Measuring Water Content of Soil Substitutes with Time-domain Reflectometry (TDR)

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ABSTRACT. Optimization of irrigation and fertilization regimes in greenhouses and other controlled environments requires accurate and frequent measurements of soil-water content. Recent studies on TDR use in gravelly soils and in closed-container studies have indicated a potential use of this method in horticulture. In this study, TDR calibration curves were determined for tuff (granulated volcanic ash), vermiculite, perlite and a mix of two composted agricultural wastes (grape marc, separated cow manure). Widely used as horticultural substrates, mixes of these materials were tested as well. For all soil substitutes tested, measured calibration results are well described by linear equations throughout tested values of water content that cover the working range in horticulture. Ledieu's equation, widely used in soils, describes fairly well the measured results for perlite, but underestimates those obtained for organic media, vermiculite (because of the presence of bound water) and tuff (probably due to water in occluded pores). The differences obtained between the measured calibration equations and Ledieu's equation indicate that in order to avoid an erroneous irrigation management, calibration is necessary whenever a new soil substitute is used.

Plants grown in containers, with a limited volume of substrate where the root system can develop, require frequent irrigation in order to prevent water-stress hazards. The timing of these irrigations can be set by clock, usually based on trial and error procedures, or by monitoring the water status of the substrate by different means (direct and indirect). Widely used in greenhouses and other controlled environments, tensiometer readings of matric potential require translation to water content via the soil-water characteristic curve. However, due to the distinct shape of the water characteristic curve of most soil substitutes, namely its strong dependence on hysteresis and the sharp decrease in water content that occur for small changes in matric potentials within the range of available water (da Silva et al., 1993; Wallach et al., 1992a, 1992b), there is a distinct advantage in scheduling irrigations according to direct measurements of water availability. These, however, are laborious and time-consuming, and progress in this area depends on the availability of accurate, nondestructive methods for continuously monitoring dynamic changes in soil-water content.

TDR is a relatively new method for direct and nondestructive measurements of volumetric water content and electrical conductivity, which is largely insensitive to variations in bulk density, temperature, salinity, and mineral composition (Dalton and van Genuchten, 1986; Davis and Chudobiak 1975; Ledieu et al., 1986; Topp et al., 1980, 1982, 1984). Because the dielectric constant of water is much higher than other constituents of the porous media (for oven-dried soil, air and liquid water the dielectric constant equals ≈ 4 , 1, and 80, respectively), a signal within a wet or moist medium propagates slower than in the same medium when dry. Thus, water content can be accurately determined by measuring the propagation time over a fixed length probe embedded in the medium. Although most studies on TDR application to soils were field studies, recent studies on its use in gravelly soils and closed containers (Anisko et al., 1994; Drungil et al., 1989; Richardson et al., 1992) have indicated a potential use of the method in horticulture,

provided that specific calibration is made. The objective of the present study was to calibrate TDR readings to measured water content for a variety of mineral and organic soil substitutes used in horticulture.

Methods and Materials

TDR uses electromagnetic wave pulses with a frequency spectrum in the 1 MHz to 1 GHz range of frequencies (Baker and Lascano, 1989; van Loon et al., 1990), which are sent along a transmission line that usually terminates in parallel stainless steel waveguides embedded in the soil. The reflected pulses exhibit perturbations in the transmission line where impedance changes occur, such as the point of pulse reflection at the connection of the cable with the steel waveguides inserted in the soil and the point of pulse reflection at the end of the waveguides. The apparent distance, L_a (m), between the two reflections is a partial function of the dielectric constant, K_a (dimensionless), of the soil surrounding the waveguides, which is in turn a function of the volumetric water content (θ).

The propagation velocity, V_p ($\text{m}\cdot\text{s}^{-1}$), relative to the velocity of electromagnetic radiation in free space ($c = 3 \times 10^8 \text{ m}\cdot\text{s}^{-1}$), can be approximated by the following equation (Topp et al., 1980):

$$V_p \approx \frac{c}{\sqrt{K_a}} \quad [1]$$

The time of wave propagation along waveguides of a given length, L (m), is

$$t = \frac{L}{V_p} \quad [2]$$

If V_p is set as the velocity of light ($V_p = c$) and L is replaced by L_a , the time of wave propagation, t (s) is obtained as

$$t = \frac{L_a}{c} \quad [3]$$

Combining Eqs. [1] and [2], and introducing Eq. [3] in the resulting expression yields

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$$\frac{La}{L} = \sqrt{Ka} \quad [4]$$

Based on Eq. 4, several empirical relationships between θ and La/L or Ka have been established in the form of polynomial equations for various types of soils (Pepin et al., 1992; Roth et al., 1992; Stein and Kane, 1983; Topp et al., 1980). Others report linear calibration equations stated in terms of the ratio La/L (Ledieu et al., 1986), or the pulse velocity, V_p (Herkelrath et al., 1991) (Table 1, Anisko et al., 1994). Although specific calibration of TDR is unnecessary for most soils (Topp et al., 1980) some media, especially soil substitutes based on organic media, seem to be an exception to general application of TDR measurements probably due to the presence of bound water (Anisko et al., 1994).

The experimental study was conducted in a greenhouse at a temperature of 23 ± 2.5 °C. The tested media, widely used by growers for different crops (Chen et al., 1988, Wallach et al., 1992a, 1992b) were as follows: i) red tuff (scoria, granulated volcanic ash), from northern Israel, ii) perlite; iii) vermiculite; iv) the solid fibrous fraction of composted separated cow manure (CSM); v) composted grape marc (CGM), based on grape skins and seeds that are left over after wine processing; and vi) a mix (50%:50%, v/v) of the two composted wastes (CGS). Both CSM and CGM were composted without additives in windrows for 6 months, and CSM was leached before use. Mixes (40%:60%, v/v) of CGS with the above mineral media were also tested.

The TDR equipment (previously checked for several soils and calibrated for water) consisted of a Tektronix 1502B time-domain reflectometer (Tektronix, Inc., Beaverton, Ore.), equipped with a 50-ohm coaxial cable leading to an impedance-matching transformer (balun), and a 180-ohm balanced antenna wire connected to two 30-cm-long probes made from stainless steel rods (0.50 cm in diameter). The initial points in Figs. 1 and 2 were measured for air-dried media. Samples of the media were then moistened in 5 to 7 steps to reach predetermined levels of volumetric water content and, for each step, the samples were thoroughly mixed and packed in twelve, 2-L plastic vessels (height = 30 cm, diameter = 10 cm). The apparent length of the TDR probe was read from the reflectometer's oscilloscope (in four replicates) by inserting the probe vertically to its full length into the tested medium, with the rods at a parallel distance of 5 cm. For each soil substitute, the relationship between θ and La/L was determined by best fit of first- and third-degree polynomials. At the end of the experiment, each vessel was emptied and the gravimetric water content of the samples was determined using standard procedures for mineral (oven-drying at 105 °C) and organic materials (oven-drying at 65 °C) (Klute, 1986).

Results and Discussion

Measured results are expressed as volumetric water content (θ) as a function of the ratio of apparent to actual length of the TDR

probe (La/L). Following the approaches Topp et al. (1980) and of Ledieu et al. (1986), cubic and linear regressions were used to fit the data. Third-degree polynomials fit the data only slightly better (avg. $r^2 > 0.99$) than linear equations (avg. $r^2 > 0.97$), and the latter will, therefore, be used in the discussion to follow due to its simple description and easy comparison to Ledieu's equation.

Figures 1 and 2 show that calibration data for the tested soil substitutes and mixes are well described by linear fits with apparently similar slopes but with different intercepts. The slopes exhibited by the mineral media (average value = 0.1172) are similar to the slope of Ledieu's equation (0.1140) which represents most of the field soils (Table 1). However, the average slope obtained for the organic media (0.1318) is higher (Table 2). Since measured results for the two types of compost show very small differences (CSM having slightly higher water contents than CGM), the discussion to follow will refer to compost as the mixture of the two (CGS; hereinafter referred to as compost mix).

With the exception of perlite, which exhibits dielectric properties similar to a regular field soil, volumetric water content was generally overestimated for the tested soil substitutes. This overestimation is very large for compost (by $\approx 0.37 \text{ cm}^3\cdot\text{cm}^{-3}$) and for peat (by $\approx 0.17 \text{ cm}^3\cdot\text{cm}^{-3}$). This phenomenon, also reported by Anisko et al. (1994) for organic media such as peat and bark, can be attributed to a larger fraction of bound water (Topp et al., 1980). Increased soil bulk conductivity was also shown to lead to overestimation of volumetric water content, explained on the basis of dispersion of the electromagnetic pulse (Dalton 1992). This can be particularly important when irrigation solutions with high electrical conductivity are used.

The effect of bound water on the calibration curves seems to exist, although to a lesser extent, in vermiculite (Topp et al., 1980) and tuff. Ledieu's equation underestimates water content for these materials by $\approx 0.12 \text{ cm}^3\cdot\text{cm}^{-3}$ for vermiculite and $0.05 \text{ cm}^3\cdot\text{cm}^{-3}$ for tuff. Exhibiting the highest intercept with the θ axis among the tested mineral media, vermiculite was also reported by Topp et al. (1980) to have dielectric properties similar to an organic soil, probably due to a high percentage of water within the structure of the mineral. Regarding tuff, the higher than expected value of θ (for a mineral medium) obtained at any given value of La/L , could be due to the presence of water in occluded pores, a phenomenon reported by Galin and Singer (1988). This, however, remains to be investigated. In all these cases, although visible to TDR, bound water is not available to plants because it is either strongly bounded to organic compounds or to the crystal structure of minerals, or is confined to occluded pores.

The soil substitutes based on mixes of mineral and organic media fall in two distinct groups depending on the organic component in the mix: peat or compost mix (Fig. 2). Slopes are higher for peat-based mixes (avg. 0.1211) than for compost-based ones (avg. 0.1116). However, in all cases, addition of either peat or the compost mix has a similar effect, namely, placing the calibration curve between the curves for the two individual basic components.

Table 1. Linear regression coefficients of the measured θ vs. La/L data for the different soil substitutes.

Soil substitute	Coefficients $\theta = \alpha + \beta(La/L)$		
	α	β	r^2
Tuff	-0.1335 ± 0.0187	0.1184 ± 0.0087	0.9934
Perlite	-0.1654 ± 0.0111	0.1152 ± 0.0072	0.9770
Vermiculite	-0.0620 ± 0.0123	0.1181 ± 0.0105	0.9867
Compost mix	0.1344 ± 0.0123	0.1312 ± 0.0152	0.9745
Peat	-0.0698 ± 0.0191	0.1323 ± 0.0095	0.9796

Fig. 1. TDR calibration curves: measured data and corresponding linear regression for the different soil substitutes tested. The solid line represents Ledieu's equation.

Fig. 2. TDR calibration curves: measured data and corresponding linear regression for the different organic and mineral soil substitutes tested. The solid line represents Ledieu's equation.

Peat, vermiculite and their mix have very similar calibration curves (Tables 1 and 2) that can be replaced by a single curve for either substrate, for example by the average of the individual curves ($\theta = -0.0659 + 0.1252 \text{ La/L}$).

When extrapolated to the La/L axis, the theoretical equations of Topp and Ledieu yield La/L (1.37 and La/L (1.55, respectively, at $\theta = 0$). A value of La/L approximately equal to 2 should be exhibited by an oven-dried soil (dielectric constant ≈ 4). However, because of the high fraction of air exhibited by most soil substitutes when dry, a smaller value of La/L can be expected. In such cases, a value of La/L closer to 1 (dielectric constant of air and the minimum value that can be measured) does not seem to be an unreasonable one. Examining the linear fits obtained in this study, one can see that when extrapolated to the La/L axis, tuff, perlite and the mix perlite + peat exhibit values of $\text{La/L} > 1$ and that for the remaining media tested La/L would become < 1 . Since this is physically impossible, we can conclude that the straight lines in Figs. 1 and 2 cannot be extrapolated for very low water contents. Outside the respective tested range, the validity of the equations determined by linear regression cannot be established without additional measurements. Below that range data probably become nonlinear, a feature that is usually not shown by typical TDR calibration curves for regular soils, with the exception of clay soils. Hook and Livingston (1996) have shown that two distinct linear regions separated by a sharp transition fit the data of Dasberg and Hopmans (1992) for Yolo clay loam. Their explanation for this phenomenon (also observed by Topp et al., 1980; Dirksen and Dasberg, 1993) is, associated with a change from bound to free water. In any case, and although the linear calibration equations of organic materials and their mixes cannot be extrapolated to the axes, their checked range of validity covers most of the working range of water contents in horticulture.

Assuming the intercept of Topp's equation with θ axis (1.37) and including this point in the set of data, the compost mix would be the only material for which a rather steep curve would develop between $\theta = 0$ and the initial measured water content, while all the other materials would show a reasonable transition from nonlinearity to linearity. Using third-degree polynomials to set the data, including the added point ($\text{La/L} = 1.37$, $\theta = 0$), the coefficients of determination obtained would still be very high (> 0.970), with the exception of the compost mix, for which a much lower r^2 (0.889) would be obtained. This can be explained by the unusually high residual volumetric water contents exhibited by composted wastes, as can be seen from their water characteristic curves (Wallach et al., 1992b). This means that the lowest attainable point in the calibration curve of a medium with bound water is not at $\theta = 0$ and that, as a consequence, the lowest attainable point is shifted upwards, as well as the entire curve (Fig. 1).

Although a simple linear equation can be used to describe measured TDR calibration data for the tested soil substitutes, Ledieu's equation cannot be applied without checking its validity,

Table 2. Linear regression coefficients of the measured θ vs. La/L data for the different mixes of organic and mineral soil substitutes.

Soil substitute	Coefficients $\theta = \alpha + \beta(\text{La/L})$		
	α	β	r^2
Tuff + compost mix	-0.0209 ± 0.0087	0.1153 ± 0.0113	0.9975
Tuff + peat	-0.1047 ± 0.0106	0.1194 ± 0.0085	0.9883
Perlite + compost mix	-0.0239 ± 0.0124	0.1085 ± 0.0101	0.9799
Perlite + peat	-0.1430 ± 0.0096	0.1203 ± 0.0136	0.9938
Vermiculite + compost mix	-0.0170 ± 0.0083	0.1111 ± 0.0093	0.9860
Vermiculite + peat	-0.0680 ± 0.0091	0.1237 ± 0.0176	0.9921

Fig. 3. Graphical representation of the suggested calibration technique, showing the actual regression line obtained for vermiculite, a hypothetical calibration point and the corrected line based on the slope of Ledieu's equation.

for two reasons: i) the different intercepts and ii) the different slopes (Tables 1 and 2), especially in the case of organic media. Our results also show that calibration procedures can be simplified when the slopes of the regression lines are similar to that of Ledieu's equation, as it is in the case of the tested mineral media. A corrected Ledieu's equation can be adopted by assuming the actual slope of Ledieu's equation and determining a corrected intercept by extrapolation using a single calibration measurement. This simple procedure is illustrated in Fig. 3 where the data for vermiculite are used as an example. The deviations between the actual and corrected lines obtained by this procedure will be greater as the calibration measurement is made farther from the working range of water contents. Although greater deviations would be obtained for the organic substrates, our results suggest that this simple procedure can also be followed when a high level of accuracy is not desired.

Automated TDR systems allowing measurements at multiple sites in a greenhouse or any other controlled environment used in horticulture can provide fast and reliable values of volumetric water content. Along with the distinct advantages of TDR over other methods used to date to monitor the highly dynamic changes in water status of soil substitutes, the possibility of directly obtaining real-time continuous measurements of volumetric water content make TDR an ideal instrument for irrigation scheduling in horticulture. Swift determination of a reliable calibration curve for a given soil substitute is, therefore, a vital step in the design of an appropriate irrigation regime with TDR.

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