An algorithm for temperature correcting substrate moisture measurements: aligning substrate moisture responses with environmental drivers in polytunnel-grown strawberry plants

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Abstract: This work aims to assess the use of temperature corrected substrate moisture data to improve the relationship between environmental drivers and the measurement of substrate moisture content in high porosity soil-free growing environments such as coir. Substrate moisture sensor data collected from strawberry plants grown in coir bags installed in a table-top system under a polytunnel illustrates the impact of temperature on capacitance-based moisture measurements. Substrate moisture measurements made in our coir arrangement possess the negative temperature coefficient of the relative permittivity of water where diurnal changes in moisture content oppose those of substrate temperature. The diurnal substrate temperature variation was seen to range from 7°C to 25°C resulting in a clearly observable temperature effect in substrate moisture content measurements during the 23 day test period. In the laboratory we measured the ML3 soil moisture sensor (ThetaProbe) response to temperature in air, dry glass beads and water saturated glass beads and used a three-phase alpha (α) mixing model, also known as the Complex Refractive Index Model (CRIM), to derive the relative permittivity temperature coefficients for glass and water. We derived the α value and estimated the temperature coefficient for water - for sensors operating at 100MHz. Both results are in good agreement with published data. By applying the CRIM equation with the temperature coefficients of glass and water the moisture temperature coefficient of saturated glass beads has been reduced by more than an order of magnitude to a moisture temperature coefficient of $<-0.00011 m^3.m^{-3}.°C^{-1}$. This laboratory method was further developed to address the diurnal substrate temperature variations seen in the substrate moisture measurements for the strawberry plants grown in coir. This was performed by deriving and calibrating a simplified (CRIM equation based) temperature correction algorithm that uses only substrate temperature and relative permittivity data. The resulting diurnal variations seen with the temperature compensated substrate moisture data now align very well with the expected diurnal water demands of the strawberry plants. To further evaluate the relationship between environmental drivers of solar radiation and vapour pressure deficit with substrate moisture the temperature correction algorithm was programmed into a GP2 Data Logger collecting solar radiation, air temperature and relative humidity data. The resulting comparison of substrate moisture responses to environmental drivers illustrated a much improved correlation using the temperature correction algorithm. We conclude that this new temperature correction algorithm addresses the effect of temperature on the relative permittivity of water which will affect all capacitance based sensor measurements in high porosity soil-free growing substrates such as coir.

Theoretical background – the Complex Refractive Index Model

The Complex Refractive Index Model (CRIM) equation is often shown as:

$$\varepsilon_{eff}^{\alpha} = (1-\varphi)\varepsilon_S^{\alpha} + \theta\varepsilon_W^{\alpha} + (\varphi-\theta)\varepsilon_A^{\alpha} \qquad (1)$$

- ε_A is the relative permittivity of air,
- ε_S is the relative permittivity of the solid material,
- ε_W is the relative permittivity of water,
- ε_{eff} is the effective relative permittivity measurement for the porous media,
    - **this is what the soil moisture sensor measures**
- φ is the porosity of the porous media,
- θ is the water content of the porous media
- α is the CRIM equation coefficient which is dependent on the structural properties of the matrix (1,5}, often quoted as 0.5 [3,4]

Laboratory experimental method

The laboratory experimental arrangement is shown below where 3 ML3 (ThetaProbes) are temperature tested in air, dry glass beads and water saturated glass beads. In the graph below we have the resulting ML3 $\sqrt{\varepsilon}$ temperature responses – the negative temperature coefficient from water and the positive temperature coefficient of glass can be clearly observed.

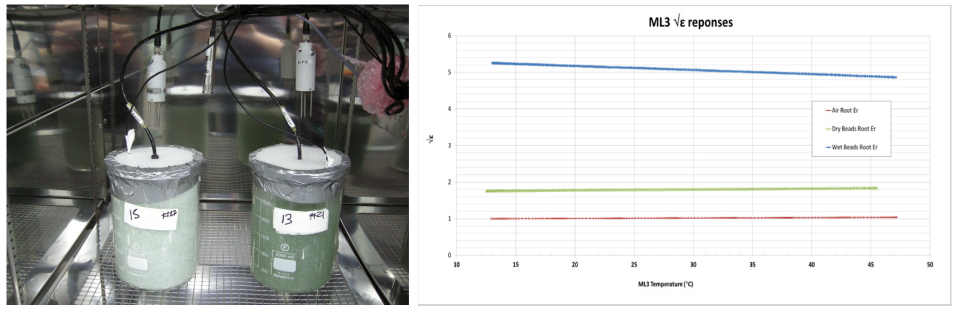


Fig. 1 – The experimental arrangement in Delta-T's temperature controller cabinet and the resulting ML3 responses in air, dry glass beads and water saturated glass beads

Applying Equation 1 to this data and a reference point of the relative permittivity of water at 20°C of 80.3, porosity of 0.372 (from the gravimetric calibration) for the saturated glass beads data and 0.353 for the dry glass beads data, one can derive an α of 0.62 which is in line with expectations for glass beads [1]. With this α value, the CRIM equation and ML3 sensor and temperature data (from the saturated glass beads) it is possible to estimate the temperature coefficient of the relative permittivity of water [2] to within ±5% of published data [6]. These results enabled us to apply a temperature correction to the water saturated beads data and to illustrate the effect of water content on the temperature response, as shown in Fig. 2 below. A similar change in temperature response with moisture level has also been observed in sand by Kizito et al. [7].

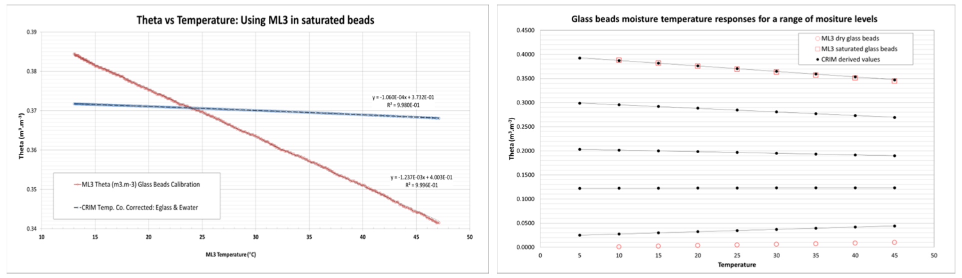


Fig. 2 – Applications of the CRIM equation to temperature corrected ML3 moisture data in water saturated glass beads and illustration of the effect of moisture level on the observed temperature response.

Coir specific moisture calibration and temperature correction

If we assume for coir bags:

- ε_A = 1 for all temperatures,
- ε_S = constant for all temperatures, and,
- the temperature coefficient of the sensor is negligible

Then we can derive the following from Equation 1

$$\theta(T) = \frac{\varepsilon_{eff}^{\alpha} - \varphi - (1-\varphi)\varepsilon_S^{\alpha}}{\varepsilon_W^{\alpha}(T) - 1} \qquad (2)$$

Porosity is assumed to remain constant in coir bags. From the raw moisture data shown in Fig.4 relative permittivity values (ε_{eff}) were obtained at 20°C to derive substrate moisture values using Equation 2, for comparison with the equation:

$$\theta = {\left(\sqrt{\varepsilon_{eff}} - a_0\right)}\Big/{a_1}$$ where a_0 = 1.16 and a_1 = 7.41 (for Delta-T's SM150)

The values for α = 0.444 and ε_S = 3.05 were fitted using the Excel Gradient function and sum of squared error calculations using an estimated coir porosity of 0.85, the resulting comparison is shown in Fig. 3. In Fig. 4 we have applied Equation 2 with the derived coefficients and a temperature correction for water [2], ≈-0.7%/°C, to the sensor data (broken green line) to create a temperature corrected response (solid blue line). This response shows greatly reduced temperature dependence and improved correlation with expected diurnal water use.

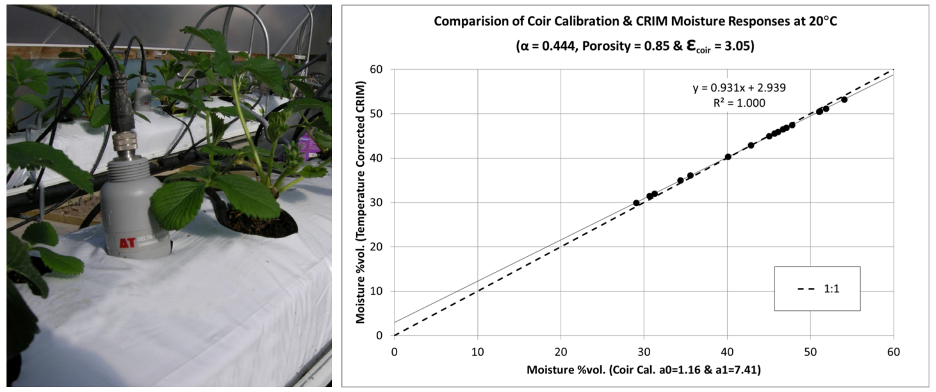


Fig. 3 – The experimental arrangement consisting of a table-top coir growing system and a comparison of gravimetric and CRIM coir calibrations.

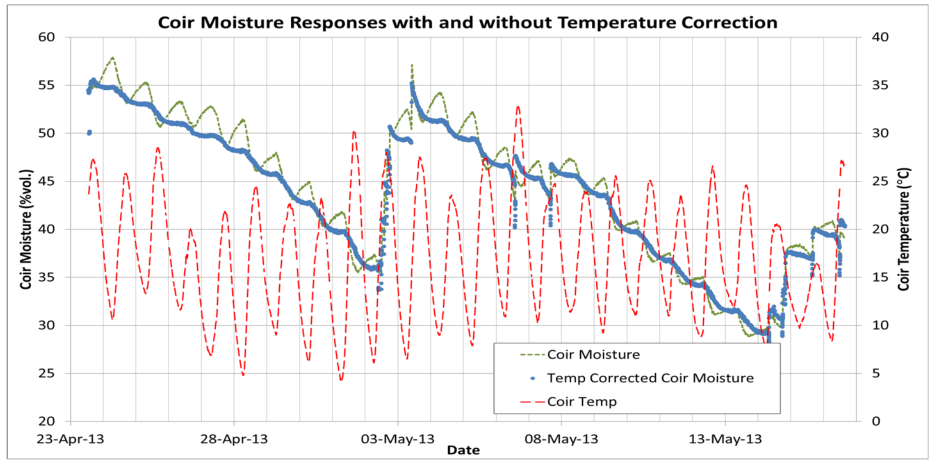
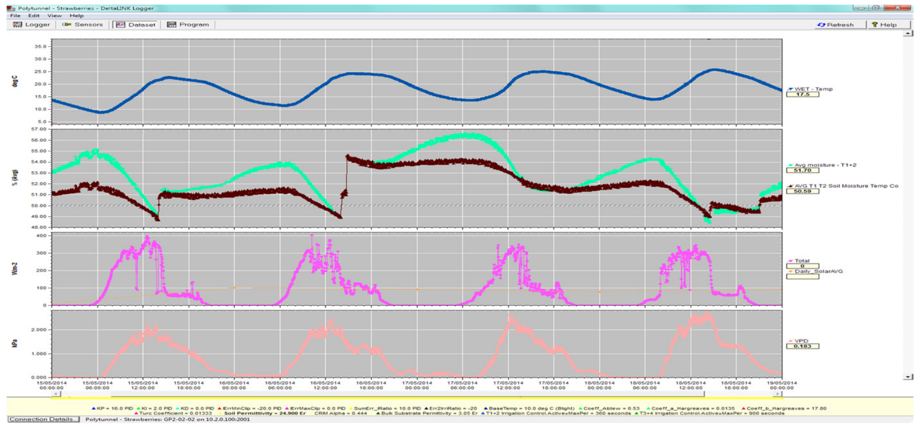


Fig. 4 – Applying temperature correction to capacitance-based measurements in coir.

Real-time evaluation using the GP2 Data Logger & Controller

Data collected, using a GP2 over a 4 day period is shown in Fig. 5 where the average moisture from 4 SM150 sensors (green line) was temperature corrected (brown line) using coir temperature data (dark blue line) and Equation 2, using the previously derived parameters. Solar radiation data from a BF5 and VPD calculated from air temperature and relative humidity data illustrates improved correlation with diurnal moisture responses when moisture data is temperature corrected.



KP = 16.0 PID KI = 2.0 PID KD = 0.0 PID IErrMinClip = -20.0 PID IErrMaxClip = 0.0 PID SumErr_IRatio = 10.0 PID Err2IrriRatio = -20 BaseTemp = 10.0 deg C (Blight) Coeff_Abtew = 0.53 Coeff_a_Hargreaves = 0.0135 Coeff_b_Hargreaves = 17.80
Turc Coefficient = 0.01333 **Soil Permittivity = 24.900 Er** CRIM Alpha = 0.444 Bulk Substrate Permittivity = 3.05 Er T1+2 Irrigation Control.Active»MaxPer = 360 seconds T3+4 Irrigation Control.Active»MaxPer = 900 seconds

Polytunnel - Strawberries: GP2-02-02 on 10.2.0.100:2001

Fig. 5 – A comparison of temperature corrected & un-corrected soil moisture responses against environmental drivers of solar radiation and VPD.

Conclusions

In this work we illustrate that moisture measurements in coir using capacitance-based moisture sensors can show variation due to the large diurnal substrate temperature excursions experienced in table-top growing systems and the temperature dependence of the relative permittivity of water. Following a laboratory based evaluation where we estimated the temperature coefficient of the relative permittivity of water at 100MHz we applied the CRIM equation with a temperature dependent relative permittivity for water and values for α and ε_S derived from coir drying data. Using Equation 2 with $\sqrt{\varepsilon_{eff}}$ sensor data resulted in diurnal moisture responses with greatly reduced temperature dependence and improved correlation with environmental drivers. We conclude that this new temperature correction algorithm addresses the effect of temperature on the relative permittivity of water which will affect all capacitance based sensor measurements in high porosity soil-free growing substrates such as coir.

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