Measuring Soil Water Content under Turfgrass Using the Dual-probe Heat-pulse Technique

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ABSTRACT. Measurements of soil water content near the soil surface often are required for efficient turfgrass water management. Experiments were conducted in a greenhouse to determine if the dual-probe heat-pulse (DHP) technique can be used to monitor changes in soil volumetric water content (θ_v) and turfgrass water use. 'Kentucky 31' Tall fescue (*Festuca arundinacea* Schreb.) was planted in 20-cm-diameter containers packed with Haynie sandy loam (coarse-silty, mixed, calcareous, mesic Typic Udifluvents). Water content was measured with the DPHP sensors that were placed horizontally at different depths between 1.5 and 14.4 cm from the surface in the soil column. Water content also was monitored gravimetrically from changes in container mass. Measurements started when the soil surface was covered completely by tall fescue. Hence, changes in θ_v could be attributed entirely to water being taken up by roots of tall fescue. Daily measurements were taken over multiple 6- or 7-day drying cycles. Each drying cycle was preceded by an irrigation, and free drainage had ceased before measurements were initiated. Soil water content dropped from ≈ 0.35 to $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ during each drying cycle. Correlation was excellent between θ_v and changes in water content determined by the DPHP and gravimetric methods. Comparisons with the gravimetric method showed that the DPHP sensors could measure average container θ_v within $0.03 \text{ m}^3 \cdot \text{m}^{-3}$ and changes in soil water content within $0.01 \text{ m}^3 \cdot \text{m}^{-3}$.

Many turf managers schedule irrigations based on estimated evapotranspiration (Kneebone et al., 1992; Qian et al., 1996), or measurements of soil water (Youngner et al., 1981). Soil volumetric water content (θ_v) is useful because it can be converted easily to the corresponding depth of irrigation water needed to replenish moisture for saturation of the soil (Kirkham, 1994). Measurements of θ_v can be performed using several techniques, including the gravimetric method (Gardner, 1986); time domain reflectometry (TDR) (Amato and Ritchie, 1995; Topp et al., 1980; Wraith and Baker, 1991); neutron probe technique (Evelt and Steiner, 1995; Gardner, 1986); and the dual-probe heat-pulse technique (Bristow et al., 1993; Campbell et al., 1991; Tarara and Ham, 1997).

The simplicity and accuracy of the gravimetric method are major advantages. The method also is well suited to measuring soil water content in the zone of active root water uptake by turf. Unfortunately, the method is time-consuming and destructive and cannot be automated. The TDR technique also can provide accurate measurements of soil water content. A significant advantage of TDR over the gravimetric method is that it permits automated, nondestructive measurements. A disadvantage of TDR is that the method requires calibration for soils high in organic matter (Herkelrath et al., 1991). Other barriers to use TDR technique in turfgrass management are instrument cost and its complexity. The neutron probe technique is well suited for measurements deep in the soil profile, but it is ineffective within ≈ 15 cm of the soil surface, the zone of active root water uptake by turf. Although the neutron probe technique is relatively easy to employ, the method is time-consuming, requires calibration, and cannot be automated. Use of a neutron probe also requires special licensing for the handling of radioactive materials.

Recently, the dual-probe heat-pulse (DHP) technique has been developed and tested for measuring θ_v and changes in θ_v ($\Delta\theta_v$) in the laboratory and in the field (Bristow et al., 1993; Campbell et al., 1991; Tarara and Ham, 1997; Ham and Knapp, 1998). A

significant advantage of the DHP technique is the ability to measure water content close to the surface of the soil (e.g., 2 cm) in a nondestructive, automated manner. This should be of great benefit in soil with turf where the root zone is shallow.

The DHP technique uses a heater and a temperature probe to determine the volumetric heat capacity of the soil, which can be converted to θ_v . Tarara and Ham (1997) describe the probe in detail and show a schematic diagram of it (see their Fig. 3). A DPHP sensor consists of two parallel probes each made out of a 1.27 mm-diameter hypodermic needle, which are held a fixed distance apart (≈ 6 mm) by inserting them through predrilled holes in a PVC block ($26 \times 16 \times 16$ mm). One needle houses the heater wire, and a voltage is applied to the wire to create a heat pulse. The other needle, which holds a thermocouple junction made out of constantan and copper, senses the heat pulse. The length of each sensor, or the length of the needles protruding from the PVC housing, is 27 to 29 mm. Figure 1 shows a photograph of a DPHP sensor.

The heat capacity of a material describes the relationship between the amount of heat added to the material and the change in temperature that results. The heat capacity of soil is highly dependent on its water content. Thus, the DPHP sensor can estimate water content and changes in water content over time by monitoring how much the soil warms when exposed to a heat pulse from the sensor's heater. The heat capacity of soil, ρc_p , is deter-

Fig. 1. A dual-probe heat-pulse sensor.

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mined by adding the volumetric heat capacities of the soil constituents (de Vries, 1966).

$$\rho c_p = 1.92 x_m + 2.51 x_o + 4.18 \theta_v \quad [1]$$

In soils with low organic matter, x_o is neglected. The value of x_m is determined by dividing the soil bulk density (known or measured) by the particle density. An average value of $2.65 \text{ Mg}\cdot\text{m}^{-3}$ is often used for particle density of soils. This equation shows that DPHP measurements of ρc_p coupled with knowledge of bulk density (i.e., x_m) and organic matter allow direct calculation of water content.

When taking measurements with the DPHP technique, a pulse of heat is applied during a fixed interval (typically 8 s) to the line source, and then the maximum rise in temperature (ΔT_m) at some distance (r) from the line source is measured. The ΔT_m is related inversely to ρc_p and θ_v . The relationship between the ρc_p ($\text{J}\cdot\text{m}^{-3}\cdot^\circ\text{C}^{-1}$) and ΔT_m ($^\circ\text{C}$) is (Campbell et al., 1991)

$$\rho c_p = q / (e \pi r^2 \Delta T_m) \quad [2]$$

where q ($\text{J}\cdot\text{m}^{-1}$) is the heat applied per unit length of the line source, e is the base of natural logarithms, and r (m) is the distance between the heat probe and temperature probe (probe spacing), ≈ 6 mm.

Substituting Eq. [2] and Eq. [1] and rearranging yields an expression that shows the relationship between θ_v and ΔT_m .

$$\theta_v = [(q / (e \pi r^2 \Delta T_m)) - (1.92 x_m + 2.51 x_o)] / 4.18 \quad [3]$$

Measurements of ρc_p and θ_v , along with soil temperature, can be taken simultaneously, frequently, and automatically at a number of locations. Because a DPHP sensor is ≈ 5.2 cm long $\times$ 1.6 cm wide $\times$ 0.6 cm high, with the probe spacing around 6 mm, the sensor allows small-scale spatial measurements of θ_v , which can be made near the soil surface where large root densities are found.

Campbell et al. (1991) reported that the resolution of $\Delta \theta_v$ with the DPHP sensor was $\approx 0.005 \text{ m}^3\cdot\text{m}^{-3}$. Tarara and Ham (1997) found that the DPHP technique could measure θ_v to within 0.02 and $0.05 \text{ m}^3\cdot\text{m}^{-3}$ in the laboratory and field, respectively. They noted that the real strength of the DPHP technique is in measuring *changes* in θ_v ($\Delta \theta_v$), because they are not affected by errors in measurements of soil bulk density and soil organic matter, if these properties do not change between sampling times. Equation [4] shows that measurements of $\Delta \theta_v$ between two sampling periods eliminates x_m and x_o .

$$\Delta \theta_v = \theta_{v,t2} - \theta_{v,t1} = (1/4.18 e \pi r^2) (q_{t2} / \Delta T_{m,t2} - q_{t1} / \Delta T_{m,t1}) \quad [4]$$

where subscripts t1 and t2 represent two sampling times. They found that the DPHP technique could measure $\Delta \theta_v$ on a daily basis to within $0.01 \text{ m}^3\cdot\text{m}^{-3}$ in nonvegetated soil columns. These results suggest that the DPHP sensors may have sufficient resolution to monitor water uptake in a root zone.

The performance of the DPHP technique has never been shown in the presence of roots. The objective of this experiment was to determine if accurate readings of θ_v and $\Delta \theta_v$ could be obtained with the DPHP technique under turfgrass in the laboratory. We chose turfgrass because it has a uniform, shallow root system, and requires frequent irrigation in many situations. If the DPHP sensor worked in the presence of roots, then it would be a valuable instrument to monitor soil water content near the surface of the soil. We present results of three greenhouse experiments done with the DPHP sensors placed at different sampling positions in soil containers planted with turfgrass.

Materials and Methods

Three experiments were conducted with a soil (A horizon) mapped as Haynie very fine sandy loam (coarse-silty, mixed, calcareous,

mesic Typic Udifluvents, 0.7% organic matter) in a greenhouse in Manhattan, Kansas. After the soil was dried, ground, and passed through a 2-mm-diameter sieve, it was moistened slightly and packed evenly in plastic cylindrical containers to a bulk density varying between 1.42 to $1.45 \text{ Mg}\cdot\text{m}^{-3}$. The containers had holes on the bottom to facilitate drainage. During packing of each soil column, DPHP sensors, as described by Tarara and Ham (1997; using 1.27 mm-diameter hypodermic needles), were placed horizontally into the column at different locations and densities, which will be defined when the results are presented. Lead wires of DPHP sensors went through holes drilled on the walls of the containers. The packed soil columns were saturated evenly from the top, and water was applied carefully to avoid disturbing the soil surface.

After the containers were allowed to drain freely for 1 week, the columns were placed on a greenhouse bench, and 'Kentucky 31' tall fescue (*Festuca arundinacea* Schreb.) was seeded ($\approx 1.6 \times 10^5$ seedlings/ m^2). A high intensity lamp (high pressure sodium) was used $24 \text{ h}\cdot\text{d}^{-1}$, except during measurements, to supplement natural light. Liquid fertilizer (1N-2P-1K) also was applied (N at $\approx 3.79 \text{ g}\cdot\text{m}^{-2}$) after the seeds germinated. Soil water content measurements were not taken until a dense plant canopy covered the soil surface. Hence, soil water lost was considered to be transpiration with minimal evaporation from the soil. Daily measurements were taken at 1630 HR over multiple 6- or 7-d drying cycles. At the end of a drying cycle, columns were rewatered and allowed to drain until free drainage ceased, and the turfgrass was trimmed to a height of ≈ 4 cm. At the completion of each study, the roots were washed from soil and root dry mass was determined by soil layer.

Measurements of ρc_p were recorded by a datalogger (CR 21X; Campbell Scientific, Logan, Utah). The initial soil temperature was measured immediately before applying an 8-s heat pulse ($q \approx 700 \text{ J}\cdot\text{m}^{-1}$) to the heater probe. The thermocouple signal was sampled at 2 Hz to determine ΔT_m . Values of q and ΔT_m along with each individual probe spacing (r) were used in Eq. [2] to calculate ρc_p at each sensor. Values of q , r , ΔT_m , and of the mineral fraction of the soil were used in Eq. [3] to compute θ_v at each sensor. In Eq. [3], x_o was considered to be zero. At the end of a drying cycle, the soil had a θ_v of $\approx 0.10 \text{ m}^3\cdot\text{m}^{-3}$, and the grass was severely wilted. The high intensity lamp was turned off 2 hours before measurements to reduce the effect of soil temperature gradients on the readings, and it was turned on again after measurements were completed. The amount of water transpired by the turfgrass also was determined using the gravimetric method by placing a container on an elec-

Fig. 2. Locations and depths below the soil surface of dual-probe heat-pulse sensors in the root zone of turfgrass grown in columns. A, Study 1; B, Study 2; C, Study 3. (A and B) Sensors at 1.6, 4.8, 8.0, 11.2, and 14.4 cm depths and placed along the axis (●); sensors at 1.6, 8.0, and 14.4 cm depths and 5.5 cm from axis (○); sensors at the 1.6, 8.0, and 14.4 cm depths and 9.0 cm from axis (□). (C) Sensors at 1.5 cm depth and at radial distances of 0, 6.04, 7.87, and 9.33 cm, respectively, from the axis (●); sensors at 4.5 cm depth and at radial distances of 0 cm, 6.97 cm, and 9.08 cm, respectively, from the axis (○); sensors at 7.5 cm depth and at radial distances of 0 and 8.50 cm from the axis (■); sensors at 10.5 cm depth and at radial distances of 0 and 8.50 cm from the axis (□).

tronic balance to record the changes in total mass of the column. The gravimetric method was considered to be the standard for reference, and readings from the DPHP sensors were compared with those from the gravimetric method.

Measurements with DPHP sensors may be affected by slight differences in soil properties, water distribution, sampling density, and water uptake patterns of roots. Therefore, three studies were conducted with different placements and densities of the DPHP sensors within a soil column. Figure 2 shows the locations of the DPHP sensors in the three studies.

STUDY 1. Two soil columns, 20 cm in diameter $\times$ 16 cm high, were packed. Each column was instrumented with five DPHP sensors placed every 3.2 cm along the center axis (Fig. 2A). Each sensor sampled a 3.2-cm layer of soil. The average volumetric soil water content for the container (θ_v) was computed as the arithmetic average of the five (θ_{vi}) values measured by the DPHP sensors. Tall fescue was planted on 18 Oct. 1996. Soil volumetric water content measured for two 7-d drying cycles: 20–26 Nov. and 1–7 Dec. 1996.

STUDY 2. One soil column, 20 cm in diameter $\times$ 16 cm high, was packed. Three DPHP sensors were placed at radial distances of 0, 5.5, and 9.0 cm from the axis of the column and at depths of 1.6, 8.0, and 14.4 cm (Fig. 2B). One DPHP sensor was placed in the center at a depth of 4.8 cm and one at a depth of 11.2 cm. A weighting equation (Eq. [5]) was developed, based on placement of the probes, to calculate the average water content of the whole soil column (θ_v).

$$\theta_v = \frac{\sum_{i=1}^n (v_i/v_t) \theta_{vi}}{\sum_{i=1}^n (v_i/v_t)} \quad [5]$$

where θ_{vi} is water content measured by DPHP sensor i , v_i is the volume of soil assigned to DPHP sensor i , v_t is the total soil volume, and n is the number of DPHP sensors. The ratio v_i/v_t represents the volume-based mass assigned to each DPHP sensor. Each of the five DPHP sensors in the center of the column had a mass of 0.0178; each of the three DPHP sensors near the outer edge of the column had a mass of 0.1200; and each of the three DPHP sensors between the center and the outer edge of the column had a mass of 0.1830. Tall fescue was planted on 7 Jan. 1997. Measurements were taken over three drying cycles: 31 Jan. to 5 Feb., 11–17 Feb., and 21–27 Feb. 1997. Root dry mass was 2.83 g with 80% of the roots in the upper two layers (i.e., 6.4 cm).

STUDY 3. The third study was carried out in a shorter soil column, 20 cm in diameter $\times$ 12 cm high, which allowed for increased sampling density. More sensors were positioned near the surface to better sample the soil with higher root density. DPHP sensors were placed at four depths. DPHP sensors at the same depth were placed radially at specific distances from the center axis of the column to equalize the mass (Fig. 2C). Four sensors that were at the 1.5 cm depth were placed at radial distances of 0, 6.04, 7.87, and 9.33 cm from the central axis; three sensors that were at the 4.5 cm depth were placed at radial distances of 0, 6.97, and

9.08 cm from the central axis; two DPHP sensors that were at the 7.5 cm and two DPHP sensors that were 10.5 cm deep were placed at radial distances of 0 cm and 8.50 cm from the central axis. Thus, sensor density was greater near the soil surface where higher root density was found. DPHP sensors that were at the same depth measured soil water contents in the same volume of soil. Equal mass simplified calculating average θ , for the column. Tall fescue was planted on 26 Mar. 1997. Measurements were taken during two drying cycles: 10–16 and 20–25 Apr. 1997. Root dry mass was 3.65 g with 70% of the roots in the upper two layers (6.0 cm). For each study, the average θ , of the container measured by the array of DPHP sensors was compared to the gravimetric measurement obtained from the balance. This comparison evaluated the integrated performance of the DPHP sensors, the sampling strategy, and the accuracy of soil bulk density estimates used in Eq. [3]. However, more emphasis was placed on comparing probe-based and gravimetric estimates of $\Delta\theta$. Successive measurements enacted in each drying cycle. As mentioned earlier, $\Delta\theta$ is not dependent on bulk density, and thus eliminates uncertainty and bias caused by positional variation in soil physical properties.

Results and Discussion

Figure 3 shows the comparison of measurements of θ , made by the gravimetric method, denoted by θ_{v-G} , and DPHP technique denoted by θ_{v-DP} , for Studies 1, 2, and 3. In this and following sections and figures, all the θ_v , θ_{v-DP} , and θ_{v-G} represent average θ_v , θ_{v-DP} , and θ_{v-G} , respectively. Excellent agreement was found in each

Fig. 3. Comparison between volumetric water content measured by DPHP sensors, denoted by θ_{v-DP} , and measured gravimetrically, denoted by θ_{v-G} , for the three different studies. (A1) Study 1, column 1; (A2) Study 1, column 2; (B) Study 2; (C) Study 3. Line of 1:1 was considered to be the reference. (∇) θ , in the first drying cycle; (+) θ , in the 2nd drying cycle; ($\bullet$) θ , in the 3rd drying cycle. θ_{v-DP} = the weighted whole-container average calculated using Eq. [5].

Fig. 4. Comparison between daily changes in volumetric water content measured with DPHP sensors, denoted by $\Delta\theta_{v-DP}$, and determined gravimetrically, denoted by $\Delta\theta_{v-G}$, during three drying cycles of the three studies. (A1) Study 1, column 1; (A2) Study 1, column 2; (B) Study 2; (C) Study 3. $\Delta\theta_{v-DP}$ represents the weighted whole-container average calculated using Eq. [5].

study. In the range of soil moisture between 0.40 and $0.10 \text{ m}^3 \cdot \text{m}^{-3}$, the root mean squared error (RMSE) of the calculated θ_v from DPHP sensors (θ_{v-DP}) and θ_v from gravimetric method (θ_{v-G}) was less than 0.01 . In the three studies, maximum discrepancy between measurements determined gravimetrically and those determined with DPHP sensors was $0.037 \text{ m}^3 \cdot \text{m}^{-3}$ and mean discrepancy of all measurements was $0.015 \text{ m}^3 \cdot \text{m}^{-3}$. Agreement was especially good in Study 3 over a wide range of soil moisture contents (0.09 to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$). In Study 3, the mean discrepancy between measurements determined gravimetrically and those determined by DPHP sensors was $0.011 \text{ m}^3 \cdot \text{m}^{-3}$. In Study 1, the DPHP sensors slightly overestimated soil moisture at almost all moisture contents measured, and in Studies 2 and 3, the DPHP sensors tended to overestimate soil moisture at low water content (Fig. 3). The observed bias between θ_{v-DP} and θ_{v-G} in Study 1 probably was caused by an error in the estimate of soil bulk density at the DPHP sensors.

The ability of the DPHP method to accurately measure soil volumetric water content decreased as the soil became drier. Even though we were unable to view the sensors in the soil, one of the potential sources for this error may have been

poor contact between the needles and the soil when the soil dried out. As soil moisture was depleted, the soil may have shrunk. This may have caused an air-filled gap to develop between the needles of the DPHP sensor and the soil sample. Hence, the maximum rise in temperature of the soil sample monitored by the DPHP sensor might have been lower than it should have been. Because θ_v determined by the DPHP sensors was related inversely to ΔT_m (Eq. 3), θ_v measured with the DPHP sensors was greater than expected. When the θ_v was lower than $0.12 \text{ m}^3 \cdot \text{m}^{-3}$, observation showed that the turfgrass was completely wilted. Under field conditions, turfgrass will be irrigated before it looks wilted. Therefore, the higher than expected θ_v that occurred in extremely dry soil would not be relevant in many applications. The DPHP sensors gave accurate measurements of soil water over the range of moisture of interest in scheduling turf irrigations.

Estimating changes in θ_v ($\Delta\theta_v$) is more important than measuring θ_v , because $\Delta\theta_v$ shows the turfgrass water use and the amount of irrigation water that must be applied. The real strength of DPHP technique is its ability to measure changes in water content over time, because they are not affected by errors in the measurement of soil bulk density and soil organic matter. Hence, we expected better performance in measuring $\Delta\theta_v$. Volumetric water contents of 2 successive days were compared, and the difference (water lost, $\Delta\theta_v$) was attributed to daily water use by the turfgrass. Figure 4 shows the water lost based on readings from DPHP sensors and on mass loss from the electronic balance. Agreement between these two methods also was excellent. The RMSEs for $\Delta\theta_v$ typically ranged from 0.003 to 0.01 . The maximum discrepancy between $\Delta\theta_v$ determined gravimetrically and with

the DPHP sensors was $\approx 0.02 \text{ m}^3 \cdot \text{m}^{-3}$. However, discrepancies were usually $< 0.01 \text{ m}^3 \cdot \text{m}^{-3}$.

In the three studies with different placements and densities of sensors, values of θ_{v-DP} from Study 1 were the farthest from the 1:1 line, and values of θ_{v-DP} from Study 3 were the closest to the 1:1 line (Fig. 3). Also, in terms of relative error, the results from Study 3 were better than those from the other two studies. This suggests

Fig. 5. Cumulative water use. The daily changes in the volumetric water content measured with DPHP sensors, denoted by $\Delta\theta_{v-DP}$, and determined gravimetrically, denoted by $\Delta\theta_{v-G}$, have been summed during the drying cycles of the three studies. (A) Study 2; (B) Study 3. $\Delta\theta_{v-DP}$ represents the weighted whole-container average calculated using Eq. [5].

that higher density of DPHP sensors might be needed for accurate measurement of water content, especially in containerized plants where a radial soil water gradient may be common. In Study 3, there was one DPHP sensor per 236 cm³ soil volume and one per 314 cm³ soil volume in the first and second layers, respectively, where most of the roots accumulated. Study 3 showed that these sampling densities are sufficient for accurate measurements of soil water content in containerized soil with plants. As mentioned, the mean discrepancy between measurements determined gravimetrically and those determined by DPHP sensors was only 0.011 m³·m⁻³ in Study 3.

Cumulative water use was determined by summing the daily changes in water content (Fig. 5). Early in a drying cycle (e.g., first 4 d), summations of measurements made with the DPHP techniques were similar to summations of those made with the gravimetric method. As the soil dried, slight overestimation of θ_v by the DPHP sensors resulted in a small underestimation of total plant water use. When greater sampling density was used, the relative errors (100% $[\Delta\theta_{v-DP} - \Delta\theta_{v-G}]/\Delta\theta_{v-G}$) of total changes in θ_v during each entire drying cycle were 4.0% and 11.0% for Study 3 and 10.0%, 9.0% and 12.0% for Study 2. In an actual water management scenario, irrigation is typically applied before water contents is severely depleted. Thus, decreased performance of the DPHP sensors at low water contents might not be a factor when used as an irrigation management tool. Changes in water content determined with the DPHP technique are not affected by errors in the measurement of soil bulk density, specific heat of the soil mineral fraction, and soil organic matter (Tarara and Ham, 1997). Therefore, the difference observed in Fig. 5 between the DPHP technique and the gravimetric method must have been due to errors analyzed above.

Conclusion

The objective of this study was to determine whether or not the dual-probe heat-pulse technique can be used to measure soil water content (θ_v) and changes in θ_v ($\Delta\theta_v$) to ascertain turfgrass water use. Excellent correlations between soil water content measured with DPHP sensors (θ_{v-DP}) and gravimetrically (θ_{v-G}) were found. The DPHP sensors allowed small scale spatial measurements of θ_v to be made near the soil surface in the presence of numerous roots. They measured θ_v and $\Delta\theta_v$ of turfgrass typically within 0.03 and 0.01 m³·m⁻³, respectively. Accuracy of measurements in dry soil ($\theta_v < 0.12$ m³·m⁻³) was reduced slightly. This reduction in accuracy, however, probably would not be important for scheduling turf irrigations, because the soil would not be allowed to get so dry under actual practice. DPHP sensors differ from other instruments in being able to measure soil volumetric heat capacity (ρc_p), soil temperature, and θ_v simultaneously, frequently, and automatically

at a number of locations. Additional field research will be required to evaluate probe performance in vegetation with different root systems and rooting depths.

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