

Use of the Dual-Probe Heat-Pulse Technique to Monitor Soil Water Content in the Vadose Zone

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ABSTRACT

The dual-probe heat-pulse (DHP) technique is emerging as a useful technique for measuring soil volumetric water content (θ). However, few published data are available regarding the performance of the DHP technique under field conditions. The objective of this study is to evaluate the effectiveness of the DHP technique for measuring θ under field conditions. We used 24 DHP sensors to monitor θ in a soybean [*Glycine max* (L.) Merr.] field during the 2001 and 2002 growing seasons. The DHP sensors demonstrated durability in field conditions and clear sensitivity to temporal and spatial variations of θ at the scale of measurement. The mean θ measured by the DHP sensors (θ_{DHP}) was on average $0.040 \text{ m}^3 \text{ m}^{-3}$ larger than the mean θ measured by soil sampling (θ_{SS}). The response of the DHP sensors was linear. Regressions of θ_{DHP} vs. θ_{SS} yielded r^2 values of 0.949 and 0.843 at depths of 7.5 and 37.5 cm. The DHP technique showed good resolution with RMSE values for the regression of 0.009 and $0.011 \text{ m}^3 \text{ m}^{-3}$ at the two measurement depths. The slopes of the regressions were 0.75 rather than 1.0. Errors in θ_{SS} are a likely cause of this low slope. We shifted all the θ values for each sensor up or down by a constant value to make the first θ measurement from each sensor equal θ determined from soil sampling near that sensor at the time of installation. This simple matching point procedure improved the accuracy of the DHP technique, resulting in a $-0.024 \text{ m}^3 \text{ m}^{-3}$ average difference between θ_{DHP} and θ_{SS} . Also, the matching point procedure markedly reduced the variability between sensors, reducing the average SD from 0.063 to $0.026 \text{ m}^3 \text{ m}^{-3}$. This procedure requires no additional soil sampling and is recommended for field applications of the DHP technique.

MEASUREMENTS of θ in the vadose zone are often needed by researchers who study components of the terrestrial hydrologic cycle or who study the many biological, physical, and chemical processes that are influenced by θ . Measurements of θ are also often utilized by irrigation managers in agriculture and horticulture. A number of useful direct and indirect techniques for measuring θ are available, each having characteristic strengths and weaknesses (Topp and Ferré, 2002). This study focuses on the DHP technique, an indirect technique that enables automated, nondestructive measurements of θ on a small volume of soil. The DHP technique for measuring θ was first suggested by Campbell

et al. (1991), and has since been utilized by several researchers (Tarara and Ham, 1997; Ren et al., 1999; Song et al., 1999; Campbell et al., 2002). These studies have shown that the DHP technique can provide accurate measurements of θ and change in θ ($\Delta\theta$) in laboratory and greenhouse settings.

However, evaluations of the effectiveness of the DHP technique in the field have been limited. In one field study, Tarara and Ham (1997) compared θ measurements from three DHP sensors with θ measurements made with a γ attenuation meter and found that the two methods agreed to within $0.05 \text{ m}^3 \text{ m}^{-3}$. In another field study, Campbell et al. (2002) compared θ measurements from 10 DHP sensors in a peat bog with θ measurements from four water content reflectometer sensors (CS615, Campbell Scientific Inc., Logan, UT).¹ They reported similar temporal patterns of θ but different mean values between the two types of sensors at the 5-cm depth. At the 30-cm depth, they reported similar mean values of θ but different temporal patterns of θ between the two types of sensors. In total, we can find only two figures in two papers comparing DHP θ measurements with independent θ measurements in the field. More extensive field comparisons between the DHP technique and other accepted techniques for measuring θ are needed to clearly define the effectiveness of the DHP technique under field conditions. The objective of this study is to evaluate the effectiveness of the DHP technique for measuring θ under field conditions.

THEORY

Dual-probe heat-pulse sensors can be used to measure soil volumetric heat capacity (C), which is directly related to θ . A brief heat pulse emitted from the heating needle of the DHP sensor is transferred through the soil, resulting in a small temperature increase (ΔT) approximately 6 mm away at the sensing needle of the sensor. The maximum value of this temperature increase (ΔT_m) is inversely related to C (Campbell et al., 1991):

$$C = q/(\pi e r^2 \Delta T_m) \quad [1]$$

where q is the heat output per unit length of the heater (J m^{-1}), e is the base of the natural logarithms, and r is the distance between the heating and sensing needles (m). Volumetric heat capacity is related to θ by

¹ Mention of products and suppliers is for the convenience of the reader and implies no endorsement on the part of the authors or the USDA-ARS.

Abbreviations: θ , volumetric water content; θ_{DHP} , mean soil volumetric water content measured by the dual-probe heat-pulse technique; θ_{SS} , mean soil volumetric water content measured by soil sampling; AWG, American Wire Gauge; C , soil volumetric heat capacity; DHP, dual-probe heat-pulse.

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$$C = \rho_w c_w \theta + \rho_b c_s \quad [2]$$

where ρ_w is the density of water (kg m^{-3}), c_w is the specific heat of water ($\text{J kg}^{-1} \text{K}^{-1}$), ρ_b is the soil bulk density (kg m^{-3}), and c_s is the specific heat of the soil solids ($\text{J kg}^{-1} \text{K}^{-1}$) (Campbell et al., 1991). Note that soil solids include both mineral and organic matter. Substituting Eq. [1] into Eq. [2] and rearranging gives the theoretical equation for determining θ by use of the DPHP technique (Bristow et al., 1993):

$$\theta = \frac{1}{\pi e r^2 \rho_w c_w} \frac{q}{\Delta T_m} - \frac{\rho_b c_s}{\rho_w c_w} \quad [3]$$

Equation [3] is based on the assumptions that the heat transfer around and through the DPHP sensor is the same as the heat transfer around an infinite line source in a homogeneous medium, that the finite duration heat pulse approximates an instantaneous heat pulse, that the heat transfer is only by conduction, that no contact resistance exists between the sensor and the soil, and that ρ_w , c_w , and c_s are independent of θ and temperature. Furthermore, in applying Eq. [3], we normally assume that all the variables other than q , ΔT_m , and θ are constant throughout the measurement period.

MATERIALS AND METHODS

Sensor Construction

Twenty-four DPHP sensors were utilized in this experiment. The heaters and thermocouples of the sensors were housed in 35.6-mm-long sections of 18-gauge (1.02 mm) stainless steel tubing. The heating needle was created by threading enameled resistance wire (79- μm diam., 205 $\Omega \text{ m}^{-1}$, Nichrome 80 Alloy, Pelican Wire Co. Naples, FL) four times through the entire length of the tubing so that the resulting heater had a resistance of approximately 820 $\Omega \text{ m}^{-1}$. The total resistance of the completed heaters was about 33 Ω . The temperature sensing needle was constructed by inserting a 36 American Wire Gauge (AWG) copper-constantan thermocouple junction (Type T, Omega Engineering, Stamford, CT) in the second tube. The interiors of the heating and temperature sensing needles were then filled with high thermal conductivity epoxy (Omegabond 101, Omega Engineering, Stamford, CT), and the heater and thermocouple wire were connected to 8.5-m-long 22-AWG stranded conductors (Pelican Wire Co., Naples, FL). The lead wires for the heating needle were copper, and the lead wires for the sensing needle were copper and constantan. The heating and temperature-sensing needles were inserted into predrilled holes in a small PVC block so that the needles were parallel and separated by about 6 mm. The needles protruded 27 mm from the PVC block, the thermocouple junction was in the center of the protruding portion of the sensing needle, and the wiring junctions between the needles and the leads were inside the hollow center of the PVC block. The cavity in the block was then filled with high thermal conductivity epoxy (RBC-4300 and A-121 epoxy hardener, RBC Industries, Warwick, RI) so that the finished sensors were waterproof and electrically insulated. Finally, the sensor leads were threaded through heavy-duty woven nylon sleeves (Protec NHS-071, Tompkins Industries Inc., Olathe, KS) to protect the leads from damage in the field.

Measurement System

The measurement system for the 24 DPHP sensors consisted of a datalogger (21x, Campbell Scientific), two multiplexers (AM416, Campbell Scientific), a reference thermistor (Model 107, Campbell Scientific), a pair of 0.27- Ω resistors wired in parallel (Philips ECG, Greenville, TN), a 5-V direct

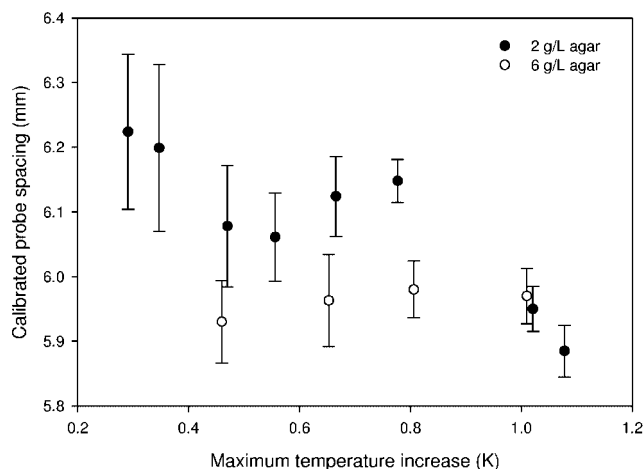


Fig. 1. Calibrated needle spacing vs. maximum temperature increase for one dual-probe heat-pulse sensor in agar-stabilized water at 2 and 6 g L⁻¹. The symbol is the mean of 10 measurements, and the error bars represent 1 SD in each direction.

current relay capable of handling up to 2 A (R40-11D2-5, NTE Electronics Inc., Bloomfield, NJ), and a deep-cycle 12-V battery. The heater leads were connected to one multiplexer, and the thermocouple leads were connected to the second multiplexer. The thermocouple multiplexer was sealed in a well-insulated protective box with the reference thermistor mounted on the center bridge of the multiplexer. The heater multiplexer and the datalogger were each sealed in separate protective boxes. The datalogger switched the multiplexer channels at the appropriate times and activated the relay to switch current to the heaters. The current to the heaters flowed through the two 0.27 Ω resistors wired in parallel, and the datalogger measured the voltage drop (ΔV) across the resistors. The relationship between ΔV and the heating power, q , is

$$q = (\Delta V/R_r)^2 R_h t_0 \quad [4]$$

where R_r is the total resistance of the paired resistors (Ω), R_h is the resistance per unit length of the heating element ($\Omega \text{ m}^{-1}$), and t_0 is the duration of the applied heat pulse (s). The sensors were heated for 8 s. The current through each heater was approximately 0.33 A, resulting in $q \approx 700 \text{ J m}^{-1}$. The temperature of each sensor was measured before heating and one time per second for 80 s after the initiation of heating.

Calibration

The needle spacing, r , for each DPHP sensor was determined by recording measurements of q and ΔT_m with the sensor immersed in water stabilized with agar (6 g L⁻¹) to prevent convection. Eq. [1] was then rearranged to solve for r with $C = \rho_w c_w = 997.5 \text{ kg m}^{-3} \times 4180.4 \text{ J kg}^{-1} \text{ K}^{-1} = 4.170 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$ (data for water at 23°C; Weast, 1978). We assumed that the agar did not significantly alter the heat capacity of the water. Campbell et al. (1991) calibrated DPHP sensors in water stabilized with agar at 2 g L⁻¹, but we found that at that concentration r was not stable when the heating power was varied. At 2 g L⁻¹ agar, r decreased as ΔT_m increased, while r was independent of ΔT_m at 6 g L⁻¹ agar (Fig. 1). These data suggest that the heat pulse induced some convection in water stabilized with agar at 2 g L⁻¹. The mean value of r for the sensors was 5.98 mm with a SD between sensors of 0.19 mm. The calibration for each sensor was repeatable with an average coefficient of variation of 1.1% across 24 replications.

Installation

The measurement system and DPHP sensors were installed at the Bruner farm field research site near Ames, IA. The cropping system at the site was conventional tillage continuous soybean. The soil at the site is mapped as a Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). The Nicollet series consists of soils formed in calcareous loamy glacial till with A horizons typically 40 cm deep. Sensors were installed in four adjoining soybean research plots each covering an area of approximately 36 m². Soybeans were planted in north-south rows spaced 76 cm apart, and there were eight rows per plot. The sensors were installed in the row directly beneath the growing soybean plants. A spade was used to dig a small hole roughly 45 cm deep beside the soybean row. Sensors were installed horizontally by using a metal blade to cut a slot in the soil on the face of the hole adjacent to the row at the desired depth. The size of the slot was slightly smaller than the size of the PVC head of the DPHP sensor. The sensor was then carefully inserted into the slot so that the sensor needles and head were surrounded by undisturbed soil. Soil was then packed tightly around the rear of the DPHP sensor and the leads to prevent channeling of water to the sensor under wet conditions. Finally, the leads from each sensor were laid to the bottom of the hole and back out the top, and soil was carefully backfilled into the hole to approximately the original bulk density.

In 2001, the soybean was planted on 18 May, and the 24 DPHP sensors were installed on 27 July. The sensors were installed at two locations in each plot. At each location, sensors were installed at depths of 7.5, 22.5, and 37.5 cm below the soil surface. In 2002, the soybean was planted on 24 May, and 24 DPHP sensors were installed on 27 June. The sensors were installed at three locations in each plot. At each location, sensors were installed at depths of 7.5 and 37.5 cm below the soil surface. In 2002, one additional DPHP sensor was sealed into a water-tight 250-mL Nalgene (Rochester, NY) bottle filled with quartz sand (Unimin silica sand, Target Products Ltd., Burnaby, British Columbia). This sensor was used to verify the stability of the results from the measurement system and was placed aboveground under a protective cover along with the datalogger and multiplexer enclosures.

Every 6 h, measurements were performed on all the DPHP sensors, and the date, time, initial temperature, voltage drop across the resistors, ΔT_m , and the time between the initiation of the heat pulse and the occurrence of ΔT_m were recorded. The data were postprocessed to calculate q and θ . The average of the θ values measured by all the DPHP sensors at each depth will from here on be referred to as θ_{DPHP} .

Soil Sampling

In 2002, we collected soil samples from the field on eight different occasions for determining θ by oven drying. The soil sampling procedure was designed to determine the average θ at 7.5 and 37.5 cm for comparison with θ_{DPHP} . Soil spatial variability and the destructive nature of soil sampling preclude a meaningful comparison of the water content determined by an individual sensor with that determined by repeated soil sampling. At each sampling, one soil sample was taken near each DPHP sensor, thus 12 samples were taken at the 7.5-cm depth and 12 at the 37.5-cm depth. The first set of soil samples was obtained by hand during sensor installation. The final set of soil samples was taken by hand during sensor extraction. The other sets of soil samples were collected with a 30-cm-long soil sampler with a 1.9-cm i.d. (JMC Sampler, Clements Associates Inc., Newton, IA). With the soil sampler we obtained

Table 1. Bulk density (ρ_b), particle size distribution, organic matter (OM) content, and specific heat (c_s) of the soil at the study site.

Depth	ρ_b	Sand	Silt	Clay	OM	c_s
cm	Mg m ⁻³	%				kJ kg ⁻¹ K ⁻¹
7.5	1.28	50	18	32	2.9	0.78
37.5	1.33	51	23	26	1.4	0.76

samples from the opposite side of the soybean row at the same depth as the sensor. The total distance from the sample location to the sensor was <1 m. The 7.5-cm sample was obtained by vertically inserting the sampler 15 cm into the soil and saving the 6.5- to 8.5-cm layer from the resulting soil core. The 37.5-cm sample was obtained by reinserting the sampler into the hole made by removing the first sample and saving the 36.5- to 38.5-cm layer from the resulting soil core. The total volume of each soil sample then was about 5.7 cm³. The sampling volume of a DPHP sensor can be approximated as follows: A cylinder with a diameter equal to the distance between the sensor needles, r , and a length equal to that of the sensor needles would enclose a volume of 0.79 cm³. This volume is an approximate lower limit on the sampling volume of the sensor. Theoretically, the radial distance from the heater at which the maximum temperature increase is 1% of ΔT_m is $2.37r$ or 1.4 cm (Campbell et al., 1991). A cylinder with a radius of 1.4 cm and a length equal to that of the sensor needles would enclose a volume of 17 cm³. This volume is an approximate upper limit on the sampling volume of the sensor. Therefore, the sensors probably sample a volume of soil between 0.79 and 17 cm³. The 5.7-cm³ volume of the soil samples falls within this range. The similarity of number, spatial distribution, and volume of samples is important for making an accurate comparison between the two techniques. The gravimetric water content of the soil samples was determined by weighing, drying for 24-h at 105°C, and weighing again. Bulk density was determined from separate soil samples taken at the site of each DPHP sensor during sensor extraction on 4 September. The average ρ_b values for the 7.5- and 37.5-cm depths in 2002 are shown in Table 1. The average θ determined from the 12 soil samples at each depth will from here on be referred to as θ_{SS} . Soil samples taken during the course of the study were used to determine selected physical properties of the soil in the laboratory. Particle size analysis was performed with the hydrometer method. Organic matter content was determined by dry combustion. And, c_s was measured by a differential scanning calorimeter (Seiko DSC220C, Perkin-Elmer Analytical Instruments, Shelton, CT). The results listed in Table 1 are the means of two replications of the particle size and organic matter measurements and three replications of the c_s measurements.

Rainfall Measurements

In 2001, rainfall was recorded at the Iowa State University Agronomy and Agricultural and Biosystems Engineering Research Farm, which is 4.0 km from the field site. In 2002, rainfall was recorded at the field site.

RESULTS AND DISCUSSION

The daily average value of θ_{DPHP} and the daily rainfall totals for the period of measurement in both years are shown in Fig. 2. The data in Fig. 2 qualitatively demonstrate the sensitivity and reliability of the DPHP technique under field conditions. During the periods of measurement, the DPHP technique captured distinct temporal

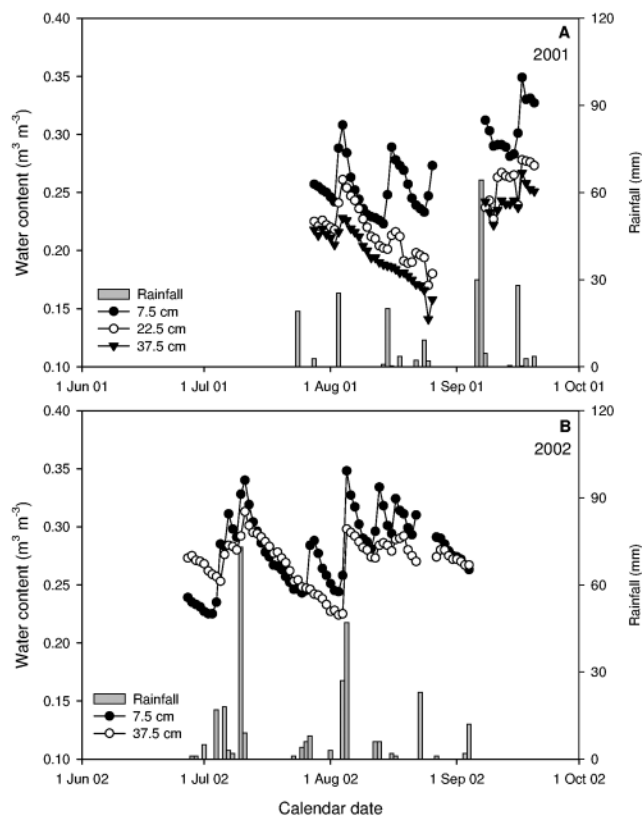


Fig. 2. Daily average of water content measured by the dual-probe heat-pulse sensors along with the daily rainfall totals for the measurement periods in (A) 2001 and (B) 2002.

variations in water content. The θ_{DHP} data show sharp increases in response to rainfall events and smooth, gradual decreases between rainfall events. The DPHP technique also captured distinct variations in water content with depth in both years. For example, the small rainfall events that occurred between 25 and 27 July 2002 resulted in a $0.05 \text{ m}^3 \text{ m}^{-3}$ increase in θ_{DHP} at the 7.5-cm depth but no increase in θ_{DHP} at the 37.5-cm depth. The DPHP results in both years also reveal the general tendency for the 37.5-cm depth to be drier than the 7.5-cm depth. In the context of this study, the ability of the DPHP technique to capture temporal and spatial variations in soil water dynamics makes it a promising technique for studying infiltration, crop water use, and evapotranspiration. The data in Fig. 2 also indicate that a DPHP system can function reliably for months at a time in a field environment with minimal intervention. The measurement system was deployed for a total of 123 d during 2001 and 2002, and all of the sensors were still functioning properly at the end of the study. During the study, only two losses of data occurred. The first loss of data occurred for 12 d (27 Aug.–7 Sept. 2001) and stemmed from a faulty splice in the reference thermistor cable. The second loss of data occurred for 5 d (22 Aug.–26 Aug. 2002) and resulted from animals causing the external battery to be disconnected from the datalogger. Visits to the site were sporadic, and maintenance was limited to downloading data and changing the external battery when it became depleted (once per season in this case).

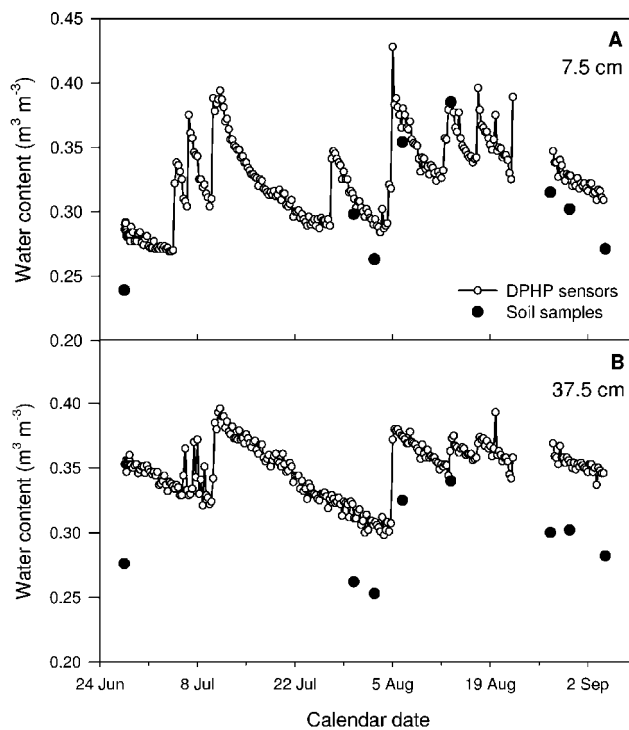


Fig. 3. 2002 time series of water content measured by dual-probe heat-pulse (DHP) sensors and by soil sampling at (A) the 7.5-cm depth and (B) the 37.5-cm depth.

Reference Sensor

The DPHP sensor sealed in the quartz sand provided a means to quantify the stability of the measurement system in the field. This reference sensor was measured for a period of approximately two months during 2002. During that time, the water content reported by the reference sensor was stable at $0.04 \text{ m}^3 \text{ m}^{-3}$ with a SD of only $0.0054 \text{ m}^3 \text{ m}^{-3}$. These data from the reference sensor show that the DPHP technique has the capability to provide stable and precise measurements of θ under outdoor ambient conditions. The ambient temperature of the sand ranged from 10 to 40°C during the measurement period. The practical value of installing a reference sensor is that it can help identify any gradual drift or sudden changes in the performance of the measurement system.

Comparison of θ_{DHP} and θ_{SS}

From here on we will focus our analysis on the results from 2002, because that is the year in which we collected extensive soil samples. Figure 3 shows the time series of θ_{DHP} and θ_{SS} for 2002. Four θ_{DHP} measurements per day are plotted in Fig. 3, with each measurement being the average value from 12 sensors at the same depth. Figure 3 illustrates the value of automated measurements of θ for describing soil water dynamics. Notice that soil samples were collected on 6 and 13 August and that the resulting θ_{SS} values show a small increase in water content during that period. In contrast, the relatively continuous θ_{DHP} data for the same period show that the period between 6 and 13 August included a

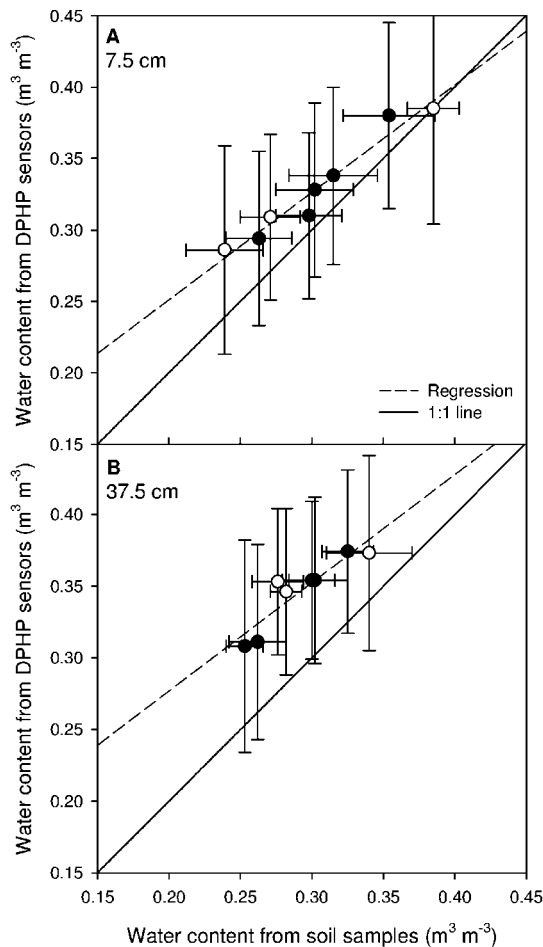


Fig. 4. One-to-one comparison of water content measured by dual-probe heat-pulse (DPHP) sensors and by soil sampling at (A) the 7.5-cm depth and (B) the 37.5-cm depth. Symbols represent the mean of 12 measurements. Error bars represent 1 SD in each direction. The open symbols identify the questionable soil sampling data discussed in the text.

distinct dry-down followed by a clear rewetting. Figure 3 also demonstrates that the DPHP technique performs with a reasonable level of accuracy under field conditions. At the 7.5-cm depth, θ_{DHP} was on average $0.025 \text{ m}^3 \text{ m}^{-3}$ larger than θ_{SS} . At the 37.5-cm depth, θ_{DHP} was on average $0.054 \text{ m}^3 \text{ m}^{-3}$ larger than θ_{SS} . The reason for the greater difference between θ_{DHP} and θ_{SS} at 37.5 cm than at 7.5 cm is unclear. The maximum absolute difference between θ_{DHP} and θ_{SS} was $0.047 \text{ m}^3 \text{ m}^{-3}$ at the 7.5-cm depth and $0.077 \text{ m}^3 \text{ m}^{-3}$ at the 37.5-cm depth. At both depths, the maximum absolute difference occurred at the time of sensor installation.

Figure 4 shows the strong linearity of the relationship between θ_{DHP} and θ_{SS} . At the 7.5-cm depth, linear regression of θ_{DHP} vs. θ_{SS} yields a coefficient of determination (r^2) of 0.949 and a root mean square error (RMSE) of $0.00907 \text{ m}^3 \text{ m}^{-3}$ (Table 2). At the 37.5-cm depth, linear regression of θ_{DHP} vs. θ_{SS} yields a slightly lower r^2 of 0.834 and a slightly higher RMSE of $0.0110 \text{ m}^3 \text{ m}^{-3}$. The small RMSE values highlight the good precision achievable with the DPHP technique in the field. These r^2 and RMSE values indicate how well mean water con-

Table 2. Results of linear regression of mean soil volumetric water content measured by dual-probe heat-pulse (θ_{DHP}) technique vs. by soil sampling (θ_{SS}).

Calibration procedure	Depth	Slope	Intercept	r^2	RMSE
	cm		$\text{m}^3 \text{ m}^{-3}$		$\text{m}^3 \text{ m}^{-3}$
Without matching point	7.5	0.750	0.101	0.949	0.00907
	37.5	0.759	0.125	0.834	0.0110
With matching point	7.5	0.750	0.054	0.949	0.00907
	37.5	0.759	0.048	0.834	0.0110

tent could be estimated with 12 DPHP sensors. They do not represent the accuracy or precision of a single DPHP sensor. At both depths the slope of the regression line is about 0.75 and the intercept is about 0.1 (Table 2). In a laboratory evaluation of the DPHP technique, Basinger et al. (2003) reported slopes ranging from 0.86 to 0.94 and intercepts ranging from 0.03 to 0.07. For the present study, the slope is lower and the intercept is higher than those reported by Basinger et al. (2003). However, both the present study and the results of Basinger et al. (2003) suggest that the DPHP technique overestimates θ and underestimates $\Delta\theta$.

In addition to showing the linearity of the DPHP sensor response, Fig. 4 also reveals the variability of water content determined by the sensors and by soil sampling. The bidirectional error bars in Fig. 4 extend one SD in each direction about the mean value (recall that each symbol in Fig. 4 represents the mean of 12 measurements) Water content determined by the DPHP sensors exhibited larger SDs than did water content determined by soil sampling. On average, the SD for the sensors was $0.063 \text{ m}^3 \text{ m}^{-3}$, and the SD for the soil samples was $0.022 \text{ m}^3 \text{ m}^{-3}$. There was no clear relationship between θ_{SS} and the SD of water content determined by the sensors; that is, the variability between DPHP sensors did not depend on soil water content. The variability shown in Fig. 4 must be attributed both to actual spatial variability of θ in the root zone of a growing soybean crop and to measurement errors.

Consideration of Error Sources

To understand why the slope of the linear regression of θ_{DHP} vs. θ_{SS} is lower-than-expected, we must consider at least three potential error sources: the θ_{SS} measurements may have contained errors, the measurements of q and ΔT_m may have contained errors, and the assumptions behind the DPHP technique may have been violated. Errors in the θ_{SS} measurements are the primary potential contributor to the lower-than-expected slope. The first set of soil samples taken during sensor installation and the last set of soil samples taken during sensor extraction may have been subject to evaporation, and the resulting θ_{SS} may have been too small. The processes of sensor installation and sensor extraction each took approximately 8 hr, during which time the soil samples were kept in moisture cans in a shaded area. Given the length of time between sampling and weighing, some potential for evaporation did exist. As noted above, the maximum absolute difference between θ_{DHP} and θ_{SS} occurred at sensor installation, and the second largest absolute difference occurred at sensor extraction. Fur-

thermore, the set of soil samples taken on 13 August may have been biased toward overestimating the true water content at 7.5 and 37.5 cm. Obtaining this set of soil samples was complicated by the compressibility and stickiness of the wet surface soil caused by rainfall on the night of 12 August and the morning of 13 August. It was difficult to ascertain the actual depth that the soil samples represented, and it is certainly possible that the soil samples represented shallower and wetter soil than intended. If so, then this set of samples would act to falsely lower the slope of the θ_{DPHP} vs. θ_{SS} regression. The three sets of questionable soil samples mentioned above are identified by open symbols in Fig. 4. Removing these samples from the analysis leads to a slope of 0.97 for the regression of θ_{DPHP} vs. θ_{SS} at both depths. This is a significant improvement and indicates that errors in θ_{SS} could be largely responsible for the lower-than-expected slope.

Errors in the measurement of q or ΔT_m are a second potential contributor to the lower-than-expected slope of θ_{DPHP} vs. θ_{SS} . If q were consistently underestimated or overestimated by some fixed percentage or by some constant value, then the error would have been automatically accounted for during sensor calibration, and it would not affect θ_{DPHP} . The same holds true for a fixed percentage-wise error in ΔT_m . The only foreseeable way in which either of these measurement errors could cause the slope of the θ_{DPHP} vs. θ_{SS} to be <1 would be if ΔT_m were consistently underestimated by some constant value. This seems unlikely.

Violations of the assumptions behind the DPHP technique are the third potential contributor to the lower-than-expected slope of the θ_{DPHP} vs. θ_{SS} relationship. Some of the assumptions behind Eq. [3] have been investigated carefully. Kluitenberg et al. (1993) investigated the effects of the assumptions that the heat transfer around the DPHP sensor is the same as the heat transfer around an infinite line source and that the finite duration heat pulse approximates an instantaneous heat pulse. They reported that for the sensor geometry and heating time used here, estimates of C obtained by Eq. [1] are within 1% of the estimates obtained by use of more rigorous models. The assumption that heat transfer occurs only by conduction has been investigated by Bilskie (1994) using a numerical model for conduction and convection heat transfer around a heat-pulse sensor. He concluded that under typical conditions, convection has no effect on ΔT at points more than 2 mm from the heater.

In applying Eq. [3], we assumed that ρ_b did not change with time; however, it is possible that ρ_b could change with time in conventionally tilled plots like the ones used in this study. If ρ_b changed with time at the measurement depths in our plots, then the difference between θ_{DPHP} and θ_{SS} should have changed with time also. Instead, the data show that θ_{DPHP} was greater than θ_{SS} by a fairly consistent amount throughout the study (Fig. 3), so change in ρ_b with time cannot adequately explain the data. It is worthwhile to note that any error in ρ_b would effect both θ_{DPHP} and θ_{SS} . For example, if the true ρ_b were 0.1 Mg m^{-3} greater than the ρ_b value used in Eq.

[3], then water content estimated by a DPHP sensor would contain a $+0.018 \text{ m}^3 \text{ m}^{-3}$ error. The same 0.1 Mg m^{-3} error in ρ_b would cause a $-0.020 \text{ m}^3 \text{ m}^{-3}$ error in θ determined by soil sampling if the gravimetric water content of the soil were 0.20 kg kg^{-1} . Then, the difference between the water contents determined with these two methods would be $+0.038 \text{ m}^3 \text{ m}^{-3}$, and the apparent error of the DPHP technique would be greater than the true error.

The effects of the remaining assumptions listed immediately following Eq. [3] are currently unknown, and one or more of these assumptions could contribute to the unexpectedly low slope of the θ_{DPHP} and θ_{SS} relationship. Additionally, the assumption employed in sensor calibration that agar-stabilized water has the same heat capacity as pure water is untested and could potentially influence the slope of the θ_{DPHP} and θ_{SS} relationship. Underestimating the heat capacity of the agar-stabilized water would lead to overestimating the needle spacing. Overestimating the needle spacing would result in a lower-than-expected slope for the θ_{DPHP} and θ_{SS} relationship.

Matching Point Procedure

Previous research has indicated that the DPHP technique excels in determining $\Delta\theta$ (Tarara and Ham, 1997). On the basis of this knowledge, we chose to apply a matching point procedure to adjust the θ_{DPHP} data. We shifted all the water content data for each sensor up or down by a constant value to make the first water content measurement from each sensor equal the water content determined from soil sampling near that sensor at the time of installation. The resulting time series graphs shown in Fig. 5 demonstrate that this matching point procedure improved the accuracy of θ_{DPHP} . The bias was not totally eliminated by use of the matching point procedure, but the absolute value of the bias was decreased. After applying the matching point procedure, θ_{DPHP} was, on average, $0.022 \text{ m}^3 \text{ m}^{-3} < \theta_{\text{SS}}$ at the 7.5-cm depth. At the 37.5-cm depth, θ_{DPHP} was on average $0.025 \text{ m}^3 \text{ m}^{-3} < \theta_{\text{SS}}$. As mentioned previously, some evaporation likely occurred from the initial set of soil samples that were used in the matching point procedure. If evaporation did occur, it could explain the observation that subsequent θ_{DPHP} values tended to be lower than θ_{SS} values. The maximum absolute difference between θ_{DPHP} and θ_{SS} was $0.047 \text{ m}^3 \text{ m}^{-3}$ at the 7.5-cm depth and $0.046 \text{ m}^3 \text{ m}^{-3}$ at the 37.5-cm depth. At both depths, the maximum absolute difference occurred on 13 August, which is when the maximum value of θ_{SS} was recorded. The temporal trend of θ_{DPHP} is unaltered by the matching point procedure.

The one-to-one comparison of θ_{SS} and θ_{DPHP} after the application of the matching point procedure is shown in Fig. 6. The r^2 , RMSE, and slope of the linear regressions of θ_{DPHP} vs. θ_{SS} are unchanged from those in Fig. 4, but the intercepts of the regression lines are reduced from about 0.1 to about 0.05. The vertical error bars in Fig. 6 highlight the reduced variability among sensors, which is the main benefit obtained by applying the

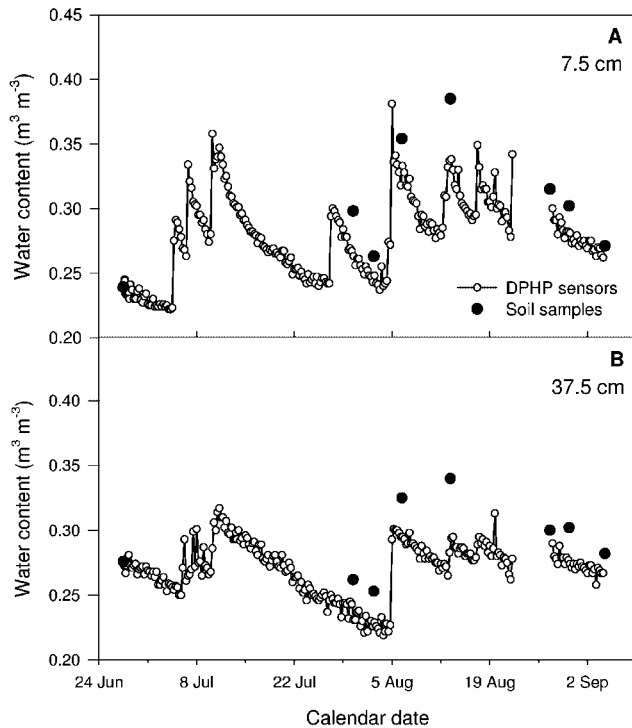


Fig. 5. 2002 time series of water content measured by dual-probe heat-pulse (DPHP) sensors after application of matching point procedure and by soil sampling at (A) the 7.5-cm depth and (B) the 37.5-cm depth.

matching point procedure. Notice that the vertical error bars in Fig. 6 are much shorter than those in Fig. 4. Applying the matching point procedure markedly reduced the variability among the DPHP sensors. Without the matching point procedure, the average SD of water content determined by the sensors was $0.063 \text{ m}^3 \text{ m}^{-3}$; after applying the matching point procedure, the average SD of water content determined by the sensors was $0.026 \text{ m}^3 \text{ m}^{-3}$. This is similar to the average SD for water content determined by soil sampling which was $0.022 \text{ m}^3 \text{ m}^{-3}$. It is reasonable to attribute most of the remaining variability between DPHP sensors to real spatial variability of θ in the root zone. The matching point procedure appears to be a simple method to obtain improved agreement between multiple DPHP sensors in the field. Such agreement among sensors is particularly important in applications where relative differences in θ between different spatial locations are of primary interest. Note that applying the matching point procedure requires no soil sampling beyond that which is normally required to use the DPHP technique. (To use Eq. [3], one must obtain soil samples to determine ρ_b .)

CONCLUSION

The results of this study demonstrate that the DPHP technique performs reliably in the field to make automated measurements of θ with high temporal and spatial resolution. The response of the DPHP sensors was linear, and the precision was excellent with RMSE values around $0.01 \text{ m}^3 \text{ m}^{-3}$. For this soil, linear regression of θ_{DPHP} vs. θ_{SS} yields a slope of 0.75 rather than 1. This

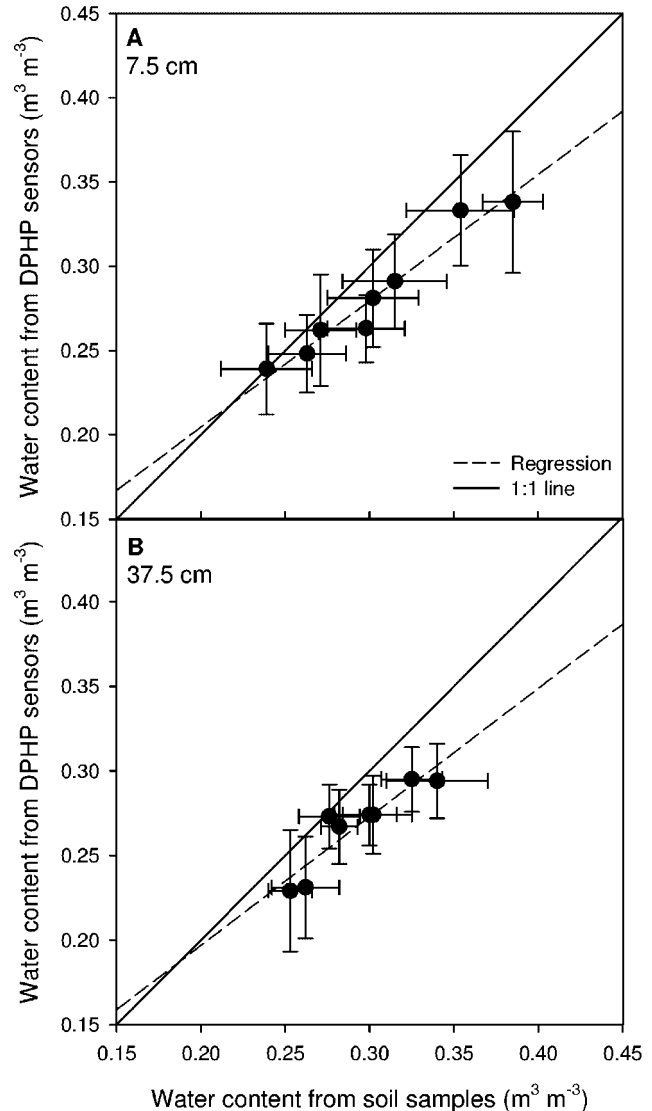


Fig. 6. One-to-one comparison of water content measured by dual-probe heat-pulse (DPHP) sensors after application of matching point procedure and by soil sampling at (A) the 7.5-cm depth and (B) the 37.5-cm depth. Symbols represent the mean of 12 measurements. Error bars represent 1 SD in each direction.

differs from the results of others who have found the slope of this relationship to be between 0.86 and 0.94, but it seems probable that errors in θ_{SS} contributed to the low slope in this study. In any case, the strong linearity of the relationship will be conducive to determining soil-specific calibrations if necessary. A matching-point procedure we adopted improved the accuracy of the technique and improved the agreement between multiple DPHP sensors in the field.

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REFERENCES

- Basinger, J.M., G.J. Kluitenberg, J.M. Ham, J.M. Frank, P.L. Barnes, and M.B. Kirkham. 2003. Laboratory evaluation of the dual-probe heat-pulse method for measuring soil water content. *Vadose Zone J.* 2:389–399.
- Bilskie, J.R. 1994. Dual probe methods for determining soil thermal properties: Numerical and laboratory study. Ph.D. diss. Iowa State Univ., Ames, IA.
- Bristow, K.L., G.S. Campbell, and K. Calissendorff. 1993. Test of a heat-pulse probe for measuring changes in soil water content. *Soil Sci. Soc. Am. J.* 57:930–934.
- Campbell, G.S., C. Calissendorff, and J.H. Williams. 1991. Probe for measuring soil specific heat using a heat-pulse method. *Soil Sci. Soc. Am. J.* 55:291–293.
- Campbell, D.I., C.E. Laybourne, and I.J. Blair. 2002. Measuring peat moisture content using the dual-probe heat pulse technique. *Aust. J. Soil Res.* 40:177–190.
- Kluitenberg, G.J., J.M. Ham, and K.L. Bristow. 1993. Error analysis of the heat pulse method for measuring soil volumetric heat capacity. *Soil Sci. Soc. Am. J.* 57:1444–1451.
- Ren, T., K. Noborio, and R. Horton. 1999. Measuring soil water content, electrical conductivity, and thermal properties with a thermo-time domain reflectometry probe. *Soil Sci. Soc. Am. J.* 63:450–457.
- Song, Y., M.B. Kirkham, J.M. Ham, and G.J. Kluitenberg. 1999. Dual probe heat pulse technique for measuring soil water content and sunflower water uptake. *Soil Tillage Res.* 50:345–348.
- Tarara, J.M., and J.M. Ham. 1997. Measuring soil water content in the laboratory and field with dual-probe heat-capacity sensors. *Agron. J.* 89:535–542.
- Topp, G.C., and P.A. Ferré. 2002. Water content. p. 417–422. *In* J.H. Dane and G.C. Topp (ed.) *Methods of soil analysis. Part 4—Physical methods.* SSSA Book Ser. 5. SSSA, Madison, WI.
- Weast, R.C. (ed.) 1978. *CRC Handbook of Chemistry and Physics.* CRC Press, West Palm Beach, FL.