WET-sensor Pore Water EC Calibration for Three Horticultural Soils

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Abstract

The WET-sensor is a frequency domain dielectric sensor that measures permittivity, conductivity and temperature, which can be used for monitoring soil water content and electrical conductivity in horticulture. By using a specific model it measures pore water conductivity as well. However, under practical circumstances, large errors have been observed using the existing model. The purpose of this study was to obtain a empirical correction for this model and to investigate the nature of the errors, so horticultural growers can use the WET-sensor to measure pore water EC in-situ. Using 36 potted samples of sand, clay and peat, the relation between permittivity, bulk EC and pore water EC was studied in a laboratory over a temperature range from 19-22 ^{o}C and a pore water EC range from 4 – 12 mS/cm. This resulted in an adaptation of the constant in the existing model and an extra second order polynomial correction factor. After temperature correction, an overall linear fit with a coefficient of 0.9948 was found at a reasonable correlation (0.79). Errors may occur up to ±40%, but for permittivity values larger than 20, errors have a maximum of ±15%. The overall standard deviation is 15%, which is in accordance with simulated results. For growers using relatively wet soils at water contents above 20%, the WET-sensor can be used to measure pore water EC in situ with a reasonable accuracy. Further study is needed to explore this correction at larger temperature ranges and for more soil types.

INTRODUCTION

Recently a frequency domain dielectric sensor has been brought onto the market that measures in situ the complex electrical permittivity (ε), conductivity (σ) and temperature (T) (Hilhorst et al., 1993; Hilhorst 1998; Balendonck and Hilhorst, 2001a,b). It is sold as the WET-sensor by Delta-T-Devices Ltd (Cambridge, UK) and can be used to measure soil volumetric water content (θ) and electrical conductivity (EC) in soil (Fig.1.). The major advantage of this sensor is that it can measure the two most valuable parameters for irrigation and fertilisation all together. Many other soil water content sensors are available, but so far as we know, none of them measures accurately EC. Therefore the WET-sensor is seen as a promising sensor for water and nutrient management in horticulture. However, one drawback is that it measures bulk EC (σ) rather than the in-situ pore water EC (σ_p) (Dirksen and Hilhorst, 1994).

Bulk EC (σ) reflects the total EC of the entire soil matrix containing soil particles, water, nutrients and air. Growers often refer to σ by using the term electrical conductivity or EC for short. Since plants take up only water-dissolved fractions, growers are mainly interested in σ_p which is the same as the EC of the liquid that can be extracted from the soil matrix either by pressing or by using a syringe. Growers can obtain σ_p also through a procedure in which a soil sample is mixed with a known volume of water to let the nutrients dissolve. The EC is measured in the resulting aqueous solution with a standard EC meter, and σ_p is found by multiplying the measured value by the mixing factor. In case the amount of added water has the same volume as the soil sample, this method is referred to as “the 1:2 extract method” (Sonneveld and van den Ende, 1971). Since all these methods involve a lot of manual work, like for soil sampling, growers are interested to use the WET-sensor as an in-situ instrument to measure pore water EC.

The pore water EC relates to σ, but this relation is strongly dependent on θ and subsequently ε. Therefore, a model was proposed to obtain σ_p from simultaneously taken readings for ε and σ with the WET-sensor (Hilhorst and Balendonck, 1999; Hilhorst, 2000). This model was developed for another version of the sensor called the Sigma-Probe, which is based on the same electronics as of the WET-sensor, but uses a single rod with embedded electrodes rather than three electrodes. Furthermore it operates at 30 MHz, which is slightly higher than the frequency used in the WET-sensor (20 MHz). Therefore, it is obvious that the validity of this model should be checked before this model can be used for the WET-sensor. Laboratory experiments and practical work (internal communication) showed that by using this model for the WET-sensor sometimes large errors may arise. Only a week correlation between the standard 1:2 volume extract method and the sensor data using the correction model was found (Balendonck et al., 2002).

From practical work in the period 2000-2002, we have seen that several sources of errors exist. First there is the spatial variability of the soil. Since reference samples were not taken at the exact spot where the sensors were placed in the soil, discrepancies could occur. Furthermore, both the 1:2 volume extract method, serving as a reference method, and the WET-sensor have a limited accuracy. Also it was observed that the placement of the WET-sensor in the soil, vertically or horizontally, influences the readings. Al this made it rather difficult to study the validity of the model under practical circumstances. Therefore, to eliminate as much of the error sources as possible, we decided to perform a well-conditioned laboratory experiment. The purpose of this study was to investigate under well-known conditions whether the pore water EC model, originally meant for the SigmaProbe, can be used, or adapted for the WET-sensor working for horticultural soils as well.

MATERIALS AND METHODS

The Pore Water EC Model

The WET-sensor is capable of measuring σ, as well as ε and temperature (T). To obtain σ_p, σ is measured and corrected for ε and T by using a simple and straightforward model. This model was already used for precision agricultural applications to measure σ_p in-situ in soil (Hilhorst and Balendonck, 1999):

$$\sigma_p = \sigma \cdot \varepsilon_{water}(T) / (\varepsilon - \varepsilon_{\sigma=0}) \qquad (1)$$

In this equation $\varepsilon_{water}(T)$ is the pure water permittivity corrected for temperature, and $\varepsilon_{\sigma=0}$ is a constant. This constant can be obtained from ε and σ measured at two arbitrary free water content values. For a number of soils, empirically, values for $\varepsilon_{\sigma=0}$ between 1.9 and 5.8 were found. These values are dependent on soil type, density, and the sensor pin-type configuration. Since for Eq. 1 it was assumed that water is not bound to the soil matrix, this model cannot be used for bound water. Neither can it be used for conductivity due to ions moving through the lattice of ionic crystals in a dry or almost dry soil. For sand, the free water content corresponds to $\theta > 10\%$. For clay this is $\theta > 12\%$. As a rule of thumb the model applies for most normal soils if $\theta > 10\%$.

Temperature Corrections

Dielectric sensor readings are dependent on temperature. In the soil top layer, where temperature is very much dependent on sunlight conditions, sometimes large temperature fluctuations are seen during the day. To allow for on-line correction, temperature is measured in the sensor. Little is found in the literature about the influence of soil texture and density on the temperature behaviour of soil water content and EC. Recently it has been shown that the temperature behaviour is dependent on soil texture (Seyfried and Murdoch, 2002). Positive as well as negative effects have been seen for different soil types. This makes temperature corrections rather ambiguous. Nevertheless, for ε and σ separately we can perform some general corrections. The ε of pure water at a specific temperature can be obtained from:

$$\log(\varepsilon_{water}(T)) = 1.94404 - 0.001991\ T. \quad (2)$$

This function was specified over a temperature range from 0 to 40°C with a maximum error of 0.3% (Kaatze, 1981). This equation can be simplified using the following approximation:

$$\varepsilon_{water}(T) = 78.487 - 0.368\ (T - 25), \quad (3)$$

where Eq. 2 was linearized around T = 25 °C. The EC depends on T and the dissolved ion types, which makes it impractical to handle this parameter just as it is measured. Growers use EC referred to a predefined reference temperature (T_{ref}), normally 25 °C. Each water–salt mixture has a specific temperature coefficient (α_i), and for average soil types a value of $\alpha_i = 0.0216\ ^oC^{-1}$ can be used (Heimovaara, 1993). The referenced pore water conductivity can be computed from:

$$\sigma_p{}^* = \sigma_p\ [1- \alpha_i\ (T - T_{ref})]. \quad (4)$$

Experiments

In the period June to September 2003 a number of experiments were conducted under laboratory circumstances. Soil samples were assembled in pots, each containing one out of three soil types (sand, clay and peat). At first, three raw samples collected from practical greenhouses were intensively mixed using a soil-mixing machine to get homogeneous mixtures. From these mixtures small samples were taken which were used for basic analysis such as for organic matter content and clay fraction. From each of the three mixtures, 6 litres of soil were used for further processing and filling pots of 2 litres contents.

Two measurement sessions were performed. In the first session the samples from all three soils were made without an EC enrichment, with an EC enrichment of 0.5 mS/cm and with an EC enrichment of 1.0 mS/cm. Each sample was made in twofold. In total 18 pots were assembled (2 x 3 soils x 3 EC treatments). In the second session only the clay mixture was used. Again the EC treatment was used as in the first session, but now the clay mixture was wetted at three different levels by adding water to the basic mixture (+10% and +20%). Again 18 samples were made (2 x 3 EC-levels x 3 water content levels). Each time the 2 litre pots were filled with exact the same weight of soil, and compacted with a force of 0.1 kg/cm^2. Replicates of these pots were assembled to obtain the reference pore water EC by measuring the EC with a standard EC-meter (corrected for 25°C) in the water mixture collected after pressing the soil samples (σ_{press}). All 36 pots were used for measurement, and in every pot a WET-sensor was placed. The WET-sensors were connected to a PC through a self-made multiplexer. Data collection was performed by a Delphi program which generated ASCII-text files. These text files were further processed using EXCEL. Readings from the WET-sensors were taken every 15 minutes during 24 hours. For two other periods of 24 hours, the sensors were rearranged over the 18 pots. This assured that the soil samples were monitored by at least 3 different WET-sensors. During the experiments, the soil samples were covered with a plastic foil to prevent from drying out. The experiments were carried out at room temperature (19 - 22 °C). For each of the 36 samples from the two sessions raw values for ε, σ and T were obtained by taking the average values over the three days for all 15-minute samples. Herewith most of the incidental errors were eliminated.

RESULTS AND DISCUSSION

From the measured data and by using Eq. 1, 3 and 4 with for $\varepsilon_{\sigma=0} = 4.1$ (Hilhorst, 2000), a graph was made for σ_{press} versus $\sigma_p{}^*$. With a linear fit a week correlation

($R^2 = 0.60$) was found. After redoing this linear fit at multiple values for $\varepsilon_{\sigma=0}$ between 3 and 10, we found a maximum correlation (R^2=0.7415) for $\varepsilon_{\sigma=0}$ = 6.2, but the curve had a direction coefficient of 2.1068 and an offset of -2.4092. Since it is obvious that at $\sigma = 0$ there can't be a non-zero value for σ_p, a second order polynomial fit was tried including (0,0) as an extra data point in the data set. This resulted in a better correlation ($R^2 = 0.8148$). The following empirical correction formula:

$$\sigma_{p(corr)} = 0.2817 \cdot (\sigma_p^*)^2 + 0.2536 \cdot \sigma_p^* + 0.1223 \qquad (5)$$

was obtained and used to get corrected values for σ_p (Fig. 2). These values were then plotted against the originally found values for σ_{press} (Fig. 3). On this data set, a linear fit was performed by forcing the fit through (0,0). A good linear behaviour was found (factor = 0.9948) at a very reasonable correlation ($R^2 = 0.7975$). In spite of this, the individual errors seem to be high. Therefore we decided to look in detail at the errors.

The errors ($\Delta\sigma_{p(corr)measured} = 100\% \cdot (\sigma_{p(corr)} - \sigma_{press})/\sigma_{press}$) were plotted against σ and ε (Fig. 4. A,B). We see from the graphs that we can get incidental errors up to ±34%. The standard deviation is 14.8%. From earlier experiments and literature we know that the accuracy of the WET-sensor for ε is ±1% (±1 from the full scale range: 1-100), and for σ it is ±1.5% (±0.03 mS/cm over the full scale range of 0 - 2 mS/cm) over the temperature range from 15 to 25 °C (Balendonck and Hilhorst, 2004). By using this initial accuracy for ε and σ we performed a simulation based on Eq 1, 2 and 4 by generating 1000 linear spread random number sets for ε and σ. The results for this are plotted in Fig. 4 C,D. We see that the magnitude of the simulated errors lie in the same range as were found from the experiments ($-30\% < \Delta\sigma_{p(corr)simulated} < +50\%$) and that the standard deviation is about 12%. The difference may come from the fact that σ_{press} has some inaccuracy as well. Furthermore we see that the errors are not depending σ. For $\varepsilon < 20$ we see that the errors become rather large (>15%). In fact the errors, as can be expected looking at Eq. 1, are more or less inversely related to ε.

It was observed that there is a slight difference in calibration between the soil types. This indicates that by using soil specific calibrations the accuracy could be enhanced slightly. However, for practical application this is not wise, since it would involve managing a large number of different soil specific curves. The fact that we find a 2nd order relation between σ_p and ε suggests that the assumption that σ_p relates to ε rather than to θ (Hilhorst, 1999) is not valid for the WET-sensor. It might be wise to explore the correction model by using the soil water content calibration ($\theta = f(\varepsilon)$) rather than using ε.

CONCLUSIONS

Based upon practical experiments an empirical calibration model for pore water EC was derived for three horticultural soil types: sand, clay and peat. To get a good correlation between pore water EC obtained by pressing soil samples and by using the WET-sensor, the model from Hilhorst for the Sigma-Probe was extended with a 2nd order polynomial correction and the constant for the model was empirically found to be 6.2. This adapted model yielded good linear results (0.995) for pore water EC with a reasonable correlation ($R^2 = 0.79$). The errors have a non-linear and inverse behaviour with respect to permittivity. For permittivity values larger than 20, the errors have a maximum of ±15%, and for lower permittivity values errors may occur up to ±40%. The overall standard deviation found was about 15%, which is in accordance with simulated results.

In principal the 3-pin WET-sensor can be used by growers and the adapted model provides a new and more manageable way to measure pore water EC in-situ. However, to get a reasonable accuracy, the operating range is limited to soil water contents that are larger than about 15%. For horticultural soils, at least in the irrigated growing layer of the soil, this restriction is not a problem.

The pore water EC model was only verified for a limited number of soils (clay, sand, peat) and for a limited temperature range (19 - 22 °C). Daily fluctuations of temperature are larger than this range and more soil types are generally in use. Therefore, to make this model available for a wider use in horticulture, it should be evaluated for a larger number of soils and a larger temperature range (f.i. 5 – 40°C). It is not likely that the accuracy of this method will be enhanced by using more refined models. The only way of getting the method better is to get more accurate readings for the basic parameters ε and σ as measured with the WET-sensor. This could be done by taking more readings with the WET-sensor and by averaging the data before using the pore water EC model.

ACKNOWLEDGEMENTS

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Figures

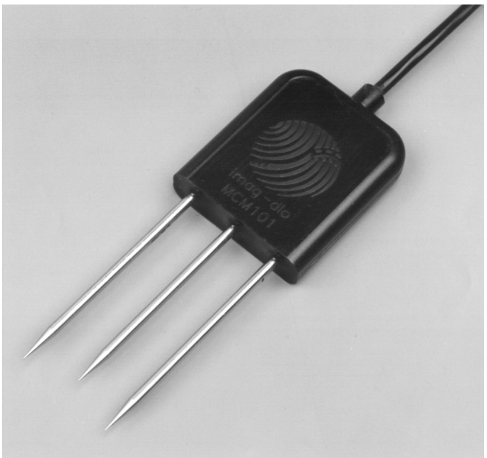

Fig. 1. Sensor for soil water content, EC, and temperature. The dimensions of the housing are 46 mm x 55 mm x12 mm, and the electrodes have a length of 68 mm, each spaced 15 mm from each other.

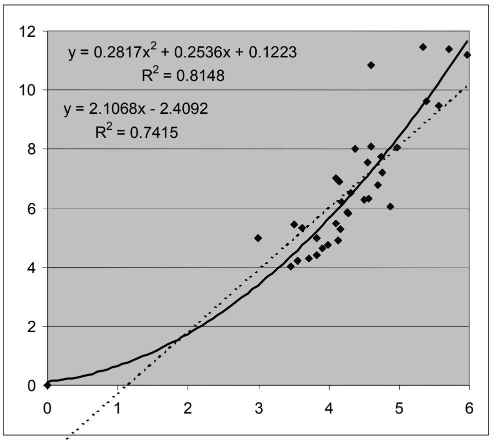

Fig. 2. σ_{press} (mS/cm) plotted against the σ_p* (mS/cm) obtained with Eq. 1, 3 and 4 and with $\varepsilon_{\sigma=0}$ = 6.2.

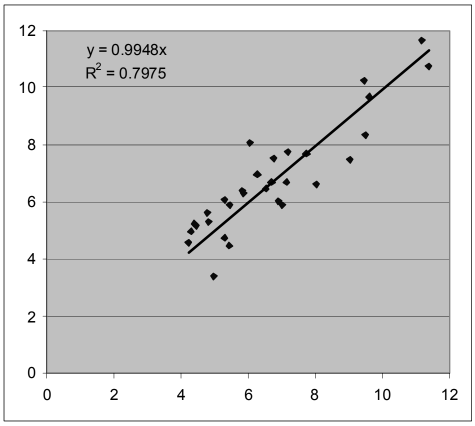

Fig. 3. $\sigma_{p(corr)}$ (mS/cm) plotted against σ_{press} (mS/cm).

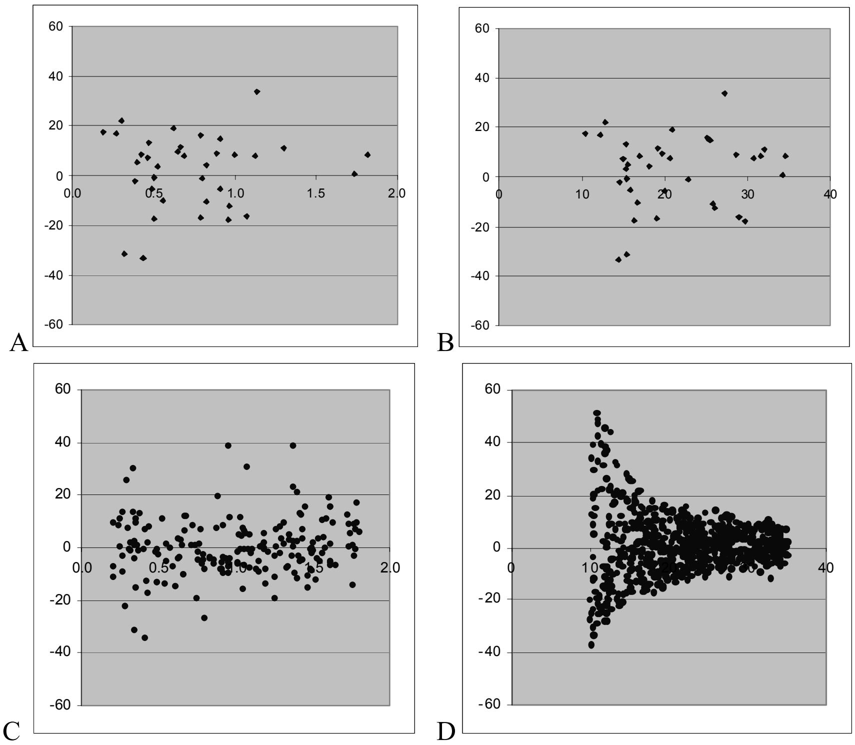

Fig. 4. Errors in $\sigma_{p(corr)}$ ($\sigma_{p(corr)}$ - σ_{press}) (%) drawn against σ (A) and ε (B) as measured and defined with the model from Eq 1. Simulated errors (%) in $\sigma_{p(corr)}$ using accuracy data for the WET-sensor, drawn against σ (C) and ε (D).