Published March 14, 2019

Notes

Field Calibration of PR2 Capacitance Probe in Pullman Clay-Loam Soil of Southern High Plains

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Core Ideas

- A noncalibrated PR2 capacitance probe showed significant deviations from actual soil water content.
- Calibration improved the accuracy and precision of soil moisture monitoring with the PR2.
- Calibration was necessary for using the PR2 probe for research-quality soil water measurements.

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Received 9 Oct. 2018.
Accepted 11 Feb. 2019.
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Agrosyst. Geosci. Environ. 2:180043 (2019)
doi:10.2134/age2018.10.0043

ABSTRACT

Multi-depth capacitance sensors are popular to monitor soil water content for scheduling irrigation thanks to their ease of operation and maintenance. The PR2/6 Profile Probe (Delta-T Devices) measures soil moisture by using either the manufacturer's built-in equation or a user-calibrated equation if the soil is high in clay or organic matter. The objectives were to evaluate the performance of the PR2/6 Profile Probe in a perennial grassland and to develop a site-specific equation to correct probe measurements in Pullman (fine, mixed, superactive, thermic Torrertic Paleustolls) clay loam soils. Permittivity recorded by the profile probe was regressed on the gravimetrically measured soil volumetric water content (VWC). Parameters were optimized to obtain least RMSEs. The default equation provided by the manufacturer estimated VWC with average RMSE and r^2 values of 0.053 m^3 m^{-3} and 0.71, respectively. New calibration coefficients were effective in explaining 91% of the variability in soil VWC measurements and reducing RMSE to 0.017 m^3 m^{-3}. The results indicate that site-specific calibration of the capacitance probe is necessary to attain research-quality accuracy and precision when applied to grasslands in Pullman clay loam and associated clay loam soils.

Abbreviations: EM, electromagnetic; RMSE, root mean square error; VWC, volumetric water content.

Accurate measurement of soil water content is essential to characterize soil water dynamics and use for irrigation scheduling. The simplest and most precise method of soil water measurement is the gravimetric technique (Gardner, 1986), which is widely used for the calibration of other methods. This method is labor-intensive, slow, invasive, destructive for use in controlled environments (Mwale et al., 2005), and impossible at a fine time scale (e.g., minutes). Introduction of the neutron scattering method revolutionized indirect measurement of in situ volumetric water content (VWC, water volume/soil volume ratio) in the early 1950s (Gardner and Kirkham, 1952). Several modifications in sensors and calibration of this method led to its high reliability and widespread use (Evett and Steiner, 1995). However, the use of the neutron scattering technique requires licensing and periodic safety training for compliance with existing radioactive hazard regulations, which is expensive and a burden to researchers (Fares et al., 2004). Neutron probes are also difficult to maintain, constitute a potential radiation hazard to users, and prevent use with unattended monitoring (Mwale et al., 2005). As an alternative, the electromagnetic (EM) probes or dielectric methods were introduced in the late 1980s and 1990s (Evett et al., 2006). These probes estimate soil water content by measuring the soil bulk permittivity (ε') or dielectric constant (k) and use a known empirical relationship between ε' or k and VWC. The commercially available EM probe types include time domain reflectometry and frequency domain reflectometry (or capacitance) probes (Mwale et al., 2005). The EM probes can provide real-time and continuous readings through automation, can be used remotely and unattended, do not require maintenance and licensing, and are relatively inexpensive (Evett et al., 2006; Kelleners et al., 2004; Muñoz-Carpena et al., 2005; Qi and Helmers, 2010).

The PR2 Profile Probe (Delta-T Devices, Cambridge, UK) is a type of multi-sensor frequency domain reflectometry probe designed to monitor soil VWC in field conditions (Qi and Helmers, 2010). The probe can give instantaneous readings as mV, permittivity, and VWC at various depths through the hand-held data logger (Fig. 1). The PR2 Profile Probe can perform repeated measurements at a fixed location or is portable to multiple locations having access tubes. The precision and accuracy of earlier model capacitance probes, such as EnvironSCAN (Kelleners et al., 2004) and PR1 (Evett et al., 2006; Mwale et al., 2005), were found to be limited by small sampling volume, sensitivity to soil pores, salinity, dissolved electrolytes, and temperature. Delta-T claimed the PR2 was an upgrade of the PR1 model with improved sensors, considered as more accurate for fine-textured and saline soils (Delta-T Devices, 2005). Humidity inside the access tube, non-uniform contact between access tube wall and soil, irregular orientation of probe in the tube, and poor field installation can vitiate permittivity readings (Morgan et al., 1999). Mwale et al. (2005) observed frequent overestimation and underestimation of soil VWC with the PR1 capacitance probe compared with gravimetric and neutron probe methods by using the manufacturer's default equation and parameters, although they found reliable relative changes in VWC. Limitations in precision and accuracy of probe responses were also noted by Evett and Steiner (1995), Evett et al. (2006, 2012), and Polyakov et al. (2005). In contrast, others reported satisfactory comparisons with the neutron probe (Hanson and Peters, 2000) and gravimetric method (Wu, 1998). Inconsistencies in the precision of measurements obtained from capacitance probe sensors suggest that soil-specific calibration of these sensors is necessary for research applications.

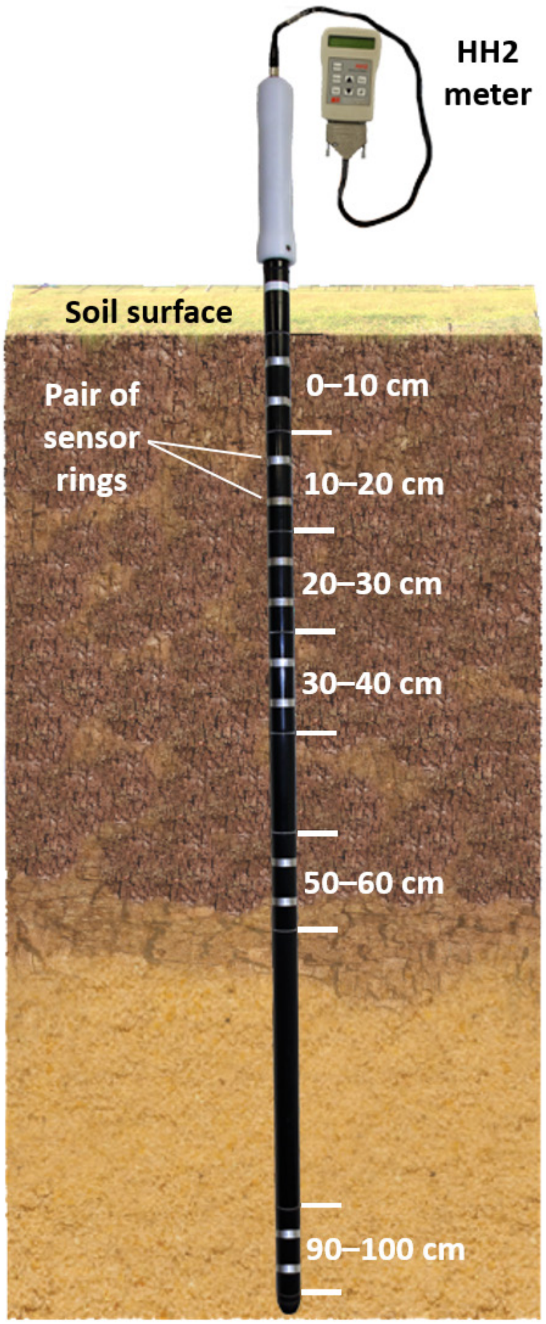

Fig. 1. PR2/6 Profile Probe (Delta-T Devices) showing stainless steel electronic rings and data recording meter (HH2). The uppermost 5 cm extends above the soil surface but within the access tube (not shown). Intervals labeled with depth increments represent soil sampling volumes and 95% influential depth of each pair of sensor rings.

Studies on the accuracy of multi-sensor capacitance probes have identified the importance of calibrating by soil depth. Evett et al. (2006) reduced the discrepancy in readings from a range of 0.09 to 0.10 to 0.04 to 0.05 $m^3\ m^{-3}$ for the PR1/6 probe by calibrating at separate soil layers to reduce axial noise of the sensors. Other studies indicated that soil-specific calibrations by depth layer provided a reliable estimate of VWC with higher r^2, and lower root mean square error (RMSE) values (Evett and Steiner, 1995; Huang et al., 2004; Morgan et al., 1999; Polyakov et al., 2005; Whalley et al., 2004). The calibration equations and parameters reported in those studies may not be valid for all soil types and conditions; indeed, the probe user manual suggests performing soil-specific calibration if the soil is heavy clay or highly organic (Delta-T Devices, 2008). There is a paucity of information on calibrating the multi-sensor capacitance probes in clay-dominated soils, such as those of the West Texas High Plains where accurate monitoring of VWC facilitates efficient allocation of irrigation water and for comparing treatments in agronomic research. Our objectives were to evaluate the performance of the PR2 Profile Probe in a Pullman clay-loam in a perennial grassland by comparing the factory default calibration with the VWC using the gravimetric method and to determine soil-specific in situ calibration equations for different soil layers to improve probe accuracy.

MATERIALS AND METHODS

Experimental Site

Field calibration of the PR2 Profile Probe was conducted at the Texas Tech Forage–Livestock Research Laboratory located near New Deal, TX (33°45′ N, 101°47′ W; 993 m altitude) in 2018. The predominant soil was Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls). The research field was nearly level, with 0 to 1% slope. The subsurface soil is characterized by calcic horizons (Bt and Btk) having illuviated clay (clay loam to clay) content overlying a secondary calcium carbonate layer (3–40% $CaCO_3$, caliche) within 60 to 130 cm of the mineral soil thickness (NRCS, 2017). Selected physical and chemical properties of studied soil are presented in Table 1. The cropping history and field layout of the research location was described by Baxter et al. (2017). The climate is semiarid, having long-term (1911–2008) mean annual precipitation of 470 mm, with peak occurrence in late spring and early summer. Kharel (2018) reported hydraulic conductivities and soil water retention characteristics of the top 20-cm soil layer.

Table 1. Selected soil properties for the studied soil at two replicate blocks in New Deal, TX.

Depth	East replicate Sand	Silt	Clay	OM†	ρ_b‡	West replicate Sand	Silt	Clay	OM	ρ_b
cm	%				Mg m^{-3}	%				Mg m^{-3}
0–10	44	19	37 cl§	3.30	1.39	60	14	26 scl	2.39	1.53
10–20	40	20	40 c	3.07	1.42	48	18	34 scl	2.33	1.51
20–30	45	17	38 cl	1.66	1.43	51	13	36 sc	1.35	1.52
30–40	42	19	39 cl	1.30	1.46	51	14	35 sc	1.14	1.49
40–50	36	26	39 cl	1.03	1.46	48	18	34 scl	0.81	1.57
50–60	39	22	38 cl	0.77	1.52	51	18	31 scl	0.61	1.64
60–70	49	16	35 sc	0.64	1.59	61	11	28 scl	0.63	1.53
70–80	54	15	31 scl	0.28	1.62	62	12	26 scl	0.39	1.67
80–90	57	13	31 scl	0.25	1.46	66	9	25 scl	0.34	1.50
90–100	58	11	31 scl	0.19	1.42	68	8	24 scl	0.32	1.50

† Organic matter content; 2 yr average.

‡ Dry bulk density of soil.

§ USDA soil classes: c, clay; cl, clay loam; scl, sandy clay loam; sc, sandy clay.

Soil sampling occurred in small plots within experimental pastures into which different alfalfa (*Medicago sativa* L.) cultivars were interseeded in October 2015 into a 14-yr-old stand of native mixed grasses: blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffths], sideoats grama [*Bouteloua curtipendula* (Michx.) Torr], buffalograss [*Bouteloua dactyloides* (Nutt.) Engelm], and green sprangletop [*Leptochloa dubia* (Kunth) Nees]. Three replications out of four were located on the east side and one at the southwest corner of the study field, characterized by slightly different soils. The pastures were managed without irrigation since establishment.

Capacitance Probe Description and Access Tube Installation

The PR2/6 Profile Probe model is a 135-cm long, sealed, polycarbonate rod of 25.4-mm diameter (Qi and Helmers, 2010), with six pairs of electronic stainless steel rings centered at 10, 20, 30, 40, 60, and 100 cm from the top (Fig. 1). The probe has a 95% vertical sensitivity within ± 50 mm of the upper ring of each pair with a range of accuracy specified from 0 to 0.4 m^3 m^{-3}. The probe can accurately operate at air temperatures from 0 to 40°C. The mV output is converted into permittivity using a polynomial equation (Delta-T Devices, 2008). Permittivity is converted to VWC either by using the default parameters or by changing parameters resulting from the user's in situ calibration. In 2017, 28 epoxy–fiberglass access tubes (ATS1, Delta-T Devices, Cambridge, UK) were installed between adjacent alfalfa rows to monitor VWC at various soil depths, 2 d after rain at the end of March 2017, which helped hydrate the soil thoroughly. The installation procedure followed the manufacturer's instructions. Care was exercised while selecting sites, augering, and inserting tubes to ensure good contact between the tube wall and soil. Pilot and finishing augers were consistently positioned straight and lubricated during installation so that wobbling and excessive hammering were avoided. Each tube was 125 cm long and had an inside diameter of 2.8 cm. The tube extended 5 cm above the soil surface. A rubber collar around the tube at the surface stabilized the soil surrounding the top of the access tube. A plastic or rubber plug firmly closed the top end of each access tube when not in use to prevent the entrance of water and debris. Tube interiors were cleaned and dried regularly by using a cleaning kit.

Gravimetric Soil Sampling

The output of the PR2 probe using its default setting was compared with the VWC (θ_v) from gravimetric (θ_g) measurements. Undisturbed soil cores were extracted using a tractor-mounted hydraulic Giddings Probe (25-TS/Model HDGSRTS; Giddings Machine Co. Inc., Windsor, CO) within a radius from 20 to 100 cm from each access tube. Although the sensing radius of the probe is 10 cm, cores were extracted outside of the sensing volume where the coring distance from the access tube was decided based on row crop location, tractor accessibility in a small plot, and possible damage to the tube or soil or vegetation around the tube. Samples were taken on 4 d (28–29 June 2018 and 4–5 July 2018). Between those days, 25 mm of rain was recorded by the onsite weather station, which resulted in a range of soil water contents over a short period. Although four replications represented the pasture trial, two replications were selected for calibration at opposite ends of the farm separated by 1.1 km. Seven cores per day from each of the blocks were extracted so that 28 (7 plots × 4 d) cores were from the west and 28 from the east sites. The Giddings stainless steel corer containing a transparent polypropylene soil tube liner (ZC-232; Giddings Machine Co.; 4.4 cm i.d.) was driven vertically into the soil to a depth of 110 cm. Silicone lubricant was sprayed on the outer surface of the liners to reduce friction and compaction of soil inside. Sampling was performed in the morning to minimize evaporation of water and build-up of humid air inside. Tube liners were transported and stored horizontally to prevent soil compaction. The liners were examined at the tube–soil interface for air gaps to avoid error in bulk density measurement. Plastic caps were fitted on the top and bottom ends of the core tube to prevent evaporation. Soil cores were taken to the lab immediately after sampling and cut into subsamples of the desired length using a hacksaw to obtain a correct sampling volume. Cores were segmented at 0 to 10, 10 to 20, 20 to 30, 30 to 40, 50 to 60, and 90 to 100 cm to represent the sensor rings at 10-, 20-, 30-, 40-, 60-, and 100-cm depths (Fig. 1). Subsamples were immediately weighed, and then oven dried at 105°C for 48 h until achieving a stable weight. Bulk density was calculated as the dry mass per unit volume of soil. The observed θ_v was calculated as the product of θ_g and bulk density using Eq. [1]:

$$\theta_v = \rho_b \times \theta_g \qquad [1]$$

where θ_v is the VWC (m^3 m^{-3}); θ_g is gravimetric water content (kg kg^{-1}), and ρ_b is the bulk density of soil (Mg m^{-3}).

Soil Permittivity Measurement and Field Calibration

A PR2/6 Profile Probe (Fig. 1) was inserted into each access tube to read voltage. Readings were taken immediately after the gravimetric soil cores were obtained in the same plot for each sampling date. Output was recorded using an HH2 Meter connected via a 1.5-m long PRC/d-HH2 cable (Delta-T Devices, Cambridge, UK) (Fig. 1). Recorded data were downloaded to a computer as an ASCII file. When power is supplied to the probe, it creates a radio signal of 100 MHz from which the sensor rings generate an EM field within 1 s, extending about 10 cm into the soil, and resulting in stable voltage output. Voltage output is converted into the square root of permittivity (√ε) by using Eq. [2] given by Delta–T Devices (2008):

$$\sqrt{\varepsilon} = 1.125 - 5.53V + 67.17V^2 - 234.42V^3 + 413.56V^4 - 356.68V^5 + 121.53V^6 \quad [2]$$

where ε is the permittivity and V is the sensor output in voltage (mV).

Permittivity is the measure of dielectric constant. From a linear function of plotting √ε against the VWC, the manufacturer determined the soil offset (a_0) and slope (a_1) that reflect the influence of the soil:

$$\theta_v = \frac{\sqrt{\varepsilon} - a_0}{a_1} \quad [3]$$

where θ_v is the VWC ($m^3\ m^{-3}$), ε is permittivity, and a_0 and a_1 are the default parameters suggested by Delta–T Devices, i.e., 1.3 and 7.7 for organic soil and 1.6 and 8.4 for mineral soil, respectively. For the typical mineral soil of this region, the default equation set in the instrument was Eq. [4]:

$$\theta_v = \frac{\sqrt{\varepsilon} - 1.6}{8.4} \quad [4]$$

Calibration of the PR2 probe was conducted in June–July 2018 by comparing default permittivity values (or θ_v) with observed θ_v obtained from gravimetric measurements at each depth. The values of a_0 and a_1 were estimated by fitting the θ_v equation (i.e., Eq. [3]) to the observed θ_v using a nonlinear least squares optimization in Excel Solver. The aim was to obtain an equation that minimized the residual sum of squares or sum of squared errors. The RMSE was set to its minimum value as suggested by Deb et al. (2013). Twenty-eight pairs (n = 28) were used to obtain the optimized parameters for each depth. The parameters a_0 and a_1 for each of the blocks and soil depths are presented in Table 2. Optimized parameters a_0 and a_1 were used for each of the depths at both sites to recalculate θ_v measured by the PR2 over a 2-yr period (2017 and 2018) by using Eq. [2] and [3]. The amount by which the modified VWC values differed from the observed VWC was quantified. Linear regressions of modified VWC against observed VWC were made to evaluate the performance of the model based on higher r^2 and lower RMSE.

Table 2. Parameters (a_0 and a_1) obtained from field calibration of PR2/6 Profile Probe for two soil types of the study area at various depths.

	East		West	
Depth	a_0	a_1	a_0	a_1
cm				
0–10	0.90	13.05	1.32	8.23
10–20	0.57	13.86	1.35	9.21
20–30	1.21	8.45	1.11	11.35
30–40	0.95	11.57	0.94	13.28
50–60	0.20	14.86	1.78	9.83
90–100	1.05	13.72	2.12	8.92

RESULTS AND DISCUSSION

Soil Properties

Particle-size distribution, bulk density, and organic matter content for the discrete soil layers down to 1 m soil depth are presented in Table 1. There was less variability in soil bulk density with soil depth at the west than at the east replicate. Mean values were close to 1.5 Mg m^{-3} for the top 0 to 60 cm and 1.54 Mg m^{-3} for 60 to 100 cm. Soil was more clayey in the east (36%) than the west (30%) replicate. The east replicate was slightly richer than the west site in organic matter content within the 0- to 60-cm soil depths, whereas the opposite was found within the 60- to 100-cm soil depth. Kharel (2018) observed similar field capacity (−0.032 MPa) and permanent wilting point (−1.50 MPa) water content values of the top 20 cm soil at the east and west replicates. Corresponding VWC values were 0.35 and 0.20 $m^3\ m^{-3}$, respectively. Saturated conductivity ranged from 74 cm d^{-1} (west replicate) to 103 cm d^{-1} (east replicates).

Accuracy of Default Equation

The square root of permittivity (√ε) (y axis) obtained from the PR2 probe was regressed against the observed soil water content obtained from gravimetric and bulk density measurements (x axis) (Fig. 2). The offset and slope of the default equation deviated from the plot of √ε vs. observed VWC. The Delta-T manufacturer's default equation consistently overestimated soil water content at √ε > 4.2 (mV > 821, $\theta_v > 0.32\ m^3\ m^{-3}$), but underestimated at √ε < 2.5 (mV < 512, $\theta_v < 0.12\ m^3\ m^{-3}$) when compared with observed VWC from gravimetric measurement. Mwale et al. (2005) reported that the PR1/6 capacitance probe overestimated VWC by 5 to 20% throughout the measurement period in a glasshouse experiment on deep sandy loam soil with bulk density ranges between 1.4 and

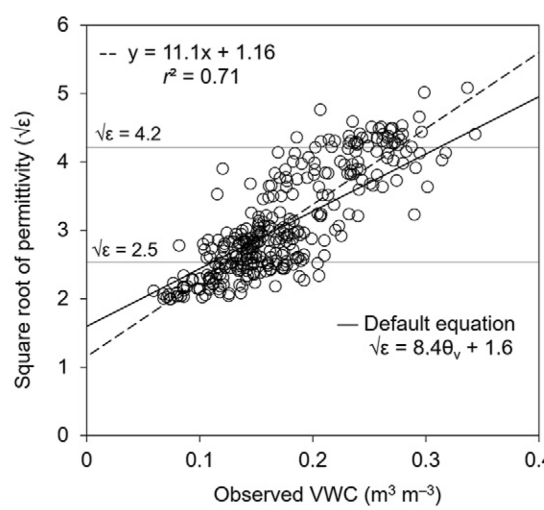

Fig. 2. Relationship between square root of permittivity measured by PR2/6 Profile Probe and observed VWC calculated from gravimetric soil water content (dashed line) and fitted regression of square root of permittivity given by Delta-T Devices and VWC (solid line).

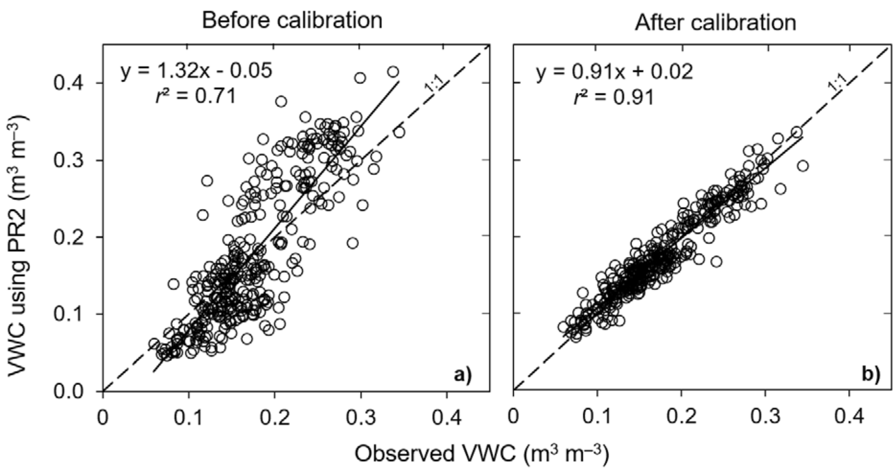

Fig. 3. Relationship between observed VWC calculated from gravimetric soil water content and VWC measured by PR2/6 Profile Probe using (a) Delta-T default parameters and (b) optimized parameters at east and west replicate soils and six depths.

1.7 g cm^{-3} and packing density varies from 1.5 g cm^{-3} on top and 2.01 g cm^{-3} on bottom, whereas the probe underestimated VWC at soil depths of 10 and 20-cm by at least 5% in another glasshouse trial on shallow sandy loam soil. They found overestimation of VWC at soil depths of 60 cm and 100 cm. Current finding was in agreement with the study of Qi and Helmers (2010), who reported that the PR2/6 probe consistently overestimated VWC at $\sqrt{\varepsilon} > 5.50$ and underestimated at $\sqrt{\varepsilon} < 3.05$ for clay-loam soils in Iowa.

Differences in soil texture could have been responsible for the observed variability with depth in the performance of the probe (Mwale et al., 2005; Seyfried and Murdock, 2004). The range of VWC estimated by the PR2 probe was 0.05 to 0.42 m^3 m^{-3}, whereas the observed VWC obtained from gravimetric measurements ranged from 0.06 to 0.34 m^3 m^{-3}. In general, the PR2 overestimated VWC at depths of 60 and 100 cm and underestimated VWC at depths of 10, 20, 30, and 40 cm. For the manufacturer's default equation, r^2 between the predicted VWC using the PR2 probe and the observed VWC was 0.71 when data from all soil depths were aggregated (Fig. 3a), whereas the RMSE value was 0.053 m^3 m^{-3}. The RMSE values increased with depths, i.e., 0.04 m^3 m^{-3} at 10 cm and 0.08 m^3 m^{-3} at 100 cm, and the r^2 was found to be independent of the soil depth (Table 3). The RMSE value was lower than the RMSE (0.085–0.093 m^3 m^{-3}) reported in the study of Qi and Helmers (2010) in Iowa, and notably lower than the RMSE (0.183 m^3 m^{-3}) reported by Huang et al. (2004) from field measurement in Manitoba, Canada. Huang et al. (2004) found that RMSE was much more dependent on soil bulk density than texture.

Field Calibration and Performance

The higher RMSE and lower r^2 values from the Delta-T default equation necessitated site-specific calibration of the PR2 probe for accurate measurement of soil water content. The field-calibrated parameter values were different from the manufacturer's recommended values ($a_0 = 1.6$, $a_1 = 8.4$) and were not uniform within the soil profile (Table 2). The parameters had no clear relationship with soil texture or bulk density at different depths, although they differed between the two replicate plots consisting of varied soil clay content and bulk density. For the east site, the value of a_0 tended to remain lower than the default value, whereas the values of a_1 were greater than the default value for all soil depths. In the west replicate, a_0 was greater at depths below 50 cm, but a_1 tended to be higher with the 30- to 40-cm depths. The slope of the equation was greater at depths where bulk density was slightly higher than other soil layers. Previous studies (Evett and Steiner, 1995; Fares et al., 2011; Gardner et al., 1998; Huang et al., 2004) reported the effects of bulk density, texture, temperature, and organic matter content on the calibration of capacitance probes. Huang et al. (2004) suggested that field-derived a_0 and a_1 values were independent of soil depth, bulk density, and texture. However, they found that soil bulk density was more relevant than texture in evaluating the probe responses. Huang et al. (2004) explained that the relationship, as also reported in other studies (Dean et al., 1987), might be affected by air gaps between the access tube and soil.

The calibration improved probe performance and was consistent between replicates, although it was not uniform for all depths. The most plausible explanation for this variation is the presence of cracks, quite normal in clay-rich soil, within the sensing

Table 3. Performance of the Delta-T default equation and calibrated equation in predicting soil moisture at various soil depths.

	Delta-T default equation				Calibrated equation			
	East		West		East		West	
Depth	r^2	RMSE†	r^2	RMSE	r^2	RMSE	r^2	RMSE
cm		m^3 m^{-3}		m^3 m^{-3}		m^3 m^{-3}		m^3 m^{-3}
0–10	0.64	0.044	0.59	0.041	0.83	0.017	0.91	0.012
10–20	0.32	0.049	0.73	0.034	0.41	0.012	0.81	0.009
20–30	0.71	0.053	0.56	0.046	0.75	0.015	0.69	0.020
30–40	0.63	0.028	0.66	0.035	0.78	0.016	0.80	0.018
50–60	0.44	0.053	0.63	0.075	0.79	0.021	0.74	0.019
90–100	0.35	0.080	0.43	0.073	0.74	0.024	0.77	0.029

† Root mean square error (RMSE) represents the standard deviation of predicted soil moisture content from the observed value.

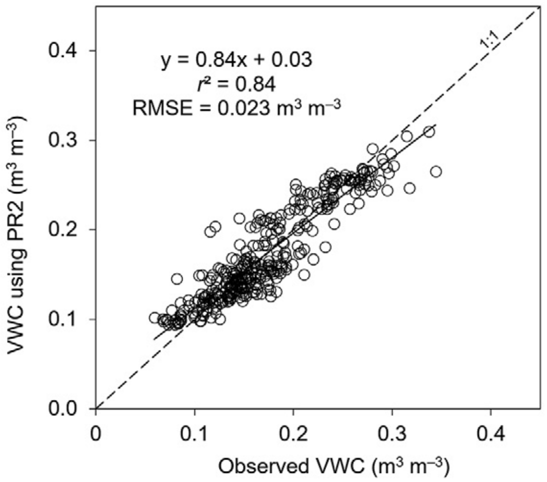

Fig. 4. Relationship between observed VWC calculated from gravimetric soil water content and VWC estimated with PR2/6 Profile Probe using optimized parameters a_0 = 0.6 and a_1 = 14.6 generated from all data points including two replicates and six depths.

volume of the soil at different depths. In most cases, r^2 and RMSE were synchronously improved by the calibration. The r^2 increased from 0.71 to 0.91, and RMSE diminished to 0.017 $m^3\ m^{-3}$ from 0.053 $m^3\ m^{-3}$ when comparing the observed VWC obtained from gravimetric measurements and the estimated (PR2 probe) VWC using the manufacturer's default equation and using all optimized parameters (Fig. 3). Using all data points, including six depths and two replicates, the a_0 value (0.6) was lowered and the a_1 value was increased (14.6) relative to the default parameter values, yielding the following equation:

$$\theta_v = \frac{\sqrt{\varepsilon} - 0.6}{14.6} \quad [5]$$

The overall calibration Eq. [5], when data from the different soil depths were aggregated for the soil profile, resulted in r^2 and RMSE of 0.84 and 0.023 $m^3\ m^{-3}$, respectively (Fig. 4). Calibration reduced the range of VWC estimated by the PR2 probe from 0.05 to 0.42 $m^3\ m^{-3}$ to 0.07 to 0.34 $m^3\ m^{-3}$, which agreed with the observed VWC values (0.06–0.34 $m^3\ m^{-3}$). Morgan et al. (1999) improved r^2 values to 0.83 and reduced RMSE values to 0.0085 for three soil types in Florida using soil-specific field calibration of a capacitance probe. Similarly, Evett and Steiner (1995) reported that r^2 and RMSE of 0.68 to 0.71 and 0.036 $m^3\ m^{-3}$, respectively, resulted from the calibration of capacitance probe gauges. Their reason for the relatively poor r^2 values was the small-scale variation in a measurement volume of the gauges. Fares et al. (2011) succeeded in reducing the RMSE from 0.074 to 0.081 $m^3\ m^{-3}$ to 0.044 to 0.065 $m^3\ m^{-3}$ for EC-10 and EC-20 capacitance probes in tropical soils of Hawaii. The results of capacitance probe calibration reported in the aforementioned studies agreed with the results presented here. As shown in Fig. 5, for the east site, the temporal changes in VWC at 10-cm soil depth using the calibrated equation was compared with the temporal changes in the uncalibrated VWC (using the manufacturer's equation) for the PR2 probe. The calibrated equation reduced the peaks of the pulses in VWC throughout the study period by correcting the overestimated and underestimated measurements of Delta-T multi-sensor capacitance probe.

The effectiveness of the calibrated equations was realized by validating coefficients obtained from one replicate to another.

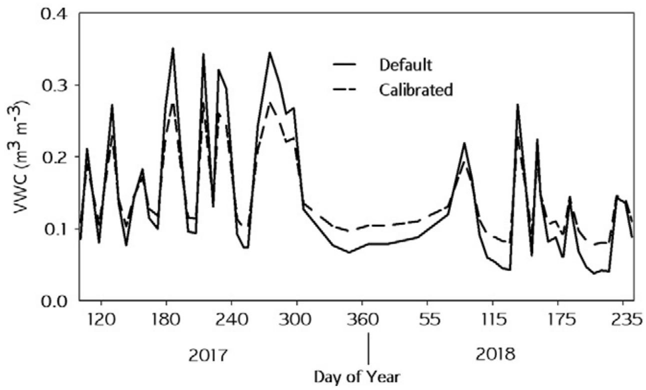

Fig. 5. Comparison of VWC recorded by PR2/6 Profile Probe as predicted by Delta-T default equation (default) and the corrected VWC modified by the optimized parameters (calibrated) for the study period at a 10-cm soil depth on the east replicate only.

Calibration coefficients obtained from the east replicate increased r^2 to 0.78 and decreased RMSE to 0.022 $m^3\ m^{-3}$ from default results when comparing the observed VWC and the corrected VWC measured by PR2 probe from west replicate. Similarly, coefficients obtained from the west replicate increased r^2 to 0.80 and decreased RMSE to 0.020 $m^3\ m^{-3}$ for the east replicate. The field calibration of PR2 Profile probe performed by other researchers may apply to this soil. The field-calibrated equations provided by Qi and Helmers (2010) for clay-oam soils in Iowa (a_0 = 0.5, a_1 = 26.7) and tested in current research increased r^2 to 0.78, but also increased RMSE to 0.060 $m^3\ m^{-3}$ relative to default results, which are not as favorable as our calibration. Current results are useful for correcting VWC measured by PR2/6 probe in similar soils in research aimed at differentiating treatment effects on one-dimensional changes in VWC in a 1 m soil profile.

We conclude that the PR2 Profile Probe could be a reliable alternative to more expensive and difficult techniques such as the neutron probe method for the precise measurement of soil VWC. With the calibrated parameters derived in this study, more than 90% of the variability in VWC can be explained by Eq. [3], a significant improvement over the default equation, which explained <75%. The variability between observed and predicted VWC produced by the PR2 was reduced by 68% using the site- and depth-specific calibration, and by 57% when using the overall equation for the entire soil profile. Calibration reduced the range of PR2 data, resulting in a range closer to observed soil VWC. Overall, this study shows that site-specific calibration will improve the accuracy of Delta-T multi-sensor capacitance probe to a level that is of acceptable accuracy for research on a high-clay grassland soil.

ACKNOWLEDGMENTS

We greatly appreciate Phil Brown, Paul Green, and Eduardo Escamilla for their technical assistance in the field. Research was supported by the CH Foundation and USDA Southern SARE grant LS17-286.

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