land areas are more handily obtained using repeated insertions of single (or a few) probes rather than by automating or re-visiting multiple fixed probes, due to cost. In cases where time-intensive spatial measurements are desired, automation of multiple fixed probes may be optimal. In the case of more substantial land areas, however, the cable length limitations (Section 3.7) will mandate that the operator transport the TDR unit among sites.

2.3. Vehicle based monitoring

Vehicle-based monitoring using TDR is in its infancy. Results using mobile platforms (Western et al., 1998; Inoue et al., 2001; Long et al., 2002) fall into two categories: stop-and-go insertion methods and on-the-fly monitoring. Both approaches have associated functional concerns. When using hydraulics to insert the TDR probe, the ‘feel’ compared to handheld insertion is lost, though probes may be inserted with much greater force. This makes insertion into stony soils a different challenge than with manual insertion, as probes pushed into the ground with a hydraulic ram may have sufficient force to push stones ahead of the rods, creating voids adjacent to the sensor and thereby preventing good contact between sensor

Fig. 1. Mobile vibrating hydraulic hammer TDR probe insertion apparatus developed by Thomsen et al. (2003). Probe rods (1-cm diameter) are spaced 10-cm apart with lengths varying between 20 and 75 cm. Small obstructions are moved to the side and insertion stops if large stones or hard layers are encountered.

and soil. A method of overcoming this has been suggested by Thomsen et al. (2003) who used a vibrating hydraulic hammer that pushed the stones to the side rather than ahead of the probe (Fig. 1). Their mobile TDR is well suited for indurate soils because insertion simply stops if the probe rods encounter stones (above a limited size) or a hard layer; stones are not just pushed out of the way. The problem with the probe head being strong enough to cope with the attendant forces is another consideration for vehicle-based monitoring. A robust probe head design that adapted to a Giddings hydraulic soil coring device was presented by Long et al. (2002).

Western et al. (1998) measured θ in the upper 0.3 m of soil on 11 occasions at 500 point locations on a 10 m × 20 m grid in southeast Australia, with a hydraulic probe insertion system mounted on an all-terrain vehicle. Two additional samplings using more intensive grids to obtain 1000 and 2000 points, respectively, were also obtained. They evaluated the spatial structure of θ using geostatistical analyses. Additional studies have also evaluated spatial variation in near-surface θ using TDR in the USA and Europe (e.g., see Table 1 in Western et al., 1998), where tens to hundreds of sample points were measured, depending on the study. Many of these studies used handheld monitoring, and some used vehicle-based monitoring approaches.

An extension of stop-and-go methods is the development of a system that can work ‘on-the-fly’. This has been an aim in agricultural research for some time, but the engineering difficulties of designing a TDR probe geometry compatible with conventional farming implements remains a challenge. Whalley et al. (1992) presented an innovative capacitance based sensor on a shank. Inoue et al. (2001) presented two parallel plate TDR probe designs (Fig. 2), which could be towed behind a tractor and appeared to give reasonable results. They did not attempt to continuously measure θ while the probes were moving. Practical issues associated with probes dragged through the soil to provide continuous readings range from robustness to maintaining soil contact to friction and geometric design. Anything that is to be dragged through the soil needs to be robust. Probes connected at the base of a metal shank must have a non-conducting mounting segment to electrically isolate the electrodes so that

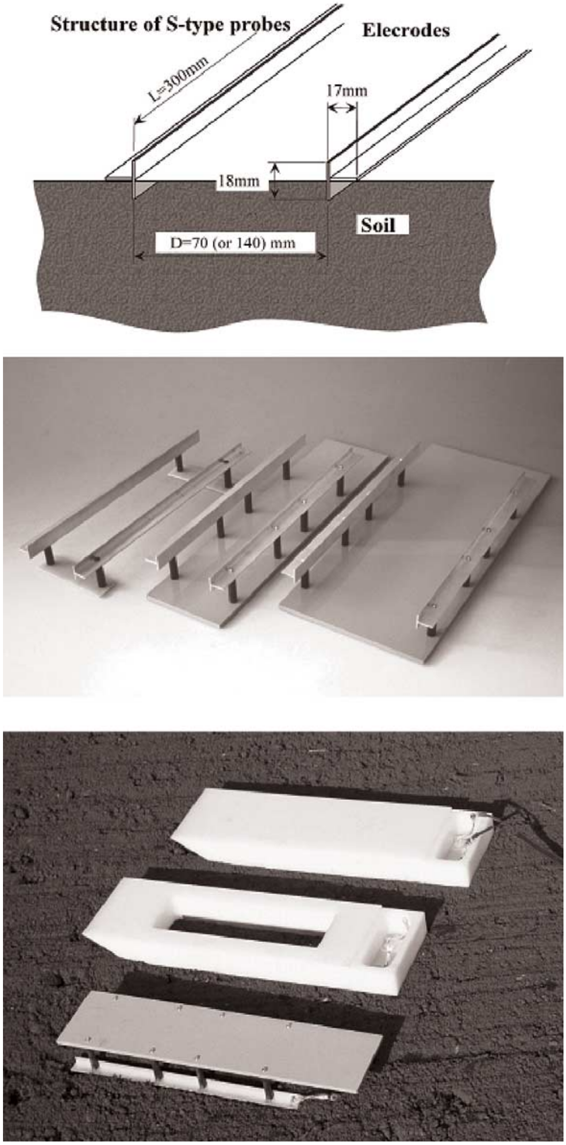

Fig. 2. Schematic (top) and photograph (middle) of sled-shaped (S-type) surface TDR probe prototypes for on-the-go measurement, from Inoue et al. (2001). Bottom panel illustrates different prototype designs using plastic or resin materials (reprinted from Agricultural Water Management, Inoue, Y., Watanabe, T., Kitamura, K., vol. 50, Prototype time-domain reflectometry probes for measurement of moisture content near the soil surface for applications to 'on the move' measurements, pp. 41–52, Copyright (2001), with permission from Elsevier).

the shank does not function as an extension of the probe. Dragging a probe through the soil generates friction and heat, and it is not known how this might affect the reading. Ambient soil temperature has been shown to influence the TDR-measured permittivity (Wraith and Or, 1999; Or and Wraith, 1999a), and EC has a temperature sensitivity of about 2% per °C (Weast, 1986; Heimovaara et al., 1995). A moving probe heated by friction might or might not heat the surrounding soil sufficiently to affect the θ and EC_a measurements. Some probe geometries, such as small plough- or torpedo-shapes, would tend to compact the soil immediately around the sensor, possibly contributing to a non-representative measurement of bulk soil conditions. Two smaller blades might reduce this effect, but these would need to be sufficiently close together to achieve a representative sampling volume. If the plates were too close, on the other hand, clogging might result, interfering with the continual flow of soil between the sensor plates.

In summary, TDR provides high spatial and temporal resolution for point measurements where probes are buried in place, and multiplexing in field applications facilitates probe arrays distanced up to about 20–30 m from the TDR instrument. While complete automation of point measurements is possible, the spatial limitations using a single TDR device make handheld monitoring appealing, in spite of the additional labor required, when point measurements are distributed over large areas. Vehicle-based monitoring using stop-and-go or on-the-fly techniques can be spatially correlated using GPS with potential to map larger areas in less time. Improvements are needed in probe design and understanding of the impact of dynamics on measurements.

3. TDR measurement principles

3.1. Measurement of apparent soil electrical conductivity

Time domain reflectometry provides a measurement of EC using the measured change in impedance across the waveform. The final impedance is evaluated at long signal travel times, where multiple reflections resulting from the probe have died out. This is equivalent to the low frequency resistance across the sample (Dalton et al., 1984; Heimovaara, 1993). Heimovaara and de Water (1993) proposed using the reflection coefficient at infinite time (ρ_∞) as a method of calculating the sample resistance:

$$\rho_\infty = \frac{V_f - V_0}{V_0} \tag{1}$$

where locations V_0 and V_f are illustrated in Fig. 3. The resistance across the electrodes is then calculated according to:

$$R_{tot} = Z_c \frac{1 + \rho_\infty}{1 - \rho_\infty} \tag{2}$$

where R_{tot} is the total resistance (Ω) of the transmission line, Z_c the TDR cable tester impedance (50 Ω), and ρ_∞ is the reflection coefficient at infinite time on the waveform, or at a point sufficiently beyond the probe where the reflection level has stabilized to a final value (e.g., V_f in Fig. 3). Heimovaara and de Water (1993) further proposed that the total

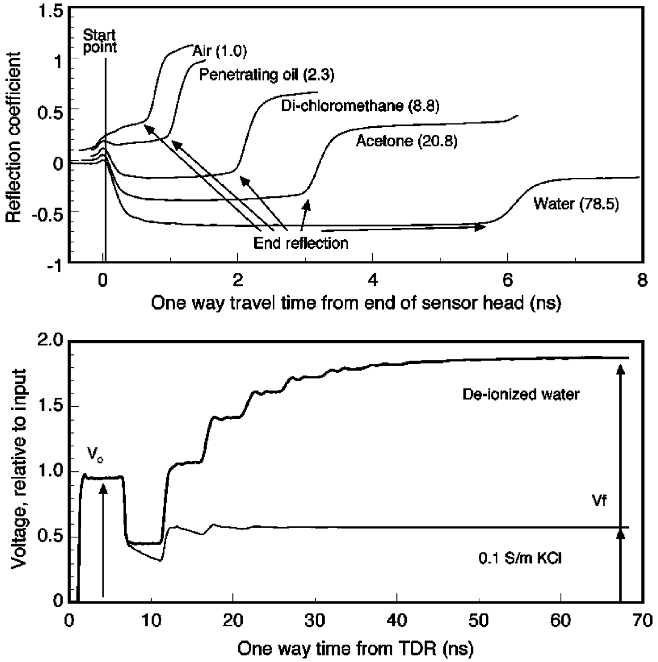

Fig. 3. *Top*: TDR travel time waveforms for probes immersed in several fluids having different dielectric permittivities (in parentheses). The location labeled "start point" represents the beginning of the probe rods, and marked "end reflection" represent the approximate end of the rods. *Bottom*: A TDR waveform showing a greater portion of the trace, from which EC_a may be evaluated. Note the much greater attenuation of the signal in KCl solution than in deionized water.

resistance was made up of two components, that of the cable (R_c) and that of the sample (R_s), $R_t = R_s + R_c$. However, more recently Castiglione and Shouse (2003) demonstrated that this intuitive relationship is inexact and presented a new procedure for calculating R_s. This method is independent of contributions from cable and fittings, and scales the waveform according to the reflection coefficient for an open circuit (ρ_{open}) and for a short circuit (ρ_{short}) in air:

$$\rho_{\text{scaled}} = 2\frac{\rho_{\text{sample}} - \rho_{\text{open}}}{\rho_{\text{open}} - \rho_{\text{short}}} + 1 \tag{3}$$

The value of ρ_{scaled} is used in Eq. (2) in place of ρ_∞ to determine the sample resistance. A convenient and accurate means to calculate EC_a is by the Giese and Tiemann (1975) approach:

$$\text{EC} = \frac{\varepsilon_0 c Z_0}{L Z_c f_T}\left(\frac{2V_0}{V_f} - 1\right) \tag{4}$$

where ε_0 is the dielectric permittivity of free space ($8.854 \times 10^{-12}\,\text{F}\,\text{m}^{-1}$), c the speed of light in vacuum ($3 \times 10^8\,\text{m}\,\text{s}^{-1}$), L the TDR probe length in m, Z_0 the characteristic probe impedance (Ω), Z_c the TDR cable tester output impedance (typically 50 Ω), V_0 the incident pulse voltage, and V_f is the return pulse voltage after multiple reflections have died out (Fig. 3). A temperature correction coefficient f_T is used to relate the measured reference solution to a desired standard temperature (e.g., Hendrickx et al., 2002; Wraith, 2003). Heimovaara et al. (1995) found that the relationship $f_T = 1/(1 + 0.019[T - 25])$ worked well for many saline solutions, using 25 °C as the standard temperature. A separate calibration procedure required to determine the probe characteristic impedance Z_0 is described in references including Hendrickx et al. (2002), Jones et al. (2002), and Wraith (2003). The quantity $\varepsilon_0 c Z_0/L$ is sometimes lumped into a geometric probe constant K (Heimovaara, 1992; Baker and Spaans, 1993), with EC estimated using

$$\mathrm{EC} = \frac{K}{Z_\mathrm{c}}\left(\frac{2V_0}{V_\mathrm{f}} - 1\right) \tag{5}$$

and K (m) calculated using Eq. (4) and the relevant physical quantities ε_o, c, and L. Alternatively, K may be evaluated empirically by immersing the probe in several solutions having known EC, and using $K = \mathrm{EC}_\mathrm{ref} Z_\mathrm{L}/f_T$, with EC_ref the known electrical conductivity of the reference solution, and Z_L the measured resistive load impedance across the probe ($Z_\mathrm{L} = Z_\mathrm{c}/(2V_0/V_\mathrm{f} - 1)$). Soil electrical conductivity measured using TDR has been found to be highly accurate by a number of users (e.g., Heimovaara et al., 1995; Mallants et al., 1996; Spaans and Baker, 1993; Reece, 1998; Hendrickx et al., 2002), who compared TDR to benchtop meter electrode or other independent measurement methods.

3.2. Measurement of soil apparent dielectric constant

An important asset of TDR is the ability to simultaneously determine both EC_a (Dalton et al., 1984) and θ (Topp et al., 1980). TDR measures the dielectric permittivity of materials surrounding the waveguide electrodes or ‘probe’. The relative permittivity (i.e., the dielectric permittivity relative to that in vacuum) for air is 1, for most soil minerals it is in the range 4–8, and that of water is 78.5 at 25 °C. It is this large relative difference between the ε of water and that of the solid and gaseous soil phases that allows accurate determination of θ by measuring the relative permittivity of soils. The origin of the high dielectric permittivity of water comes from the asymmetry of positive and negative charges on the water molecule, leading to a permanent dipole. When placed in an alternating electric field such as that produced by a TDR cable tester, the molecules overcome their random thermal motion and align with the applied field. The process of alignment leads to the storage of electrical energy, which is released once application of the electric field ceases; this is the principle of a capacitor. The storage of electrical energy is termed the real part of the relative dielectric permittivity (ε'_r). Most materials also contain some actual charge carriers; in soils this might be through ionic conductivity, for example. The loss of energy due to actual charge carriers is described by the imaginary part of the permittivity (ε''_r), termed the dielectric loss. The combination of storage and loss leads to a complex permittivity (von Hippel, 1954; Topp et al., 2000):

$$\varepsilon^*_\mathrm{r} = \varepsilon'_\mathrm{r} - \mathrm{j}\left(\varepsilon''_\mathrm{relax} + \frac{\sigma_\mathrm{dc}}{2\pi f \varepsilon_0}\right) \tag{6}$$

where, ε_o is the permittivity in vacuum, $\varepsilon''_{\text{relax}}$ the losses due to molecular relaxation, and σ_{dc} is due to electrical conductivity where f is frequency and j is the imaginary number, $j^2 = -1$. In order to accurately estimate θ in soils the aim is to maximize the real permittivity and minimize the imaginary permittivity, as only the former is related to the volume fraction of water molecules in the volume of soil containing a sensor.

Time domain reflectometry measures the propagation velocity (v_p) of transverse electromagnetic waves through the material surrounding the transmission line (probe). A TDR instrument consists of a voltage generator that creates a step pulse (square wave) containing a broad frequency band, with a bandwidth that typically lies between about 10 kHz and 1 GHz. The step pulse propagates down a transmission line and enters the TDR probe buried in the soil. At the end of the probe the signal encounters an open circuit and is reflected back to the TDR where it is sampled relative to the outgoing pulse. The velocity of signal propagation in the soil sample is determined directly by the dielectric properties of the soil, ε_r (Topp et al., 1980):

$$v_p = \frac{2L}{t} = \frac{c}{\sqrt{\varepsilon_r}} \tag{7}$$

wher L is the length of the probe in meters and t is the time in seconds for a round-trip (back and forth). Equating these and rearranging gives the round trip propagation time of the wave as a function of both the length of the probe and the permittivity of the material:

$$t = \frac{2L\sqrt{\varepsilon_r}}{c} \tag{8}$$

Some typical TDR waveforms are presented in Fig. 3. Measurement of the one-way travel time is shown from the place marked ‘start’ to those marked ‘end reflection’. The waveforms illustrate how the speed of the electromagnetic wave in water is much lower than that in air, because of the much higher ability of water to store electrical potential energy when under the influence of an electric field. Calibration of sensors is recommended to obtain greatest accuracy in permittivity measurement. This may be performed using air and water (Heimovaara, 1993) to obtain an accurate electrical probe length (L), which may be slightly different than the physical probe length. Calibration is described in detail in Robinson et al. (2003).

Because in many soils the EC_a is less than $\sim 2\,\text{dS m}^{-1}$, the relative soil permittivity measured using TDR is generally considered as the real part ε', and is termed the apparent dielectric constant K_a. However, in saline soils and some clay soils the ionic conductivity and molecular relaxation effects may cause a reduction of the electromagnetic wave velocity. This is a topic of continuing investigation.

3.3. *Calibration for determining soil water content from dielectric constant*

Water content is determined from K_a through calibration. An empirical equation for mineral soils (Topp et al., 1980) has proved successful in most sands and loams, soils that do not contain substantial amounts of clay and its associated bound water: $\theta = (-530 + 292K_a - 5.5K_a^2 + 0.043K_a^3) \times 10^{-4}$. Topp et al. (1980) also presented an equation for organic soils that differ from mineral soils due to their high porosity and bound water content (Schaap et al., 1996): $\theta = (-252 + 415K_a - 14.4K_a^2 + 0.22K_a^3) \times 10^{-4}$. Topp et al. (1980) stated an expected average calibration accuracy of about ±0.013 for mineral soils and ±0.018 for organic soils, based on evaluation of a number of different soil materials. This may be improved through soil-specific calibration. Many additional empirical calibration equations have been presented in the literature (e.g., Ledieu et al., 1986; Roth et al., 1992; Jacobsen and Schjonning, 1993). An alternative to empirical calibration relationships is the use of dielectric mixing models, which are discussed by Jones et al. (2002), Ferré and Topp (2002), Robinson et al. (2003), and others. The latter are based on physical/conceptual rather than empirical principles, but success in applying these has been mixed relative to use of empirical calibrations.

3.4. Estimating soil matric potential using TDR

Time domain reflectometry-based probes or techniques to estimate the soil matric potential (h) status have also been evaluated. Soil matric potential represents the energy status of soil water, and is important to a number of processes including water holding capacity, water flow, water bio-availability, and plant water uptake (Hillel, 1998; Or and Wraith, 1999b). Baumgartner et al. (1994) and Whalley et al. (1994) used porous segments as part of conventional TDR rods that allowed them to function as tensiometers. Or and Wraith (1999c) stacked porous ceramic and plastic disks having different pore size distributions within a coaxial cage TDR probe. The θ–h relationship of the aggregated set of disks was calibrated, so that h of the soil was inferred by measuring θ of the porous probe after coming to equilibrium with h of the soil. Noborio et al. (1999) coated a portion of standard TDR probes in gypsum. Signal travel times through the soil and gypsum were separately evaluated to estimate the respective θ (soil) and h (gypsum, and by inference, soil). Wraith and Or (2001) used reference porous media having known $\theta(h)$ to equilibrate with soil matric potential. A standard TDR probe was inserted into the reference medium and another probe into the adjacent target soil. Monitoring θ in both probes during wetting and/or drying allowed inference of the $\theta(h)$ relationship of the target soil. Probes that function as tensiometers are limited to the h range of 0 to about −100 kPa, while the other designs noted above can function over greater wetness ranges, with some potentially functioning from saturation to air-dry.

3.5. Determination of EC_s and ionic solute concentrations

The EC_s is of significant interest because it relates directly to the ionic strength of the soil solution, rather than providing only an integrated measure of the electrical conductivity of the bulk soil (EC_a). The latter is related in a complex way to the soil θ, EC_s, soil geometry (solid particle and pore size distribution and pore continuity), clay content, and other factors, which may greatly complicate its interpretation for land management.

Because TDR can measure both EC_a and θ, it has been used to estimate EC_s under variable θ, as occurs in the field. A model describing the functional relationships of EC_a, EC_s, θ, and soil geometry is required, and several have been proposed and used (e.g., Rhoades et al., 1976, 1989; Mualem and Friedman, 1991; Hilhorst, 2000). Alternatively, linear calibrations of the θ–EC_a–EC_s relationship have been used (e.g., Kachanoski et al., 1992; Ward et al., 1994; Vogeler et al., 1997). Details of such models, their calibration requirements or methods, and evaluation under a range of transient soil wetness conditions are provided in these and other papers or review chapters including Noborio et al. (1994), Heimovaara et al. (1995), Risler et al. (1996), Mallants et al. (1996), Persson (1997), Das et al., (1999), Hilhorst (2000), Noborio (2001), Hendrickx et al. (2002), and Wraith (2003). In cases where the θ and the EC_a vary along TDR probes, differential spatial weighting of these attributes may lead to errors on estimating EC_s (Ferré et al., 2000).

A further extension of measured soil EC_s using TDR is the potential for estimation of the concentration of specific ionic solutes. Simple, often linear calibrations may be used to relate the concentration of dissolved ionic species including nitrate to the EC_s. An example of this application is provided in Section 4, and others may be found in Nissen et al. (1998), and other references.

3.6. TDR applications in saline soils

The TDR waveform reflections necessary for travel time measurements of soil water content can become completely attenuated in saline soils and other electrically ‘lossy’ materials. Although the ability to measure EC in saline soils is maintained, θ determination fails as the critical waveform locations become progressively less distinguishable. Factors such as soil texture, soil salinity, cable length, probe geometry, and θ all influence signal attenuation. Nadler et al. (1999) found that at field capacity water content in sandy and loamy soils, conventional TDR analysis could be effectively used for θ measurements up to EC_a of approximately $2\,\mathrm{dS\,m^{-1}}$. Time domain reflectometry applications are, therefore, limited to soils with moderate to low salinity unless measures are taken to preserve the waveform reflection occurring at the end of the waveguide. Rod coatings have been successfully used to reduce signal attenuation and preserve information needed to evaluate the dielectric constant in highly saline soils. Because these coatings significantly influence the resulting permittivity ε_r, specific θ–ε_r calibration is required for measurements using coated rods, making this a less appealing method (Nichol et al., 2002). Unfortunately, coated rods also make measurement of EC extremely difficult or ineffective.

Another method for extending TDR water content determination to saline soils uses a combination of short TDR probes (for reduced attenuation; e.g., Dalton and van Genuchten, 1986; Jones and Or, 2001; Jones et al., 2002; Persson and Haridy, 2003) and waveform transformation to the frequency domain (Heimovaara, 1994; Friel and Or, 1999; Jones and Or, 2001). In a comparison, traditional travel–time analysis provided reliable dielectric measurement for 10- and 15-cm long probes up to $EC_s \approx 6\,\mathrm{dS\,m^{-1}}$, while for frequency domain analysis, 2- and 3-cm long probes extended dielectric determination by a salinity factor of 4–5 in a silt loam soil (Jones and Or, 2001).

Conversion of the TDR waveform to the frequency domain provides frequency-dependent dielectric constant in addition to other information such as electrical conductivity, relaxation frequency, and static and high-frequency permittivities, which may be extracted using optimization procedures (Heimovaara, 1994; Friel and Or, 1999; Weerts et al., 2001; Huisman et al., 2002). Despite the laborious nature of this approach, including fast

Fourier transformation of the waveform and fitting of an appropriate model to the transformed scatter function, the procedure has the potential to be automated to make it more amenable to real-time measurements and to extend water content determination in saline soils.

3.7. TDR probe design and instrumentation considerations

Probe design is an important consideration when using TDR. The sampling volume of a probe cannot be seen but depends on the probe geometry. Sampling volumes are discussed in detail by Baker and Lascano (1989), Knight (1992), Knight et al. (1994, 1997), Ferré et al. (1998), Ferré and Topp (2002), Robinson and Friedman (2000), Robinson et al. (2003), and others. Different probe configurations will result in different spatial sensitivities, and this should be considered in developing specific measurement applications.

Long cables used for connecting probes to the cable tester reduce the frequency content of the waveform and attenuate (round off) waveforms making them harder to interpret. The use of higher quality coaxial cable such as RG-8 will lead to some improvement, but the maximum practical combined cable length is about 20–30 m, unless salinity and clay contents are low (Jones et al., 2002).

Time domain reflectometry equipment is commercially available from a number of vendors (see discussions or lists in e.g., Jones et al., 2002; Evett, 2000; Ferré and Topp, 2002; Robinson et al., 2003), who generally provide accompanying probes and analysis software. High quality standard or specialty probes may also be handily fabricated by users. Excellent public domain TDR control and analysis software programs are readily available (Jones et al., 2002), primarily for the Tektronix 1502B/C instrument; many are compatible with commercial signal multiplexers to facilitate automating and multiplexing of measurements. All commercial TDR equipment is amenable to θ measurement, though some do not facilitate measurement of EC_a. Some instruments that are marketed as TDR are actually based on other, sometimes related, electromagnetic techniques. Many of these sensors have substantial limitations relative to true TDR, so potential users should closely evaluate equipment and review papers (including those referenced herein) before purchase.

Summarizing, TDR provides electrical conductivity and dielectric permittivity measurements that require analysis and calibration for extracting EC_s and water content information. The K_a–θ relationship is generalized for mineral soils by the Topp et al. (1980) equation but benefits from specific calibrations for high surface area materials such as clays and organic soils. Knowledge of the water retention properties of reference porous media facilitates inference of matric potential from dielectric measurements (e.g., ε–θ–h). Solution electrical conductivity can be derived from EC_a and θ determinations, and specific ionic concentrations may be estimated through further soil-specific calibration. Water content determination can be extended to saline conditions using short TDR probes and waveform transformation and analysis. Basic components of TDR measurement systems include the cable tester, multiplexer, commercial or public domain analysis software, and probes that may be purchased ready-made or custom built.

4. Applications: spatial characterization of electrical conductivity and water content in surface soils

In this section we discuss a few specific applications of TDR to spatially characterize the EC and θ of surface soils. We focus on vehicle-based mapping of soil water content in hilly glaciated landscapes of northern Montana, USA, and on monitoring nitrate concentrations (based on TDR EC measurements) and θ using distributed, fixed TDR probe arrays.

4.1. *Field mapping with vehicle-mounted TDR*

There is strong interest in mapping methods for spatial characterization of soil wetness, because of the sensitivity of crop yields, crop quality, and soil fertility to spatial variability in plant-available water, particularly under rainfed conditions. This information has much to offer precision agriculture, which is concerned with the placement of fertilizers and other farm chemicals in accordance with site-specific differences in soil fertility and crop growth (Robert, 1993).

Researchers in Montana are exploring the use of TDR for integration with precision agriculture. A heavy-duty soil probe was constructed for use with a hydraulic soil sampling machine that enables the insertion of a waveguide to 60-cm depth (Long et al., 2002). A grid of easting, northing, and soil water points can be obtained along transects over farm fields by means of a truck-mounted soil sampling machine and a global positioning system (GPS) receiver. The point coordinates can be processed using interpolation software to develop maps depicting the spatial variations in volumetric soil water content.

The mobile TDR platform has been used in landscapes that exhibit the gently rolling hills characteristic of the glaciated plains region in northern Montana. Variability in soil properties as a function of position on the landscape was not random for an alternate fallow-winter wheat field near Fife, Montana, USA, in 1998, and an alternate fallow-spring wheat field near Havre, Montana, in 2000 (Fig. 4) where gravimetric soil water content and volumetric soil water content (by TDR) were obtained. For instance, maps showed a tendency for near-surface (0–60 cm depth) water contents to be smaller in upper slope positions where runoff is greater and soil erosion has historically occurred. Meanwhile, measurements of soil θ derived from both methods tended to be larger in lower slope positions where runoff likely accumulated from the upper slopes (Fig. 4). Water contents were measured on a 100 m × 100 m grid for both gravimetric and TDR methods, at both locations.

The correlation coefficients relating gravimetric soil water content to volumetric water content had modest values of 0.51 ($n = 75$, $P < 0.05$) for the site near Havre and 0.42 ($n = 70$, $P < 0.05$) for the site near Fife. Thus, the spatial pattern of each variable is suggested to be similar. In addition to specific measurement uncertainties inherent in both methods, the TDR θ readings may have been influenced by the high clay and salt contents of the glacial till and glacio-lacustrine soils at these sites. Measurements of profile θ, soil NO_3–N, grain yield, and grain protein tended to increase from upper to lower slopes (Table 1). The lower topographic locations, on average, had the highest observed soil profile available water and NO_3–N fertility levels.

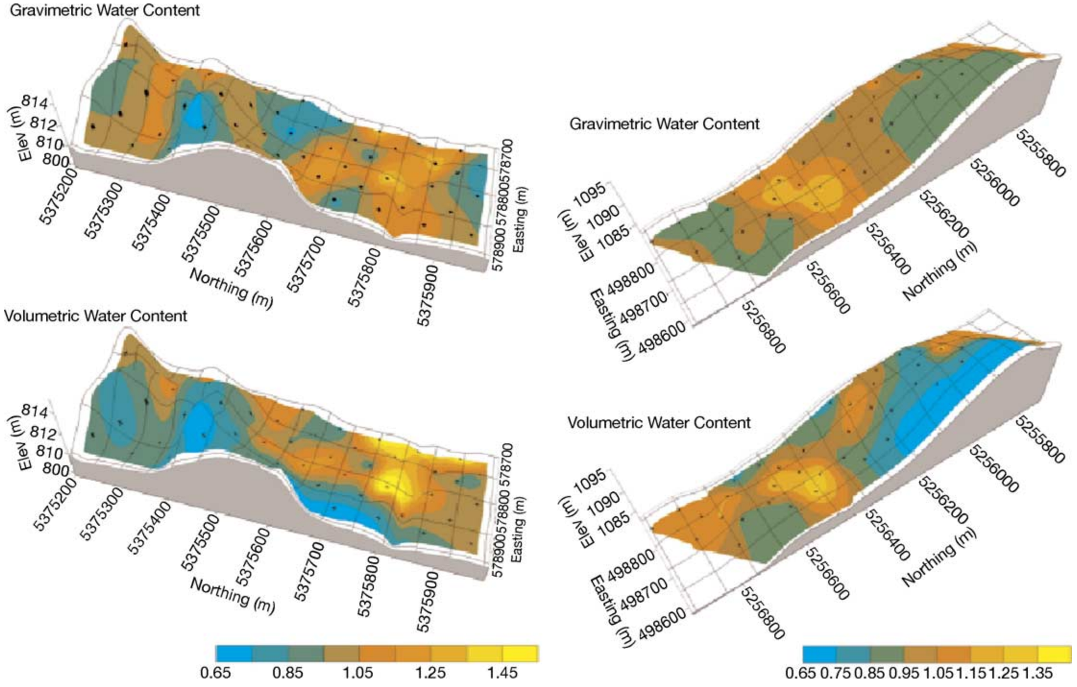

Fig. 4. Contour maps of gravimetric and volumetric water content for alternate fallow-spring wheat field near Havre, Montana (left), and alternate fallow-winter wheat field near Fife, Montana (right), in relation to local topographic relief. Black dots represent sampling points where measurements of water content were obtained. To allow visual comparison, the interpolated values of each map were normalized to a common scale by dividing each value by the average of all points.

Table 1
Comparison of mean early-season soil water contents, soil NO_3–N, grain yield, and grain protein concentration in landscape elements divided on the basis of slope position at two locations in northern Montana, U.S.A., during 1999 (Fife) and 2000 (Havre)

Slope position	Gravimetric soil water content (kg/kg)	Volumetric soil water content ($m^3\ m^{-3}$)	Soil NO^3–N concentration (kg/ha)	Grain yield (kg/ha)	Grain protein (g/kg)
Fife, MT					
Upper	0.15	0.40	56	5173	127
Middle	0.16	0.45	56	5106	128
Lower	0.18	0.48	75	5375	131
Havre, MT					
Upper	0.11	0.24	58	1881	166
Middle	0.12	0.30	65	1942	169
Lower	0.12	0.30	74	1915	171

Soil θ were measured during October for the winter wheat crop at Fife and May for the spring wheat crop at Havre, while the remaining attributes were obtained at the end of the growing season.

These observations are consistent with terrain modeling theory, which hypothesizes that the distribution of hydrologic processes and thus the distribution of soil and microclimate attributes that may determine crop production potential are modified by topography (Moore et al., 1993; Gessler et al., 2000). Local relief controls much of the distribution of soil moisture in the glaciated plains region, such that lower slope positions are likely to be areas of accumulation of water runoff derived from surrounding higher slopes (Montagne et al., 1982). In addition, north-facing slopes are cooler than south slopes, windward slopes have more evaporative desiccation and are often blown free of snow, leeward slopes collect more snow, and cool air drains into low areas.

Average yield of spring wheat (obtained by on-combine yield monitoring) did not increase appreciably from upper to lower slopes at Havre because of extremely dry conditions during 2000, which may have severely limited the amount of topographic water redistribution. Note that soil NO_3–N concentrations were similar for both locations/years, but yields were substantially lower and grain protein was higher for the dryer 2000 growing season at Havre (Table 1). Both gravimetric and TDR results indicate pre-plant levels of θ at Fife during fall 1998 as much wetter than for spring 2000 at Havre (Table 1). Based on our experiences in this area, the measured grain yield and protein values are consistent with the soil moisture measurements in Table 1, as low θ tends to produce small yields but high grain protein, and high θ large yields but low grain protein (Terman et al., 1969).

The results presented here suggest that TDR is a potentially useful tool for creating soil water maps that are needed for precision agriculture. Map resolution will depend upon the spatial scale of sampling desired for obtaining soil water measurements, and the available resources in time and labor.

4.2. *Soil water content and nitrate concentrations using fixed probe arrays*

A fixed TDR array was used to continuously monitor soil θ and EC_a within a peppermint (*Mintha piperita* L.) field over two growing seasons in northwest Montana

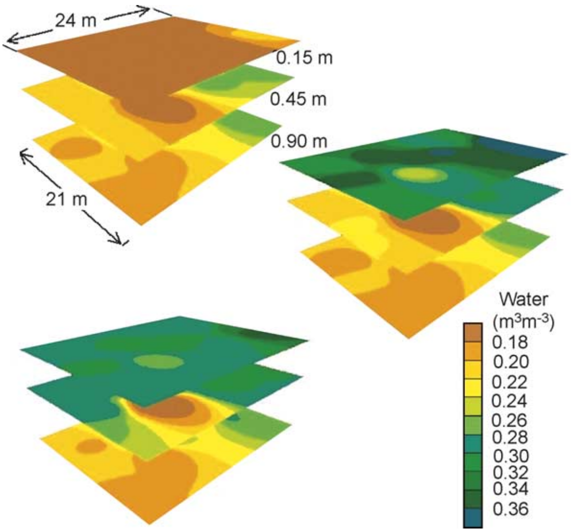

Fig. 5. Measured soil θ at 15- (top panel in each set), 45-, and 90-cm depths under irrigated peppermint in Creston, MT, USA, measured using automated TDR. The top panel represents 1 day pre-irrigation, the middle panel 1 day post-irrigation, and the bottom panel 2 days post-irrigation.

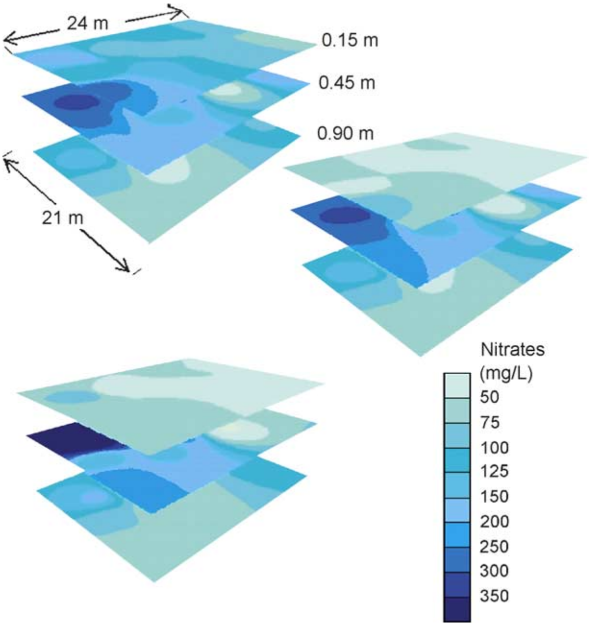

Fig. 6. Estimated soil nitrate concentrations at 15- (top), 45-, and 90-cm depths under irrigated peppermint in Creston, MT, USA. Nitrate concentrations were calculated based on a calibrated model of soil solution EC_s as a function of TDR-measured θ and EC_a, then a linear calibration of soil nitrate concentration vs. EC_s (Das et al., 1999). The top panel represents 1 day pre-irrigation, the middle panel 1 day post-irrigation, and the bottom panel 2 days post-irrigation.

(Wraith and Das, 1998; Das et al., 1999). Probes (0.3-m long, 0.0032-m rod diameter, and 0.025-m rod spacing) were buried at 0.15, 0.45, and 0.90 m depths at 12 locations in a 21 m × 24 m field area, and measured every 6 h for about 100 days using a datalogger system. The field was fertilized and irrigated according to conventional producer protocols, and applied *N* rates were well within those used in peppermint production. The field soil was a fine sandy loam (coarse-loamy, mixed Pachic Udic Haploborolls) with little difference in physical and chemical properties in the upper meter (Das et al., 1999). Because the soil water regime was not constant, three physical-conceptual models were calibrated to the field soil and used to compensate for the strong influence of variable θ on measured EC_a. The models of Rhoades et al. (1976, 1989) and Mualem and Friedman (1991) were used to estimate the soil solution EC_s from measured θ and EC_a, a unique feature of the TDR method. A soil-specific linear calibration of EC_s versus soil nitrate concentration was used to provide nearly real-time estimates of soil nitrate concentrations within the field. Similar methods could be used to provide real-time monitoring capability to land managers. Details concerning instrumentation, models, and calibration procedures are provided in Das et al. (1999). However, that paper focused on the calibration methods and a comparison of measured versus predicted θ, EC_s, and nitrate concentrations with independent results based on soil coring. The spatial patterns of these attributes have not been previously presented.

Selected results are presented in Figs. 5 and 6, which illustrate soil θ and NO_3–N concentrations 1 day before, 1 day after, and about 3 days after an irrigation event. Even though the field soils appeared quite uniform based on excavation of multiple pits, there was substantial measured spatial variability in θ, EC_s, and NO_3–N concentrations (Figs. 5 and 6). For example, measured soil water contents differed by greater than 10% for the 0.15 m depth the day following irrigation (Fig. 5). Measured NO_3–N concentrations ranged from <50 to >350 mg/l at 0.45 m depth (Fig. 6). The upper left and lower right portions of the panels represent the uphill and downhill ends of a ∼6% south-facing slope, but measured variations in θ, EC_s, and NO_3–N do not appear to follow the topographic gradient.

Soil nitrate concentrations were very low (>50 mg/l) at 0.9 m depth at the beginning of the season, but appreciable NO_3–N was leached to this depth during the latter part of the growing season, sufficient to provide measured concentrations of >350 mg/l (data not shown). The maximum rooting depth for peppermint in this area is about 1 m, indicating that such near-real-time information could be effectively used in irrigation and fertilizer management to prevent leaching of NO_3–N below the root zone. A subsequent study using the same soil (Mullin, 2000) indicated a potential sensitivity of about 0.20–0.90 mg/l for measured changes in soil NO_3–N concentration under transient soil θ and EC_a conditions.

5. Conclusions

Time domain reflectometry has the unique ability to measure both soil θ and EC_a, providing singular opportunities for enhanced precision management of agricultural fields. Many of the fundamentals of TDR measurements, and of their applications, are well-established, while some are still under development. For routine agricultural use, advances in mobile TDR platforms will be needed to circumvent the limitations of multiple instrumentation and probe costs and finite cable lengths. Once such platforms become available in reliable and affordable packages, their combination with existing spatial technologies should greatly advance the state of precision management based on soil EC_a, soil water, and other relevant soil properties.

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