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ESTIMATING THE SUBSTRATE WATER STATUS USING CAPACITANCE MEASUREMENTS

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Abstract

The suitability of capacitance probes for measuring the actual variations in substrate water content in container-grown ornamental species (Lawson cypress) was examined. The probes were installed in the plant containers. Weighing measurement data on water loss was used to assess the actual changes in substrate water content (plant water use). In an additional test, an evaluation of temperature sensitivity of the capacitance probe was performed under laboratory conditions. The probe was placed in a container containing the growing medium (peat substrate) with a defined (stable) moisture content. The substrate temperature was modified and the changes in probe output were recorded. The experiment demonstrated the existence of the effect of temperature on the quality of soil moisture measurements conducted with the capacitance method. The accuracy of the results obtained from measurements with dielectric sensors in relation to the data obtained by means of weighing platforms depended largely on the temperature profile of the measured medium. It was demonstrated that temperature variations explained 99% of the observed differences in the results of moisture content measured with the capacitance method. Due to the fact that there is no possibility of developing universal factors (for different sensors and substrates) for correcting the influence of temperature, this relationship should be defined independently for a given type of crop and the measuring system available.

Keywords: moisture sensor, irrigation, ornamental nursery, weighting lysimeter

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INTRODUCTION

The profitability of producing irrigated crops is directly related to water management. Irrigation scheduling based on measurements or estimations of crop water needs is one of the most important practices for irrigation management. Proper water management will increase yields and improve crop quality, conserve water, save energy and reduce environmental pollution.

Much research has focused on quantifying plant water use and on establishing optimum schedules in irrigated crops (e.g. Bussi et al. 1999, Jovicich et al. 2003, Żarski et al. 2011, Rolbiecki and Chmura 2015, Treder et al. 2015 a, b). A number of methods are available to assist growers in determining when water is needed and how much is required. For greenhouse crops, a commonly used irrigation control algorithm is based on measurements of the amount of solar energy that reaches plants. An irrigation event is triggered when a threshold value of light energy has been achieved. This method has some disadvantages: it does not function well under low-light conditions (De Graaf 1988) and does not take into account other factors affecting plant water usage (e.g. humidity, temperature, plant condition or stage of growth).

Another approach is to characterize soil/substrate water status by measuring water content or water potential using different methods of varying complexity and accuracy (Jones, 2004). Soil/substrate moisture measurement techniques have been the subject of many tests and reviews (Zazueta and Xina 1994, Christensen 2005, Klamkowski and Treder 2008). The choice of a proper method is determined by many factors such as type of soil/growing medium, the accuracy required, type of measurement (water potential, water content), cost and ease of use. In the light of technical progress, using soil moisture measurements is currently one of the simplest ways to make improved water management decisions. Direct (oven-dry) method of moisture determination is accurate, but it is time – and labour-consuming and does not allow measurement replication in the same location (destructive sampling of soil/substrate is necessary). Instead, many indirect methods are available to monitor soil/substrate moisture content. These methods estimate moisture using a relationship (calibrated) with another measured variable. The suitability of each method depends on cost, intended use, ease of installation and accuracy.

Among the sensor types available on the market, capacitance sensors that measure the electric permittivity of a medium are increasingly being used as a tool for monitoring soil/substrate water content. The availability of various sensor models, their decreasing cost and the possibility of measurement automation are the main factors explaining the success of this technique.

To be able to understand water content measurements, a basic knowledge of soil/substrate properties is necessary to use moisture data in irrigation management. Alternatively, weight-based methods that rely on measuring the loss of water from containers (evapotranspiration) can be used for assessing changes in soil/substrate water status (weighing lysimeters) (Marek *et al*. 2006, Treder *et al*. 2015 a, c). Lysimeter measurements do not provide direct information on the actual water content in soil/substrate, but it is possible to calculate such data on the basis of weight changes, and use them to estimate the amount of irrigation required to replace the loss of water (Howell *et al*. 1995, Prehn *et al.* 2010, Treder *et al*. 2015 a, b).

The electric permittivity measured by capacitance probes is not only influenced by the water content but also by other soil/substrate physico-chemical properties and structural characteristics like texture, density, conductivity or temperature (Verhoef *et al*. 2006). The last-mentioned parameter seems to be the most important because of its unpredictable variability. The soil temperature (especially near the surface) varies significantly during the course of a day and therefore can affect the patterns of moisture measurements. This problem is of special importance for container-grown crops in soil or soilless substrates. Due to the limited volume of the substrate (high and rapid temperature fluctuations over time) and altered microclimate (if cultivated under protected conditions), the influence of temperature must be considered as a significant factor affecting the measurement process.

Details of temperature effects on soil/substrate dielectric properties are still not well understood and are being developed (Wraith and Or 1999, Drnevich *et al.* 2001). In this study, we evaluated the suitability of capacitance probes for measuring the actual variations in substrate water content in container-grown ornamental species (Lawson cypress). Weighing measurement data on water loss was used to assess the actual changes in substrate water content. In addition, the sensitivity of the sensor to substrate temperature fluctuations was investigated.

MATERIALS AND METHODS

The study was performed in 2015 at the experimental nursery of the Research Institute of Horticulture, Skierniewice, Poland. The objects studied were 2 year-old Lawson cypress plants (*Chamaecyparis lawsoniana,* 'Columnaris') cultivated in 2.5 L plastic containers filled with a peat substrate (TS 1, Klasmann, Germany). The plants were irrigated with a computer-controlled drip system (the same amount of water was applied to all plants). The substrate water status was evaluated according to an algorithm based on weight changes. The algorithm used an electronic scale (weighing platform, HTY, RADWAG, Poland) to measure the weight of the containers with the growing medium (16 containers with plants were placed on a single weighing platform). Water use was measured by analyzing the changes in the weight of the growing medium over specified time-periods. Continuous in-situ measurements were recorded at 15 min. intervals and transmitted to a data logger (personal computer with analytical software installed). On the basis of the weight measurements, the average water content in the substrate was evaluated. To define a model for determining the substrate moisture content based on weight measurements, the weight of the plants was determined at high moisture (44 kg corresponded to 45% v/v as determined with the oven-dry method), and the weight of the containers with the substrate and plants was estimated for a low level of moisture (26 kg corresponded to 2%). The following equation was used for converting the weight to moisture data: "moisture = 2.39 × weight – 60.11".

5TE capacitance probes (Decagon Devices, USA) were installed in the plant containers. One probe was inserted in the container placed at the edge of the weighing platform (peripheral location), and another one in the container situated in the central part (middle) of the platform. The sensors continuously (sampling interval was 5 min.) measured the water content, temperature and electrical conductivity of the substrate. The data were collected by a logger unit (EM-50G, Decagon Devices, USA) and wirelessly transmitted to the personal computer (access to the data was granted through a dedicated web site).

In an additional test, an evaluation of temperature sensitivity of the capacitance probe (5TE, Decagon Devices, USA) was performed under laboratory conditions. The probe was placed in a container containing the growing medium (peat substrate) with a defined moisture content. The water content was kept stable during the experiment (water loss was prevented by sealing the container). The substrate temperature was modified by changing the ambient temperature using cooling and heating compartments. Moisture and temperature measurements were collected using the EM-50 logger (Decagon Devices, USA).

Multi-day datasets (temperature, moisture) were used for statistical analyses. Regression analyses were applied to find the relationship between temperature and moisture values. Correlation (r) or determination (R^2) coefficients were computed to measure the strength of the relationship between these variables. Statistical analyses were performed using Statistica software package (StatSoft Inc, USA).

RESULTS AND DISCUSSION

Based on the analysis of the weight of the containers with plants, the actual changes in the water content of the substrate in the containers placed on the weighing platform were determined (Fig. 1). The observed changes in substrate moisture content were the result of water uptake by the plants, evaporation from the substrate, and the irrigation applied.

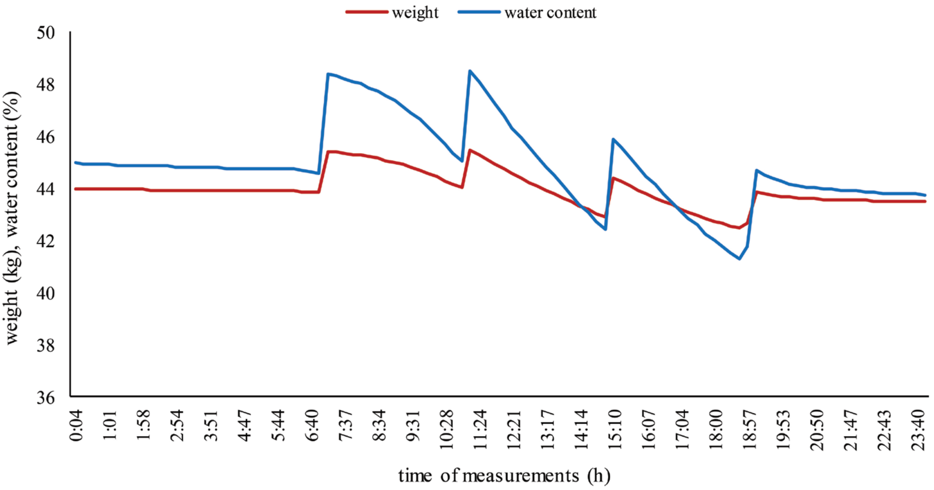

Figure 1. Diurnal course of variations in container weight and water content of the substrate (example data).

Figure 2 shows an example of the changes, recorded over 48 hours (4-5 August 2015), in weight of containers with plants and substrate moisture content measured by the capacitance probes and calculated with the gravimetric method.

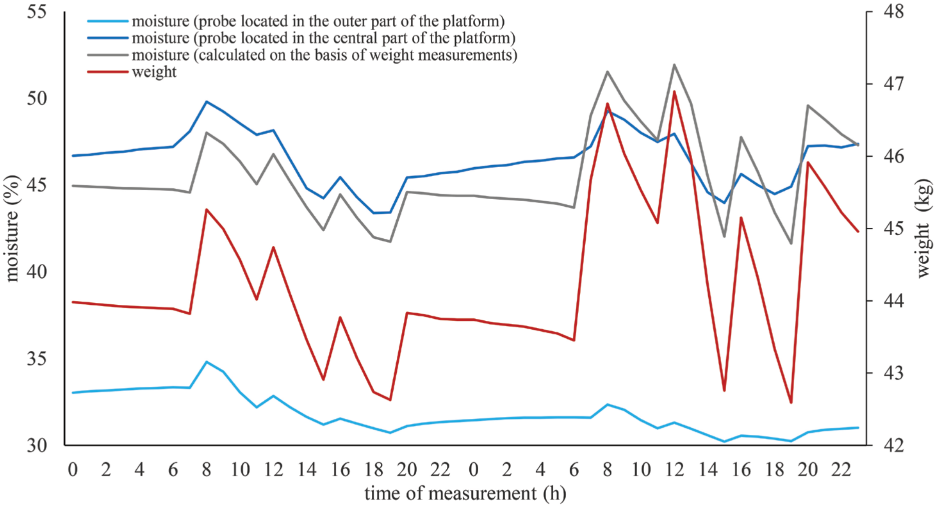

Figure 2. Diurnal changes in weight and substrate moisture (determined with capacitance probes and on the basis of weight measurements; example data)

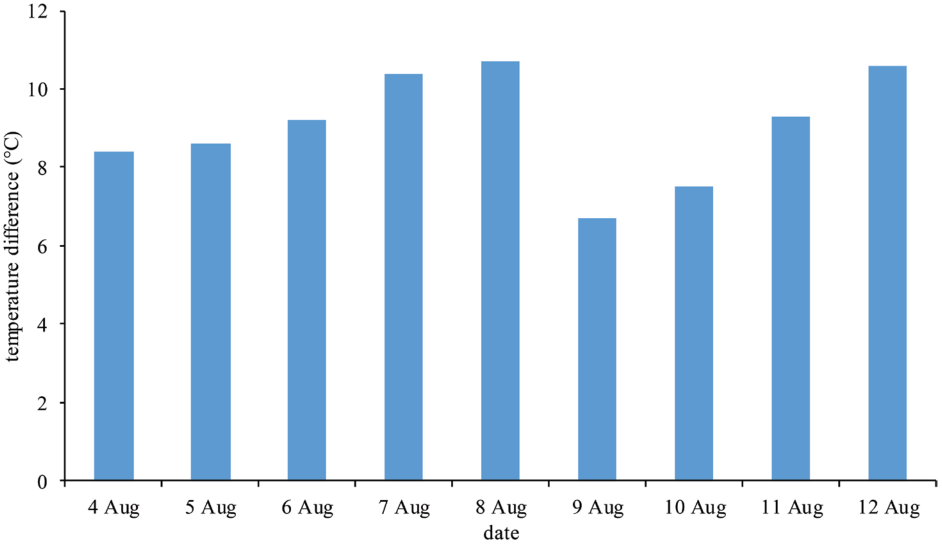

Figure 3. Differences between substrate temperatures measured with capacitance probes located in in the central and the outer part of the weighing platform

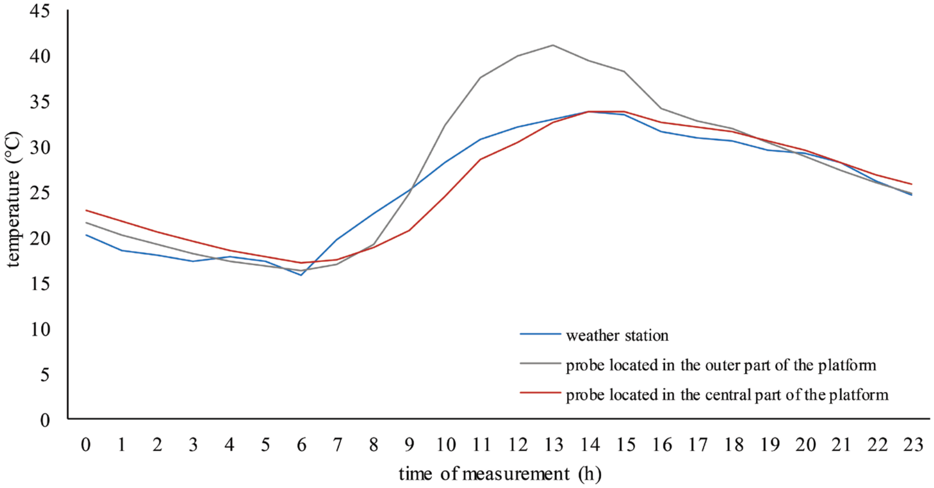

Figure 4. Comparison of the daily course of air temperature (measured with a weather station) and soil temperature measured by capacitance probes (located in different areas of the weighing platform; example data – 4 Aug)

The changes in substrate moisture measured with the capacitance probes were similar to the actual changes in the water content of the substrate (determined with the gravimetric method). Differences were observed, however, in the amplitude of the changes, especially in comparison with the probe in the container located at the periphery of the weighing platform (Fig. 2). Considerable differences in the changes of moisture content between the results obtained with the capacitance probes and weight measurements were observed in the afternoon hours (seen in the example past 8 pm). The capacitance probes recorded then an increase in moisture content, while the analysis of the data from the weighing platform indicated a decrease.

The differences between the patterns of moisture changes observed for the sensors located at different points could have been caused by the influence of substrate temperature. To verify this hypothesis, an assessment of the changes in substrate temperature over the analyzed period was performed. It was found that there were considerable differences, amounting to more than 10°C, in the levels of substrate temperature between the probes placed in different areas of the weighing platform (Fig. 3). The temperature measured by the sensors located in the containers at the periphery was higher and showed greater fluctuations during the day (Fig. 4). The diurnal amplitude of the temperatures for the probes located in the outer part of the platform was in the analyzed period approx. 8°C higher than the values recorded by the sensors in the containers located in the central part.

Temperature may influence the output of a dielectric moisture sensor through direct effects on the probe circuitry, through effects on the dielectric permittivity of water, and through effects on water-soil/substrate interaction. It is known that the dielectric permittivity of water changes with temperature (decreases by approx. 0.7% per 1°C in the temperature range 5-35°C), but the theories explaining the influence of temperature on soil dielectric properties are relatively new and are still being improved (Campbell 2002, Seyfield and Grant 2007, Chanzy *et al*. 2012).

For modern and high quality sensor systems, the temperature sensitivity of the capacitance measurements is in most cases not influenced by the sensor construction itself, but rather by the electrical characteristics of the soil/growing medium, which is sensitive to temperature fluctuations (Campbell 2002). It has been shown that soil characteristics influence the way in which changing temperature affects dielectric permittivity and thus the probe moisture reading. In some experiments, an increase in soil temperature caused a decrease in the dielectric permittivity measured by these probes, while in others (for soils with significant amounts of clay-size particles), a positive correlation between temperature and soil dielectric properties was found (Pepin *et al.* 1995, Wraith and Or 1999, Drnevich *et al.* 2001). Because of these complex interactions, it is impossible to determine a generic correction factor for temperature that can be applied to many probe types, soils and growing substrates.

An attempt was made to precisely analyze the effect of temperature on the readings of the capacitance probes used in the experiment. For this purpose, the moisture content and temperature were measured in a substrate placed in a sealed container so that the water content in the substrate would remain constant during the experiment. The substrate temperature varied from approx. 10 to 36°C (the temperature of the substrate was measured by the capacitance probe recording at the same time its moisture content).

The shape of the curves in Figure 5 clearly indicates that the temperature of the medium in which the measurement is taking place has an effect on the quality of the moisture readings generated by the probes. For the analyzed temperature range, the observed differences in moisture content were as high as 2% (v/v). Verhoef *et al.* (2006) found not particularly large (in absolute terms) variations in soil moisture (0.01-0.02 m^3 m^{-3}) as an effect of temperature during a summer day (UK). However, these relatively small variations may result in unreliable estimation of evaporation (considering that moisture changes are integrated over the soil profile) and become undesirable when diurnal values of water loss are required (e.g. to establish diurnal water balance). According to the probe manufacturer, the maximum temperature sensitivity (measurement performed in soil) for a capacitance probe is estimated at ~0.003 m^3 m^{-3} per 1°C (Campbell 2002).

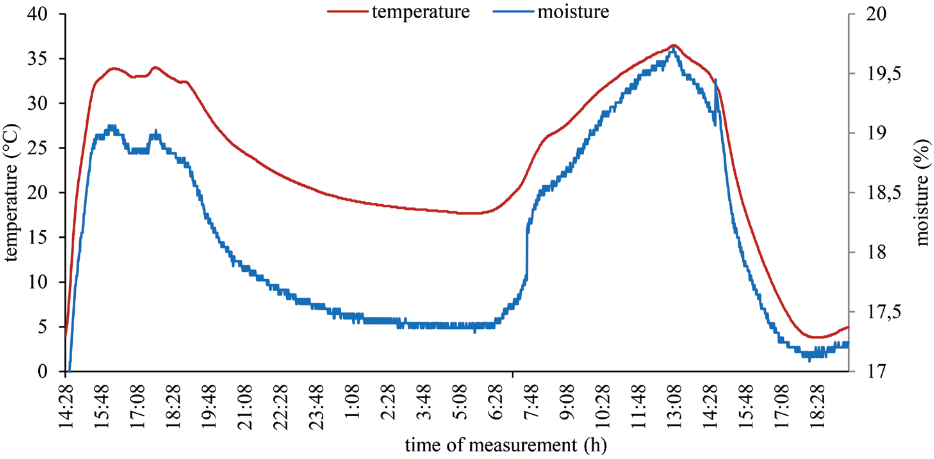

Figure 5. Fluctuations in substrate temperature and moisture recorded by a capacitance probe (example data, water content was kept at a constant level)

A mathematical description of the relationship between the changes in temperature and moisture content generated from capacitance measurements is shown in Figure 6. The analysis was performed separately for the periods in which the temperature increased and decreased. In both cases, linear correlations were obtained, indicating that temperature was the main factor (99%) explaining the observed variability in substrate moisture. Our further analyses showed that the pattern of the observed changes might differ for various (real) moisture levels (data not presented). If temperature data are available at the same location as the capacitance sensor, then a regression strategy could be used to relate the true water content values to the measured ones and to the temperature data.

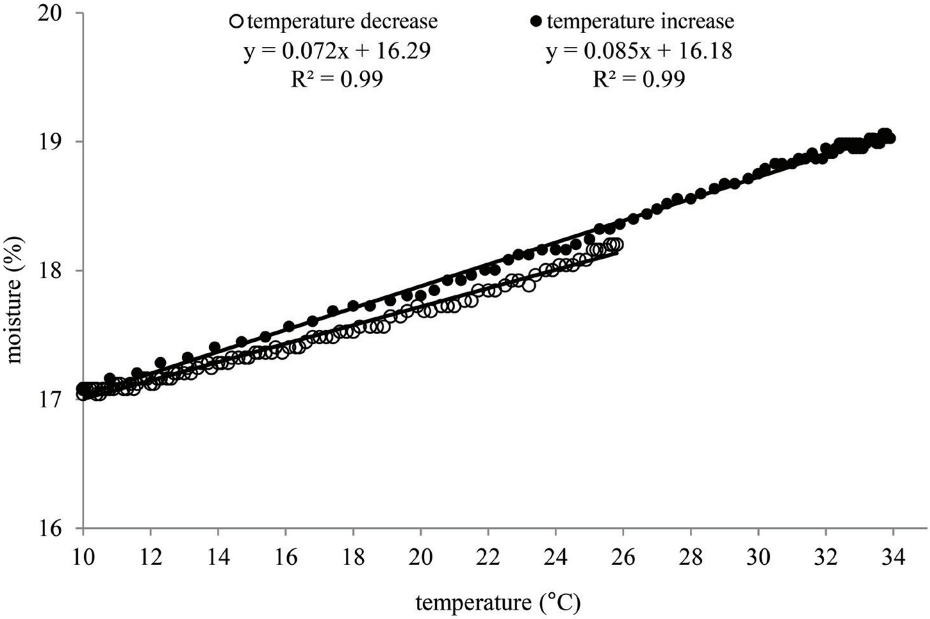

Figure 6. Relationship between the values of substrate temperature and moisture (instantaneous values, water content was kept at a constant level; analysis performed separately for periods of temperature increase and decrease).

Chanzy *et al.* (2012) found a linear relationship between temperature and the soil dielectric permittivity (for a given water content). However, the slope varied between samples taken from the same soil, which made the characterization of the influence of temperature more complex and unpredictable. The authors proposed to use diurnal patterns of the measured dielectric permittivity and soil temperature to create an algorithm designed to estimate the relationship parameters (the slope). In a study performed by Campbel (2002), the temperature dependence in coarse-textured soils was low. In contrast, in soils with a fine texture, the temperature dependence was noticeable. The author states that in most field applications, temperature dependence plays a minor role in probe output changes because temperature fluctuations decrease with soil depth and increasing plant cover. However, for container-grown crops this effect should not be ignored, as there can be large and unpredictable changes in substrate temperature, and because of the lack of thorough research on the effect of temperature on the quality of the readings generated by probes placed in soilless substrates.

CONCLUSIONS

Direct measurement of the weight of growing containers is the only method that allows determination of the actual changes in the water content of the substrate (without affecting its structure) during cultivation. However, due to the fact that weight measurements provide average data (for containers) on the water content of the substrate, it is useful to conduct additional monitoring of substrate moisture by taking point measurements with measuring probes. This is also due to the periphery effects, demonstrated in the experiment, that are associated with different profiles of substrate temperature changes in different areas of the crop stand, which can affect the moisture content readings in individual containers.

When dielectric sensors are used to monitor changes in substrate moisture, factors that can affect the results should be taken into account. Due to the unpredictable variability as to the time of occurrence and the magnitude of fluctuations, the most important of these factors appears to be temperature. The experiment demonstrated the existence of the effect of temperature on the quality of soil moisture measurements conducted with the capacitance method. The accuracy of the results obtained from measurements with dielectric sensors in relation to the data obtained by means of weighing platforms depended on the temperature profile of the measured medium. It was demonstrated that temperature variations explained 99% of the observed differences in the results of moisture content measured with the capacitance method.

To obtain reliable data on the changes in soil moisture content in order to be able to control the irrigation of plants, it is necessary to consider the influence of temperature. Otherwise, inaccurate results for moisture content may lead to an erroneous determination of dosages and frequencies of irrigation, with the result that the plants will receive insufficient or excessive amounts of water (water stress conditions, water and energy losses). Due to the fact that there is no possibility of developing universal factors (for different sensors and substrates) for correcting the influence of temperature, this relationship should be defined independently for a given type of crop and the measuring system available.

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