

Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest

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Abstract: We compared the accuracy and precision of three devices for measuring soil water content in both natural and repacked soils and evaluated their temperature sensitivity. Calibrations were developed for a capacitance instrument (ECH2O), a time domain reflectometry cable tester (CT), and a water content reflectometer (WCR) in soils collected from the Wind River and H.J. Andrews Experimental Forests. We compared these calibrations with equations suggested by manufacturers or commonly used in the literature and found the standard equations predicted soil moisture content 0%–11.5% lower ($p < 0.0001$) than new calibrations. Each new calibration equation adequately predicted soil moisture from the output for each instrument regardless of location or soil type. Prediction intervals varied, with errors of 4.5%, 3.5%, and 7.1% for the ECH2O, CT, and WCR, respectively. Only the ECH2O system was significantly influenced by temperature for the range sampled: as temperature increased by 1 °C, the soil moisture estimate decreased by 0.1%. Overall, the ECH2O performed nearly as well as the CT, and thanks to its lower cost, small differences in performance might be offset by deployment of a greater number of probes in field sampling. Despite its higher cost, the WCR did not perform as well as the other two systems.

Résumé : Les auteurs ont comparé l'exactitude et la précision de trois systèmes de mesure du contenu en eau du sol dans des sols naturels et reconstitués et ils ont évalué leur sensibilité à la température. Des calibrages ont été effectués pour un instrument à capacitance (ECH2O), un analyseur de câble (AC) qui fonctionne en réflectométrie dans le domaine temporel et un réflectomètre du contenu en eau (RCE) dans des sols prélevés dans les forêts expérimentales Wind River et H.J. Andrews. Ils ont comparé ces calibrages avec les équations suggérées par les fabricants ou couramment utilisées dans la littérature, et ils ont trouvé que les équations standard prédisent un contenu en eau du sol de 0 % à 11,5 % plus faible ($p < 0,0001$) que celui des nouveaux calibrages. Chaque nouvelle équation de calibrage prédit adéquatement l'humidité du sol à partir de la lecture de chaque instrument peu importe la localisation ou le type de sol. Les intervalles de prédiction varient avec des erreurs respectives de 4,5 %, 3,5 % et 7,1 % pour l'ECH2O, l'AC et le RCE. Seul le système ECH2O est influencé par la température dans les limites de l'échantillonnage; la mesure de l'humidité du sol diminue de 0,1 % pour une augmentation de la température de 1 °C. Globalement, la performance de l'ECH2O est presque aussi bonne que celle de l'AC et, grâce à son coût plus faible, les petites différences de performance peuvent être compensées par l'utilisation d'un plus grand nombre de sondes pour l'échantillonnage sur le terrain. En dépit de son coût plus élevé, le RCE n'a pas performé aussi bien que les deux autres systèmes.

[Traduit par la Rédaction]

Introduction

Researchers require safe, nondestructive techniques that accurately quantify volumetric soil water content. Historically, researchers were required to destructively sample a site to quantify the gravimetric soil moisture or use radioactive ma-

terial to quantify the volumetric soil moisture. Fortunately, new techniques have been developed that take advantage of the high dielectric constant of water to quantify the volumetric water content of soil (θ). The most common instruments use the capacitance technique or time domain reflectometry (TDR) (e.g., Topp and Davis 1985). However, the accuracy and precision of these instruments vary, and the calibration of these instruments may change with soil type, electrical conductivity, and temperature (Topp et al. 1980; Topp 1987; Pepin et al. 1995; Seyfried and Murdock 2001; Wraith and Or 2001). With so many options available at a variety of costs, information is needed to help researchers determine the appropriate instrument to use for their research.

The instruments that use the capacitance technique or TDR to determine θ rely on the high dielectric constant of water (80) relative to mineral soil (3–5) and air (1), because water in the soil will influence the propagation of an electric signal through the soil medium. Both these techniques use empirical relationships between the soil water content and the change

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in an electrical signal to estimate θ . Three common instruments available for the measurement of θ are the ECH2O soil moisture probe (hereafter referred to as "ECH2O"; Decagon Devices, Pullman, Washington, USA), the TDR cable tester (hereafter referred to as "CT"; we used model 1502C, Tektronix, Inc., Beaverton, Oregon, USA), and the water content reflectometer (hereafter referred to as "WCR"; we used the CS615 from Campbell Scientific, Logan, Utah, USA; since our measurements Campbell Scientific has introduced a new model).

The ECH2O calculates the apparent soil dielectric constant (K_a) of a soil by measuring the charge time of a capacitor in the soil. If the applied voltage is known, the time required to charge the capacitor is related to the output voltage of the instruments. Hence, the K_a of the surrounding medium can be described as

$$[1] \quad K_a = \frac{1}{t} \left[\frac{RA}{S} \ln \left(\frac{V - V_f}{V_i - V_f} \right) \right]$$

where t is time, R is the series resistance, A is the area of the plates, S is the separation between the plates, V is the output voltage, V_i is the starting voltage, and V_f is the applied voltage. An empirical equation is used to describe the relationship between the output voltage and θ .

The CT uses TDR to estimate θ . TDR determines K_a by measuring the time required for an electromagnetic pulse to travel up and down a pair of metal transmission lines of a fixed length (e.g., Topp et al. 1980). The high dielectric constant of water relative to soil and air will delay the propagation of the electromagnetic pulse. Hence, K_a is positively associated with increasing volumetric soil water content and can be expressed as

$$[2] \quad K_a = \left(\frac{c \times t}{2L} \right)^2$$

where c is the propagation velocity of an electromagnetic wave in free space (i.e., the speed of light), t is signal travel time, and L is the length of the transmission lines. Using an empirical equation, θ can then be calculated as a function of K_a .

The WCR also propagates a signal along two parallel rods, but instead of measuring the propagation time of an electromagnetic pulse, the WCR uses the capacitance of the soil to predict K_a (Dean et al. 1987; Paltineanu and Starr 1997). The high dielectric constant of water relative to soil and air will influence the capacitance of the soil, and this will, in turn, affect the oscillating frequency of the electromagnetic pulse produced by the WCR. Hence, the WCR is referred to as a frequency domain reflectometer (FDR). The oscillating frequency (15–45 MHz) produced by the WCR is scaled down by circuitry in the WCR to a signal that can be monitored by a datalogger and used to estimate θ .

Electrical conductivity of the soil medium may affect the relationships between θ and the electronic signals of these instruments. The dielectric constant for mineral soil generally ranges from 3 to 5, but soils with high electrical conductivities (e.g., high salt content) may have higher dielectric constants. The manuals for the ECH2O and WCR state that the factory calibration will accurately predict θ if the electrical conductivity is $<1 \text{ dS}\cdot\text{m}^{-1}$ (Campbell Scientific 1996) or if the

sand–clay content of the soil is not "too" high. If the electrical conductivity is greater than $1 \text{ dS}\cdot\text{m}^{-1}$ and (or) the sand or clay content of the soil is high or a greater precision is needed in the estimates, past research suggests that the instrument be calibrated for the specific soil (Starr and Paltineanu 2002).

Temperature may also influence how these instruments estimate θ (Pepin et al. 1995; Seyfried and Murdock 2001; Wraith and Or 2001; Campbell 2001). For example, for temperatures from 5 to 35 °C the dielectric constant of water decreases by $0.7\% \cdot ^\circ\text{C}^{-1}$ (Campbell 2001) and can influence K_a (Pepin et al. 1995; Wraith and Or 2001). The manufacturer found that in sandy and loamy soils, the ECH2O had only a small change in water content due to differences in temperature, but in clays showed changes of $0.003 \text{ m}^3\cdot\text{m}^{-3}\cdot^\circ\text{C}^{-1}$ (Campbell 2001). The CT has been found to have a temperature dependency across soil types (Pepin et al. 1995; Persson and Berndtsson 1998). For the WCR, the manufacturer provides a temperature correction because of known temperature sensitivity (Campbell Scientific 1996), and in clays it had changes in water content up to $0.005 \text{ m}^3\cdot\text{m}^{-3}\cdot^\circ\text{C}^{-1}$ (Campbell 2001). Hence, it may be necessary for individual users to calibrate the instruments for their specific measurement conditions, including temperature, if precise estimates of θ are required.

Wraith and Or (2001) suggested that the standard TDR technique will accurately predict in situ θ based on calibrations in repacked soil, where the secondary structure of the soil is removed. Other studies have also suggested that to get the greatest precision, probes should be calibrated using repacked soil cores (Starr and Paltineanu 2002). However, by repacking soil the macrostructure is altered and may no longer represent natural soil structure under field conditions. More research is needed to verify that the common volumetric soil moisture probes can indeed be calibrated using repacked soil cores.

The purpose of this study was to develop calibration equations to predict soil moisture content of two soils in the Western Cascades using the ECH2O, CT, and WCR soil moisture instruments and compare their accuracy, precision, and temperature sensitivities. We define accuracy as the ability of the instrument (ECHO, WCR, and CT) to estimate the actual soil moisture value. Precision was defined as the repeatability of a measurement, as defined by Bloom (1989). In order to examine these relationships, we designed experiments to answer the following questions:

- (1) What empirical equation(s) best describe the relationship between the output of these instruments and the moisture content of soils collected from two sites in the Western Cascades?
- (2) Given that most applications of these tools are in natural soils and manufacturers suggest using repacked soils for calibration, does the output to soil moisture relationship differ between natural and repacked soils?
- (3) What improvement in measurement accuracy is obtained by using site-specific calibrations for these soils compared with previously determined calibration equations suggested by manufacturers or commonly used in the literature (hereafter referred to as standard calibration equations)?
- (4) Do variations in temperature over the normal range encountered in these soils significantly affect the output to soil moisture relationship?

- (5) How does precision vary among the three instruments tested?

Materials and methods

Instruments

ECH2O

A Decagon Devices Inc. model EC-20 probe with a 20-cm plate. Signal output ranges between 250 and 1000 mV at 2500-mV excitation. The manufacturer provides an equation that is reported accurate within 3% θ if the soil does not have “high” sand content, clay content, or electrical conductivity. The manufacturer has determined that the instrument is weakly sensitive to changes in temperature and therefore does not suggest the need for a temperature correction (Campbell 2001).

CT

A Tektronix model 1502C cable tester with two parallel 33 cm long \times 4 mm diameter stainless steel rods that were set 5 cm apart. A commonly used method for interpreting the nanosecond signal was created by Topp et al. (1980); however, we used a slightly different method created by Gray and Spies (1995) because it was calibrated for soils in the Pacific Northwest. Each has a different calibration equation to relate θ to K_a .

WCR

A Campbell Scientific, Inc. model CS615 with 30-cm rods (3.2 mm diameter and 3.2-cm spacing) connected to a circuit board. The circuit board is enclosed in epoxy and acts as a bistable multivibrator. Past research indicates that WCR is sensitive to temperature (Seyfried and Murdock 2001). To address this issue Campbell Scientific provides a temperature-dependent calibration equation:

$$[3] \quad \theta_{\text{corrected}} = \theta_{\text{uncorrected}} - (T - 20)\text{Coef}_{\text{temp}}$$

where T is the soil temperature and $\text{Coef}_{\text{temp}}$ is described as

$$[4] \quad \text{Coef}_{\text{temp}} = -3.46 \times 10^{-4} + 0.019\theta_{\text{uncorrected}} - 0.045\theta_{\text{uncorrected}}^2$$

Study area

Samples were collected from two old-growth forest sites in the Pacific Northwest. These sites were selected because they are frequently used for ecological research and the soils are widely representative of forested regions in the Pacific Northwest. One site was in the Wind River Canopy Crane Research Forest (WR), located in the Western Cascades of Washington (45.82°N, 121.90°W). Soils are described as medial, mesic, Entic Vitrandis; they are typically deep, well drained, medium textured (Shaw et al. 2004), have a bulk density between 0.7 and 1.1 g·cm⁻³ (Klopatek 2002), and electrical conductivity assumed to be <1 dS·m⁻¹. Samples taken from this site had loamy to sandy loam soil textures. Dominant species of vegetation include western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (>450 years old) (Shaw et al. 2004). The area receives over 2500 mm of annual precipitation, less than 10% of which falls between June and September.

Samples from within the H.J. Andrews Experimental Forest (HJA) in the central Oregon Cascades (44.2°N, 122.2°W) were from alluvial soils of volcanic origin. These HJA soils are reddish brown, have gravelly clay loam texture, and are formed into highly defined, coarse aggregates (Ranken 1974) with an electrical conductivity of <1 dS·m⁻¹ (Van Verseveld, personal communication, 2004). HJA soils for all experiments were collected from within a 5-m² area located on a small alluvial fan and were sandy loam to sandy clay loams. The vegetation is dominated by 350- to 480-year-old western hemlock and Douglas-fir, with a young western hemlock understory (Swanson and Jones 2002).

Experiments

Four experiments were performed. The first examined relationships between θ and the electronic signals (output) of the three instruments inserted into intact soils that retained their natural structural characteristics. These soils represent typical field conditions where macropores, soil aggregates, rocks, and large organic material are present. The second experiment examined relationships between θ and the output of the three instruments inserted into repacked, homogeneous soils. In this case the secondary structure of the soil, such as macropores, soil aggregates, rocks, and large organic material, had been removed. The third experiment was designed to evaluate the effects of soil temperature on the relationships between θ and the output of the three instruments. Soil temperatures were varied within the range of field conditions. For all three instruments, we also compared the predictions from standard calibration equations with the predictions from the equations we generated and tested the influence of the PVC tube size on the instrument output. The fourth experiment evaluated the influence of the size of the soil core on instrument output.

Field methods

To collect soil samples, 34.5 cm long \times 10.1 cm diameter plastic PVC tubes were pounded vertically into the mineral soil (litter layer removed). This size core was deemed appropriate for (1) ECH2O because the signal propagates between 0 and 2 cm away from the plate surface (Campbell 2003); (2) CT because of the appropriate ratio of rod spacing to tube diameter (Knight 1992) and by previous examination (Gray and Spies 1995); and (3) the WCR because it is similar to the CT. Care was taken to minimize compaction and to excavate samples with soil structure intact. The lower end of the core was sealed with plastic. Fifteen cores (five for each probe type) were taken at each site — WR (collected early September 2002) and HJA (collected 8 November 2002) — for a total of 30 samples.

Lab methods

The experiments were performed indoors in a laboratory; air temperature was approximately 22 ± 2 °C).

Experiment 1

Cores were randomly assigned to one of the three instruments, and one probe was inserted into each. Thus, among the 15 cores from a site, there were five replications of each of the three instruments. Because probe lengths varied among instruments, soil depth was adjusted in the tubes such that

inserted probes extended to within 1 cm of the bottom. Thus, soil volumes for the ECH2O, CT, and WCR were 1722.6, 2764.1, and 2523.7 cm³, respectively.

After installing the instruments, water content of the soil cores was altered by periodically adding small increments of deionized water. The amount of water added at each time interval to each core was adjusted for volume such that ECH2O, CT, and WCR cores received 48, 80, and 72 cm³ of water, respectively, producing a total range in soil moisture of 4%–34% over the course of the experiment. The most effective and least disruptive way of adding water to the soil was to gently pour it on the surface and allow a few seconds for the water to soak in before adding more. After each water addition, 24–48 h elapsed to allow for equilibration of moisture throughout the soil volume before measurements were recorded by weighing the cores. The total mass of tubes, soil, water, and instrumentation was monitored to the nearest tenth of a gram using a model 6001T My-Weigh balance (Phoenix, Arizona, USA). Manual measurements of ECH2O, CT, and WCR output were recorded (CR10X, Campbell Scientific, Inc., for ECH2O and WCR, Hewlett Packard 200LX, Palo Alto, California, USA, for CT) at the time of each weighing.

At the end of experiment 1, soils were dried at 105 °C to a constant mass. Actual θ was calculated as the mass of water in grams (equivalent to the volume of water in millilitres) divided by the total soil volume. The mass of water was determined by subtracting dry soil, probe, and tube masses.

Experiment 2

The dry soil samples from experiment 1 were removed from tubes and crushed to remove secondary soil structure, then repacked into the tubes to the same bulk density (0.82–1.02 g·cm⁻³ depending on sample). Rocks and large organic material, such as roots, >10 mm were excluded. For two of the 30 samples a small amount of extra soil (collected from the same locations) was required to replace the extracted rock and (or) root material. As with experiment 1, instruments were assigned to soil samples, and θ was monitored at regular intervals as soils in the cores incrementally wet up to near full saturation.

Experiment 3

At the end of experiment 2, samples were sealed to prevent evaporation and subjected to three temperature treatments, 4 °C (walk-in cooler), 22 °C (ambient air), and 31 °C (drying oven). Initial soil moisture content for each core was different and fell within the range of 15%–30%. Cores were held at each temperature for 72–96 h prior to measurements. In all cases, the entire instrument was at the same temperature as the soil when the measurements were recorded.

Experiment 4

Three samples, one for each instrument type, were dried at 105 °C and then repacked in the PVC tube. Instruments were installed in each sample, mass was recorded, and a measurement was taken as described in experiment 1. Additional measurements were collected after the core was surrounded by 0.02 m³ of soil at approximately 0.06 m³·m⁻³ θ (dry soil) and 0.02 m³ of soil at approximately 0.21 m³·m⁻³ θ (wet soil). Cores were incrementally wetted up to a “mid” saturation level of approximately 0.2 m³·m⁻³ and a “high”

saturation level of approximately 0.4 m³·m⁻³. All measurements were repeated at both “mid” and “high” saturation levels. At the end of this experiment the WCR and ECH2O instruments were successively installed in the CT soil core to determine the accuracy of the instrument relative to other instruments.

Model selection and analyses

Calibration equations were determined using the PROC MIXED module of SAS version 8 (SAS Institute Inc. 1999) to derive multiple linear regression (MLR) equations with measured values of θ as the dependent variable. The independent variables included output from instruments (ms, K_a, or mV) along with, depending on the experiment, covariates for site and soil structure (natural or repacked soils). We examined both linear and nonlinear (polynomial) equations for the relationship of θ to output for each instrument and evaluated whether the nonlinear equations significantly improved the prediction. A linear equation was selected for the ECH2O, a quadratic equation for the WCR, and a hyperbolic equation for the CT based upon goodness of fit (Mallow's Cp statistic and mean square error or standard error of estimate), as well as the number of individual cores that were best represented by the chosen equation. Once the form of the equation was selected, Aikake information criteria were used for variable selection for ECH2O and WCR and adjusted R² was used for the CT. A final equation was selected based upon low variability (lowest root mean square error), goodness of fit, and practicality for experimental application. This final equation was used to derive predicted values of θ . Paired Student's *t* tests were conducted on the predicted value of θ versus actual values of θ to examine temperature sensitivity.

Results

For all three instruments we found values of θ predicted using standard calibration equations were substantially different (maximum errors were 11.5% θ) from measured θ . Variables for site and soil structure were statistically significant in most of the equations we derived (*p* < 0.0001) (Table 1). Predicted θ was lower in repacked soils than in natural soils by 0%–3% θ for ECH2O and 1%–3% θ for the CT, but for both instruments the calibration for repacked soils fell within the 95% prediction interval for the calibration for natural soils. The same was true for variation by site. Predicted θ was different for HJA versus WR soils by 0%–3% θ for ECH2O (HJA lower), 0%–1.5% θ for CT (WR lower), and 3.5%–6.5% for WCR (WR lower); however, for each instrument the calibration for one site fell within the 95% prediction interval of the calibration for the other site, thus they were not significantly different.

We determined that the improved applicability and greater practicality of a single calibration equation justified the removal of the other variables (Table 1, Fig. 1). For the range of θ relevant to this study, full models differed in their predictions of θ by <3.8%, <1.0%, and <5.5% for the ECH2O, CT, and WCR, respectively. The 95% prediction intervals for most full models encapsulated this variability. Prediction intervals for all equations were nearly or entirely overlapping, suggesting little to no reduction in error (of slope, intercept,

Table 1. Equations, parameter estimates, and associated error (root mean square error (RMSE), R^2 , and confidence (CI) and prediction (PI) intervals) for regressions of θ ($\text{m}^3\cdot\text{m}^{-3}$) on the sensor output (x , units are mV for ECH2O, K_a for CT, and ms for WCR) for data in reduced (“combined”) and full models based upon soil structure and site.

| | β_0 | β_1 | β_2 | AIC | RMSE or SEE ^a | Adj. R^2 | Avg. CI (%) ^b | Avg. PI (%) ^b |
|--|-----------|-----------|-----------|-------|-----------------------------|------------|-----------------------------|-----------------------------|
| ECH2O ($\theta = \beta_0 + \beta_1 x$) | | | | | | | | |
| Combined | -0.24508 | 0.000795 | — | 596.5 | 0.023 | 0.92 | 0.38 | 4.5 |
| Natural ^c | -0.23722 | 0.000794 | — | 598.5 | 0.022 | 0.93 | 0.51 | 4.3 |
| HJA | -0.24700 | 0.000816 | — | 605.4 | 0.019 | 0.95 | 0.64 | 3.8 |
| WR | -0.26635 | 0.000872 | — | 605.4 | 0.019 | 0.95 | 0.64 | 3.8 |
| Repacked ^c | -0.25601 | 0.000799 | — | 598.5 | 0.022 | 0.93 | 0.51 | 4.3 |
| HJA | -0.24961 | 0.000778 | — | 605.4 | 0.019 | 0.95 | 0.64 | 3.8 |
| WR | -0.26896 | 0.000834 | — | 605.4 | 0.019 | 0.95 | 0.64 | 3.8 |
| CT ($\theta = \beta_0 x / (\beta_1 + x)$) | | | | | | | | |
| Combined ^d | 1.0016 | 26.5247 | — | — | 0.018 | 0.90 | 0.35 | 3.5 |
| Natural ^d | 0.7889 | 18.0496 | — | — | 0.014 | 0.94 | 0.39 | 2.8 |
| HJA | 0.6707 | 14.0599 | — | — | 0.011 | 0.94 | 0.47 | 2.4 |
| WR | 0.9233 | 22.4382 | — | — | 0.015 | 0.93 | 0.61 | 3.2 |
| Repacked ^d | 0.9453 | 26.4126 | — | — | 0.015 | 0.91 | 0.41 | 3.0 |
| HJA | 0.7630 | 18.8649 | — | — | 0.015 | 0.95 | 0.44 | 2.4 |
| WR | 1.2145 | 38.1878 | — | — | 0.012 | 0.91 | 0.52 | 2.5 |
| WCR ($\theta = \beta_0 + \beta_1 x + \beta_2 x^2$) | | | | | | | | |
| Combined ^e | -1.60362 | 3.21178 | -1.34786 | 468.1 | 0.036 | 0.80 | 0.71 | 7.1 |
| Natural ^e | -1.52218 | 3.05004 | -1.26435 | 464.7 | 0.036 | 0.80 | 0.85 | 7.1 |
| HJA ^c | -1.91660 | 4.07211 | -1.87715 | 514.2 | 0.028 | 0.88 | 1.14 | 5.6 |
| WR ^c | -2.10346 | 4.27316 | -1.92544 | 514.2 | 0.028 | 0.88 | 1.14 | 5.6 |
| Repacked ^e | -1.52910 | 3.05004 | -1.26435 | 464.7 | 0.036 | 0.80 | 0.85 | 7.1 |
| HJA ^c | -1.80277 | 3.68562 | -1.60120 | 514.2 | 0.028 | 0.88 | 1.14 | 5.6 |
| WR ^c | -1.98963 | 3.88667 | -1.64949 | 514.2 | 0.028 | 0.88 | 1.14 | 5.6 |

Note: Number of samples for ECH2O is 260 and WCR is 249; CT combined equation has 187 samples. Best fit models are listed in order by their degree of statistical relevance. Also see Fig. 1.

^aECH2O and WCR have mean square error (MSE); CT has SEE (standard error of estimate).

^bCI and PI for WCR are much more variable than those of ECH2O and CT.

^cSlopes are not statistically different ($p > 0.05$), but the full model had a better fit.

^dFound the need for additional parameters because of their significant influence on both intercepts and slopes ($p < 0.05$).

^eSlopes are not statistically different ($p > 0.05$), therefore the reduced model was used.

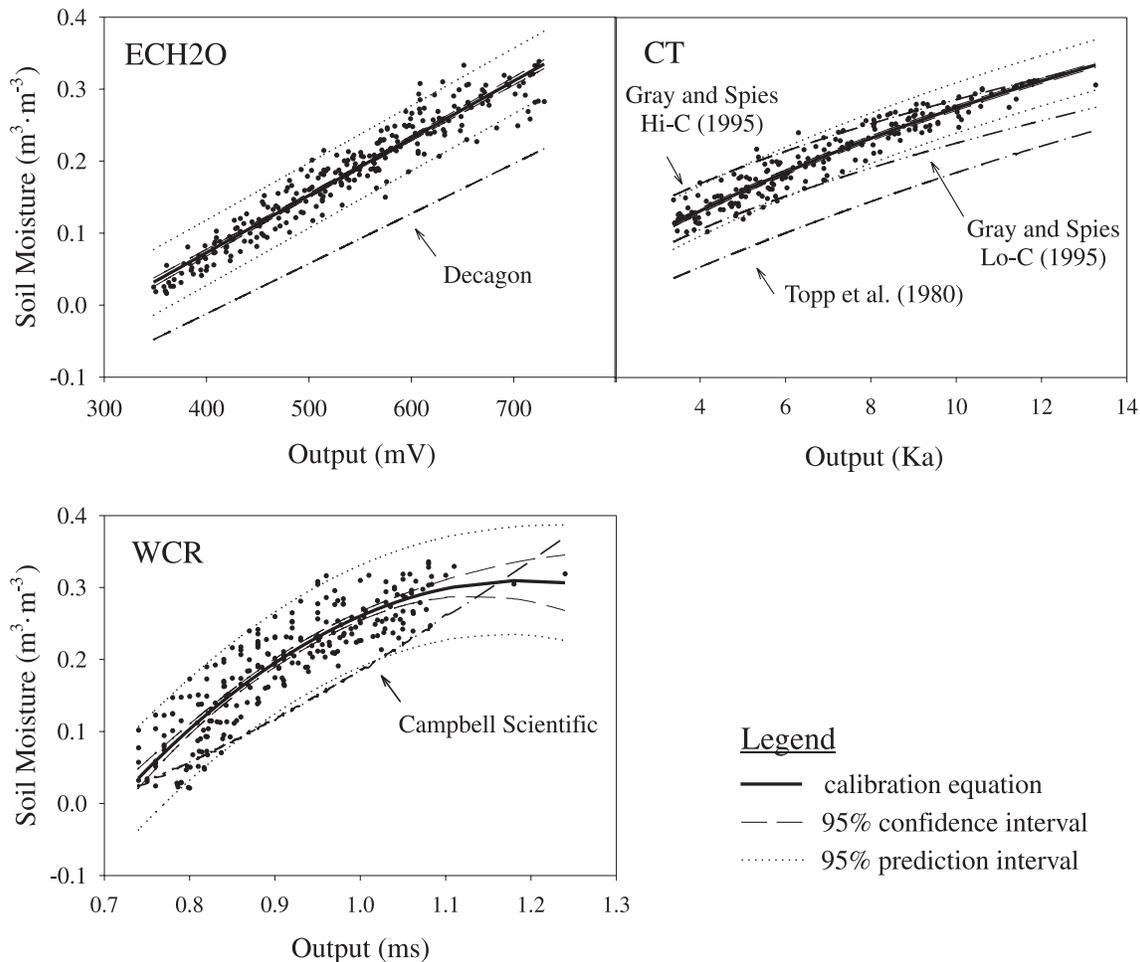
or R^2) by having separate equations for site or soil structure. Precision gained by using full over reduced models is beyond what is required in many applications. For example, a reduced model for ECH2O that did not include either site or structure variables yielded a predicted θ of $0.272 \text{ m}^3\cdot\text{m}^{-3}$; when indicator values for structure and site are included the predictions of θ ranged from 0.256 to $0.298 \text{ m}^3\cdot\text{m}^{-3}$.

Following this logic, we used combined data from the two sites and first two experiments in examining differences between the “combined” calibration equations for each instrument and standard calibration equations (Table 2, Fig. 1). For ECH2O, the equation provided by Decagon underestimated θ by 8%–11.5% compared to our combined calibration equation. This estimate was significantly lower ($t_{259} = 18.86$, $p < 0.0001$) than the suggested precision of 3% (it is supposed to be accurate within 1% if a site-specific calibration is used). For the CT, the Topp et al. (1980) equation underestimated θ by approximately 8%, significantly lower ($t_{186} = 32.93$, $p < 0.0001$) than the 1.3% precision the authors

suggest. Furthermore, the low-carbon (Lo-C) and high-carbon (Hi-C) equations generated by Gray and Spies (1995) for soils collected near our samples underestimated θ by 2.5%–6% and 0%–4%, respectively; significantly lower (Lo-C: $t_{186} = 58.39$, $p < 0.0001$; Hi-C: $t_{186} = 34.55$, $p < 0.0001$) than the 3% precision suggested. The Campbell Scientific calibration equation for the WCR largely falls within the prediction interval of the combined equation for the majority of the range (0%–8% precision). Nevertheless, it was significantly different ($t_{248} = 8.13$, $p < 0.0001$) than the combined equation, likely because of differences in the trend of the soil moisture data.

Only the ECH2O sensor had any indication of sensitivity to temperature (Fig. 2). At 31°C , our combined calibration equation for ECH2O underestimated θ by approximately 1.9% ($t_7 = 2.56$, $p < 0.04$). Although there were no statistically significant differences at lower temperatures, it is important to note that, for the range sampled, as temperature increased by 1°C , ECH2O predictions of θ decreased by 0.1% ($F_{[1, 22]} =$

Fig. 1. “Combined” calibration equations (see Table 1) with confidence intervals, prediction intervals, and standard calibration equations (see Table 2).



7.79, $p < 0.01$). Despite these results, the error due to temperature fell within the 95% prediction interval, suggesting a temperature correction is not necessary unless greater precision is required. Both WCR and CT predicted θ within 1% of actual values for the temperature range examined. The Campbell Scientific temperature correction for the WCR did not improve the estimate of θ .

As in other studies (Jacobsen and Schjonning 1993; Dirksen and Dasberg 1993), the CT appeared to have a slight sensitivity to bulk density. Bulk density of our samples ranged between 0.79 and 0.96 $\text{g}\cdot\text{cm}^{-3}$; when bulk density was lower than 0.88 $\text{g}\cdot\text{cm}^{-3}$ true θ was underestimated by <2.4%, and at bulk density greater than 0.88 $\text{g}\cdot\text{cm}^{-3}$ true θ was overestimated by <2.6% (Fig. 3), both of which are within the prediction interval of the combined equation. This suggests that some caution should be considered when using the CT to compare soils with large differences in bulk density. The ECH20 and WCR probes were not sensitive to bulk density.

The size of the PVC tubes used in this study (10 cm) did not influence the measurements taken by the instruments. There was no apparent sensitivity of an instrument's measurement to the medium outside the PVC tube, whether in air, dry soil, or wet soil. All measurements made by ECH20 and WCR for a given medium outside the PVC tube were within 0.005 $\text{m}^3\cdot\text{m}^{-3}$ of each other. Measurements made by

the CT for a given medium outside the PVC were more variable depending on the true θ of the sample ($\pm 0.033 \text{ m}^3\cdot\text{m}^{-3}$). Regardless, there was no clear trend based upon the media outside of the tube, and we conclude that this factor did not influence the development of our calibrations.

Discussion

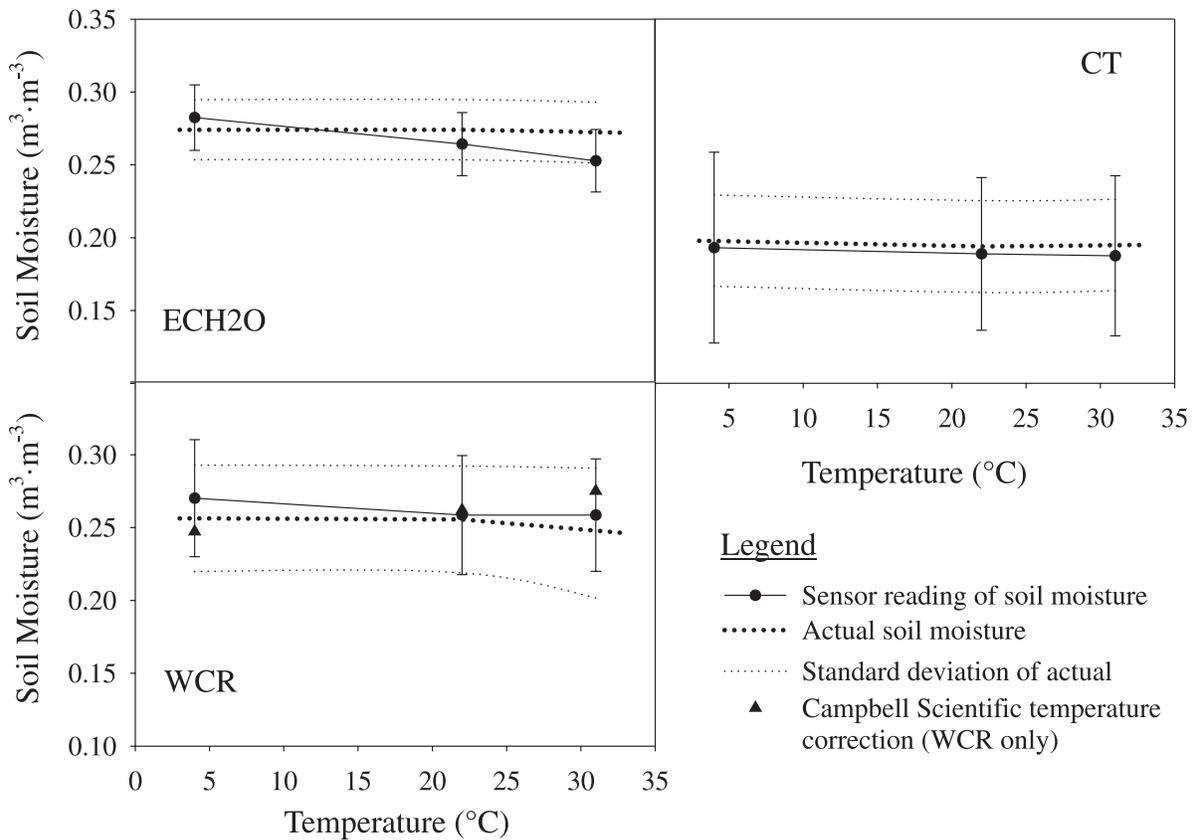
We found that for all three instruments we investigated, standard calibration equations did not accurately predict moisture content of the two forest soils we investigated; a new calibration was necessary to accurately predict soil moisture. Statistical analyses used in model selection suggested a need for site- or site- and structural-specific models. However, we found that the errors introduced by using a single equation were small and not of practical importance (hydrologically or ecologically). Despite small differences associated with soil structure, we conclude that it does not matter whether calibration is done with natural or repacked soils if the soil is similar in structure to the soils in this study. And despite small differences between sites, we conclude these differences are within the range necessary for practical use. Therefore, we combined data from both sites and experiments for the creation of our calibration equations. Regardless, new calibrations should be conducted for other study sites.

Table 2. Description of error associated with standard calibration equations, and a comparison between the mean predicted value of θ from the “combined” equation of this study (Table 1) and the mean predicted value of θ from the standard equations (also see Fig. 1).

| Calibration eq. ^a | | Stated error | Mean difference in “combined” vs. standard predicted θ |
|------------------------------|--|--------------|---|
| ECH2O | | | |
| Combined | | 4.5% | — |
| Decagon | $\theta = -0.29 + 0.000695x$ | 3.0% | 8%–11.5% |
| CT | | | |
| Combined | | 3.5% | — |
| Topp et al. (1980) | $\theta = 4.3 \times 10^{-6}x^3 - 5.5 \times 10^{-4}x^2 + 0.0292x - 0.053$ | 1.3% | ~8% |
| Gray and Spies (1995) Lo-C | $\theta = -0.1016 + 0.1034n^b$ | 3.0% | 2.5%–5% |
| Gray and Spies (1995) Hi-C | $\theta = -0.0320 + 0.1005n^b$ | 3.0% | 0%–4% |
| WCR | | | |
| Combined | | 7.1% | na |
| Campbell Scientific | $\theta = -0.187 + 0.037x + 0.335x^2$ | 2.0% | 0%–8% |

^aUnits for θ are $m^3 \cdot m^{-3}$. x represents output: units are mV for ECH2O, K_a for CT, and ms for WCR.
^b $n = K_a^{1/2}$.

Fig. 2. Influence of temperature on instrument predictions of average θ versus actual θ . Sensor reading of soil moisture is based on the combined calibration equation, and error bars represent standard deviation. Number of samples for ECH2O = 8, CT = 10, and WCR = 9.



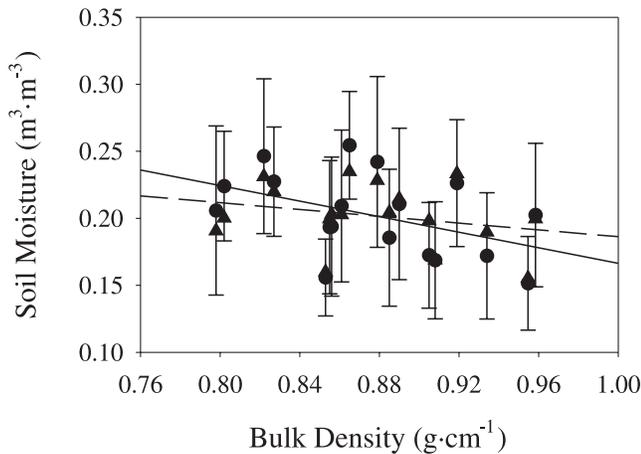
Calibration equations

For both ECH2O and CT, the combined equations appear to have relatively similar slopes to those of some of the standard calibration equations (the Decagon and Topp et al. (1980) equations, respectively). This suggests that past research using these instruments and associated standard calibration equations in HJA and WR soils correctly described soil moisture change, either temporally or spatially, even though absolute values of θ would have been underestimated. The indication

that slopes are similar among calibration equations suggests it may be possible to calibrate the ECH2O by measuring a new intercept.

Despite similar slopes, the considerable amount of research conducted on CT calibration suggests that new calibrations may be necessary in different soils. Although we expected that the Gray and Spies (1995) equation for the CT would be similar to that of this study, we found some differences to their predictions of change in θ . Nevertheless, overall error

Fig. 3. Influence of bulk density on CT predictions of actual θ versus predicted θ . Circles and solid line represent actual θ ; triangles and broken line represent predicted θ (using combined calibration). Error bars represent variation around actual θ .



was similar and the prediction intervals overlap, especially at lower values of K_a . Differences between the Gray and Spies (1995) calibration and the “combined” calibration are not due to differences in trace interpretation. Their algorithm for trace interpretation, developed using soils from locations near our study sites, was used in this study. Their method was compared to the Topp et al. (1980) method, and we found very little difference in resulting θ (<2% error, results not shown). Differences in how a CT trace is interpreted may depend on soil type (Gray and Spies 1995).

The WCR calibration equation provided by the manufacturer, Campbell Scientific, portrayed a different trend and variability that was much greater than expected. WCR probes apparently require a more elaborate multipoint calibration, indicating that new calibrations should be conducted for sites where our equations are not applicable. Campbell Scientific suggests that their newer version of the WCR, the CS616, is less variable.

Our calibration equations are only valid for the range of soil moisture sampled in this study and for the soils from WR and HJA. Even if other sites have sandy loam soils, as both of our sites do, we recommend that researchers develop new calibrations specifically for those soils. Even though WR and HJA both have sandy loam soils, they produced different calibration equations. These differences were not practically significant in our study, but they could be in other cases. Differences in soil electrical conductivity or bulk density could also result in calibration equations that differ from ours.

We suggest that new calibrations use a PVC tube with a diameter larger than 10 cm if calibrating the CT. Although the diameter of the PVC tube did not significantly affect the measurements made by the CT, upon further analysis we noticed a considerable amount of variation. Furthermore, Knight (1992) found that most of the instrument sensitivity depends on the ratio of rod spacing to size. Gray and Spies (1995) determined that based upon the work by Knight, using a 10 cm diameter tube, 7.4% of the energy around the rods could be sampling air. Thus, a larger size diameter PVC may improve the quality of future calibrations.

Instrument precision and accuracy

Once calibrated, ECH2O, the least expensive of the three instruments, was nearly as accurate and precise as the CT. ECH2O had only slightly larger prediction intervals (4.5%) than the CT (3.5%), which is considered one of the most reliable soil moisture content devices. If testing was done on a larger range of θ , it may be possible that a polynomial fit would reduce error and have a better fit.

Although the manufacturer states that ECH2O does not have sensitivity to temperature, we found that it does have a slight tendency to decrease as temperature increases. The combined calibration equation for the ECH2O was less precise as the soil became moist. This is not likely attributable to changes in temperature, because through the first two experiments temperature was held constant. Campbell (2001) suggests that the sensor board encasing the electrical circuitry can influence the temperature sensitivity under maximum load, and measurements could be influenced by the dielectric constant of both sensor board and water. Our experiment was conducted under maximum load, so some temperature sensitivity may be expected.

Strong temperature sensitivity was not observed for the CT in this study, but a large amount of variation from the mean was observed. Persson and Berndtsson (1998) found that changes in temperature could explain >92% of the observed variation in water content, although they also found a decreasing trend in observed water content as temperature increased. It is possible that we did not see a temperature response in our study because of the relatively narrow range of temperature; an effect might be apparent over a larger range.

Past studies indicate that WCR sensors have a temperature sensitivity, which we did not observe (Seyfried and Murdock 2001; Campbell Scientific 1996). Campbell Scientific (1996) says that the need for a temperature correction depends on the variability of temperature along the length of the probe and the magnitude of correction dependent on soil water content. For this experiment, the entire core was at the same temperature and θ at the time of measurement and may not have demonstrated a need for a temperature correction.

Although we concluded there was no practical difference based on soil structure, the calibrations for repacked soils did predict lower θ than calibrations for natural soils for both the ECH2O and CT. Some of this difference may be due to soil characteristics related to site. Also, despite efforts to keep the bulk density the same between experiments related to soil structure, repacked soils had on average 0.01g/cm³ lower bulk density than natural soils. Lower bulk density for the CT can result in the calibration predicting lower θ values and may account for the majority of the difference between repacked and natural soils for this instrument. ECH2O did not show any sensitivity to bulk density.

Each instrument had 10% or more of the data removed prior to the calculation of a calibration equation because output values were out of range or masses were erroneous. ECH2O data were most consistent; only one of the five sensors produced erroneous data. Depending on site, that sensor reported data significantly outside reasonable values of θ (e.g., reading negative values of θ), although the trend of the data was similar to that of the other sensors. More than one-third (36%) of the CT data were removed, one-quarter to one-third of which was from each core in natural soils on the

Table 3. Comparison of ECH2O, CT, and WCR soil moisture sensors.

| | ECH2O | CT | WCR |
|--|--|--|---|
| Standard equations vs. new “combined” equation | Slopes similar but standard equation underestimates θ | Topp et al. (1980): slopes similar but underestimates θ Gray and Spies (1995): intercepts similar but slopes differ | Standard equation reflects a different trend and does not fit data |
| Strengths | Data can be recorded continuously; easy to install at depth; inexpensive; reusable | Can save signal for trouble-shooting and QA-QC ^a ; rods are relatively inexpensive and equipment reusable; does not require additional power source; works in decayed wood ^b | Data can be recorded continuously; reusable |
| Weaknesses | Slight temperature sensitivity; calibration equation is not as good in very dry and moist extremes; does not perform as well in rocky soils ^c ; requires additional power source and datalogger | Not good in very dry soils unless additional equipment ^d ; data from point in time; must interpret signal; clips not secure and can create noise; if not automated, must carry heavy main instrument in field; slightly affected by bulk density ^e | High variation; difficult to tell whether prongs are bent or splayed when in the soil; expensive; requires additional power source and datalogger |
| Expense (for: 1, 10, 50) ^f | ~\$100, \$1000, \$3000 | ~\$12,000 for all | ~\$150, \$1500, \$7500 |
| Accuracy and precision once calibrated | Accurate and relatively precise | Accurate and a little more precise than ECH2O | Accurate but not precise |

^aQA-QC, quality assessment and quality control.

^bGray and Spies (1995).

^cECH2O manual.

^dUse of remote diode shorting can improve instrument readings (Hook et al. 1992).

^eThis study; Jacobsen and Schjonning (1993); Dirksen and Dasberg (1993).

^fDoes not include the cost of a data storage device. WCR requires an additional cost for wire.

same days, suggesting operator error. In repacked soils, the CT did not accurately record the trace in the initial stages of wetting-up period after oven-drying soils, requiring the removal of most of the initial drying up data. Other inaccuracies are likely associated with a discontinuity in the soil column that could be creating “noise” in the trace signal. This may be due to rocks, macropores, decayed wood, or other such discontinuities. Just over 14% of the WCR data was removed; a single sensor provided one-third of the erroneous data while monitoring natural soil cores. Problems with the one sensor may have been due to either trouble with the installation of the dual rod instrument or discontinuities in the soil column as explained above for the CT. Most of the remaining two-thirds of bad data were likely due to operator error.

Experimental use

All three instruments are currently being used in forestry studies that require measurements over large areas, steep terrain, and remote locations. This type of use requires sensors that are portable, inexpensive enough to be used over large areas, and reliable. It is important to evaluate their relative strengths and weaknesses before deciding on which sensor best fits a project (Table 3). Under our measurement conditions, the accuracy and precision of the ECH2O and CT combined equations were similar. ECH2O is appropriate for studies that require high-frequency temporal data, and because of their comparatively low cost, these probes can be deployed in reasonably large numbers. However, it is necessary to install a datalogger (both “wired” and wireless options are available). CT is a good choice for studies that use repeated manual measurements. Advantages are that the steel rods are very inexpensive and can be deployed in very large numbers and the system does not require any power in the

field between measurements. A disadvantage is that the measurements can be labor-intensive; however, it can become less labor intensive if automated (Evet 1998). The WCR is not as reliable as we had expected. Not only was the WCR least precise of the three instruments, but without proper calibration, spatiotemporal trends would likely be inaccurate. However, we note that a new model of the WCR became available after we conducted our tests, and the new model may be much more reliable.

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