Soil temperature correction of field TDR readings obtained under near freezing conditions

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Kahimba, F.C. and Sri Ranjan, R. 2007. **Soil temperature correction of field TDR readings obtained under near freezing conditions.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 1.19 - 1.26. The quantity of spring snowmelt infiltration and runoff depends on the antecedent soil moisture conditions at the time of soil freezing. Determining the soil moisture status at any particular time during the freezing process requires an understanding of the vertical distribution of liquid and frozen water content within the soil profile. This study investigated the effects of soil freezing and thawing during the fall, on partitioning of soil water into the frozen and unfrozen components as a function of depth. Time domain reflectometry (TDR) with 35-mm miniprobes was used to determine the unfrozen water content. The total water content was determined using the neutron scattering method. Comparison between the two methods was made, and a temperature calibration method was developed to account for the effect of change in soil temperature on the accuracy of the TDR measurements. A combination of TDR and neutron scattering methods was also used to quantify the frozen and unfrozen soil water content within the soil profile as the soil freezing progressed with time. The temperature calibration method developed in this research could be used for adjusting field TDR readings taken at temperatures below the temperature used for obtaining the probe constant during laboratory calibration. **Keywords**: soil temperature, soil water content, TDR miniprobes, soil freezing.

Au printemps, les quantités d'eau d'infiltration et de lessivage provenant de la fonte des neiges dépendent des conditions antécédentes de teneur en eau du sol au moment du gel de celui-ci. Pour déterminer l'état de la teneur en eau du sol à un moment particulier durant le processus de gel, il est nécessaire de connaître la distribution verticale de l'eau et de la glace contenues dans le profil du sol. Dans cette étude, les effets du gel et du dégel dans le sol pendant l'automne ont été examinés en séparant l'eau du sol dans ses phases solide et liquide en fonction de la profondeur. La réflectométrie en domaine temporel (TDR) au moyen de mini-sondes de 35 mm a été utilisée pour déterminer la teneur en eau. La teneur en eau totale a été déterminée en utilisant la méthode à diffusion de neutrons. Une comparaison entre les deux méthodes a été faite et une méthode de calibration par température a été développée pour tenir compte de l'effet du changement de température du sol sur la précision des mesures TDR. Une combinaison de TDR et de méthodes à diffusion de neutrons a été utilisée pour quantifier le contenu en glace et en eau dans un profil de sol durant le processus de gel du sol. La méthode de calibration par la température développée dans ce projet de recherche pourrait être utilisée pour ajuster les lectures TDR faites au champ prises à des températures sous la température utilisée pour obtenir la constante de la sonde durant la calibration en laboratoire. **Mots clés**: température du sol, teneur en eau du sol, mini-sondes TDR, gel du sol.

INTRODUCTION

Soil freezing and thawing processes play a major role in soil water movement in seasonally frozen soils. The quantity and distribution of soil water content during the fall, when soil begins to freeze, influences the freeze-thaw behavior of the soil during the spring snowmelt (Luo et al. 2002). Understanding the soil moisture distribution during the fall and early winter requires measurement of both the frozen and unfrozen (liquid) parts of the total soil water content because the soil is partly frozen.

There are various methods for measuring soil water content. They range from classical methods such as neutron scattering using the neutron moisture meter (NMM), electrical conductivity, and gravimetric, to modern sensor methods based on capacitance such as time domain reflectometry (TDR), frequency domain reflectometry (FDR) (Seyfried and Murdock 2001; Warrick 2002; Evett 2000, 2003a; Evett et al. 2002; Topp et al. 2003). Despite the innovations of these modern non-destructive and high precision methods, both the classical and the modern methods encounter particular problems related to physics of the methods i.e. accuracy and precision of the measurements, coverage and volume of measurements, and varying soil conditions (Evett 2000; Warrick 2002).

A study by Seyfried and Murdock (2001) showed that the sensitivity of the water content reflectometer (WCR) instrument varies with temperature, and the temperature effects also vary with water content and the type of soil. Soil moisture measurements in partly frozen soils in particular pose a challenge to many methods, such as TDR and WCR, due to the existence of water in both liquid and frozen conditions. Evett (2003b) noted that when the TDR method was used, the decrease in permittivity of water as it freezes hindered accurate measurement of frozen water content in the soil.

In this study, two methods of soil moisture measurements (TDR and NMM) were used to measure the unfrozen and total soil water content. The TDR, being dependent on the dielectric constant of the media in which the probe is embedded, measures only the unfrozen water content of the soil. The method involves measurement of travel time of the electromagnetic wave (EM) along wave guides of known length placed in the soil. The measured travel time is related to the dielectric constant of the medium in which the wave is moving. The dielectric constant

(K_a) is then related to the volumetric liquid water content (θ_v), since changes in θ_v are directly related to the change in K_a (Evett 2000). This is attributed to the significant difference between the dielectric constant of water and that of other soil materials (K_{water} = 78.5 at 25°C, K_{air} = 1.0, K_{ice} = 3.2, and K_{soil} = 3 - 7 depending on soil composition and texture) (Warrick 2002; Tardif 2002; Evett 2003b). As the soil freezes, the dielectric constant of frozen water decreases significantly from that of unfrozen water due to inability of the water molecules to rotate freely in the electromagnetic field used in the TDR measurement method. This allows for the unfrozen part of water content to be determined.

The neutron scattering technique on the other hand, measures the total (frozen and unfrozen) soil water content using a neutron moisture meter (NMM). It uses a radioactive source emitting fast neutrons, and a counter for detecting slow neutrons thermalized by the hydrogen atoms in the soil water, whether in the frozen or unfrozen state (Evett 2000, 2003a). The loss in the kinetic energy of the neutrons varies depending on the type of soil constituents they collide with. When neutrons collide with hydrogen atoms that are similar in weight, they are thermalized leading to a reduction in their kinetic energy (Evett 2003a). The concentration of the thermalized neutrons is a measure of the number of hydrogen atoms, which is related to the total volumetric water content (Evett 2003a). Calibrations are normally performed to account for sources of hydrogen in the soil other than water, such as humus and organic matter, and other efficient neutron thermalizers (carbon, nitrogen and oxygen). The relationship between thermalized neutron counts and the volumetric water content depends on field calibration for each specific soil.

Studies have described the potential for the use of TDR and NMM in partitioning the total water content into frozen and unfrozen water (Baker and Allmaras 1990; Herkelrath and Delin 1999). However little has been documented on the freeze-thaw processes during the fall as the soil starts to freeze. In addition, the accuracy of TDR soil moisture measurements in the field at varying soil temperatures along the soil profile needs more attention.

Spaans and Baker (1995) studied the use of TDR in frozen soils and found that calibration of TDR probes using water and soil in the laboratory does not give accurate results in the field when the soil is partly frozen. Tardif (2002) suggested a temperature correction on soil moisture sensors depending on the manufacturer's recommendations. Seyfried (2004) also showed that field measurements made in partly frozen soils using TDR probes calibrated in the laboratory were not accurate.

Soil temperature and field TDR measurements

The accuracy of determining the apparent dielectric constant (K_a) of the soil is one of many factors that affect the accuracy of measuring soil water content with TDR. In the early developments of TDR (Topp et al. 1980), it was assumed that the method is less sensitive to temperature variations and soil factors with an accuracy of 0.013 m^3/m^3. Further research on TDR measurements has shown that factors such as soil texture, bulk density, soil water content, and soil temperature all affect the accuracy of TDR measurements (Pepin et al. 1995; Or and Wrath 1999; Gong et al. 2003; Robinson et al. 2003). Errors in applying the Topp's calibration equation (Topp et al. 1980) without any correction are more pronounced especially in soils with large specific surface area and high salinity (Persson and Berndtsson 1998; Gong et al. 2003). Persson and Berndtsson (1998) suggested a temperature correction factor for water content measurement in the range between -0.00253 and -0.00419. The same study also reported a decrease of K_a of pure water and wet soils with an increase in temperature and an increase of K_a with an increase in temperature when the soil was dry. Seyfried and Murdock (1996) obtained similar results regarding the influence of total soil water content, especially in frozen soils, and concluded that the amount of liquid water in frozen soil depends on the amount of total water content.

The TDR measurements obtained in various types of soils such as sand, silt loam, and clay showed that K_a is less affected by water content of coarse textured soil compared to fine textured soils that have a large specific surface area (Pepin et al. 1995; Persson and Berndtsson 1998; Wrath and Or 1999; Gong et al. 2003). The impact of a combination of factors such as water content, soil texture, and soil temperature on the accuracy of TDR measurements has been reported in a contradictory manner (Or and Wrath 1999; Gong et al. 2003). In their studies, Or and Wrath (1999) and Wrath and Or (1999) have given a clear description on how these three factors interact with each other and hence affect the accuracy of TDR measurements. In brief, they describe that for soils having high moisture content, the TDR measured K_a decreases with an increase in temperature and an increase in the bound water content. The bound water is not detected by the TDR and hence has less influence on the changes observed in the measured K_a with temperature. At very low moisture content, an increase in temperature causes the bound water to become free causing a net increase in K_a with an increase in temperature.

To account for these changes in K_a with temperature, the measured K_a needs to be adjusted to a standard temperature. The normal practice as reported in the literature is to adjust to a temperature that had been used during the calibration of the TDR probes. Weast (1986), as reported by Or and Wrath (1999), developed an equation relating K_a of free water with temperature, and normalizing the values to 25°C (Eq. 1):

$$\varepsilon_w(T) = 78.54[1 - 4.579 \times 10^{-3}(T-25) + 1.19 \times 10^{-5}(T-25)^2 - 2.8 \times 10^{-8}(T-25)^3] \quad (1)$$

where:

$\varepsilon_w(T)$ = dielectric permittivity of free water and
T = temperature (°C).

Other studies that have used 25°C as a baseline for adjusting TDR measurements are Wrath and Or (1999) and Robinson et al. (2003).

The objective of this research was to develop a temperature calibration method for field TDR measurements at different soil temperatures under soil freezing and thawing conditions. The success of the temperature calibration was useful in partitioning the total water content determined by NMM into unfrozen and frozen water contents within the soil profile.

MATERIALS and METHODS

The field plots were located at Carman, Manitoba, at the Carman Research Station of the University of Manitoba, about

90 km southwest of Winnipeg, Manitoba. The plots are part of a long-term crop rotation study looking at the water use of different cropping systems: oats with berseem clover cover crop, oats alone, fallow, and native prairie. Soils in the selected experimental plots are well drained fine sandy loam soils, (well drained Hochfeld from sub group Orthic Black). The average particle size distribution of the soil was 76% sand, 8% silt, and 16% clay, with average depth of 0.7 m to a clay layer (Mills and Haluschak 1993).

The water content, at different depths within the soil profile, was measured using two different methods i.e. time domain reflectometry (TDR) and neutron moisture meter (NMM). The TDR measures only the unfrozen water content of the soil, while the NMM method measures the total water content. Multiple measurements over several days were taken after each snow fall event to track the movement and state of water within the vertical soil profile. The soil and atmospheric temperatures fluctuated much above and below 0°C during and after the different snow fall events during late fall. Late fall weather in southern Manitoba is usually characterized by periods of snow fall followed by warmer weather before the onset of the winter snow fall. It is this period of temperature fluctuation under near freezing/thawing conditions that was investigated in this study. The soil temperature profile was measured using thermocouples. Milder temperatures following early snowfall events resulted in snowmelt infiltration events prior to soil freezing with the arrival of winter weather.

TDR instrumentation

The TDR miniprobes used in this field study were calibrated in a laboratory experiment at an average temperature of 25±0.2°C using water and soil columns. The TDR used miniprobes that were 35-mm long stainless steel rods (1.59-mm diameter) in a 3-rod configuration placed in a single plane at a spacing of 6 mm, centre to centre. The rods were connected to an outer conductor coaxial cable type RG-58 50Ω, with lengths 2.0, 2.5, and 3.0 m, depending on the depth of installation within the soil profile. Procedures for making the miniprobes are described in Sri Ranjan and Domytrak (1997). Evett (1994) found that the 3-rod configuration gave better soil moisture measurement compared to the 2-rod probe. The need for an impedance matching transformer used in the 2-rod configuration is also eliminated due to the semi-coaxial nature of the 3-rod configuration (Evett 1994).

Field installation

The TDR probes were installed in an existing long-term cropping systems trial established at the Carman Research Station of the University of Manitoba. Two of the cropping systems' treatments used in this research were no-till cultivation of oats with berseem clover cover crop and oats alone. Three replicates of measurement locations were selected in each cropping system to minimize errors due to soil heterogeneity. At each measurement location, five TDR probes were installed at depths of 0.1, 0.2, 0.4, 0.6, and 0.8 m from the ground surface. The probes were installed at an angle of 60° from the horizontal to prevent any preferential flow in the vertical direction. A 19-mm diameter hole was made by pushing a metal rod, along a specially made guide, to a depth 50 mm shorter than the desired depth of installation of the probe. The TDR miniprobe was inserted into this hole using a specially made insertion tool and the probe ends were pushed into the soil to attain better soil contact in the last 35 mm. The steel rods of each probe were arranged in the same plane so that each leg would be at the same distance from the ground surface. The hole was then back-filled with industrial bentonite to avoid preferential flow along the coaxial cable extending to the ground surface. The angled installations and sealing procedures have also been described by Dahan et al. (2003) for deeper soil layers. The installation in that study however involved large diameter holes up to 200 mm, drilled at an angle of 45 degrees from the horizontal. Topp et al. (2003) also used both angle, vertical, and horizontal probe installations and commented that the installation at an angle gave more reliable data.

The maximum vertical depth of installation within the soil profile was 0.8 m. Of the 60 TDR miniprobes installed in the field, 20 probes had thermocouples attached to them for monitoring soil temperature. The temperature was monitored at the same depths used for TDR measurements. A digital thermocouple thermometer (Fluke 51 II Digital Thermometer, Fluke Corporation, Everett, WA) with a precision of 0.1°C was used for the temperature measurements. Probes in the field were connected using a 17.5-m long extension cable (RG-58 50Ω coaxial cable), to a Tektronix 1502B metallic cable tester (Tektronix, Inc., Redmond, OR) located in a warm cubicle (tractor cab). Information recorded by the cable tester was then downloaded into a notebook for further analysis. Data from the TDR measurements were analysed to determine the quantity of liquid water as a function of depth as the soil continued to freeze.

Measurements using neutron moisture meter (NMM)

A profiling neutron moisture meter (NMM) (Troxler Model 4300 Depth Moisture Gauge, Troxler Electronics Laboratories Inc., Research Triangle Park, NC) was used to measure the total volumetric water content. Measurements were taken in the same plots in which the TDR probes were installed. The NMM sphere of influence of measurements, in which about 98% of the counted thermalized neutrons pass to reach the detector, is governed by a radius defined by Eq. 2 (Troxler 2001).

$$R = 280 - 270M \tag{2}$$

where:

R = sphere radius of influence in the soil (mm) and
M = soil moisture content (Mg/m^3).

The maximum radius of influence from the centre of the access tube is 280 mm when the soil is completely dry. Hence to avoid interference of TDR probes with the NMM measurements, the TDR probes were installed at a distance of 500 mm from the NMM access tubes. This distance was considered far enough to avoid interference between the two methods, and close enough for the comparison of the two methods under similar soil moisture states. Calibration of the NMM gauge was done by measuring soil moisture at intervals of 0.2 m from 0.2 to 1.8 m depth and comparing against the gravimetric method along with bulk density measurements made on undisturbed soils samples obtained from the same field. Samples for the gravimetric method were taken at the same depth intervals within 500 mm distance from the access tubes. A calibration equation was then derived and used for subsequent measurements.

Three sets of measurements were taken within the soil profile during each data collection (TDR, NMM, and soil temperature profiles). Data collection started in August 2005 when the soil was still unfrozen and progressed until January 2006 when the soil had already begun to freeze. Comparison was made between TDR and NMM data before and after soil freezing. Before soil freezing, ideally the TDR liquid water content was expected to be equal to the NMM total water content, since both methods measured water that was in the liquid (unfrozen) state. Temperature measurements were used to determine how the variation in soil temperature affected the accuracy of TDR measurements as compared to the neutron moisture meter. Statistical analysis was performed using a Statistical Analysis System (SAS) software version 9.1 (SAS, Inc., Cary, NC) to compare the uncorrected and corrected values of TDR moisture content against the NMM measurements. Water content measurement using both methods progressed during the fall and winter when soil in the top layers had frozen.

Development of a temperature calibration method applicable to TDR measurements

The apparent dielectric constant (K_a) for water decreases from about 88 near freezing to about 70 at 50°C (Warrick 2002). A third-order polynomial regression equation (Eq. 3) was derived ($R^2 = 1.0$) using the relative permittivity of liquid water and the corresponding temperature at 0.1 MPa pressure (atmospheric pressure) using data obtained from Table 19 of Fernandez et al. (1997). The data were taken for the temperature range of 0 (273.15 K) to 40°C (313.15 K), which is the range of normal soil temperatures.

$$K_T = K_0 - 0.401T + 8.988\times10^{-4}T^2 - 1.414\times10^{-6}T^3 \qquad (3)$$

where:

K_o = dielectric constant of liquid water at 0°C ($K_o = 87.898$) and

K_T = apparent dielectric constant of water at the desired temperature, T.

The probes used for this experiment were calibrated at a temperature of 25°C. This temperature has also been reported to be the base line temperature at which the TDR over-predicts the volumetric water content as the temperature decreases (Wrath and Or 1999). The temperature data from Table 19 in Fernandez et al. (1997) was adjusted by subtracting 25°C to establish a regression equation (Eq. 4) with a K_a value corresponding to the baseline temperature:

$$K_T = K_{25} - 0.3572(T-25) + 8.250\times10^{-4(}(T-25)^2$$
$$-1.000\times10^{-6}(T-25)^3 \qquad (4)$$

where: K_{25} = dielectric constant of liquid water at 25°C and 0.1 MPa ($K_{25} = 78.434$).

The field measured dielectric constant (K_{field}) should be adjusted using Eq. 5 to a K_a corresponding to 25°C (K_{adj}).

$$K_{adj} = K_{field} + 0.3572(T_{soil} - 25) - 8.250\times10^{-4}(T_{soil} - 25)^2$$
$$-1.000\times10^{-6}(T_{soil} - 25)^3 \qquad (5)$$

where: T_{soil} = field soil temperature at depth of interest (°C).

The K_a values adjusted to a soil temperature of 25°C were used in Eq. 6 (Topp et al. 1980) to determine liquid water content.

$$\theta_v = -5.30\times10^{-2} + 2.92\times10^{-2}K_{adj} - 5.50\times10^{-4}K_{adj}^2$$
$$+4.30\times10^{-6}K_{adj}^3 \qquad (6)$$

where: θ_v = volumetric soil water content.

RESULTS and DISCUSSIONS

Soil temperature affects the TDR measurement of the dielectric constant and thus a temperature correction had to be carried out to adjust the field measured dielectric constant. Before the ground is frozen, the water content measured by the TDR miniprobes, adjusted for temperature, and the NMM readings should be identical since both methods measure the soil water in the liquid state. Therefore, the temperature corrected soil water content data obtained by the TDR miniprobes were compared to the total soil water content measured by NMM to verify the accuracy of the TDR readings.

Influence of soil temperature on TDR measurements

Soil moisture measurements using TDR and NMM were compared in the field at various soil temperatures before soil freezing. The aim was to determine how the variation in soil temperature affects the TDR readings. The readings were taken when the soil temperatures were below 25°C, the temperature used for laboratory calibration of the TDR probes. On November 22, 2005, the soil temperature in the cover crop treatment varied from 6.5°C near the surface to 2.3°C at 0.8-m depth. For the treatment without a cover crop, the temperature was 8.8°C near the surface and 2.5°C at 0.8-m depth. The TDR and NMM soil moisture measurements were compared at soil temperatures lower than the probes' calibration temperature of 25°C (Figs. 1 and 2). The uncorrected TDR moisture measurements for the two treatments before soil freezing were not comparable to the NMM measurements. The TDR method overestimated the amount of field soil moisture at lower soil temperatures (Figs. 1a and 2a). The overestimation of TDR measurement at lower soil temperatures is attributed to the fact that TDR measures the dielectric constant of water (K_a value) that changes with temperature (Tardif 2002; Topp and Davis 1985). The K_a value of unfrozen water increases with decreasing temperature. Hence there was a need to develop an equation for correcting the TDR dielectric constant measurement in the field to enable accurate measurement at any soil temperature range. The NMM method used for comparison is not affected by temperature variations. The neutron moisture meter used in this study had been calibrated in the same field using the gravimetric method.

Temperature correction of field TDR measurements

The equation derived for adjusting the field TDR measurements (Eq. 5) was used to determine the temperature-corrected dielectric constants, (K_{adj}). These adjusted K_a values were then used to obtain the volumetric soil moisture values using Topp's model (Eq. 6). The soil moisture measurements obtained from the adjusted K_a values were compared with the results obtained by NMM prior to soil freezing. A paired t-test was done using the SAS program to analyze the data for the two different methods of measurement. In both the cover cropped and the non-cover cropped treatments, there was a significant difference

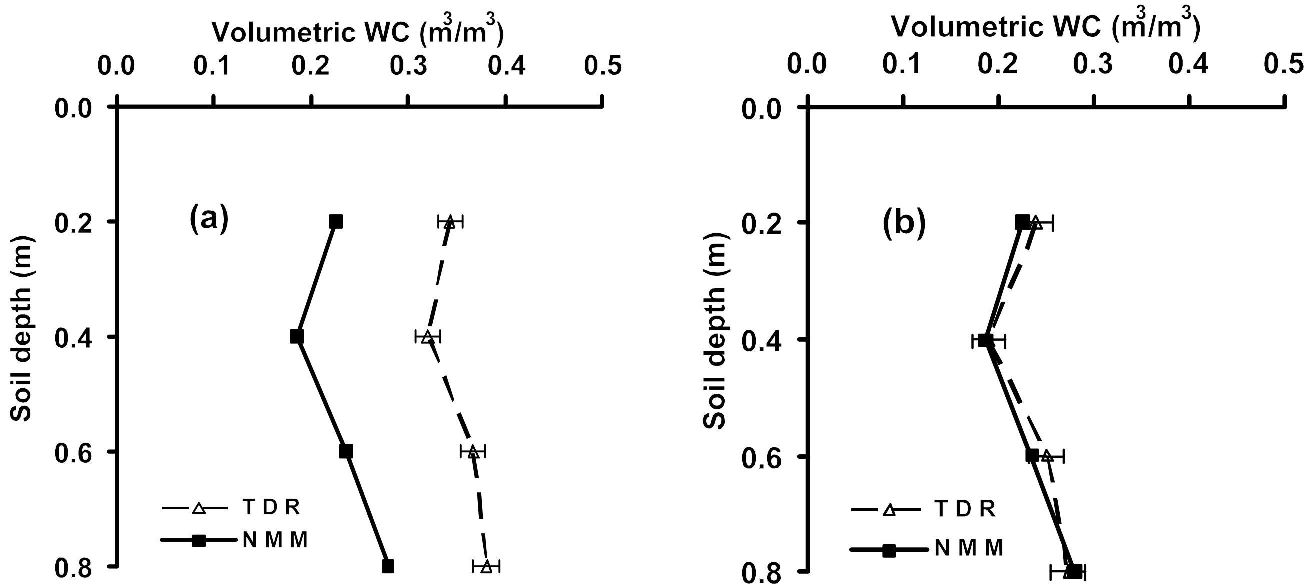

Fig. 1. Comparison of TDR and NMM soil moisture measurements on the cover-cropped treatment at temperature range 6.5 to 2.3°C on November 22, 2005: (a) before temperature correction, and (b) after temperature correction. TDR measurements were taken as average of three replicates.

between TDR and NMM measurements prior to temperature corrections (P = 0.001). After adjusting for the difference in temperature, the difference in water content measured by the two different methods was not significant (P = 0.14). The soil moisture content, prior to doing the temperature correction on the dielectric constant, was overestimated by an average of 0.10 m^3/m^3 above the NMM measured data. This difference disappeared after the temperature correction was done on field measured K_a values.

The temperature corrected TDR measurements corresponded well with the NMM prior to soil freezing for both treatments (Figs. 1b and 2b). This was because the total soil moisture measured by NMM was the same as liquid moisture content measured by TDR when the water in the soil remained unfrozen. Comparison of the two methods has also been done by Brendan (2003). However, that study did not account for field variation of the soil temperature in the range used in this study.

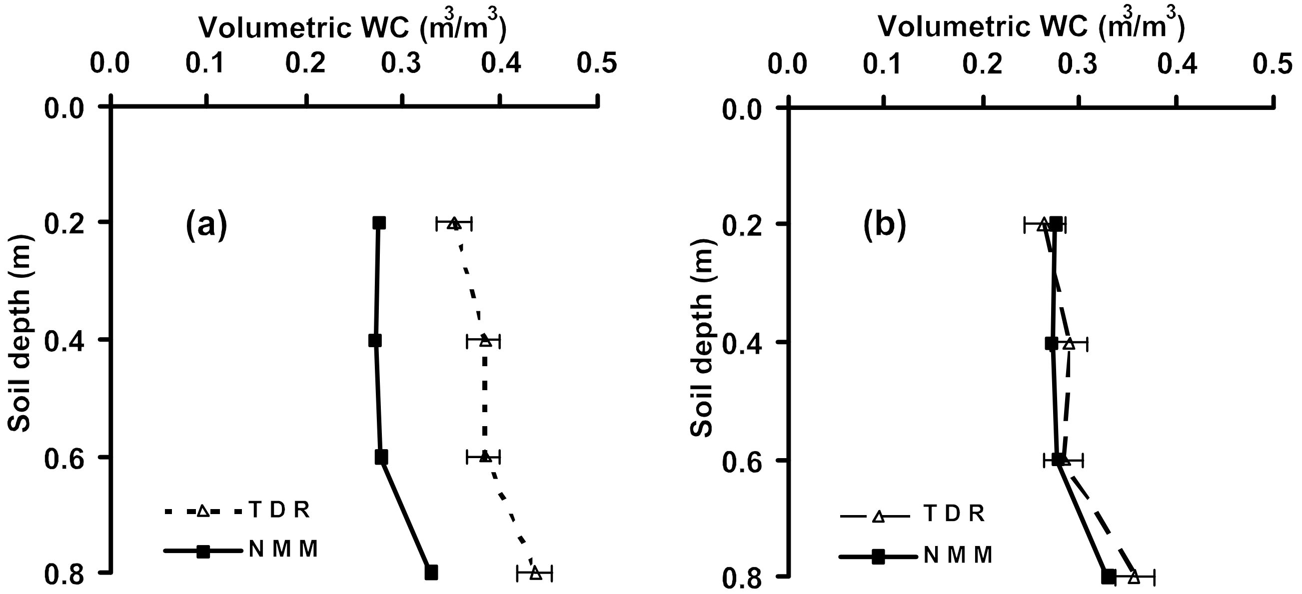

Fig. 2. Comparison of TDR and NMM soil moisture measurements on the non-cover-cropped treatment at temperature range 8.8 to 2.5°C on November 22, 2005: (a) before temperature correction, and (b) after temperature correction. TDR measurements were taken as average of three replicates.

Table 1. Soil temperature, unfrozen, and total water contents at various depths along the soil profile in the cover-cropped treatment on December 13, 2005.

Depth (m)	Temperature (°C)	Unfrozen water content (m^3/m^3)	Total water content (m^3/m^3)	Frozen water content* (m^3/m^3)	Percentage frozen (%)
0.20	-0.3	0.00	0.34	0.34	100.00
0.40	0.6	0.06	0.20	0.14	70.00
0.60	1.6	0.14	0.19	0.05	26.31
0.80	2.8	0.22	0.25	0.03	12.00

*Frozen water content was calculated as the difference between total water content (NMM method) and unfrozen water content (TDR method).

Table 2. Soil temperature, unfrozen, and total water contents at various depths along the soil profile in the non-cover-cropped treatment on December 13, 2005.

Depth (m)	Temperature (°C)	Unfrozen water content (m^3/m^3)	Total water content (m^3/m^3)	Frozen water content* (m^3/m^3)	Percentage frozen (%)
0.20	-0.5	0.00	0.38	0.38	100.00
0.40	0.4	0.00	0.26	0.26	100.00
0.60	1.5	0.10	0.27	0.17	62.96
0.80	2.5	0.15	0.31	0.16	51.61

*Frozen water content was calculated as the difference between total water content (NMM method) and unfrozen water content (TDR method).

Using TDR and NMM for soil moisture partitioning during soil freezing

As the soil started to freeze, the liquid and total soil water contents started to diverge. During late fall and early winter in December, water content measured by the TDR method was found to be less than that measured by the NMM method. The difference between the two measurements indicated the amount of soil moisture content in the frozen state (Tables 1 and 2). By December 13, 2005, the soil layers on the treatment that had oats with berseem clover cover crop had completely frozen to a depth of 0.2 m, and at 0.8-m depth only 12% was frozen (Table 1). On the treatment with oats alone, the soil had completely frozen to a depth of 0.4 m, and it was 51% frozen at 0.8-m depth (Table 2).

The TDR liquid water content and NMM total water content taken on January 30, 2006, at different depths within the soil profile, for the treatment that had oats alone during the summer, are presented (Fig. 3). The ground had frozen to a depth of 0.4 m by January 30, 2006. Below that depth, the soil was partly frozen, signified by the presence of some liquid water content less than the total water content. The soil temperatures were 0.2, 0.4, 1.0, and 1.6°C at 0.2, 0.4, 0.6, and 0.8 m, respectively. At a depth of 0.6 m, for example, the total water content was 0.25 m^3/m^3 and the liquid water content was 0.14 m^3/m^3. The difference between the two values gave the amount of frozen water content as 0.11 m^3/m^3 at that depth. Baker and Allmaras (1990) also demonstrated the possibility of using TDR and NMM to partition liquid and frozen water content in the soil during spring snowmelt. However their study did not cover the freeze-thaw interactions in the fall as the soil freezes. Hence a combination of TDR and NMM methods could be used as a means for studying the amounts and redistribution of soil water content especially during the fall to spring seasons when the soil water may exist in both the frozen and unfrozen states.

CONCLUSION

Time domain reflectometry and neutron scattering methods using NMM were used to measure the soil water content in partly frozen agricultural soils. The influence of soil temperature on the accuracy of TDR measurement was investigated. The TDR method overestimated the actual field soil moisture content at lower soil temperatures below 25°C ($\alpha = 0.05$). Therefore, a temperature calibration method was developed and used for adjusting the measured field dielectric constant of the soil. The adjusted dielectric constant was used to determine the soil water content at different soil temperatures. There was no significant difference ($\alpha = 0.05$) between the TDR and NMM readings after adjusting the TDR readings for temperature. The mean difference between the two methods was 0.01 m^3/m^3 . The calibration method developed in this study can be used for adjusting field TDR readings taken at temperatures below or above the probes' laboratory calibration temperatures.

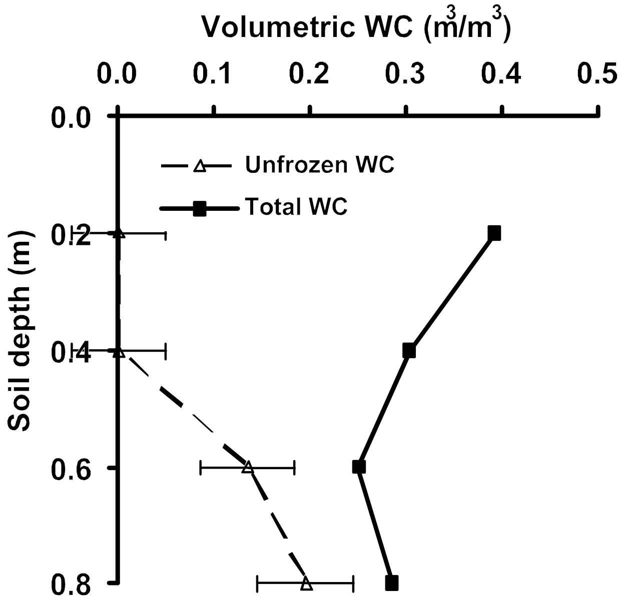

Fig. 3. Variation of liquid (unfrozen) and total water content with depth for the non cover-cropped treatment on January 30, 2006. Error bars indicate standard errors of measurements.

A combination of both TDR and NMM measurements have been used to partition total soil water content into unfrozen and frozen amounts. In addition to determining the depth of frozen soil layer, a combination of the two methods can be used to partition the total water content into frozen and unfrozen states at different depths within the soil profile. Simultaneous use of both the TDR and NMM methods can be a valuable tool for studying the soil moisture distribution and free water migration within the soil profile during the fall, winter, and spring in seasonally frozen agricultural soils.

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