The Calibration of WET-Sensor for Volumetric Water Content and Pore Water Electrical Conductivity in Different Horticultural Substrates

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Abstract

A frequency domain dielectric sensor (WET®), which measures permittivity (ε), temperature (T, °C) and bulk electrical conductivity (σ, dS/m) simultaneously in the same soil volume, was calibrated for the volumetric water content (θ, m^3 m^{-3}) and the salinity of both pore water (σ_P) and water extract (σ_E) in different horticultural substrates: peat, pumice, perlite, peat-perlite and peat-pumice. The experiment was conducted under laboratory conditions over a T range between 22 and 28°C using plastic pots filled with each substrate, irrigated to fully container capacity with nutrient solutions of known concentrations and let to dry (in air) to θ ranging from approx. 0.20 and 0.50 m^3 m^{-3}. In order to avoid the development of significant gradients in substrate moisture and salinity, the pots did not host plants and the evaporation from the top surface was prevented by means of a plastic wrap. Pore water was collected by centrifugation, whereas water extract was obtained by means of 1 substrate: 2 water suspension method. The values of both ε and σ were corrected for T. The main results of the experiment are the following: i) θ calibration was faintly dependent on the type of substrate and was only slightly affected by the salinity of irrigation water; ii) a significant linear relationship was found between σ_E and σ_P, with the slope dependent on the type of substrate; iii) the linear relationship of ε against θ was highly significant and unaffected by the salinity of irrigation water; iv) at least in the peat-pumice mixture, the only substrate used for this kind of calibration, the linear regression between σ and σ_P was markedly affected by θ, since the slope decreased with increasing θ.

INTRODUCTION

With respect to soil culture, container-grown plants necessitate much more water and fertilisers and, due to the widespread practice for growers to overirrigate their plants, the environmental impact in term of water use and nutrient leaching through runoff may be considerable. Therefore, a precise control of irrigation and fertigation is necessary and this, evidently, requires an accurate estimation of plant evapotranspiration. A possible approach to efficient irrigation management entails the use of root zone sensors to regulate the frequency and, possibly, the water dose by monitoring continuously the tension or the volumetric water content (θ, m^3 m^{-3}) of growing media. In the recent past, a new generation of dielectric sensors has been developed to be used for the control of irrigation in both soil and soilless culture. These sensors are meant to measure both θ and the salinity (namely, electrical conductivity or EC) of growing media, thus providing the possibility to control the fertilisation as well, for example by adjusting the concentration

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of the fertigation water on the basis of the measured EC.

WET® is a frequency domain dielectric sensor that was originally designed and produced by IMAG-DLO Wageningen, NL (Balendonck and Hilhorst, 2001; Balendonck et al., 2005); it is manufactured and sold by Delta T-Devices (Burwell, Cambridge, UK). WET® measures permittivity (ε), bulk electrical conductivity (σ, dS m^{-1}) and temperature (T, °C) simultaneously in the same soil volume, and predicts the pore water EC (σ_P, dS m^{-1}) from the first two quantities and the pore water permittivity (ε_{water}, corrected for T).

In a few laboratory experiments, WET® was calibrated for θ and the salinity of both pore water (σ_P) and water extract (σ_E) in different substrates, such as peat, pumice, perlite, peat-perlite and peat-pumice mixtures. Particular attention was paid to the peat-pumice mixture, which is the most used substrate in the nurseries around Pistoia (Tuscany, Italy), the most important area in Europe for outdoor production of ornamental nursery stocks.

MATERIALS AND METHODS

The experiments were conducted under laboratory conditions over a T range between 22 and 28°C using 24 cm-diameter plastic pots filled with approximately eight liters of different substrates. In each experiment, the pots were abundantly irrigated with nutrient solutions of known salt concentrations (with EC up to approx. 4.0 dS m^{-1}), which had been were prepared by dissolving a commercial soluble fertiliser in tap water. Following the cessation of free drainage, the substrate was removed from the pots and let to dry (in air, in a shaded glasshouse) to desired moisture level; after appropriate mixing, in order to ensure moisture uniformity, the pots were filled again with the substrate and then measured with WET® sensors.

The WET® was inserted from above with half the plastic housing pushed into the substrate, while keeping a reasonable distance of at least 5 cm from the edges of the containers. Some precautions were used to avoid the development of vertical or horizontal gradients for both moisture content and salinity: the pots did not contain plants and were covered with plastic wrap to prevent evaporation from the top surface. Invariably, θ and the salinity levels were determined in each pot at the end of measurements, respectively, by weighing the substrate before and after oven-drying (at 105°C) and by measuring both σ_P and σ_E with a bench EC-meter. Pore water was collected by means of centrifugation, whereas water extract was obtained by means of 1 substrate: 2 water suspension method (Sonneveld and van Ende, 1971). The values for ε and σ were corrected for T according to Balendonck and Hilhrost (2001). Porosity, bulk density and the volumetric content of air and water at full container capacity were also determined *in situ* by means of a simplified method (Fonteno, 1996, with minor modifications; see Table 1): briefly, these parameters were computed by weighing the substrate in the pots after water saturation, then after free drainage of gravitational water and finally following oven-drying.

In each experiment, four or eight identical sensors were taken from a production pre-series (MCM101) of the commercially available WET-sensor supplied by Delta-T Devices. The sensors were calibrated by Delta-T Devices according to the standard procedure for low salinity (0 – 2 dS/m). They were connected via a self-made RS232 multiplexing system to a PC that processed sensor outputs to produce θ, ε and σ readings.

RESULTS AND DISCUSSION

The variability coefficient for the means of sensor data never exceeded 10%, therefore in the following figures the results have been reported as mean values of four or eight measurements. In a preliminary experiment, the calibration was performed inserting the sensors in a pot with increasing or decreasing moisture content or salinity. No hysteresis was found for both ε and σ (data not shown) and the pot volume (for pot diameters equal to 12, 16, 20 or 24 cm) did not affect sensor readings (data not shown).

A second experiment was carried out using different substrates with θ ranging from approx. 0.20 and 0.50 m^3/m^3; this experiment was conducted twice with similar results. The relationship between this quantity and ε was found to be fairly independent on the nature of substrate (Fig. 1); a significant (p<0.001) polynomial regression was computed with a determination coefficient of 0.90. The inverse equation can be used to estimate θ from the measurement of ε:

$$\theta = 0.0594 + 0.0230 \cdot \varepsilon - 0.0002 \cdot \varepsilon^2 \qquad m^3\ m^{-3}\ (1)$$

This curve can be approximated with the following equation

$$\theta = 0.044 + 0.102 \cdot \sqrt{\varepsilon} \qquad m^3\ m^{-3}\ (2)$$

The influence of the substrate on the relationship among θ, ε and σ_P (and σ_E) was studied by using the mixtures under investigation after they were moistened to container capacity with nutrient solutions of different salinity levels. There was a significant linear relationship between σ_P and σ_E with the slope less steep for the peat-containing mixtures (Fig. 2). Moreover, the relationship between σ and σ_P (and σ_E as well, therefore) was largely dependent on the type of substrate (Fig. 3).

In the last experiment, only the peat-pumice mixture was used. It was found that in the considered range of substrate moisture (0.19, 0.27, 0.36 or 0.47 $m^3\ m^{-3}$), the linear regression between ε and θ was not affected by the salinity of irrigation water (Fig. 4). By contrast, the linear relationship between σ and σ_P depends on ε (Fig. 5), with a significant (R^2 = 0.997) negative multiplicative relationship between the slope (a) and ε:

$$a = 2088.487 \cdot \varepsilon^{-1.836} \qquad \text{dimensionless}\ (3)$$

The following equation was used to estimate σ_P from WET® readings for ε and σ:

$$\sigma_P = a \cdot \sigma \qquad dS\ m^{-1}\ (4)$$

with the coefficient a calculated with equation (3).

Equation (4) was not more adequate than the Hilhorst's model (Hilhorst, 2000), which was applied using multiple values for the constant $\varepsilon_{\sigma=0}$ between 3 and 10 (6.2 is the value used for the fit line in Fig. 6), as reported by Balendonck et al. (2005) for horticultural substrates.

$$\sigma_P = \cdot\sigma \cdot \frac{\varepsilon_{water}}{(\varepsilon - \varepsilon_{\sigma=0})} \qquad dS\ m^{-1}\ (5)$$

Recently, in a study on the performance of WET® sensor in volcanic soil, Regalado et al. (2007) found that the empirical relationships between σ_P and σ was better described by the Vogeler et al. (1996) model than by Hilhorst's model.

In conclusions, empirical calibration models for both θ and σ_P were derived from laboratory experiments with different horticultural substrates. While the relationship between θ and ε was not affected by the nature of growing media, a substrate-specific calibration was necessary for the salinity of the water available to the plants in the substrates moistened at container water capacity. At least for the peat-pumice mix, in conformance with Regalado et al. (2007), further work is required to design an adequate equation for the determination of σ_P from simultaneous WET® readings for ε and σ.

ACKNOWLEDGEMENTS

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Tables

Table 1. Porosity, bulk density and the air and water volumetric content at full container capacity in different horticultural substrates used for WET® calibration. Mean values (± s.d.) of 4 replicates. The determinations were conducted using a simplified method.

Substrate	Bulk density ($kg \cdot m^{-3}$)	Porosity (% vol.)	Air capacity (% vol.)	Water capacity (% vol.)
Peat:pumice (1:1, v:v)	277.4 ± 6.3	80.0 ± 2.6	23.4 ± 3.2	56.6 ± 3.2
Pumice	409.3 ± 4.8	73.0 ± 0.2	34.8 ± 0.3	38.3 ± 0.3
Perlite	85.6 ± 4.3	74.8 ± 1.1	55.2 ± 1.6	19.5 ± 1.6
Peat:perlite (1:1, v:v)	97.4 ± 0.5	81.7 ± 2.7	26.5 ± 3.2	55.3 ± 3.2
Peat	98.1 ± 1.1	86.0 ± 1.1	28.5 ± 1.7	57.4 ± 1.7

Figures

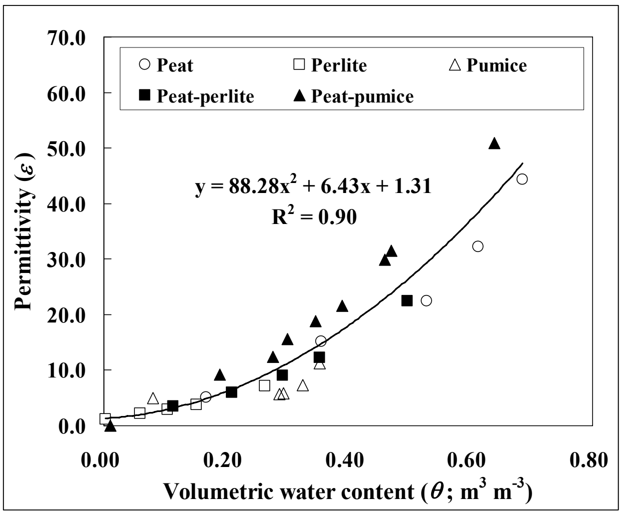

Fig. 1. The relationship between permittivity (ε, as measured by means of WET® sensor) and volumetric water content (θ) in different horticultural substrates.

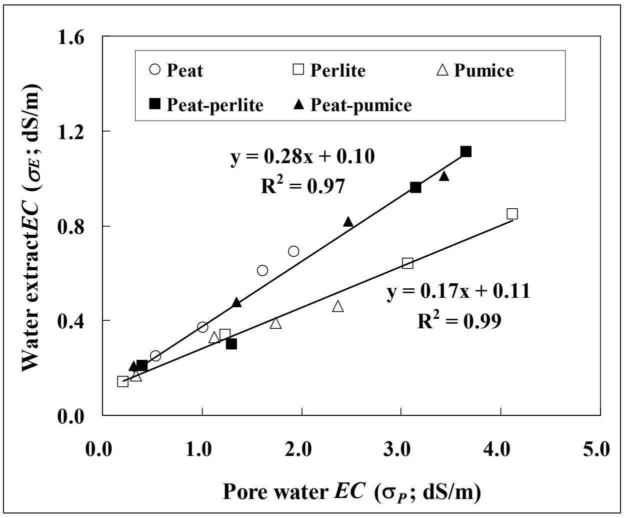

Fig. 2. The relationship between pore water EC (σ_p) and water extract EC (σ_e) for different horticultural substrates. Pore water was collected by means of centrifugation, whereas water extract was obtained by means of 1 substrate: 2 water suspension method.

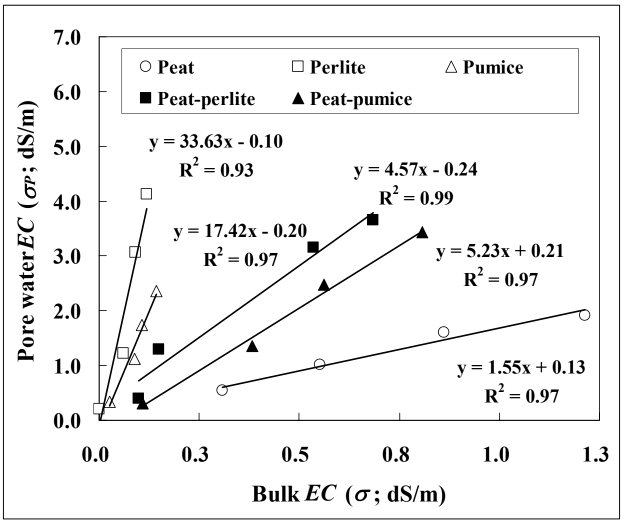

Fig. 3. The relationship between bulk EC (σ, as measured by means of WET®sensor) and pore water EC (σ_P) in different horticultural substrates.

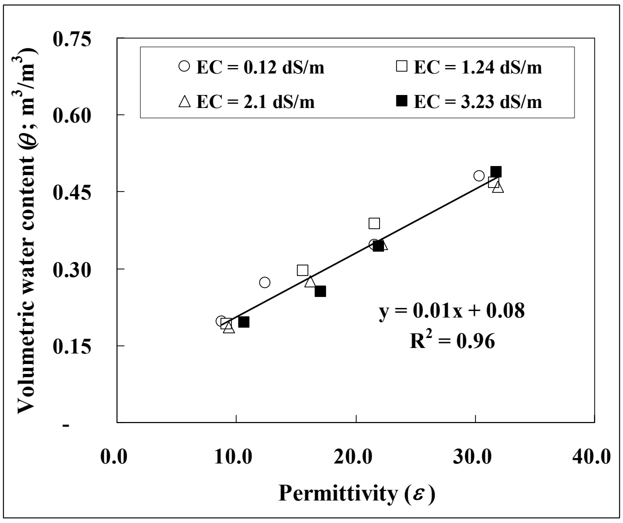

Fig. 4. The relationship between permittivity (ε, as measured by means of WET® sensor) and volumetric water content (θ) in a peat-pumice mixture irrigated to container water capacity with nutrient solutions of different salinity (EC; the values are reported in the box).

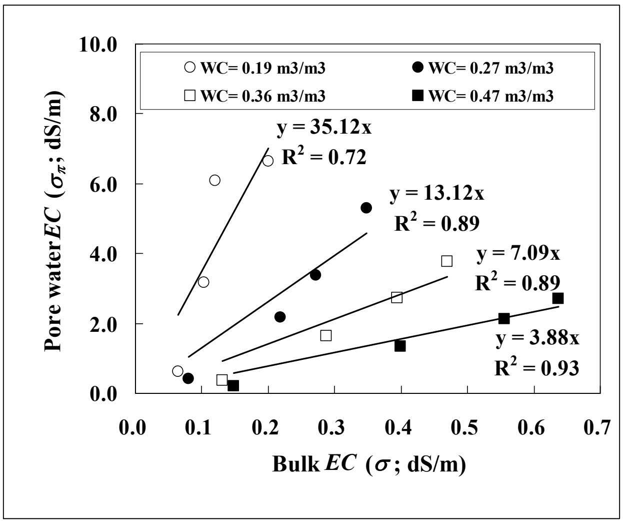

Fig. 5. The relationship between bulk EC (σ, as measured by means of WET®sensor) and pore water EC (σ_P) in a peat-pumice mixture irrigated to container water capacity with nutrient solutions of different salinity (EC; the values are reported in the box) and then dried in air to desired water content (WC).

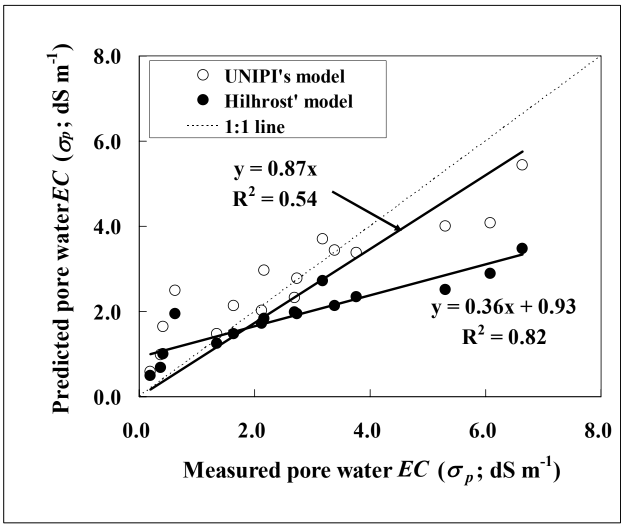

Fig. 6. The relationship between measured and predicted values of pore water EC (σ_p) in a peat-pumice mixture irrigated to container water capacity with nutrient solution of different salinity (EC) and then dried in air to desired volumetric water content (θ). The EC was measured in the water collected by centrifugation or calculated from the bulk EC (ε) provided by WET® sensor using two different equations (see text for details).