

Core Ideas

- Temperature variability and hysteresis and probe variability affect sensor measurements.
- Probe-to-probe variability is significant but random.
- Temperature variability is the major source of error in sensor performance.
- Magnitude of temperature-induced error is a function of water content and sensor type.
- Dependent calibration functions could improve sensor measurement performance.

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Temperature and Probe-to-Probe Variability Effects on the Performance of Capacitance Soil Moisture Sensors in an Oxisol

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Reliable and accurate monitoring of soil water content (θ) across the landscape is indispensable for many water resources applications. Capacitance-based in situ soil water content measuring devices are extensively used despite their sensitivity to soil properties besides water content, e.g., temperature and organic matter content. The main goals of this study were to: (i) examine the effects of temperature, hysteresis of the temperature response, and probe-to-probe variability on the performance of three (5TE, EC-5, and EC-TM) single capacitance sensors (SCS) in a Hawaiian Oxisol; and (ii) develop empirical calibration equations to correct for temperature and improve measurement accuracy. The SCS raw output and thermocouple temperature measurements were recorded at 1-min intervals during heating and cooling cycles between 1 and 45°C. The three SCS and thermocouples were inserted in uniformly packed soils with θ varying from 0 to 0.55 m³ m⁻³. We used three probes for each SCS, and the entire experiment was replicated with two heating and cooling cycles. Temperature, hysteresis, and the probe-to-probe variability effects were highly significant ($p < 0.05$) for all three SCS. Estimated θ using soil-specific calibrations at 25°C significantly increased with increasing temperature for all SCS. The 5TE sensor showed increasing temperature sensitivity with increasing water content. However, the EC-5 and EC-TM sensors exhibited a bidirectional response to temperature, with the highest sensitivity at ~ 0.10 m³ m⁻³ water content. An empirically derived temperature-dependent calibration equation substantially reduced the variability (>90% reduction in interquartile range) in measured water content due to changing soil temperature. Applying differing temperature corrections for heating and cooling did not improve the calibration any further.

Abbreviations: SCS, single capacitance sensors.

Real-time soil water content monitoring in the vadose zone is essential for optimum irrigation scheduling as well as for many other hydrologic applications, e.g., water allocation and groundwater recharge calculations. Soil water content is also a major factor that determines plant growth and solute transport in irrigated and unirrigated areas. Soil water content measurements are difficult to carry out on a consistent and spatially comprehensive basis (Bindlish et al., 2006). The need for accurate measurement of soil moisture at spatial and temporal scales for hydrologic, climatic, agricultural, and domestic applications has led to the development of different soil moisture content measurement methods (Minet et al., 2012). The available soil water content measurement methods are classified as direct or indirect (Dobriyal et al., 2012). The only direct method is the gravimetric method or thermostat-weight technique; all others fall in the category of indirect methods. Except for remote sensing, all the other methods used for soil moisture estimation are ground based, where the sensors are placed in direct contact with the soil.

The most accurate method of measurement of the soil water content has been the gravimetric method (Gardner, 1986). However, the gravimetric method is destructive, laborious,

and does not allow for real-time measurement of soil water content. During the past few decades, several techniques have been adopted for nondestructive soil water content monitoring that include neutron thermalization (Greacen, 1981), electrical resistance (Spaans and Baker, 1992; Seyfried, 1993), time domain reflectometry (Topp et al., 1980; Cassel et al., 1994), and electrical capacitance (Fares and Polyakov, 2006). Dielectric-based single capacitance soil water monitoring sensors are popular among the scientific and agricultural community worldwide as a tool for better agricultural water and nutrient management. During the last decades, considerable progress has been made in soil moisture sensor technology to automatically measure soil moisture in situ based on electromagnetic methods. These sensors are simple to use and easy to install; their measurements are in real time and simultaneous across the landscape.

Capacitance soil water content measurement sensors respond to the dielectric permittivity (ϵ) of the soil–water–air mixture. The relative dielectric permittivity of water, ϵ_r (~ 80 at room temperature), is large compared with those of the soil matrix ($\epsilon_r < 10$) and air ($\epsilon_r \approx 1$) and thus dominates the air–soil–water mixture (Seyfried and Murdock, 2004; Fares et al., 2009). A calibration equation is developed and used to estimate the soil water content based on the sensors' response to the dielectric permittivity of the soil–water–air mixture (Fares et al., 2009). However, great variability and sensitivity of the ϵ_r of soil minerals (4–9) and dry plant tissue (1–4) make it necessary to calibrate these sensors for a particular soil to improve the performance of the sensors.

Decagon Devices has produced several single capacitance sensors (SCS) for measuring soil water content, e.g., the EC-5, EC-TM, and 5TE probes. Decagon's first-generation SCS (EC-10 and EC-20) have a single blade that is 10 and 20 cm long, respectively. In contrast, the newer SCS (EC-5, EC-TM, and 5TE) have more than one 5-cm-long blade. These newer SCS were modified from older models to minimize their sensitivity to bulk electrical conductivity, soil temperature variations, and electrical interference in the field (Parsons and Bandaranayake, 2009). Operating frequency is one of the primary factors affecting the sensitivity of capacitance-based sensors to soil variables, e.g., soil texture, electrical conductivity, and temperature (Kizito et al., 2008). As the operating frequency of sensors decreases, the influence of soil texture, electrical conductivity, and temperature on the dielectric constant becomes larger (Kelleners et al., 2004; Kargas and Kerkides, 2010). Topp (2003) reported that frequencies of 400 to 500 MHz could be effective in decreasing dielectric losses due to ionic conductivity in clay soils. Similarly, Escorihuela et al. (2007) observed a bidirectional influence (a positive gradient at low levels of soil moisture and a negative gradient beyond a threshold moisture level) of temperature on the dielectric constant for a sensor operating at 100 MHz. In other words, they found that the temperature effect on the dielectric constant is different for bound and free waters in soil. Kizito et al. (2008) also tested EC-5 and 5TE probes between 5 and 150 MHz measurement frequencies; they found that the 70-MHz frequency

was optimal for these sensors because it corresponded with their low sensitivity to confounding soil environmental factors. The manufacturer claims that these new sensors are cost effective. These sensors also have the advantage of measuring more than one parameter simultaneously, i.e., temperature (T), electrical conductivity, and volumetric water content (θ), some of which can be used in correcting the capacitive measurements, if required. These sensors, however, can show probe-to-probe variability (e.g., Sakaki et al., 2008), which will affect the accuracy of their soil water content measurements (Rosenbaum et al., 2010).

Temperature effects on dielectric permittivity measurements are significant near the surface where the soil temperature is substantially influenced by diurnal temperature fluctuations (Jones et al., 2005). A sensor's ambient temperature influences the dielectric permittivity measurements by changing the dielectric properties of the measured medium and the response of the sensor itself. Therefore, these two effects have to be assessed separately (Jones et al., 2005). Although it is known that the dielectric permittivity of water decreases with increasing temperature, the temperature dependence of the measured permittivity of soil is influenced by other factors (Wraith and Or, 1999). Soils with low surface area (e.g., sandy soils) typically show a decrease in dielectric permittivity with increasing temperature, often proportional to the soil water content. However, the dielectric permittivity of soils with a high surface area (e.g., clay soils) shows an increase due to the release of bound water from the clay minerals as the temperature increases (Wraith and Or, 1999; Rosenbaum et al., 2011).

Although the new SCS, e.g., EC-5, EC-TM, and 5TE, are an improvement over the older EC-10 and EC-20, several studies have indicated their sensitivity to soil environmental factors. Bogaen et al. (2007) reported that conductivity effects were less pronounced in the EC-5 than the older EC-20 sensor due to the higher operating frequency, but temperature changes had a significant influence on sensor apparent water content readings. Parsons and Bandaranayake (2009) reported a 1% increase in EC-5 apparent water content readings in a Candler fine sand (a hyperthermic, uncoated Lamellic Quartzipsamment) when the temperature was increased from 3 to 38°C. Moreover, they also reported significant probe-to-probe variability in the measured water content using EC-5 along with the effects of compaction. The EC-5 raw sensor output in Candler fine sand increased by $\sim 22\%$ when the soil bulk density was increased from 1.1 to 1.6 Mg m⁻³. Kizito et al. (2008) found that an increase in temperature of 10°C can cause an overestimation of 5TE measured soil water content by 0.02 m³ m⁻³.

Fares et al. (2007) reported statistically significant effects of temperature hysteresis on multi-capacitance sensors in a quartz sand from Florida. Kargas and Soulis (2012) showed a different water content response to temperature using the 10HS sensor operating at 70 MHz oscillator frequency in clay and sandy soils. They reported that the temperature effect was

more pronounced at higher and lower water contents in clay and sandy soils, respectively. This difference in the water content response to temperature between clay and sandy soils was attributed to the release of bound water from the clay minerals as the temperature increased. However, Kargas and Soulis (2012) further added that the temperature dependence of soil water measurement in coarse soils is low, regardless of the actual soil water content, and it can be accurately predicted. On the contrary, in fine-textured soils, the temperature dependence of soil water measurement is greater, suggesting a relationship between bound water and temperature. Based on the results of Fares et al. (2007) and Kargas and Soulis (2012), we hypothesized that measured water contents using SCS in a Hawaiian Oxisol with high clay content would have strong temperature dependency and that the relationship between measured water contents and media temperature would not be unique and would present hysteresis effects. Hawaiian Oxisols have uniquely high hydraulic conductivity and infiltration rates despite their high clay content because of the very strong, fine structural aggregation resulting from their advanced weathering. Therefore, in a Hawaiian Oxisol, the temperature dependency and hysteresis effect are likely to be more pronounced than in sandy soils.

An extensive review of the literature showed very few studies on the temperature hysteresis effects on soil water content measurements, e.g., Fares et al. (2007). Fares et al. (2007) showed that there is a statistically significant amount of temperature hysteresis in water, air, and quartz sand media. Thus, there is a strong need to evaluate the sensitivity of soil water content measurements using SCS to media temperature both in heating and cooling regimes under different soils and develop correction factors for minimizing the temperature hysteresis effect. Therefore, the objectives of this study were to evaluate three SCS in terms of (i) their sensitivity to varying soil temperature and its effect on θ measurements, (ii) the effects of soil temperature hysteresis on θ measurements, and (iii) probe-to-probe variation in measured θ , and then (iv) develop temperature dependent calibration equations to minimize the temperature effect on θ measurements.

Materials and Methods

Description of Single Capacitance Sensors

The three SCS used in this experiment were 5TE, EC-5, and EC-TM sensors (Decagon Devices). The 5TE sensor has a very similar design to that of the EC-TM, but it has an improved factory calibration procedure. The SCS in general have low power requirements and higher measurement frequencies. Similar to the EC-10 and EC-20 sensors, these new SCS have flat copper electrodes positioned in one plane and sealed in epoxy-impregnated fiberglass. However, as opposed to EC-10 and EC-20, the newer SCS have more than one blade, which are about 5 cm long. The electrodes have no direct contact with the medium, and the

electromagnetic field generated by the electrodes extends through the fiberglass and into the medium surrounding the sensor. The sensor averages the volumetric water content throughout its entire length and has little sensitivity at the extreme edges (Fares and Polyakov, 2006). If water content measurement in a narrow soil layer is required, the sensor needs to be installed horizontally (Fares and Polyakov, 2006). The SCS are easy to install and well suited for use at shallow depths; however, soil temperature fluctuations at such depths are higher and could affect the performance. The design and principles of operation of the SCS are described in the manufacturer's calibration manuals (Decagon Devices).

All the sensors used in this study are designed to measure the dielectric permittivity of soil media using capacitance technology with an oscillator running at 70 MHz. The sensor response in terms of electromagnetic response voltage or derived dielectric permittivity of the soil media can be calibrated against the known soil water content. In the EC-TM and 5TE sensors, a thermistor is in thermal contact with the sensor prongs to provide the soil temperature. Additionally, the 5TE can also measure bulk electrical conductivity and uses using a five-point calibration in dielectric liquids to provide dielectric permittivity measurements more accurate than the previous SCS. However, the EC-5 is one of the widely used SCS with a good performance in soils (Bogena et al., 2007; Kizito et al., 2008; Ventura et al., 2010).

Description of Hawaiian Tropical Oxisol

This study was conducted in the fine-textured Wahiawa Oxisol (a very-fine, kaolinitic, isohyperthermic Rhodic Haplustox), formed in residuum and alluvium weathered from basalt. In general, Oxisols are soils with low-activity clay that develop under conditions of intense and/or prolonged weathering typical of tropical climates (Lal and Greenland, 1984). In Hawaii, these soils have formed from weathered basaltic lava material. Oxisols cover large areas on the older islands of Kauai and Oahu but only small areas of west Maui, and they are not found on Hawaii, the youngest island. Oxisols are infertile because they have experienced intensive weathering, which has removed most of the weatherable minerals (i.e., silicate clays), leaving behind the insoluble oxides of Fe and Al (Buol, 2006). These Oxisols have unique physical properties. The oxide clay minerals form exceptionally strong aggregates that behave like sand particles, allowing the soils to drain water well and also support heavy loads even when they are wet. Oxisols commonly have higher hydraulic conductivity and infiltration, even with high clay content, because of very strong, fine structural aggregation. Also, Oxisols are morphologically uniform to a considerable depth (Beinroth et al., 1999). With the addition of lime to raise the pH and increase the Ca level and application of sufficient amounts of fertilizer, Oxisols can be transformed into very productive agricultural soils (Deenik and McClellan, 2007). These soils have been extensively used in Hawaii for irrigated

sugarcane (*Saccharum officinarum* L.) and dry land pineapple (*Ananas* Mill.).

Soil samples were collected in bulk from the Poamoho Experimental Station (−158.0887 longitude and 21.5380 latitude) on the island of Oahu, Hawaii. This soil has approximately 70 to 80% clay-size particles with a bulk density ranging from 1.2 to 1.45 g cm^{−3}, available water of 0.11 to 0.13 cm³ cm^{−3}, and 2 to 5% organic matter in the top 30-cm soil profile (USDA–NRCS, 2009).

Laboratory Setup and Measurements

Soil Column Packing

Undisturbed soil cores (7.5-cm height and 2.5-cm internal radius) were collected in five replicates from the 5- to 20-cm soil layer and processed to determine the bulk density and soil total porosity following standard procedures (Grossman and Reinsch, 2002; Flint and Flint, 2002). Soil samples were air dried for 24 h, and plant roots, gravel, and other foreign materials were removed from the samples before passing through a 2-mm sieve. The equivalent amount of water to bring 0.5 kg of air-dried soil to 0, 0.10, 0.20, 0.25, 0.30, 0.35, 0.40, 0.47, and 0.55 m³ m^{−3} water content (θ) was added assuming a 1.1 g cm^{−3} bulk density of the soil after packing. To minimize evaporative loss and ensure a uniform water content, the soil and water were quickly hand mixed to obtain a homogeneous mixture. The mixture was then transferred to a 1-L glass jar in small increments while compressing the soil in the jar with a plastic tamper to compact the soil to the desired 1.1 g cm^{−3} bulk density. After transferring approximately 3/4 of the soil mixture, soil moisture sensors and thermocouples were inserted vertically before adding the remaining soil. The glass jars were carefully covered with Parafilm to avoid any evaporative loss during the experiment. To avoid any interference between the thermocouples and soil moisture sensors, the proper distance between them was maintained. Soil packing was repeated for the three SCS, with three probes of each SCS type (i.e., 5TE, EC-5, and EC-TM sensors) in two replicates ($n = 3 \text{ SCS} \times 3 \text{ probes} \times 2 \text{ replicates}$). The SCS outputs (i.e., raw counts) and thermocouple readings (°C) for all treatments and replicates were logged at 1-min intervals with EM50 dataloggers (Decagon Devices) and CR-10 dataloggers (Campbell Scientific), respectively. To facilitate the performance comparisons between different SCS sensors, the raw sensor outputs (raw) can be converted to apparent water content using the manufacturer's default calibration equations (θ_{pd} , m³ m^{−3}):

$$\theta_{pd}(5TE) = 3.44 \times 10^{-11} \times \text{raw}^{-3} - 2.2 \times 10^{-7} \times \text{raw}^{-2} + 5.84 \times 10^{-4} \times \text{raw} - 5.3 \times 10^{-2} \quad [1a]$$

$$\theta_{pd}(EC-5) = 8.5 \times 10^{-4} \times \text{raw} - 0.48 \quad [1b]$$

$$\theta_{pd}(EC-TM) = 1.087 \times 10^{-3} \times \text{raw} - 0.629 \quad [1c]$$

However, characterizing the sensor performance using default calibration equations seems unrealistic. These default calibration equations were developed for mineral soils and a limited water content range (e.g., for the EC-5, the default calibration was developed within the 0–0.35 m³ m^{−3} volumetric water content range). To overcome some of these limitations, we have developed soil-specific calibration equations at a reference temperature (T_r) of 25°C to convert the raw sensor output (raw) to θ_{pr} . The raw sensor outputs were fitted using the following equations:

$$\theta_{pr}(5TE) = 0.2975 \times \ln(\text{raw}) - 1.564 \quad [2a]$$

$$\theta_{pr}(EC-5) = 0.892 \times \ln(\text{raw}) - 5.659 \quad [2b]$$

$$\theta_{pr}(EC-TM) = 0.001287 \times \text{raw} - 0.685 \quad [2c]$$

Temperature and Hysteresis Effects

Packed soil columns were placed in an insulated plastic cooler used as a water bath for heating and cooling cycles. During the heating cycle, the temperature was gradually increased from 1 to 45°C using aquarium heaters (Tetra). Cooling from 45 to 1°C was achieved by adding ice in small increments. A submerged pump was used to circulate the water to obtain a homogeneous temperature throughout the water bath. Additionally, we manually monitored the temperature throughout the plastic cooler to identify any non-uniform cooling or heating. Each sensor was subjected to two cycles of heating and cooling to observe the temperature hysteresis effect.

Statistical Analysis

An analysis of variance (ANOVA) was conducted to test the effect of temperature (T), hysteresis (H), probe (P), and water content treatments (θ) on the apparent water content readings of the three tested sensors using the ANOVA function in the R statistical software (R Core Team, 2015). To quantify the effect of temperature on the sensor water content measurement, linear regressions at different water contents were established for apparent water content as a function of media temperature during the heating and cooling cycles. The slope of the regression, which is described in more detail below, is a reasonable indicator of the response of the sensors to any temperature effect.

Development of Temperature-Dependent Calibration Equations

As demonstrated in previous studies (i.e., Fares et al., 2009; Saito et al., 2009), changes in θ_{pr} (or θ_{pd} if the manufacturer's default calibration is being used) with temperature at a given water content θ can be expressed as a linear function of temperature (T) and thus the slope ($d\theta_{pr}/dT$) can be expressed as

$$\frac{d\theta_{pr}}{dT} = f(\theta) \quad [3]$$

Integrating Eq. [3] using $\theta_p = \theta_{pr}$ at $T = T_r$ results in

$$\theta_p = \theta_{pr} + f(\theta)(T - T_r) \quad [4]$$

The value of θ_{pr} will be a function of the raw sensor output:

$$\theta_{pr}(\text{raw}) = g(\text{raw}) \quad [5]$$

Substituting Eq. [5] into Eq. [4] will result in a temperature-dependent final calibration equation:

$$\theta_p(\text{raw}, T, \theta) = g(\text{raw}) + f(\theta)(T - T_r) \quad [6]$$

The first term on the right-hand side of Eq. [6], $g(\text{raw})$, represents the default or soil-specific calibration equation at the reference temperature (Eq. [2]). The second term, $f(\theta)(T - T_r)$, provides the temperature correction when the measurement temperature is different from the temperature at which the calibration equation was developed (i.e., $T \neq T_r$). To evaluate the performance of this temperature-dependent calibration function, we compared θ_p with and without a temperature correction term.

To solve Eq. [6] for θ , we first developed an empirical relationship to describe $f(\theta)$ and $g(\text{raw})$. Based on the coefficient of determination (R^2) obtained using different empirical functions (e.g., linear or exponential), we can best fit $d\theta_{pr}/dT$ vs. θ data for the three sensors using a third-order polynomial equation:

$$f(\theta) = a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3 \quad [7]$$

where a_0 to a_3 are fitting coefficients. The value of $g(\text{raw})$ was approximated by θ because we used the soil-specific calibration Eq. [2]. When a soil-specific calibration equation is not available, similar to Saito et al. (2009) $g(\text{raw})$ can be developed after relating the θ_{pd} estimated from manufacturer's default calibration and θ . Also, fitting $f(\theta)$ requires prior knowledge of θ , but in practice θ is unknown. Therefore, for practical application of the proposed temperature-dependent calibration equation, $f(\theta)$ can be developed by relating $d\theta_{pr}/dT$ with θ_{pr} at $T = T_r$. If available, $f(\theta)$ can also be directly substituted from published studies.

Results and Discussion

Single Capacitance Sensor Performance with Default and Soil-Specific Calibration

The apparent water content at 25°C reference temperature was largely underestimated by the manufacturer's default calibration equations for two of the three SCS—the EC-5 and EC-TM (Fig. 1A). However, the default calibration equation for the 5TE sensor overestimated the θ_{pd} by 0.05 and 0.02 $\text{m}^3 \text{m}^{-3}$ for actual water contents (θ) of 0 and 0.10 $\text{m}^3 \text{m}^{-3}$, respectively. In general, the underestimation of θ_{pd} increased with

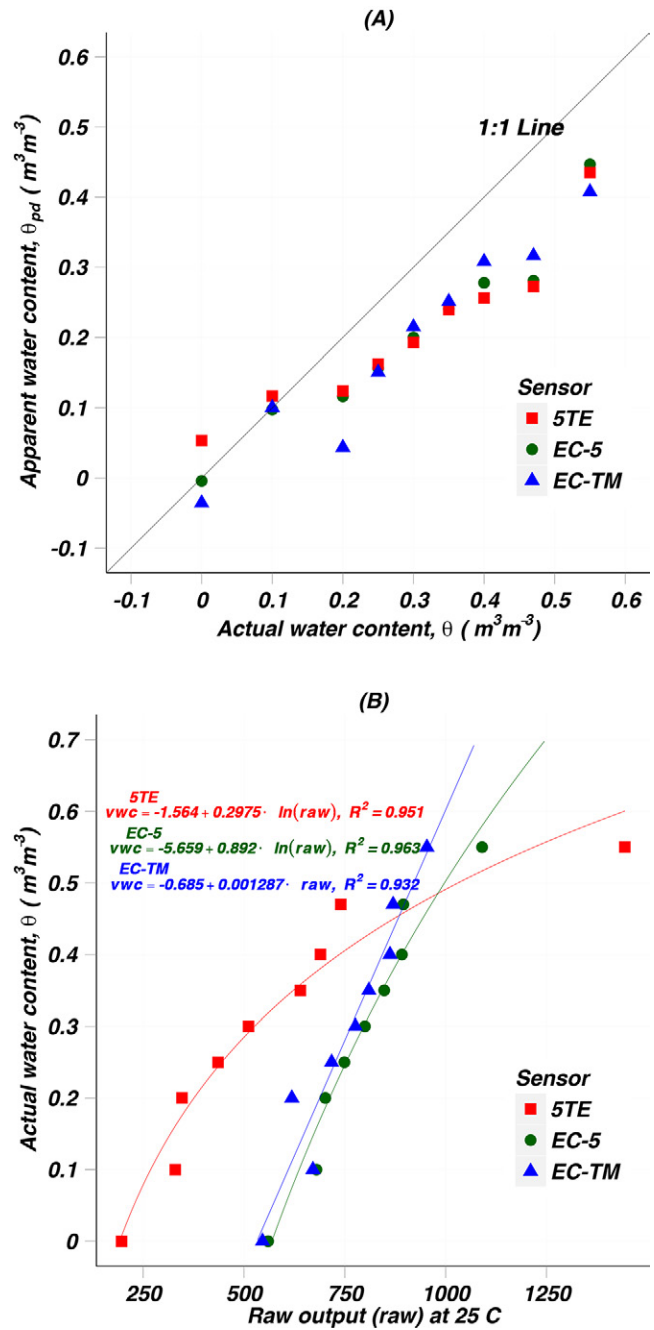


Fig. 1. (A) Relationship between actual water content and apparent water content at 25°C reference temperature estimated using the manufacturer's default calibration, and (B) soil-specific calibration functions developed by relating the average (across all probes, replications, and heating and cooling cycles, $n = 12$) single capacitance sensor output (raw count) at 25°C reference temperature with actual water content.

increasing water content up to 0.47 $\text{m}^3 \text{m}^{-3}$ and then slowly declined, a pattern that was consistent across all three SCS. The maximum underestimation of θ_{pd} was $\sim 0.20 \text{ m}^3 \text{m}^{-3}$ for the 5TE and EC-5, which occurred at $\theta = 0.47 \text{ m}^3 \text{m}^{-3}$ for both SCS. In contrast, the EC-TM underestimated θ_{pd} by a maximum of 0.15 $\text{m}^3 \text{m}^{-3}$, which occurred at $\theta = 0.20$ and 0.47 $\text{m}^3 \text{m}^{-3}$. The severe underestimation of θ_{pd} by the EC-TM at $\theta = 0.20 \text{ m}^3 \text{m}^{-3}$ seems to be an outlier for reasons we are

unable to explain. Nonetheless, given the limitations of the manufacture's default calibration (e.g., the range of θ considered during calibration) and the variability in soil properties, large errors in soil water content measurements are not surprising and consistent with previous SCS evaluations (e.g., Parsons and Bandaranayake, 2009; Saito et al., 2009). For accurate soil water content measurements, soil-specific calibration of individual SCS is essential.

As mentioned above, the soil-specific calibration curve developed by relating the θ to the average sensor output (raw count) across all probes, heating and cooling cycles, and replications ($n = 12$) at a reference temperature of 25°C showed a strong nonlinear relationship ($R^2 > 0.95$) for the 5TE and EC-5 and a strong linear relationship ($R^2 = 0.93$) for the EC-TM (Fig. 1B). The root mean squared error (RMSE) was 0.03, 0.04, and 0.05 $\text{m}^3 \text{m}^{-3}$ for the EC-5, 5TE, and EC-TM, respectively. In contrast, the apparent water content estimated using the default calibration equation (i.e., θ_{pd}) not only showed poor agreement with the actual θ (R^2 range for the three SCS of 0.90–0.94) but also showed significantly higher error. The RMSE based on the default calibration was $\sim 0.11 \text{ m}^3 \text{m}^{-3}$ for the three SCS. These results show a significant improvement in prediction accuracy of apparent water content when using soil-specific calibration.

Temperature Effect and Probe-to-Probe Variations

The apparent water contents (θ_{pr}) were estimated for all temperature treatments and probes using the soil-specific SCS calibration equations (Eq. [2]) developed at the reference temperature ($T_r = 25^\circ\text{C}$). Irrespective of SCS type, there was a statistically significant effect of temperature, hysteresis, and probe-to-probe variation on θ_{pr} (Table 1). The variability in θ_{pr} due to temperature treatments, hysteresis, and probe-to-probe variability for a given SCS and θ are shown in Fig. 2A. The variations in estimated θ_{pr} expressed in the form of the interquartile range (i.e., the difference between the 25th and 75th percentile θ_{pr} values) at different values of θ ranged between 0.02 and 0.08 $\text{m}^3 \text{m}^{-3}$ for the 5TE, 0.01 and 0.09 $\text{m}^3 \text{m}^{-3}$ for the EC-5, and 0.02 and 0.11 $\text{m}^3 \text{m}^{-3}$ for the EC-TM. This indicates that the bulk of θ_{pr} estimates can be subjected to an error up to 0.08 to 0.11 $\text{m}^3 \text{m}^{-3}$ for the three SCS; this error is due to soil temperature effects and probe-to-probe variability.

To examine the effects of temperature and hysteresis alone, Fig. 2A was recreated after averaging the θ_{pr} between the three probes (Fig. 3). We assumed that averaging θ_{pr} across the three probes would smooth out the probe-to-probe variations so that the residual variability in the estimated θ_{pr} could be solely driven by variability in temperature and hysteresis. The interquartile range of θ_{pr} after removing the probe-to-probe variability, at different values of θ , ranged between 0.003 and 0.06 $\text{m}^3 \text{m}^{-3}$ for the 5TE, 0.01 and 0.04 $\text{m}^3 \text{m}^{-3}$ for the EC-5, and 0.02 and 0.06 $\text{m}^3 \text{m}^{-3}$ for the EC-TM. This indicates that

Table 1. The analysis of variance for sensor outputs as a function of temperature (T), hysteresis (H), probe (P), and water content (θ). Non-significant interaction terms are not reported.

Source	df	Type I sum of squares	Mean square	Fvalue	Pr > F
EC-TM Sensor					
T	44	2.052	0.0466	1809.9	<0.0001
H	1	0.051	0.0512	1985.4	<0.0001
P	2	0.03	0.0151	585.99	<0.0001
θ	8	111.787	13.9734	542210	<0.0001
$T \times H$	44	0.002	0.0001	2.0089	<0.0001
$T \times P$	88	0.019	0.0002	8.2455	<0.0001
$H \times P$	2	0	0	1.118	<0.0001
$T \times \theta$	352	0.241	0.0007	26.523	<0.0001
$H \times \theta$	8	0.019	0.0024	93.073	<0.0001
$P \times \theta$	15	1.795	0.1197	4644.4	<0.0001
$T \times P \times \theta$	660	0.021	0	1.2519	<0.0001
$H \times P \times \theta$	15	0.008	0.0005	20.392	<0.0001
5TE Sensor					
T	44	1.565	0.0356	1349.20	<0.0001
H	1	0.062	0.0622	2360.50	<0.0001
P	2	0.125	0.0625	2370.80	<0.0001
θ	8	119.097	14.8872	564670.00	<0.0001
$T \times H$	44	0.002	0	1.61	0.0070
$T \times P$	88	0.018	0.0002	7.71	<0.0001
$H \times P$	2	0.001	0.0003	12.03	0.0001
$T \times \theta$	352	0.436	0.0012	46.93	<0.0001
$H \times \theta$	8	0.015	0.0019	70.95	<0.0001
$P \times \theta$	15	1.652	0.1101	4176.40	<0.0001
$T \times P \times \theta$	660	0.08	0.0001	4.58	<0.0001
$H \times P \times \theta$	15	0.012	0.0008	29.15	<0.0001
EC-5 Sensor					
T	44	1.051	0.0239	380.22	<0.0001
H	1	0.006	0.0061	97.089	<0.0001
P	2	1.182	0.5908	9403	<0.0001
θ	8	129.915	16.2393	258470	<0.0001
$T \times H$	44	0.012	0.0003	4.3121	<0.0001
$T \times P$	88	0.009	0.0001	1.5963	0.00044
$H \times P$	2	0.002	0.0009	14.054	<0.0001
$T \times \theta$	352	0.184	0.0005	8.3281	<0.0001
$H \times \theta$	8	0.031	0.0039	61.626	<0.0001
$P \times \theta$	16	1.595	0.0997	1586.7	<0.0001
$H \times P \times \theta$	16	0.049	0.003	48.329	<0.0001

while removing the probe-to-probe variability reduced some of the measurement errors, the range in estimated θ_{pr} attributed to temperature alone cannot be ignored for sensors exposed to high diurnal media temperature fluctuations, especially for sensors close to the surface. Comparison of interquartile ranges in θ_{pr} during pre- and post-probe-to-probe variability smoothing shows that the effects of probe-to-probe variability on the estimated θ_{pr} is somewhat random (Fig. 2B). These probe-to-probe variations in estimated θ_{pr} are consistent with those reported by Parsons and Bandaranayake (2009) and

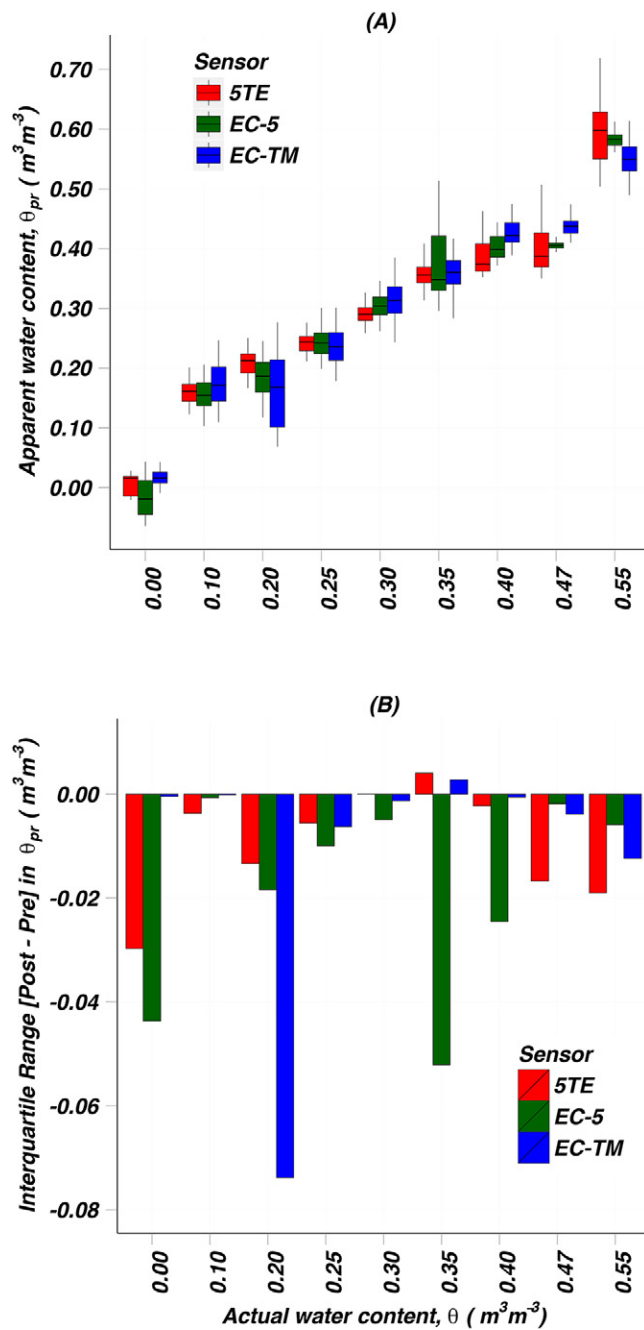


Fig. 2. (A) Box plot showing the variability in apparent water content due to soil temperature and probe-to-probe variability along with temperature hysteresis; the horizontal line inside the box represents the median value, the box itself represents the interquartile range (IQR) (25th–75th percentile range), and the whiskers are the lowest and highest values that are within 1.5IQR of the 25th and 75th percentiles; and (B) reduction in IQR (shown as the difference between post- and pre-smoothing) after the probe-to-probe variability in apparent water content was removed.

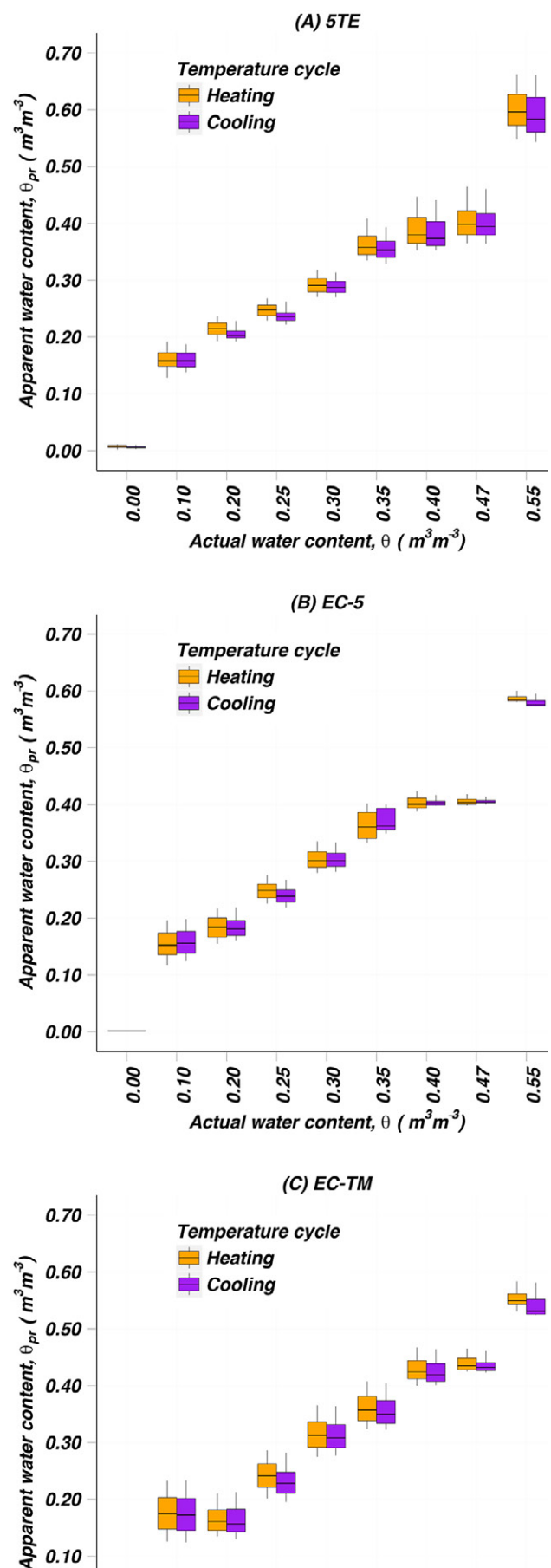


Fig. 3. Box plot showing the variability in apparent water content due to soil temperature alone (after probe-to-probe variability was removed) during the heating and cooling cycles for the (A) 5TE, (B) EC-5, and (C) EC-TM sensors. The box itself represents the interquartile range (IQR) (25th–75th percentile range) and the whiskers are the lowest and highest values that are within 1.5IQR of the 25th and 75th percentiles.

in contrast to Kizito et al. (2008), who reported no significant probe-to-probe variations for all tested EC-5 probes.

Although the effect of temperature hysteresis was statistically significant for all three SCS (Table 1), there were no consistent patterns in terms of interquartile range at various θ values (Fig. 3). This is contrary to the findings of Saito et al. (2009), who showed no hysteresis effect for EC-5 and 5TE sensors in a loess soil (in China). However, similar to probe-to-probe variability, the effects of hysteresis on the estimated θ_{pr} seems to be somewhat random. The mean and interquartile ranges in θ_{pr} are significantly different for heating and cooling at only certain values of θ (Fig. 3). On average, there is no difference in the interquartile range of the estimated θ_{pr} between heating and cooling cycles for all three SCS (Fig. 3). Similar hysteresis effects were reported in previous studies when evaluating multi-capacitance probes and earlier SCS prototypes, e.g., the EC-10 and EC-20 (McMichael and Lascano, 2003; Fares et al., 2007).

As was mentioned above, changes in θ_{pr} with temperature at a given water content can be expressed as a linear function relating θ_{pr} with soil temperatures (Fig. 4A). The strength of this linear relationship is very strong, as indicated by the high values of R^2 at different θ levels, which ranged from 0.83 to 0.99 for the 5TE, 0.74 to 0.99 for the EC-5, and 0.87 to 0.99 for the EC-TM during heating cycles and from 0.87 to 0.99 for the 5TE, 0.62 to 0.99 for the EC-5, and 0.82 to 0.99 for the EC-TM during cooling cycles. Across all SCS, probes, and heating-cooling cycles, θ_{pr} increased with increasing temperature. The slope of the linear response $d\theta_{pr}/dT$ ($\text{m}^3 \text{m}^{-3} \text{ } ^\circ\text{C}^{-1}$) varied with θ for all three SCS (Fig. 5). The maximum values of $d\theta_{pr}/dT$ during heating cycles were 0.003, 0.0022, and 0.0026 for the 5TE, EC-5, and EC-TM, respectively. Similarly, the maximum values of $d\theta_{pr}/dT$ during cooling cycles were 0.0029, 0.0018, and 0.0026 for the 5TE, EC-5, and EC-TM, respectively. For the 5TE and EC-5, the maximum values of $d\theta_{pr}/dT$ reported in this study are higher than those reported by Saito et al. (2009) for a loess soil. This indicates that SCS sensors are more sensitive to temperature in the Wahiawa Oxisol than in loess.

The $d\theta_{pr}/dT$ for the 5TE generally increased with increasing θ . However, for the EC-5 and EC-TM, $d\theta_{pr}/dT$ showed a bidirectional relationship with increasing θ (Fig. 5). The fitting coefficients for the $f(\theta)$ and their corresponding R^2 values during heating and cooling cycles are also summarized in Table 2. In terms of pattern, the $d\theta_{pr}/dT$ for the EC-TM and EC-5 increased with increasing θ up to $0.10 \text{ m}^3 \text{m}^{-3}$, after which it started decreasing and then started increasing again (more so in cooling than in heating cycles) near $\theta \approx 0.45 \text{ m}^3 \text{m}^{-3}$. There was also significant probe-to-probe variability (shown by error bars) in terms of $d\theta_{pr}/dT$, especially for the 5TE and EC-TM sensors. Probe-to-probe variation in $d\theta_{pr}/dT$ was more prominent at higher water contents (Fig. 5).

These bidirectional patterns for the EC-5 are consistent with those reported by Saito et al. (2009) for the same sensor type in four different soils. On the other hand, for the 5TE, the response of $d\theta_{pr}/dT$ to θ in this study did not follow a bidirectional pattern as reported by Saito et al. (2009) for different soils. Escorihuela et al. (2007) reported a similar bidirectional response of the dielectric constant to soil temperature and attributed it to the competing influence of bound and free water that have an opposite dielectric response to soil temperature (Pepin et al., 1995; Seyfried and Murdock, 2004). For an Oxisol, Wraith and Or (1999) showed an increase in the dielectric constant with increasing temperature at low θ for soils with a significant specific surface area (bound water dominates the soil-water mixture) but decreased with increasing temperature at high θ (free water dominates the soil-water mixture). Hence, the $d\theta_{pr}/dT$ increases with increasing θ to a point where free water starts dominating bound water. At high θ , when free water starts dominating the soil-water mixture, the $d\theta_{pr}/dT$ declines. However, this phenomenon is more pronounced for the EC-5 and EC-TM than the 5TE. The second positive gradient near saturation is a bit surprising and cannot be explained by the mixing of bound and free water. One explanation could be the effects of evaporation and condensation (based on Fig. 5, it seems more of a condensation issue than evaporation) during the heating and cooling cycles along with water movement and formation of non-uniform profile at higher water content. Although the glass jars were sealed, the soil moisture redistribution from evaporation and condensation within the jar and around the probe may cause the variation in sensor response. This evaporation and condensation was noticed across all water contents, but this may have played a larger role at high than low θ .

Temperature Effect Correction

The effects of temperature correction on the estimated θ_{pr} were evaluated using the three SCS. The estimated θ_{pr} values for each SCS were averaged for heating and cooling cycles, two replications, and three probes ($n = 12$) and corrected using Eq. [6]. The temperature-corrected θ_p values for a given θ were nearly constant across the entire temperature range (i.e., $1\text{--}45^\circ\text{C}$) for the three SCS (Fig. 4B). The effectiveness of the temperature correction for the three SCS was gauged by comparing the slope of the $\theta_{pr}\text{--}T$ relationship (i.e., $d\theta_{pr}/dT$) before and after temperature correction. The range of the reduction in slope magnitude for the 5TE, EC-5, and EC-TM was 49 to 165, 83 to 123, and 82 to 137%, respectively (Table 3). A slope reduction of $>100\%$ indicates that, in some cases, $d\theta_{pr}/dT$ after temperature correction reduced to a negative value. This marginal overcorrection can be attributed to the uncertainties associated with the fitting of $f(\theta)$. The coefficient of determination for $f(\theta)$ fitted using the average $d\theta_{pr}/dT$ between heating and cooling cycles and probes ranged between 0.84 (EC-TM) and 0.89 (EC-5). Nonetheless, the absolute $d\theta_{pr}/dT$ values

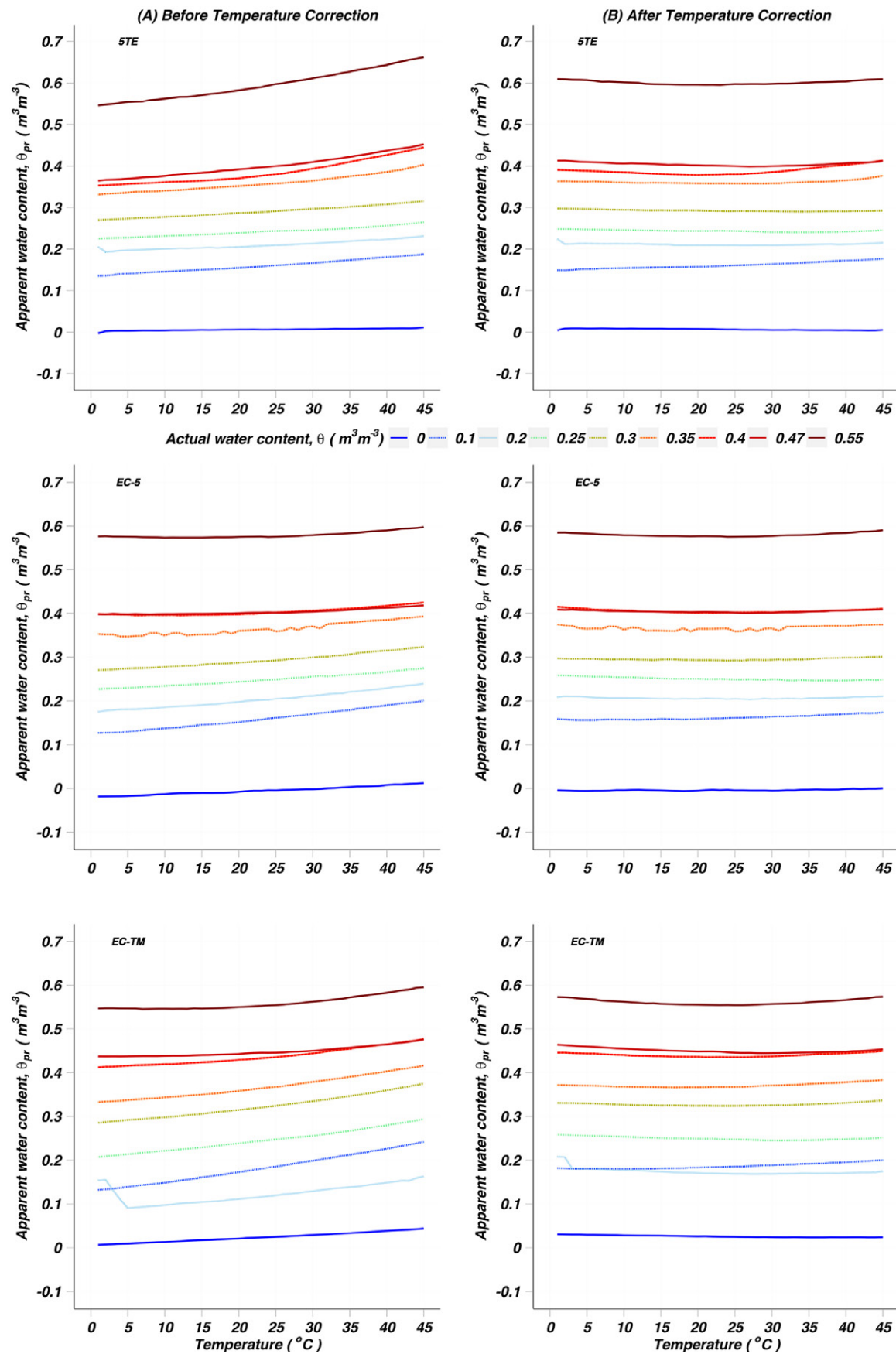


Fig. 4. Apparent water content as a function of the soil temperature at different water contents (0, 0.10, 0.20, 0.25, 0.30, 0.35, 0.40, 0.47, and 0.55 $\text{m}^3 \text{m}^{-3}$) (A) before and (B) after temperature correction.

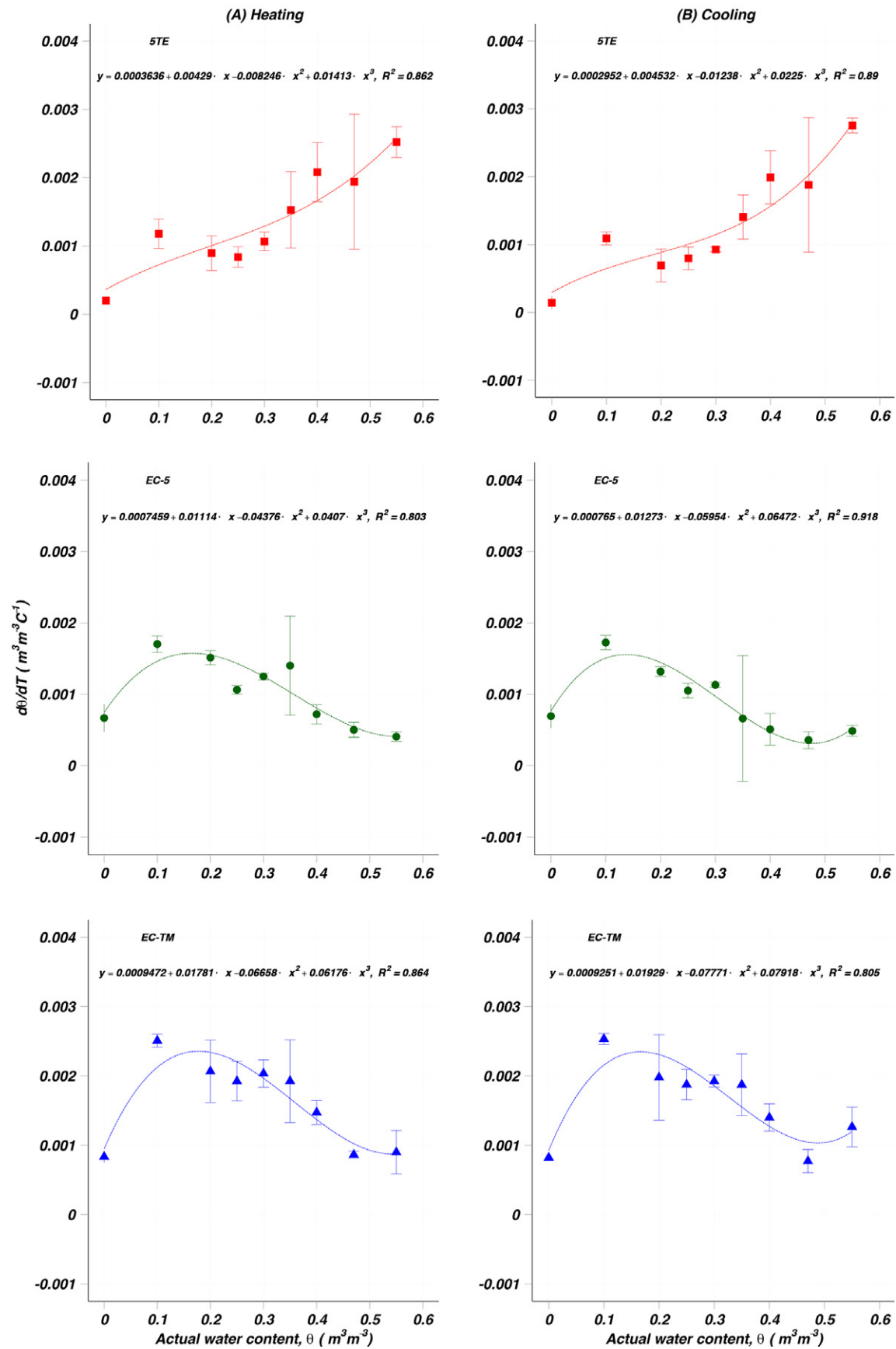


Fig. 5. Variability in the apparent water content sensitivity to temperature ($d\theta_{pr}/dT$) as a function of actual water content during (A) heating and (B) cooling temperature cycles.

Table 2. Fitting parameters (a_0 – a_3 , $^{\circ}\text{C}^{-1}$) and coefficient of determination (R^2) for describing the effect of the measured water content θ on the slope of the temperature response (Eq. [3]) during heating and cooling cycles.

Sensor	$f(\theta)$				
	a_0	a_1	a_2	a_3	R^2
Heating					
5TE	3.636×10^{-4}	4.290×10^{-3}	-8.246×10^{-3}	1.413×10^{-2}	0.86
EC-5	7.459×10^{-4}	1.114×10^{-2}	-4.376×10^{-2}	4.070×10^{-2}	0.80
EC-TM	9.472×10^{-4}	1.781×10^{-2}	-6.658×10^{-2}	6.176×10^{-2}	0.86
Cooling					
5TE	2.952×10^{-4}	4.532×10^{-3}	-1.238×10^{-2}	2.250×10^{-2}	0.89
EC-5	7.650×10^{-3}	1.273×10^{-2}	-5.954×10^{-2}	6.472×10^{-2}	0.92
EC-TM	9.251×10^{-4}	1.929×10^{-2}	7.771×10^{-2}	7.918×10^{-2}	0.81

following temperature correction are significantly smaller than those before the temperature correction (Table 3). These substantial reductions in the slopes (i.e., $d\theta_{\text{pr}}/dT$) after correcting for the temperature effect indicate the relative effectiveness of the proposed technique in mitigating the temperature effect on the estimated θ_{pr} as measured with the 5TE, EC-TM, and EC-5 sensors. As mentioned above, some of the uncertainties (i.e., overcompensation) can be minimized by having an improved $f(\theta)$ fitting that better captures the bimodality (Fig. 5). In this experiment, we used only nine water content levels that were non-uniformly distributed between 0 and $0.55 \text{ m}^3 \text{ m}^{-3}$. The number of water content levels can be increased, especially at lower water contents where the mixing of bound and free water occurs.

Temperature-Dependent Calibration

The effectiveness of the temperature-dependent calibration equation (Eq. [6]) was assessed using three different temperature correction scenarios. In the first scenario, there was no temperature correction applied, i.e., $f(\theta) = 0$. In the second scenario, we ignored the effects of hysteresis, and $f(\theta)$ was developed and used after averaging $d\theta_{\text{pr}}/dT$ across all probes and heating and cooling cycles. In the third scenario, different $f(\theta)$ were developed for heating and cooling cycles (Fig. 5). The calibration Eq. [6] was solved for θ using the root finder function *fzero* in the R statistical software (*pracam* package) after substituting the θ_{p} and T combined with $f(\theta)$ and $g(\text{raw})$. We found that the temperature-dependent calibration can significantly reduce the variability in the estimated θ_{p} due to soil temperature across all three SCS (Fig. 6). The interquartile range following the temperature-dependent calibration ranged between 0.0 and $0.01 \text{ m}^3 \text{ m}^{-3}$ for the 5TE, 0.0 and $0.03 \text{ m}^3 \text{ m}^{-3}$ for the EC-5, and 0.0 and $0.01 \text{ m}^3 \text{ m}^{-3}$ for the EC-TM (Table 4). This shows >90% reduction in the interquartile range when using the temperature-dependent calibration. However,

Table 3. Effect of temperature correction on the magnitude of average slopes for the three tested sensors (5TE, EC-TM, and EC-5).

Water content	Slope ($d\theta_{\text{pr}}/dT$) Magnitude					
	5TE		EC-TM		EC-5	
	Before	After	Before	After	Before	After
$\text{m}^3 \text{ m}^{-3}$	$\text{m}^3 \text{ m}^{-3} ^{\circ}\text{C}^{-1}$					
0.00	0.0002	−0.0001	0.0008	−0.0002	0.0007	0.0001
0.10	0.0011	0.0006	0.0025	0.0004	0.0017	0.0004
0.20	0.0008	−0.0001	0.0019	−0.0004	0.0014	0.0000
0.25	0.0008	−0.0001	0.0019	−0.0002	0.0011	−0.0002
0.30	0.0010	−0.0001	0.0020	0.0001	0.0012	0.0001
0.35	0.0015	0.0001	0.0019	0.0003	0.0010	0.0001
0.40	0.0020	0.0005	0.0014	0.0001	0.0006	−0.0001
0.47	0.0019	−0.0001	0.0008	−0.0003	0.0004	0.0000
0.55	0.0026	0.0000	0.0011	0.0000	0.0004	0.0001

applying different correction functions [i.e., $f(\theta)$] during heating and cooling cycles showed no further improvement in θ_{p} . Also, after applying the temperature-dependent calibration equation, the reduction in the error of θ_{p} for the EC-5 at $\theta = 0.35$ was small (Table 4). This one exception can be attributed to a poor fit of $f(\theta)$ due to a higher variability in $d\theta_{\text{pr}}/dT$ at $\theta = 0.35$ (Fig. 5). Nonetheless, these results confirm that the temperature-dependent calibration of SCS is effective and required for accurate estimation of the soil water content.

Conclusions

Soil moisture sensor response to environmental conditions (e.g., temperature, salinity, and organic matter content) and intra-sensor variability adds significant uncertainty to their measurements. Efforts have been made to not only develop soil-specific calibration equations but also evaluate and correct the sensor response to temperature and salinity. In this study, we evaluated the performance of three sensors (5TE, EC-TM, and EC-5) in a tropical Oxisol, the Wahiawa Oxisol of Hawaii. We found that the manufacturer's default calibration equations systematically underestimated the actual water content. Also, all the three sensors showed a positive linear response to temperature between 1 and 45°C at all water contents evaluated (~ 0 – $0.55 \text{ m}^3 \text{ m}^{-3}$). Among the three sensors, temperature sensitivity (expressed as the linear slope of the soil water content–temperature relationship) of the 5TE generally increased with increasing water content. In contrast, the EC-TM and EC-5 sensitivity to temperature followed a bidirectional relationship with water content. The statistical analysis revealed that temperature effect, hysteresis, and probe-to-probe variation were statistically significant ($P < 0.05$) for all the sensors. While probe-to-probe variability and the effects of hysteresis on the estimated water content seem to be somewhat random,

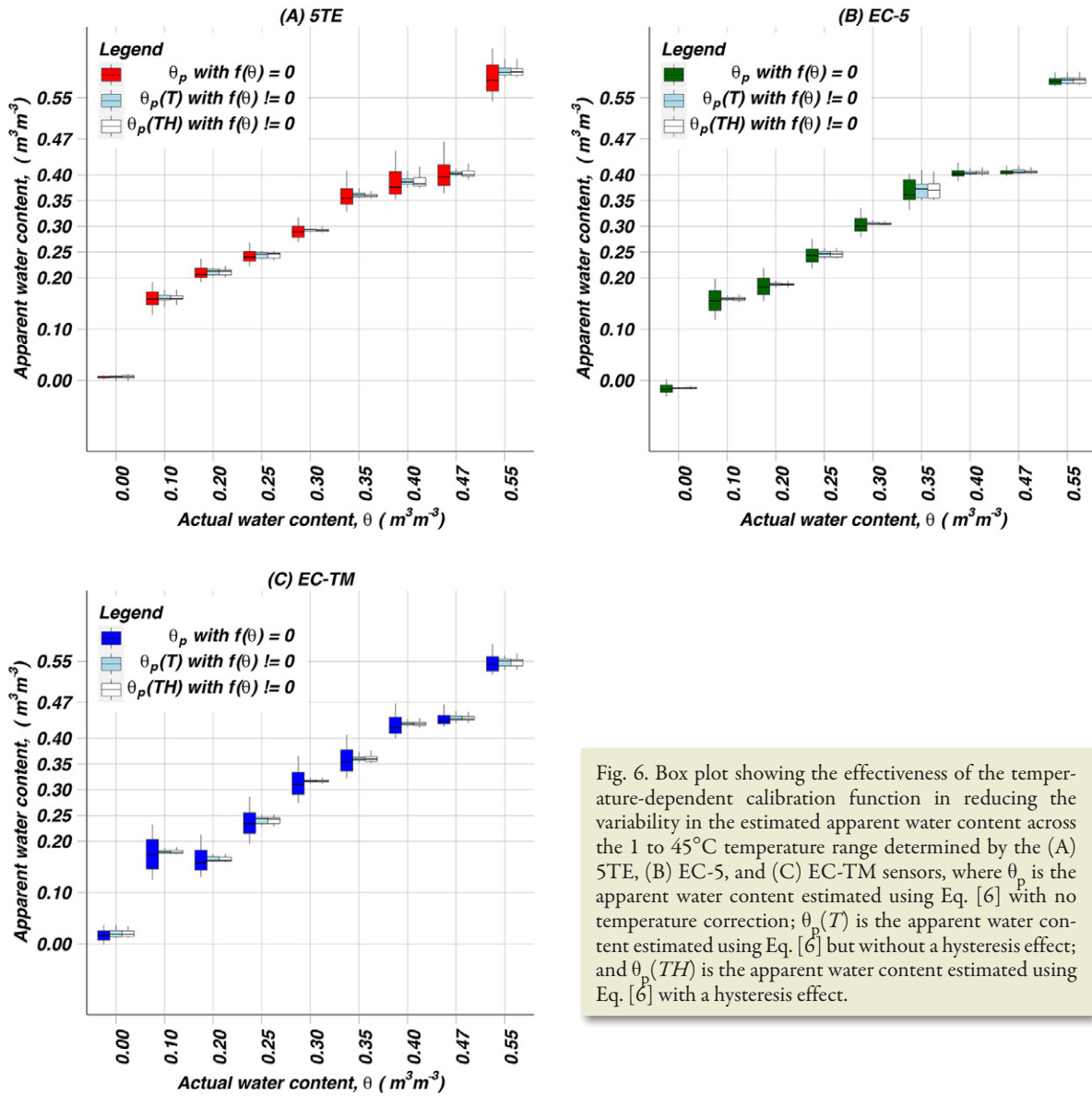


Fig. 6. Box plot showing the effectiveness of the temperature-dependent calibration function in reducing the variability in the estimated apparent water content across the 1 to 45°C temperature range determined by the (A) 5TE, (B) EC-5, and (C) EC-TM sensors, where θ_p is the apparent water content estimated using Eq. [6] with no temperature correction; $\theta_p(T)$ is the apparent water content estimated using Eq. [6] but without a hysteresis effect; and $\theta_p(TH)$ is the apparent water content estimated using Eq. [6] with a hysteresis effect.

Table 4. Effects of temperature correction on the variability in the estimated apparent water content θ_p due to soil temperature across all three sensors.

Water content $m^3 m^{-3}$	Interquartile range†								
	5TE			EC-5			EC-TM		
	θ_p	$\theta_p(T)$	$\theta_p(TH)$	θ_p	$\theta_p(T)$	$\theta_p(TH)$	θ_p	$\theta_p(T)$	$\theta_p(TH)$
	$m^3 m^{-3}$								
0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.01
0.10	0.02	0.01	0.01	0.04	0.01	0.01	0.06	0.00	0.01
0.20	0.02	0.01	0.01	0.03	0.00	0.00	0.04	0.01	0.01
0.25	0.02	0.01	0.01	0.03	0.01	0.01	0.04	0.01	0.01
0.30	0.02	0.00	0.00	0.02	0.00	0.00	0.04	0.00	0.00
0.35	0.03	0.01	0.00	0.04	0.03	0.03	0.04	0.01	0.01
0.40	0.04	0.01	0.02	0.01	0.00	0.01	0.03	0.01	0.01
0.47	0.04	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
0.55	0.06	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01

† θ_p is the apparent water content estimated using Eq. [6] with probe-to-probe variability removed and no temperature correction; $\theta_p(T)$ is the apparent water content estimated using Eq. [6] but without a hysteresis effect; $\theta_p(TH)$ is the apparent water content estimated using Eq. [6] with a hysteresis effect.

varying soil temperature can systematically reduce the sensor accuracy. Temperature-dependent calibration functions can be used to improve the performance of these sensors by minimizing the effects of substrate temperature on the estimated water content.

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