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ScienceDirect

Scientia Horticulturae 112 (2007) 227–234

SCIENTIA HORTICULTURAE

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Calibration and performance of moisture sensors in soilless substrates: ECH_2O and Theta probes

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Received 24 January 2006; received in revised form 8 November 2006; accepted 6 December 2006

Abstract

Reliable and affordable moisture sensors for measuring the water content in soilless substrates are limited. In this study, we examined the efficacy of two moisture sensors (ECH_2O-10 and Theta probe ML2X) for measuring water content in soilless substrates. We developed calibration equations and analyzed the effect of increasing electrical conductivity (EC) and substrate temperature on the voltage output of probes. We found that a single equation (one for each probe) could be used to adequately measure water content in different custom-made substrates maintained at low EC and a substrate temperature of ~23 °C. The calibration equation developed for the Theta probe from substrates maintained at low EC could also be used in two commercial substrates with high EC (2.0–5.0 dS m^{-1}). Further measurements in substrates maintained at different water contents and EC levels indicated that the output of the ECH_2O-10 probe, but not the Theta probe, was significantly affected by substrate EC. The lack of a substrate EC effect on the Theta probe readings was surprising, because the probe was sensitive to EC when fertilizer solutions with different ECs were measured. Increasing the temperature of the substrate from 10 to 40 °C increased the voltage output of ECH_2O-10 probes by 1.88 mV $°C^{-1}$, or on average 0.0022 m^3 m^{-3} water content per °C. There was no effect of increasing substrate temperature on the Theta probe. It was concluded that ECH_2O-10 probes can be used in greenhouse operations requiring less measurement precision (like irrigation), however for accurate measurements of water content, the Theta probe is preferred.

Keywords: Dielectric constant; Electrical conductivity; Greenhouse irrigation; Water content

1. Introduction

In recent years, regulations on agricultural water use have become more strict due to increased urbanization and population growth. Water resources for agriculture (including horticulture) are likely to decrease in the future (Jury and Vaux, 2005). In light of these observations, it is important to irrigate greenhouse crops judiciously. Greenhouse crops are commonly irrigated based on the visual appearance of the substrate or plants, or with the use of irrigation timers. To irrigate potted plants (e.g., bedding plants) grown in soilless substrates with the right amount of water, it is important to accurately measure the substrate water content to decide when and how much irrigation is required. Mere visual observations of the substrate and/or plants or periodic irrigation using timers are not accurate and will not result in efficient irrigation practices.

In spite of the availability of soil moisture sensors like tensiometers (Van Der Veken et al., 1982; Smajstrla and Locascio, 1996; Krüger et al., 1999), neutron probes (Black and Mitchell, 1968; Gear et al., 1977; McFall, 1978) and time domain reflectometry (TDR) probes (Topp and Davis, 1985), moisture sensors are rarely used to control irrigation in greenhouse (potted plant) production. The main reasons for not using moisture sensors to control irrigation are high costs, unsuitable size, and unreliable measurements of the available moisture sensors. For example, sensors like TDR probes can provide reliable measurements, but the required equipment is expensive and cumbersome. To optimize space utilization, greenhouse crops are grown in small containers. This limits the suitability of sensors like neutron probes which require a large volume for installation and measurement. Greenhouse crops are usually grown in soilless substrates with high porosity. A large fraction of pores are typically filled with air. When a moisture sensor like a tensiometer is inserted into soilless substrates, a significant area of the sensor surface may be in contact with air. This could result in cavitation of the tensiometer, causing

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doi:10.1016/j.scienta.2006.12.013

erroneous and unreliable measurements. As it is difficult to hold the tensiometer firmly in a soilless substrate, the sensor is easily displaced which can cause a loss of contact between the tensiometer cup and the substrate. This also can cause cavitation. Hence, there is a need to screen and identify new moisture sensors suitable for soilless substrates.

Two moisture sensors have recently become available: (1) the ECH_2O dielectric aquameter (Decagon Devices, Pullman, WA, USA) and (2) the Theta probe ML2X (Delta-T devices, Cambridge, UK). A set of five ECH_2O probes with a datalogger (EM 50, Decagon Devices) and software costs approximately \$900 and ECH_2O probes are cheaper when purchased in bulk. The price of a Theta probe ML2X with an HH2 moisture meter for recording measurements is approximately \$1000. These probes are available in convenient sizes (sensor lengths are 6 cm for Theta probes and 10 and 20 cm for ECH_2O probes, respectively). An important differences between the two types of probes is that ECH_2O probes are designed to be buried in the soil or substrate for longer periods, while the Theta probe can either be buried or inserted into the substrate for instantaneous spot measurements. While the Theta probe has been tested for use in soilless substrates (Hansen and Christman, 2004), the ECH_2O probe has not.

Both ECH_2O and Theta probes estimate the substrate water content by indirectly measuring the dielectric permittivity (or dielectric constant) of the substrate. The main components of a soilless substrate that affect the dielectric constant are substrate water content, air, and solid matrix. The dielectric constant of water at a temperature of 20 °C is large (~80.4) compared to that of air (~1) or solid matrix (~2 to 8). Therefore, a change in the substrate water content can result in a significant change in the dielectric constant of the substrate. By developing an analytical relationship between changing water content and the associated change in dielectric constant, the volumetric water content of the substrate can be indirectly estimated (Topp, 2003).

The details of the measuring technique for the Theta probe can be obtained from Gaskin and Miller (1996). The Theta probe is equipped with an oscillator to send a 100 MHz signal (electromagnetic wave) into the built-in transmission line. The transmission line consists of an array of four coaxial rods and has an impedance (resistance) to the signal flow. The impedance of the transmission line depends on the medium surrounding the coaxial rods, hence signal transmission is affected by the medium. When the transmission line is inserted into a soilless substrate, it is impedance changes, and causes a proportion of the incoming signal to reflect back to the oscillator. The reflected signal interferes with the incoming signals to produce a standing wave along the transmission line. The amplitude of the standing wave is proportional to the impedance along the transmission line, which in turn is proportional to the dielectric constant of the substrate. The change in the amplitude can be measured as an analog voltage output. As the dielectric constant of the medium is proportional to the water content (Topp and Davis, 1985), changes in the volumetric water content cause changes in the amplitude of the standing wave or the analog voltage output. This principle is used in calibration of the probe.

The ECH_2O probes are capacitance probes equipped with a capacitor. Three copper plates run along the length of the probe (one of them connected to a positive terminal and the other two to a negative terminal), and form a parallel-plate capacitor. These plates are enclosed inside the body of the sensor. When the voltage is applied across the copper plates, an electromagnetic field is generated and charges the capacitor. The capacitance (amount of charge held at any voltage) of the capacitor changes with the medium due to the interaction of the electromagnetic field with the medium. For example, when the sensor is inserted into a moist substrate (with a large dielectric constant), there is an increase in the capacitance of the capacitor and an increase in the time required to charge the capacitor. By keeping the applied voltage constant, and measuring the time required to charge the capacitor, its capacitance can be estimated. The dielectric constant can be estimated from the capacitance, area of copper plates, and separation between the copper plates. The region of the measurement by ECH_2O probes is approximately 0.7–1 cm around the sensor and runs along the length (both sides) of the probe (10 or 20 cm, depending on the probe model).

Although it has been indicated that water content is the major factor affecting dielectric permittivity of a substrate (called 'real permittivity'), other substrate-related factors like EC, temperature, and bulk density can cause dielectric loss and affect the permittivity of a substrate (called 'imaginary permittivity'). Greenhouse crops are supplied frequently with water-soluble fertilizers resulting in significant concentrations of ions of fertilizer salts in the substrate. The presence of charged particles, like ions of fertilizer salts, in the vicinity of the electromagnetic field generated by probes can attenuate the electromagnetic energy and influence the measurement of probes (Hansen and Christman, 2004). Similarly, probe measurement can be affected by substrate temperature. The dielectric constant of water decreases with increasing temperature (~0.4 $°C^{-1}$; Murrell and Jenkins, 1994). Temperature can also affect sensor electronics, in turn affecting the voltage output of probes. Fluctuations in the substrate temperature can be significant and may affect the measurement of the probe (unpublished results).

Keeping these issues in mind, our objectives were to calibrate the ECH_2O-10 dielectric aquameter and Theta probe ML2X for measuring the water content in soilless substrates and to study the effect of EC and substrate temperature on ECH_2O-10 and Theta probe output.

2. Materials and methods

2.1. Calibration studies

2.1.1. Methods

Probes were calibrated for custom-made substrates with different organic (peat and pine bark) and inorganic components (perlite and vermiculite), while keeping the ratio of organic to inorganic components constant (60% organic), and for substrates with different ratios of organic to inorganic components. In both studies, the EC of the pore water in substrate was low (0.25–0.75 dS m^{-1}; SigmaProbe EC1, Delta -T, Burwell, Cambridge, UK). Along with these custom-made substrates, two commercial mixes having 60% peat and 40% perlite (Fafard 2P, Fafard Inc., Anderson, SC, USA) and 36% peat, 27% pine bark, 15% perlite, and 22% vermiculite (Fafard 4P), both having a high EC (2.0–5.0 dS m^{-1} substrate solution EC) were used to test the developed calibration equations.

In this experiment, custom-made substrates were prepared by mixing different volumes of peat, pine bark, perlite, and vermiculite. Different organic compositions were peat (60%, v/v), peat and bark in equal volumes (30% each), and pine bark (60%). For each organic composition, three inorganic compositions, i.e., perlite (40%), perlite and vermiculite (20% each), and vermiculite (40%), were used, resulting in nine different substrates. The EC of the substrates was low since no fertilizer was added. To obtain a range of water contents in each substrate, from dry to near saturation, different volumes of deionized water were added to each substrate and mixed thoroughly to obtain uniformity. Substrates were then transferred into beakers (1120 mL).

To prepare substrates with different proportions of organic to inorganic components having a particular substrate composition, peat:perlite ratios of 80:20, 60:40, 40:60, and 20:80% were used. Different substrate water contents for these and two commercial mixes were also prepared as mentioned above by mixing substrates with different volumes of deionized water.

2.1.2. Measurements

In total, we used 10 ECH_2O-10 probes and one Theta probe in the study. Two ECH_2O-10 probes were inserted into each beaker containing the substrate. The ECH_2O-10 probes were inserted completely into the substrate. A CR10X datalogger (Campbell Scientific, Inc., Logan, UT, USA) was used to excite and measure the output from the ECH_2O-10 probes. The datalogger supplied 2.5 V of excitation to the ECH_2O-10 probes and the output was measured as analog voltage in the range of 250–900 mV (dry to near saturation). The output from ECH_2O-10 probes was measured at 2 s intervals. The measurement was recorded after attaining a stable voltage output. The Theta probe was inserted into the substrate in one beaker at a time for measurement after switching-off the ECH_2O-10 probes. The transmission rods of the Theta probe were completely inserted into the substrate for measurement. The output from the Theta probe was measured using a digital multimeter (DM 350A, A.W. Sperry, Hauppauge, NY) or moisture meter (HH2, Delta-T, Burwell, Cambridge, UK).

Before inserting any probe, the initial weight of the beakers and substrate was determined. Probes were inserted carefully so as to not compress the substrate during insertion. After measuring the output from the probes, the substrate in the beakers was dried in a forced-air oven maintained at 80 °C. The substrate was weighed after drying, and used to determine the substrate water content. The substrate water content was determined by converting grams of water in the substrate to milliliter of water assuming that 1 g of water = 1 mL.

2.1.3. Analysis

There was one trial for different custom-made substrates, however there were five separate trials for the two commercial substrates. Data obtained using custom-made substrates were analyzed using GLM procedure of SAS (SAS institute, Cary, NC, USA) with $P < 0.05$ considered significant. A mixed model comprising of both class and continuous variables was used in this analysis. Water content was tested as a dependent variable with substrates as independent class variables, and voltage as independent continuous variable. The relationship between water content and voltage was determined by developing quadratic equations using the regression procedures of SAS. Data obtained from commercial substrates were analyzed similarly using GLM and regression procedures of SAS. Differences among 10 ECH_2O-10 probes were tested in this analysis by considering probes as a class variable along with substrate type.

2.2. Electrical conductivity responses

2.2.1. Methods

The effect of EC on probe output was studied in both solutions and soilless substrates. Responses of probe output to increasing solution EC were determined by adding different volumes of a concentrated fertilizer solution (15-5-15 Cal-Mag, The Scotts Co., Marysville, OH, USA) to deionized water and measuring probe output at each concentration.

ECH_2O-10 and Theta probe responses to changing substrate EC were measured in a substrate comprising of 60% peat and 40% perlite. Initially, substrates with different water content were prepared as described earlier. To each substrate at a particular water content, concentrated fertilizer solution was added in incrementing volumes to increase the substrate EC. At any time, the total volume of concentrated fertilizer solution added was less than 1% of total volume of the substrate.

2.2.2. Measurements

Output of probes was measured at each EC level. Electrical conductivity of the pore water present in the soilless substrates was determined with pore water conductivity sensor (Sigma probe) or solution (Field Scout soil EC probe, Spectrum Technologies, Plainfield, IL, USA). Because the Sigma probe cannot measure the EC in dry substrates, substrates with a water content $>0.25\ m^3\ m^{-3}$ were used in this study. After measurements, the substrate in the beakers was dried in a forced-air oven maintained at 80 °C. The dry weight of the substrate was used to determine water content as described earlier.

2.2.3. Analysis

There were five trials in the solution and substrate studies. Similar to the analysis described in calibration procedure, a mixed model comprising both class and continuous variables was used. Voltage was tested as a dependent variable and solution EC as independent continuous variable. In the substrate EC response study, voltage was tested as dependent variable and water content and EC were treated as independent continuous variables. Responses were studied using both linear and nonlinear regression procedures of SAS.

2.3. Temperature responses

2.3.1. Methods

To determine the effect of substrate temperature on probe measurement, beakers containing substrate (60% peat and 40% perlite) were placed in a growth chamber (Conviron CMP 4030, Winnipeg, Manitoba, Canada) with the lights off. The growth chamber was programmed to increase the chamber temperature from 10 to 40 °C in increments of 2 °C. The temperature in the growth chamber was raised only after the substrate temperature stabilized. Substrate temperature was measured using T-type thermocouples connected to a thermocouple thermometer (Digi-Sense 91100-50, Cole-Palmer instrument Co., Vernon Hills, IL, USA). The effect of substrate temperature on ECH_2O-10 probe output was studied at three substrate water contents, i.e., 0.12, 0.25, and 0.35 $m^3\ m^{-3}$, however for the Theta probe, temperature responses were studied only at a water content of 0.25 $m^3\ m^{-3}$. The water content in the substrate was maintained constant for all measured substrate temperatures. This was accomplished by tightly fastening a paraffin film on top of each container after inserting the probes leaving no space between the substrate and paraffin to avoid evaporative water loss.

2.3.2. Measurements

Output of the probes was recorded at each substrate temperature after the substrate temperature has stabilized. Measurements were taken twice at each temperature level. At the end of the study, beakers were re-weighed and compared with their initial weight as a check against evaporative moisture loss during the experiment.

2.3.3. Analysis

Data were analyzed by multiple regression with voltage output from the probes as the dependent variable and different water contents and temperatures as independent continuous variables. The linear regression procedure of SAS was used to analyze these responses.

3. Results and discussion

3.1. Calibration of probes in soilless substrates

The response of ECH_2O-10 and Theta probe output to increasing substrate water content was similar among the nine substrates having different organic and inorganic compositions. For both probe types, and in all nine substrates, there was an increase in the voltage output with increasing substrate water content in the studied range of 0–0.5 $m^3\ m^{-3}$ (Fig. 1). The fitted equations adequately ($0.95 < R^2 < 0.96$) described the response of voltage of both probes to increasing substrate water content. The nine different substrates studied had relatively low pore water EC (0.25 $dS\ m^{-1}$ at high water content and 0.75 $dS\ m^{-1}$ at low water content). Although the type of organic and inorganic components varied among the substrates, the proportion of organic to inorganic matter remained constant (60:40). These results indicate that regardless of the type of the organic and inorganic components used in preparing substrate, a single calibration equation can be used to estimate substrate water content in these nine substrates with 60% organic and 40% inorganic components.

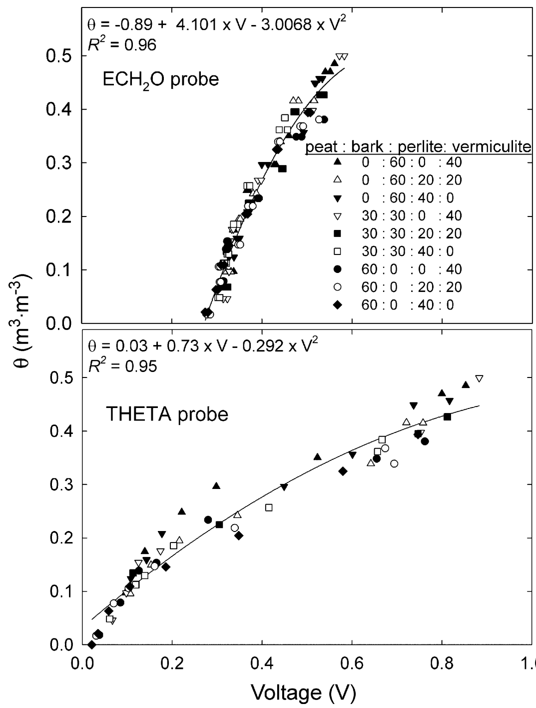

Fig. 1. Relationship between water content of the substrate (θ) and the voltage output of ECH_2O-10 and Theta probes in nine different substrates having 60% organic and 40% inorganic components.

A single calibration equation sufficiently described the ECH_2O-10 and the Theta probe responses when the data from nine substrates with different organic and inorganic components were combined with the data from the different ratios of peat and perlite (i.e., varying ratios of organic and inorganic components) (Fig. 2). This indicates that there was no significant effect of different organic and inorganic fractions on the dielectric permittivity of the substrate. The change in dielectric permittivity is seen only due to an increase in substrate water content. This is a significant finding because it indicates that separate calibrations may not be necessary for ECH_2O-10 and Theta probes in different soilless substrates with an EC < 1.0 $dS\ m^{-1}$.

When the developed calibration equations for ECH_2O-10 and Theta probes using the custom-made substrates (Figs. 1 and 2) were compared with the calibration equations for the two commercial substrates (Fafard 2P and 4P), only the response of the Theta probe was similar in all substrates (Fig. 3). Both commercial substrates contained starter fertilizer and the measured pore water EC at high to low water contents ranged from 2 to 5 $dS\ m^{-1}$, respectively. We fitted a single calibration equation (Fig. 3) that can be used to adequately describe the response of Theta probe output to increasing water content for soilless substrates with different compositions and

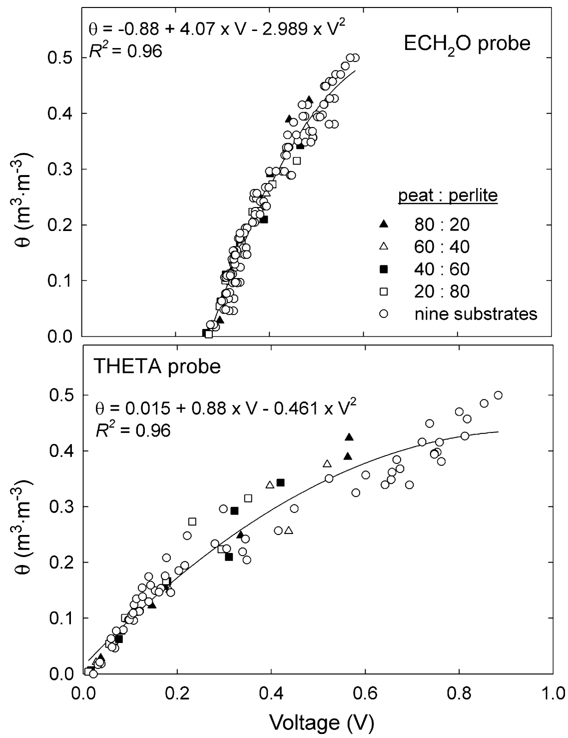

Fig. 2. Relationship between volumetric water content of the substrate (θ) and the voltage output of ECH_2O-10 and Theta probes. Data include both nine substrates with different organic (60%) and inorganic components (40%) (see Fig. 1 for more details) and substrates having different proportions of peat and perlite. Fitted equations are for combined data.

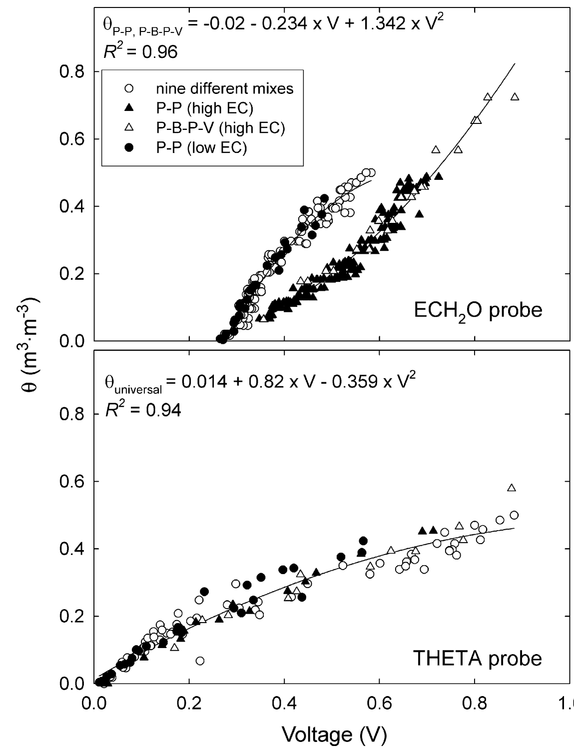

Fig. 3. ECH_2O-10 and Theta probe calibration equations for two commercial substrates (P–P indicates peat–perlite and P–B–P–V indicates peat–bark–perlite–vermiculite) with high EC, and 13 substrates with low EC (see Figs. 1 and 2 for more details on these 13 substrates). The equation for the ECH_2O-10 probe is for two commercial substrates with high EC only. The equation for the Theta probe is for all 15 substrates combined.

EC levels. However, the response of ECH_2O-10 probes to increasing water content was different between the commercial and custom-made substrates (Fig. 3). Presence of fertilizer salts increased the ECH_2O-10 probe output at any substrate water content. Based on these results, the Theta probe seems to be insensitive to substrate EC, while the ECH_2O-10 probe is not.

Statistical analysis indicated no significant differences among different ECH_2O-10 probes. Hence it is inferred that probe-specific calibrations are not necessary for ECH_2O-10 probes. This could not be verified for the Theta probe as we used only one probe in these studies.

Robinson et al. (2003) indicated that the dielectric loss increases not only with increasing EC, but also with decreasing frequency of the propagation wave. Frequencies of 400–500 MHz were shown to be effective in decreasing dielectric losses due to ionic conductivity in clay soils (Topp et al., 2003). The maximum frequency of electromagnetic waves generated by ECH_2O-10 and Theta probes were 20 and 100 MHz, respectively. A lower frequency of the propagation wave perhaps makes ECH_2O-10 probes more vulnerable to increased dielectric losses in saline substrates than Theta probes. Although the frequency of the Theta probe was lower than that recommended as the ‘effective’ frequency to decrease ionic losses in the literature (i.e., 400–500 MHz), it appears that Theta probe measurements were insensitive to substrate EC (Fig. 3).

3.1.1. *Ready-to-use coefficients for the Theta probe*

The voltage of Theta probe can be linearly related to the square root of dielectric permittivity ($\sqrt{\varepsilon} = 1.1 + 4.44V$, $r^2 = 0.99$, where V is dielectric permittivity and V is voltage (see Gaskin and Miller). It has been shown that a simple universal linear relationship exits between dielectric permittivity and water content ($\sqrt{\varepsilon} = a_0 + a_1\theta$; Whalley, 1993; White et al., 1994). In fact, these two equations are used to estimate water content from voltage output and pre-determined coefficient values (a_0 and a_1) by the HH2 moisture meter (Delta-T devices) of the Theta probe. We calculated values for coefficients a_0 and a_1 based on the equation in Fig. 3 in our study. The calculated values for a_0 and a_1 were 1.19 and 8.67 (see Gaskin and Miller for a description of calculation procedure). These values are close to those recommended by the manufacturer for organic soils (1.3 and 8.6, respectively, for a_0 and a_1). As our values are based on different substrates, we recommend our coefficients for use with a HH2 moisture meter (Delta-T devices) to estimate water content in soilless substrates.

3.2. *Effect of electrical conductivity on probe measurement*

Both ECH_2O-10 and Theta probes were found to be sensitive to fertilizer salts or ions in solutions (Fig. 4). The response of probes to solution EC differed, with an increase in EC either causing a rise to a maximum output (ECH_2O-10 probe) or a

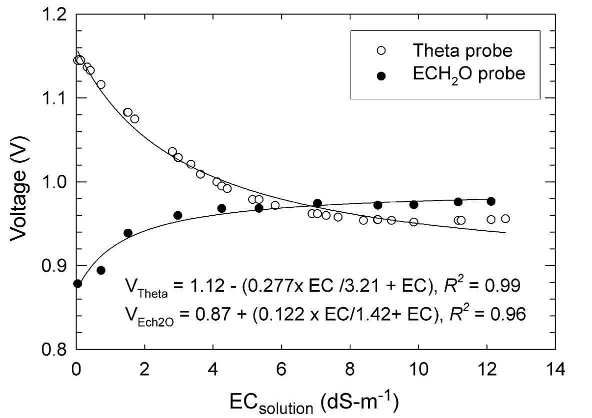

Fig. 4. Effect of increasing electrical conductivity of fertilizer solution ($EC_{solution}$) on the output of ECH_2O and Theta probes. The sensing parts of the probes were completed submerged in the solutions.

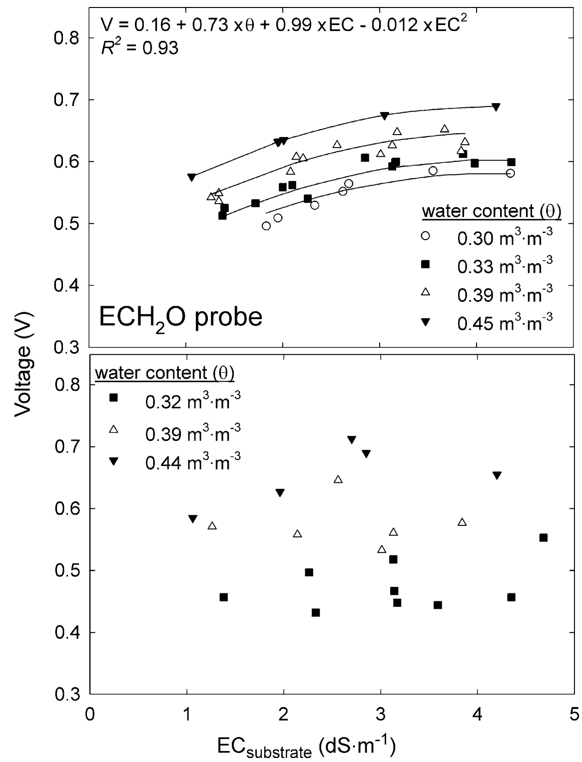

Fig. 5. Effect of increasing electrical conductivity of the substrate ($EC_{substrate}$) at different substrate water contents on the output of ECH_2O-10 and Theta probes. There was no significant effect of EC on Theta probe output.

decrease to a minimum (Theta probe). For both probes, the output changed rapidly within the range of 0–3.0 dS m^{-1} and at higher EC levels there was a relatively small change in the output. When the solution EC was increased from 0 to 3 dS m^{-1}, the output of ECH_2O-10 probes increased by approximately 9.1% (∼880 to 960 mV) and a further 2.4% increase in ECH_2O-10 probe output was seen at an EC of 12 dS m^{-1} compared to that at 3 dS m^{-1} (Fig. 4). The Theta probe output decreased from 1145 to 1020 mV (10.9%) with increasing solution EC from 0 to 3 dS m^{-1} (Fig. 4). A further increase in EC decreased the output to 940 mV at an EC of 12 dS m^{-1} (7.9% lower than that at 3 dS m^{-1}). Gaskin and Miller described a very similar response of probe output to solution EC.

The different responses of probes to increasing solution EC can be attributed to the mechanism of operation of these probes. The presence of ions in the solution surrounding the sensor will attenuate the electromagnetic signal which is a result of dissipation or loss of electric energy to the ions. In the case of the Theta probe, this attenuation (Gaskin and Miller) results in an overall decrease in the amplitude of the electromagnetic wave travelling through the sensor, hence a decrease in analog voltage output with increasing solution EC. The response of ECH_2O-10 probes is different because, due to the attenuation of the electromagnetic signal, it takes more time to charge the capacitor to the same level at a given applied voltage. As this time increases, the voltage output of the probe increases.

When the effect of the substrate pore water EC on ECH_2O-10 probe output was tested at different substrate water contents, the probe response was affected by both water content and EC (Fig. 5). The ECH_2O-10 probe output responded in a quadratic fashion to increasing EC of the pore water. This EC response was similar at different substrate water contents (Fig. 5). Similar to the effect seen in solution, the effect of increasing EC was greatest at low EC. The effect of increasing substrate EC on Theta probe output was not statistically significant ($P = 0.153$) at the three studied water contents (Fig. 5). This was surprising given the effect of EC on the Theta probe output, when the probe was used in solutions rather than soilless substrates (Fig. 4).

3.3. Effect of substrate temperature on probe measurement

There was a linear increase in ECH_2O-10 probe output with increasing temperature of the substrate, independent of the substrate water content (1.88 mV °C^{-1}, Fig. 6). This translates to a change in estimated water content of 0.0018 and 0.0026 m^3 m^{-3} °C^{-1} for a substrate at 0.12 and 0.34 m^3 m^{-3}, respectively (based on the calibration equation for commercial mixes in Fig. 3). There was no change in the Theta probe output when the substrate temperature was increased from 10 to 40 °C (Fig. 6).

An earlier study by Baumhardt et al. (2000) indicated that under saturated soil conditions, increasing substrate temperature had a greater effect on capacitance probes than on TDR probes (estimated water content increased by 0.04 and 0.02 m^3 m^{-3} for a 15 °C change for capacitance and TDR probes, respectively). The rate of increase in voltage with increasing temperature for ECH_2O-10 (capacitance) probe was approximately 0.033 m^3 m^{-3} for a 15 °C change in the substrate temperature in our study. Our results agree with those of Baumhardt et al. (2000) in that ECH_2O-10 (capacitance) probe output was significantly affected but Theta probe output (which uses wave reflection, like TDR, for estimating dielectric permittivity) was not affected by temperature. Several studies have indicated a linear decrease in the water content measured by TDR probes with increasing substrate temperature when the water content is above 0.30 m^3 m^{-3} and no change in measured water content with increasing temperature when the substrate water content is below 0.30 m^3 m^{-3} (Wraith and Or, 1999; Gong et al., 2003).

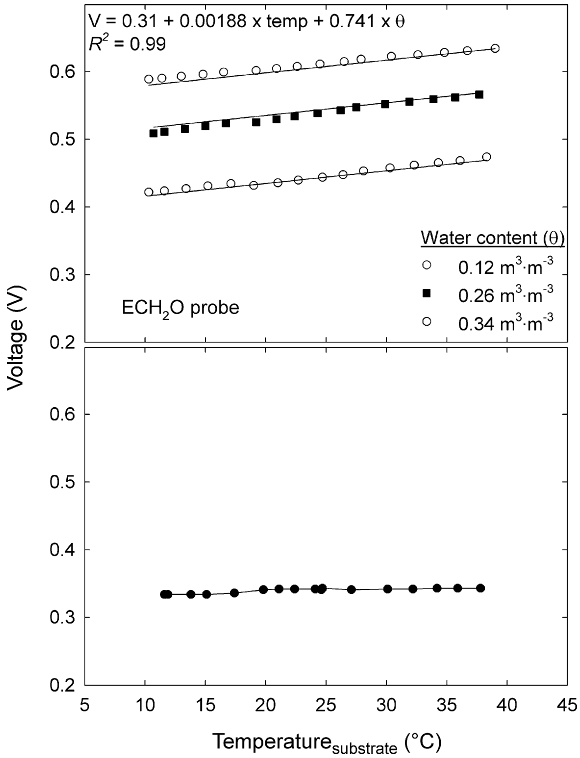

Fig. 6. Effect of increasing substrate temperature on the output of ECH_2O and Theta probes. Responses were measured at three water contents for ECH_2O probes, whereas the Theta probe was measured at one water content.

Under conditions of low soil water content, a large fraction of the water is held by the solid surface as bound water which releases as free water when the temperature is increased. This increase in free water offsets the decrease in dielectric permittivity of water with increasing substrate temperature ('thermodielectric effect'), hence the net result is little or no change in the measured water content (Wraith and Or, 1999). As the substrate water content was 0.25 $m^3\ m^{-3}$ when the Theta probe response to substrate temperature was measured, it is likely that the lack of change in the output is due to the interplay between a decrease in dielectric permittivity and an increased release of bound water.

4. Conclusions

Our objective was to calibrate ECH_2O-10 and Theta probes for measuring water content of greenhouse substrates and study the effect of substrate EC and temperature on probe measurements. The following conclusions were drawn based on the results from this study:

(i) When the substrate pore water EC levels are <1.0 dS m^{-1}, ECH_2O-10 probes can accurately measure the water content of the substrate. Substrate EC has the greatest effect between 1.0 and 3.0 dS m^{-1}. However, considering their low cost (~$60 if >11 probes are purchased) and the fact that high accuracy may not be required for irrigation purposes, ECH_2O-10 probes can be recommended for greenhouse use, and especially for crops grown with low EC (≤1.0 dS m^{-1}). At higher pore water EC levels (>3.0 dS m^{-1}), a separate calibration can be used as there is little increase in the effect of substrate EC on probe output above 3.0 dS m^{-1}. Temperature compensation can be used to improve the performance of the ECH_2O-10 probes to minimize the effects of substrate temperature on probe output. ECH_2O-20 probes have similar responses to changes in temperature and substrate EC as ECH_2O-10 probes, while newer ECH_2O probe models (ECH_2O-5 and ECH_2O-TE), which use a higher measurement frequency, are less sensitive to substrate EC and temperature (our unpublished results) and thus may be better choices for soilless substrates.

(ii) Substrate EC and temperature were shown to have little or no effect on Theta probe output, despite EC effects on probe output when fertilizer solutions were measured. It is also shown that one calibration can be used to describe the response of the Theta probe in different soilless substrates. Hence, the Theta probe is suitable for precise measurements of water content.

Acknowledgment

We thank Mark Blonquist, technical service, Apogee Instruments, Logan, Utah, USA for his helpful comments on this manuscript.

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