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Measuring Soil Water Content in the Laboratory and Field with Dual-Probe Heat-Capacity Sensors

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ABSTRACT

Dual-probe heat-capacity sensors were constructed and tested in laboratory and field conditions to determine their application for measuring volumetric soil water content (θ_v). The dual-probe technique uses a transient heat pulse and a temperature sensor to determine the volumetric heat capacity of the soil (ρc_p), which can be subsequently converted to θ_v for a nonswelling soil if bulk density is known. In 1994, 24 dual-probes were simultaneously tested using a multiplexed data acquisition system. In the laboratory, probes were calibrated to the known heat capacity of water. Following calibration, the probes correctly estimated ρc_p of glass beads and water-saturated glass beads to within 2.2 and 0.2% of their calculated values, respectively. Gravimetric and dual-probe estimates of θ_v were compared using the Tempe pressure cell technique to desorb soil columns. The two methods agreed to within 0.03 m^3 m^{-3} and 0.04 m^3 m^{-3} in two soil types, over a range of θ_v from 0.45 m^3 m^{-3} to 0.10 m^3 m^{-3}; estimates of the change in θ_v ($\Delta\theta_v$) between desorption steps agreed to within 0.01 m^3 m^{-3}. In the field, beneath bare soil, estimates of θ_v among three dual-probes installed at the same depth agreed, on average, to within 0.02 m^3 m^{-3}. The probes detected $\Delta\theta_v$ within 30 min during the 21-d field trial. Dual-probe and gamma-attenuation measurements of θ_v agreed to within 0.05 m^3 m^{-3}. In 1995, probe design was improved to produce more robust, reliable instruments. Sixteen probes were installed 10 cm beneath a drip-irrigated row crop. A consistent difference in θ_v of $\approx$0.10 m^3 m^{-3} between mulch-covered and bare soil beds was detected during the 25-d trial. The dual-probe heat-pulse technique for measuring θ_v has direct applicability in agronomic and horticultural production, where small-scale, automated measurements of θ_v are needed.

THE DUAL-PROBE HEAT-CAPACITY SENSOR (dual-probe) has been developed to provide small scale, frequent measurements of soil thermal properties: volumetric heat capacity (ρc_p), thermal conductivity, and thermal diffusivity. The heat capacity of soil influences both the storage and transfer of heat, so it is a necessary parameter in models of soil temperature and heat flow. In a nonswelling soil, changes in ρc_p are due primarily to changes in soil water content; hence, an application of the dual-probe is to allow calculation of volumetric soil water content (θ_v) from measurements of ρc_p.

The heat-pulse technique for measuring ρc_p is based on an idealized scenario for conduction in a solid material, in which a pulse of heat is released instantaneously by a line source of infinite length (Carslaw and Jaeger, 1959, p. 258). In an actual sensor, a heater wire is enclosed in a needle probe of finite length; the heat pulse is applied during a fixed interval, typically 8 s (e.g., Campbell et al., 1991; Bristow et al., 1993). The increase in temperature that occurs as the heat pulse propagates through the medium is detected by a sensor enclosed in a second needle probe at a known distance from the source. An estimate of ρc_p is directly related to the energy released by the source and inversely related to the maximum rise in temperature that occurs at the temperature sensor (Campbell et al., 1991).

Bristow et al. (1993) applied the heat-pulse technique to determine θ_v by using a relationship commonly attributed to de Vries (1963), in which ρc_p is approximated as the sum of the heat capacities of soil constituents. Given a value of ρc_p from the dual-probe, the relationship is solved for θ_v. Bristow et al. (1993) performed laboratory experiments to compare estimates of the changes in soil water content ($\Delta\theta_v$) from dual-probe measurements to $\Delta\theta_v$ measured by gamma attenuation. Dual-probes predicted $\Delta\theta_v$ to within 0.04 m^3 m^{-3} of gamma-attenuation estimates at depths of 1, 3, and 8 cm in containers of repacked soil in which θ_v was varied. Each of their three dual-probe sensors included two needle probes that were 28 mm long, constructed from No. 20 hypodermic tubing, and mounted 6 mm apart. Noborio et al. (1996) constructed a combination dual-probe–TDR (time domain reflectometry) apparatus

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Abbreviations and variables: c_p, heat capacity; ρc_p, volumetric heat capacity; PVC, polyvinyl chloride; q, heat pulse; r, distance between heater and temperature sensor; r', calculated r; TDR, time-domain reflectometry; T_i, initial temperature; ΔT_m, maximum rise in temperature at distance r; X_m and X_o, mineral and organic fraction of soil sample; θ_v, volumetric soil water content.

also with No. 20 hypodermic tubing, but the needle probes were 75 mm long and 10 mm apart. In laboratory experiments, estimates of θ_v by TDR and the dual-probe were compared with gravimetric measurements. The largest differences between dual-probe estimates and gravimetric measurements of θ_v occurred at high values of θ_v. Below water contents of 0.30 $m^3\ m^{-3}$, most dual-probe estimates were within 0.06 $m^3\ m^{-3}$ of the gravimetric values. Both Bristow et al. (1993) and Noborio et al. (1996) noted that dual-probe estimates of θ_v are sensitive to errors in *probe spacing* (i.e., the distance between the heater and the temperature sensor). Although the reports of Bristow et al. (1993) and Noborio et al. (1996) documented the performance of the dual-probe heat-capacity sensor in measuring θ_v, their experiments were conducted in a relatively controlled, laboratory setting. Currently, no results have been published from tests of dual-probes under field conditions. In addition, no data have been collected from multiple dual-probe instruments that are operated simultaneously, which is the next logical step in the development of a useful field instrument.

Our experimental objectives concerned both the construction and testing of dual-probe heat-capacity sensors. Our first objective was to construct sensors robust enough for field use and to operate a number of dual-probes at the same time. Secondly, we wanted to assess the performance of the dual-probes in terms of repeatability and reliability in estimating ρc_p. Finally, we wanted to use a combination of laboratory and field experiments to determine the accuracy of the dual-probe heat-pulse method for estimating θ_v and $\Delta\theta_v$.

THEORY

A dual-probe heat-pulse instrument with a temperature sensor positioned a fixed distance from a line heat source can measure the volumetric heat capacity of soil as

$$\rho c_p = \frac{q}{\pi e r^2 \Delta T_m} \qquad [1]$$

where ρc_p is in J m^{-3} °C^{-1}; q is the amount of energy applied per unit length of heater (J m^{-1}); e is the base of the natural logarithms; r is the distance between the heater and the temperature sensor (m); and ΔT_m is the maximum rise in temperature (°C) that occurs at the distance r from the heater (Campbell et al., 1991). This model is for an idealized heater that is infinitely long and releases heat (q) in an instantaneous pulse. Kluitenberg et al. (1993) determined that for typical probe geometry and heating times, the errors in ρc_p that are associated with this model are negligible (<1%).

The relationship between the volumetric heat capacity and the volumetric water content (θ_v) of soil can be expressed by an equation commonly attributed to de Vries (1963):

$$\rho c_p = 1.92X_m + 2.50X_o + 4.18\theta_v \qquad [2]$$

where X_m, X_o, and θ_v are the mineral, organic, and water fractions of the sample, respectively. The leading coefficients represent the volumetric heat capacity (MJ m^{-3} °C^{-1}) of each soil constituent. If bulk density and organic content remain constant at a given location, then temporal variations in ρc_p are due to corresponding variations in θ_v. Substituting Eq. [1] into Eq. [2] and rearranging terms yields an expression for determining soil water content ($m^3\ m^{-3}$) from dual-probe measurements:

$$\theta_v = \frac{\left(\frac{q}{e\pi r^2 \Delta T_m}\right) - (1.92X_m + 2.50X_o)}{4.18} \qquad [3]$$

Figure 1 shows simulated output from a dual-probe following the application of an 8-s heat pulse in a sandy loam soil with water contents of 0.1 and 0.3 $m^3\ m^{-3}$. The data were generated using an analytical model for a pulsed, infinite, line source (Kluitenberg et al., 1993), where q = 600 J m^{-1}, r = 0.006 m, and X_m = 0.54. The resultant curves show that the range of ΔT_m is small (<1.5°C) and that ΔT_m decreases as θ_v increases. Typically, ΔT_m occurs less than 60 s after the heat pulse, but the exact time of ΔT_m varies with probe geometry and the thermal diffusivity of the soil. The determination of ρc_p and θ_v, however, requires only ΔT_m, not its relative time of occurrence (Eq. [1] and [3]).

Eq. [3] can be rearranged to solve for ΔT_m:

$$\Delta T_m = \left[\frac{e\pi r^2}{q}(1.92X_m + 2.50X_o + 4.18\theta_v)\right]^{-1} \qquad [4]$$

Figure 2 shows ΔT_m simulated for a full range of θ_v, using the same inputs as Fig. 1. From oven-dry to saturated soil, ΔT_m varies by only about 1.2°C; therefore, accurate measurements of ΔT_m are required to correctly estimate θ_v. Taking the partial derivative of ΔT_m with respect to θ_v yields the sensitivity of the temperature rise to the change in soil water content:

$$\frac{\partial \Delta T_m}{\partial \theta_v} = \frac{-4.18q}{e\pi r^2 (1.92X_m + 2.50X_o + 4.18\theta_v)^2} \qquad [5]$$

For a given θ_v, the sensitivity of ΔT_m (inset, Fig. 2) increases as more energy is applied to the probe (q), but decreases with larger probe spacings and higher bulk densities. If one considers the range of water contents in a typical agricultural soil (0.05 to 0.35 $m^3\ m^{-3}$), the average sensitivity of the dual-probe is about 2.5°C per unit change ($m^3\ m^{-3}$) in water content; that is, a 1% change in θ_v causes a 0.025°C change in ΔT_m. For copper–constantan thermocouples, a 1% change in θ_v would cause only a 1 μV change in the electrical signal. Hence, if thermocouples are used to measure ΔT_m, dataloggers with adequate resolution (e.g., 0.33 μV) are required to detect small changes in θ_v.

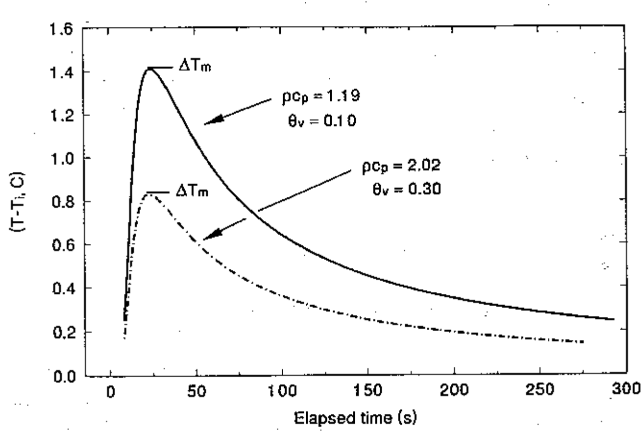

Fig. 1. The change in soil temperature ($T - T_i$) as a function of θ_v, following the release of an 8-s pulse of heat from the dual-probe heater. Curves were simulated as representative of a sandy loam soil where q = 600 J m^{-1}, r = 0.006m, and X_m = 0.54 (Eq. [3]). Units of ρc_p are MJ m^{-3} °C^{-1}; units of θ_v are $m^3\ m^{-3}$. ΔT_m (°C) refers to the maximum rise in temperature detected at the thermocouple probe.

SOURCES OF ERROR

To successfully estimate θ_v with dual-probe heat-capacity sensors, one must measure the following: q, r, ΔT_m, and X_m, or soil bulk density. In Eq. [3], q and ΔT_m must be measured for every estimate of θ_v, whereas only single, fixed inputs of r and X_m are required for each instrument at a given location, assuming that bulk density remains constant with time. However, estimates of ρc_p are most sensitive to errors in probe spacing (Campbell et al., 1991; Kluitenberg et al., 1993, 1995). For example, Campbell et al. (1991) showed that a 2% error in r leads to a 4% error in ρc_p. The sensitivity of Eq. [1] to errors in r shows that probe spacing must be measured accurately and that the needle probes themselves must be rigid enough to withstand installation into soil without bending.

Because the thermocouple is housed in a stainless steel hypodermic needle filled with thermally conductive epoxy, both of which have thermal properties different from those of soil, the heat pulse may travel through the temperature probe differently than through soil. Contact resistance between the soil and the needle probe may reduce the magnitude of the heat pulse crossing the probe (Incropera and De Witt, 1990, p. 86), thereby decreasing ΔT_m and leading to overestimates of ρc_p and θ_v. Errors in ΔT_m also may be caused by the analog-to-digital (A/D) conversion of the temperature signal, but these can be minimized by increasing the sampling frequency of the data logger, using high resolution data logging equipment and applying enough power to the heater probe to ensure that ΔT_m exceeds 0.5°C (Bilskie, 1994).

Although ΔT_m varies with ρc_p and θ_v (Fig. 1), q can be selected to produce an adequate temperature signal ($\Delta T_m >$ 0.5°C) for the expected range of θ_v. The value of q depends on the resistance of the heater and the amount of current that is passed through it, which is usually determined by measuring the voltage drop across a precision resistor installed in series with the probe's heater. Accuracy in measuring q can be improved by proper selection of the precision resistor and by using accurate, high resolution equipment to measure resistance and voltage. Lastly, if no other measurement or model errors are present, one must still use an accurate value for the bulk density of the sample and, in soils with high organic contents, an accurate value for the soil organic fraction. This may require that bulk density be sampled directly at the dual-probe, after completion of the dual-probe measurements. Although this is true for estimates of θ_v, if bulk density and soil organic matter are constant with time, such accuracy is not necessary to estimate $\Delta\theta_v$.

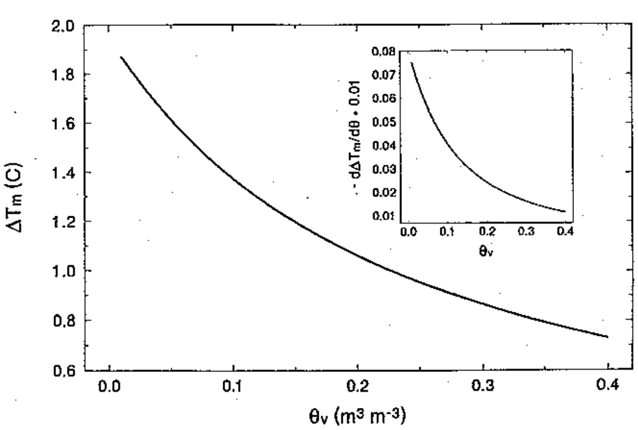

Fig. 2. Expected relationship between ΔT_m measured by the dual-probe and volumetric soil water content (θ_v) for a sandy loam soil. The inset depicts instrument sensitivity, i.e., changes in ΔT_m with respect to changes in θ_v, as a function of θ_v. Plotted values were calculated from Eq. [4] and [5] using the same input data listed for Fig. 1.

MATERIALS AND METHODS

Probe Construction

In 1994, 30 dual-probes were constructed using No. 20 hypodermic needles (0.902 mm o.d., 0.584 mm i.d., 0.152 mm wall thickness; Monoject, St. Louis, MO) as housings for the heat source and the temperature sensor. The beveled tip and aluminum hub of each needle were removed. Pairs of needles were mounted in parallel and held a fixed distance apart (≈6 mm) by inserting them through predrilled holes in a PVC block (26 by 16 by 6 mm; Fig. 3). Effective probe lengths, or the length of needle protruding from the PVC housing, were 27 to 29 mm. Heater probes were made by threading a single strand of Evanohm enameled wire (0.062-mm diam., 444 Ω m^{-1}, Evanohm R Alloy; Carpenter Technology Corp., Orangeburg, SC) through a needle four times, creating a double loop. The heater wire was spliced onto 4.75-m copper leads (28-American Wire Gauge [AWG], 9L28026 ribbon cable; Belden Wire and Cable, Richmond, IN). The average total resistance of a finished heater was 78 Ω (1776 Ω m^{-1} of heater probe). Temperature sensor probes were made by longitudinally centering a Type T thermocouple junction (0.079-mm diam., 40-AWG, TT-T-40-SLE; Omega Engineering, Stamford, CT) in the second needle. The thermocouple wire was continuous from the junction to the data acquisition system. Both needles were filled with thermally conductive epoxy (RBC-4300 and A-121 epoxy hardener; RBC Industries, Warwick, RI), as was the cavity in the PVC housing; therefore, finished probes were electrically insulated and waterproof.

In 1995, 30 probes were built using No. 18 hypodermic needles (1.27 mm o.d., 0.084 mm i.d., 0.203 mm wall thickness; Monoject, St. Louis, MO) to improve rigidity and to help maintain a fixed probe spacing when the instrument was inserted into soil. A lower resistance heater wire (210 Ω m^{-1}) with more durable enamel was substituted (0.079-mm diam., Nichrome 80 Alloy; Pelican Wire Co., Naples, FL). The average total resistance of a finished heater was 38 Ω (840 Ω m^{-1} of heater probe). The lower resistance alloy wire allowed us to apply 12 V to the probe to achieve the desired energy input during the heat pulse. Needle probes were filled with a more viscous epoxy (Omegabond 101; Omega Engineering, Stam-

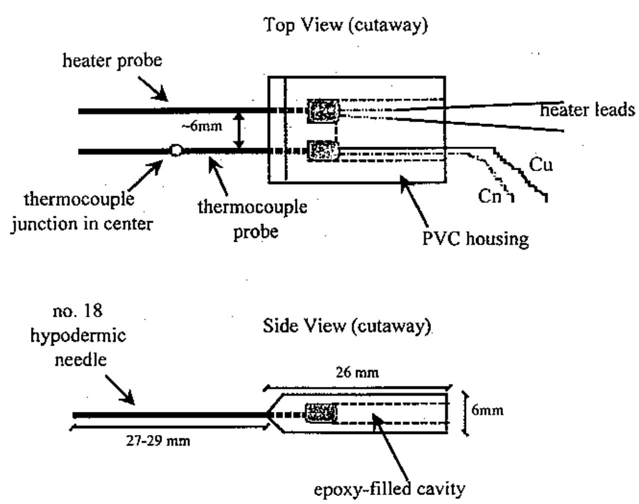

Fig. 3. Schematic diagram of dual-probe heat-capacity sensor (not drawn to scale).

ford, CT), but the PVC housing was filled with the same epoxy used in 1994.

Laboratory Testing

All probes built in 1994 were tested for reliability and accuracy of determining ρc_p in media of known heat capacities. In the first medium, water was stabilized with agar (2 g L^{-1}) to reduce free convection. We did not determine if the agar affected the heat capacity of the solution and accepted the published value of ρc_p for water at 20°C (4.18 MJ m^{-3} °C^{-1}). Two other media, one composed of dry glass beads and one of glass beads saturated with water, were selected to represent the extreme values of ρc_p that one might encounter in an agricultural soil. Glass beads (Spheriglass; Potters' Industries, Persippine, NJ) were packed to a bulk density of 1600 kg m^{-3}. Values of ρc_p for the glass bead media were calculated from an average specific heat (c_p) of soda lime glass (0.87 J g^{-1} °C^{-1}), an average density (ρ) of the composite glass (2500 kg m^{-3}), and the volume fraction of glass spheres in the container (Bansal and Doremus, 1986, p. 35). The heat capacity of the dry glass beads was calculated as 1.38 MJ m^{-3} °C^{-1}; the heat capacity of the water-saturated glass beads was 2.90 MJ m^{-3} °C^{-1}, based on the volume fractions and heat capacities of water and glass. Probes were suspended in each medium such that both the needles and the PVC housing were submerged. Twenty-four probes were tested at the same time, using a data acquisition system composed of a datalogger, multiplexer, and relay driver (CR21-X, AM416, A6REL-12; Campbell Scientific, Logan, UT). Details of the design of the hardware–software system are available from the authors upon request.

Measurements of ρc_p in each test medium were recorded at 30-min intervals for 48 h. The data acquisition protocol was as follows: the initial temperature of the medium (T_i,°C) was measured immediately prior to the application of an 8-s heat pulse to the heater probes ($q \approx 700$ J m^{-1}). The value of ΔT_m was determined by recording the thermocouple temperature every 0.5 s for 60 s and subtracting T_i. Values of q and ΔT_m were used in Eq. [1] along with inputs of individual probe spacings (r) to compute ρc_p at each dual-probe. The amount of energy applied to the heater probe (q) was measured by placing a precision resistor (1 Ω, ±0.1%; VPRS, Vishay Resistors, Malvern, PA) in series with the power supply and the dual-probe heater. The voltage drop across the precision resistor was used to determine the current applied to the heater probe, according to Ohm's Law. During these and other laboratory tests, approximately 2000 heat pulses were applied to each dual-probe.

Estimates of ρc_p by Eq. [1] are most sensitive to measurement errors in probe spacing. In 1994, for each probe, the distance between needles (r) was measured to within 0.0025 mm, under a microscope equipped with a vernier scale. Data collected from the water–agar medium were subsequently reanalyzed by inserting the known heat capacity for water into Eq. [1] and solving for r. This calculated value of probe spacing will be denoted by r'. This method of calibrating dual-probes to a known heat capacity (Campbell et al., 1991) uses calculated probe spacing to account for nonideal heat flow between the heater and the thermocouple junction and extraneous factors in sensor materials or geometry that may affect the accuracy of a dual-probe measurement. In 1995, all new probes were tested in the water–agar medium and calibrated to the heat capacity of water. The calculated probe spacing (r') for each instrument was then used for determining ρc_p in soil columns and in the field.

Soil Column Desorption

Two dual-probes were affixed from opposite sides of a Tempe pressure cell [Product 1405, with No. 1435B1M3 1-bar (0.1 MPa), high-flow ceramic plate; Soil Moisture, Santa Barbara, CA] and centered vertically. Oven-dried, ground soil, moistened with 1 mM $CaSO_4$ solution was hand packed in columns (8.9 cm diam., 3.0 cm high) and around the two dual-probes at midcolumn height. Two columns of Haynie sandy loam (coarse-silty, mixed, calcareous, mesic Mollic Udifluvents) were packed to a bulk density of 1420 kg m^{-3}; two columns of Kahola silt loam (fine-silty, mixed, mesic Cumulic Hapludolls) were packed to bulk densities of 1260 and 1100 kg m^{-3}, respectively. The organic matter content in the two soils was 0.7 and 2.75% by volume, respectively, as determined by the Walkley–Black method (Schulte, 1980, p. 5–8). After the columns had been saturated from below with distilled water, free water was allowed to drain, and the columns were left to equilibrate overnight. The soil columns were desorbed at constant temperature (20°C) by applying incremental pressure to the Tempe cells, in a series of equilibrium steps (Klute, 1986), at 24-h intervals. Kahola silt loam was desorbed in the following steps: 10, 20, 33, 65, and 95 kPa. Haynie sandy loam was desorbed in smaller steps at low pressures (2, 5, 7.5, 10, 15, 20, 33, 65, and 95 kPa) because of the soil's water-retention characteristics. During the desorption, heat pulses were applied to the dual-probes every hour. A 30-min delay occurred between pulses applied to probes in the same soil column to avoid the effects of residual heat or temperature gradients created by the pulse from the companion probe. The soil columns were weighed to the nearest 0.1 g every 24 h. Following desorption, the soil was oven dried (105°C for 24 h), and gravimetric water contents associated with each pressure step were converted to volumetric values (θ_v) as described by Klute (1986).

The specific heat of each soil (c_p) was analyzed with a differential scanning calorimeter (Perkin-Elmer model DSC-2) at the Thermophysical Properties Research Laboratory (Purdue University, West Lafayette, IN). The specific heats of Haynie and Kahola soils were 0.7590 and 0.7650 J g^{-1} °C^{-1}, respectively, at 26°C. Assuming a particle density of 2650 kg m^{-3}, the heat capacity of the soil mineral fraction would be approximately 2.0 MJ m^{-3} °C^{-1}, which is close to de Vries' (1963) value of 1.92 MJ m^{-3} °C^{-1}. Because most users of the dual-probe will not know the specific heat of soil minerals, we elected to use de Vries' value in all calculations, to emulate how the instruments would be used in the field.

Field Trials

In 1994, 24 dual-probes were installed at several depths in a 1- by 1-m plot of Eudora silt loam (coarse-silty, mixed, superactive, mesic Fluventic Hapludolls) near Manhattan, KS (39.12° N, 96.35° W; 324 m above sea level) as part of a separate experiment on near-surface soil heat flux. Probes were installed horizontally by excavating an area to the desired depth, and then gently depressing the probe to ensure good contact between the needles and the soil. The excavated area was carefully backfilled to approach its original bulk density. Access tubes for the gamma attenuation meter were installed at the north and south ends of the 1- by 1-m plot. The gamma probe was calibrated according to the method of Van Bavel et al. (1985). The plot was irrigated to near saturation over 24 h, using a fine mist to avoid ponding, runoff, and surface crusting. The soil was allowed to dry and was protected from rewetting by a retractable, automated rain shelter (12 by 12 m). Because of accidental continuous heating of the dual-probes at the onset of the field trial, most of the heating elements were damaged. Consequently, results of the 1994 field trial will report the performance of three instruments installed at 4.5 cm that operated successfully for 21 d. Heat pulses were applied to the probes every 30 min during the trial.

In 1995, 16 dual-probes were installed beneath a drip-irri-

Table 1. Mean measured (r) and calculated (r') spacing between dual-probe needles, with standard errors and coefficient of variation, for 24 probes built in 1994.

Statistic	Probe spacing†			
		r'		
	r	Water	Dry beads	Wet beads
	mm			
$\bar{x}$	5.75	5.87	5.81	5.85
SE	0.020	0.003	0.002	0.002
CV, %	1.65	2.09	1.74	1.79

† Probe spacing was calculated in three media of known heat capacities: water stabilized with agar ("water"), dry glass beads ("dry beads"), and glass beads saturated with water ("wet beads").

gated tomato (*Lycopersicon esculentum* Mill. cv. Mountain Pride) crop on Haynie sandy loam, 1.6 km west of the 1994 site. One-half of the crop had been transplanted onto plastic mulch-covered beds; the other half had been transplanted onto bare soil. Because the probes built in 1995 contained sturdier needles, they were inserted horizontally at the desired depth (10 cm), directly into an excavated soil face. Data were collected every 2 h for 25 d, during which time no instruments failed. Values of ρc_p were converted to θ_v by Eq. [2]. At the end of the experiment, soil bulk density was measured volumetrically at each probe.

RESULTS AND DISCUSSION

Table 1 lists the mean values of measured (r) and calculated (r') probe spacings for 24 of the dual-probes built in 1994. Calculated values of r' were in good agreement, regardless of test medium, but were all slightly larger ($\approx$0.1 mm) than measured values. Correlation coefficients for the relationship between r' and r were 0.84, 0.81, and 0.74 for water, dry glass beads, and water-saturated glass beads, respectively, which suggests that variation in probe spacing causes the variability in ρc_p measurements, among probes immersed in the same medium. These results support the use of the calibration technique that we described in the methods, in which the input value of probe spacing for each instrument is calculated so that the probe is calibrated to the known heat capacity of water. Calibration to a known heat capacity eliminates the need for precise, accurate, physical measurements of the distance between the heater and the thermocouple junction, and it corrects the probe's estimate of ρc_p for nonideal heat flow. Despite the slight bias between r' and r, the results in Table 1 indicate that r' is stable and repeatable, and that the r' measured in one medium can be applied to measurements collected in other media.

The key to successful use of the dual-probe is not the magnitude of r or r' per se, but that r' is known and remains fixed. Once the instruments are calibrated in water, the distance between the needle probes must remain constant. Therefore, the probes must be installed in the soil with care. The use of sturdier hypodermic needles to house the heater and thermocouple should be investigated, particularly if the instruments will be developed further for use by agricultural producers.

Table 2 shows that the r' determined in water does produce accurate estimates of ρc_p in other media. By inserting r' from water into Eq. [1], the heat capacities of dry glass beads and water-saturated glass beads were

Table 2. Heat capacities (ρc_p) of three test media: actual values, and values estimated using dual-probes and either measured (r) or calculated (r') probe spacing. Dual-probe estimates are means of 2304 observations from 24 instruments.†

Medium‡	ρc_p		
		Dual-probe estimate¶	
	Actual§	r	r'
	MJ m^{-3} °C^{-1}		
Water	4.18	4.36	4.18
Dry beads	1.38	1.41	1.35
Wet beads	2.90	3.02	2.90

† Standard errors (SE) for all estimates of ρc_p were <0.003 MJ m^{-3} °C^{-1}.
‡ Media of known heat capacities: water stabilized with agar ("water"), dry glass beads ("dry beads"), and glass beads saturated with water ("wet beads").
§ Published or calculated values, as described in the text.
¶ Heat capacities estimated by the dual-probes were calculated using Eq. [1] with either r or r' based on calibration in water.

estimated to within 2.2 and 0.2% of their calculated values, respectively. The overall standard error of the mean for the 24 test instruments was less than 0.003 MJ m^{-3} °C^{-1} in all three media, which shows that all probes estimated ρc_p at nearly its actual value. Lack of drift and the small amount of noise in the estimate of ρc_p support the dual-probes' repeatability. The largest standard deviation from the mean ρc_p estimated by a single dual-probe was 0.07 MJ m^{-3} °C^{-1}, which occurred in the agar-stabilized water.

Figures 4a and 4b show θ_v with time for one column of each soil type that was desorbed in the Tempe pres-

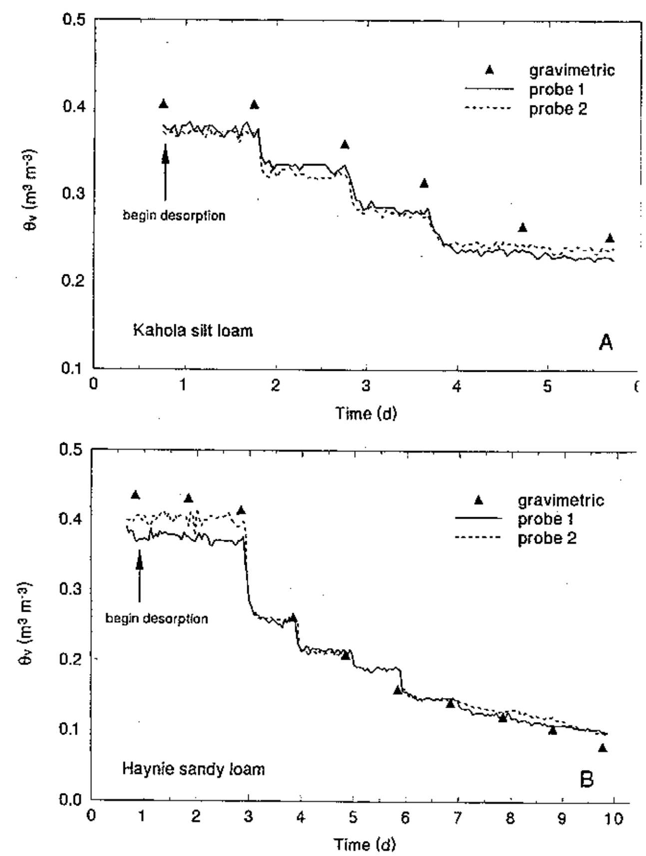

Fig. 4. Soil water content (θ_v) of (a) Kahola silt loam and (b) Haynie sandy loam, estimated by dual-probe and gravimetric method during soil column desorption in Tempe pressure cells. Pressure steps ranged from 2 to 95 kPa at 24-h intervals.

sure cells. Desorption of additional soil columns (data not shown) produced nearly identical results. The mean absolute differences between the dual-probe and gravimetric estimates of θ_v were 0.04 m^3 m^{-3} in Kahola silt loam and 0.03 m^3 m^{-3} in Haynie sandy loam. Dual-probes estimated the cumulative water losses from columns to within 0.03 m^3 m^{-3} of the gravimetric estimate for Haynie sandy loam and to within 0.01 m^3 m^{-3} for Kahola silt loam. The dual-probes responded rapidly to the water loss induced by the step changes in pressure; in addition, probe output was very stable after the soil column had equilibrated. At high values of θ_v, estimates from the two probes in the column of Haynie sandy loam (Fig. 4b) differed, but at lower θ_v, the estimates converged. This behavior may be caused by errors in the measurement of ΔT_m. Because ΔT_m is smaller in wet soil than in dry soil, the relative magnitude of a measurement error in ΔT_m might be larger in wet soil (Fig. 1). One should apply enough power to the heater to minimize the error caused by small values of ΔT_m. Alternatively, one can program the datalogger to automatically change q (i.e., heating time) according to θ_v, thereby maintaining a nearly fixed ΔT_m (e.g., 1.0°C). Dual-probes in the Kahola silt loam (Fig. 4a) consistently underestimated θ_v. The most probable explanation for this result is that of an error in the measurement of soil bulk density because the disagreement was nearly constant over a range of θ_v. Equation [3] shows that errors in X_m and X_o would cause the same effect. The bulk density value estimated for the entire soil column may have differed from that between the dual-probe needles, or from the bulk density of the layer that contained the dual-probes.

Figure 5 shows combined data from the desorptions of soil columns in Tempe pressure cells. The regression shows that on average, the probes tended to slightly underestimate θ_v compared with gravimetric measurements. Disagreement between gravimetric and dual-probe estimates in Fig. 5 could be caused by measurement error in ΔT_m or in q, by model error, by error in the gravimetric method itself, or by the use of incorrect

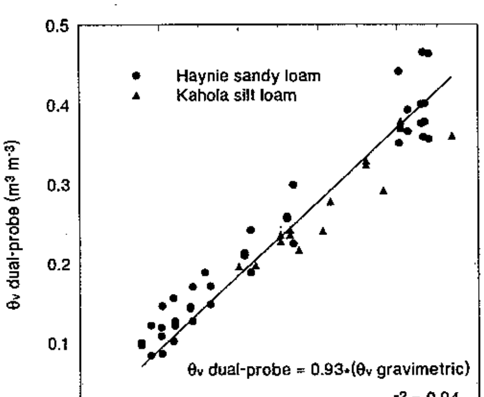

Fig. 5. Comparison between volumetric soil water content (θ_v) estimated by dual-probe and gravimetric methods, from pressure-cell desorptions of soil columns for two soil types. Dual-probe estimates were made using the calculated probe spacing (r'). The regression equation was computed by forcing the intercept through the origin.

physical constants in Eq. [3]. Errors associated with the gravimetric method of estimating θ_v are discussed by Gardner (1986). However, potential error resulting from the physical constants used in Eq. [3] warrants further discussion here.

Accurate measurement of θ_v depends on accurate estimates of the specific heat of the soil constituents and soil bulk density (Eq. [3]). We previously stated our rationale for using de Vries' (1963) estimates of the specific heats of soil minerals and soil organic matter. The following calculation is useful to illustrate the effect of soil bulk density on calculations of θ_v. If a value of 1400 kg m^{-3} were used in Eq. [3] for soil whose true bulk density is 1300 kg m^{-3}, θ_v would be reported as 0.19 m^3 m^{-3} instead of its actual value of 0.21 m^3 m^{-3}. This hypothetical error of approximately 0.02 m^3 m^{-3} is not larger than the total error in θ_v that we observed during the soil column desorptions. However, for certain research applications, very accurate measurements of bulk density will be needed to estimate θ_v to within 1%. For practical application of dual-probes in agricultural production, small errors in estimating bulk density and the use of de Vries' estimate of the heat capacity of soil minerals would not seriously affect estimates of θ_v for the grower. In greenhouse, nursery, and some landscape applications, however, where soilless media predominate, one would need to analyze both the volumetric composition of these products and the heat capacities of their solid constituents. Not only must these values be tabulated, but the shrink–swell characteristics of soilless media must be determined for the dual-probe technique to be useful in the horticulture industry.

If the bulk density and organic matter content of the soil are not known, but remain constant with time, the dual-probes would still correctly estimate changes in θ_v. For many applications, it is $\Delta\theta_v$ that is important, because this value indicates the amount of water that was lost by evaporation, transpiration, and drainage. Figures 6a and 6b show the loss of water ($\Delta\theta_v$) from soil columns at each equilibrium step of the desorption process. Values of $\Delta\theta_v$ determined by the dual-probe and gravimetric methods were nearly identical. The mean absolute difference in estimates between two probes in the same column was 0.004 m^3 m^{-3}. These data show the true strength of the dual-probe heat-pulse technique, that of indicating $\Delta\theta_v$ with time, especially in the range of θ_v typically found in agricultural production.

Figure 7 shows θ_v estimated by three dual-probes at the same depth in the 1994 field trial. All three instruments were in good agreement. Although gamma attenuation measurements were collected up to 0.5 m away from an individual dual-probe, the two methods agreed to within 0.05 m^3 m^{-3}. As in the laboratory, the dual-probes responded rapidly to changes in θ_v, indicated here by irrigation and heavy rain. The sole discrepancy between gamma attenuation and dual-probe estimates of θ_v may have been due to soil bulk density, which was measured at the end of the experiment, between the gamma access tubes. This value probably differed from that of the repacked soil between the needles of an individual dual-probe. Additionally, settling may have occurred in the dual-probe area after the heavy rain on

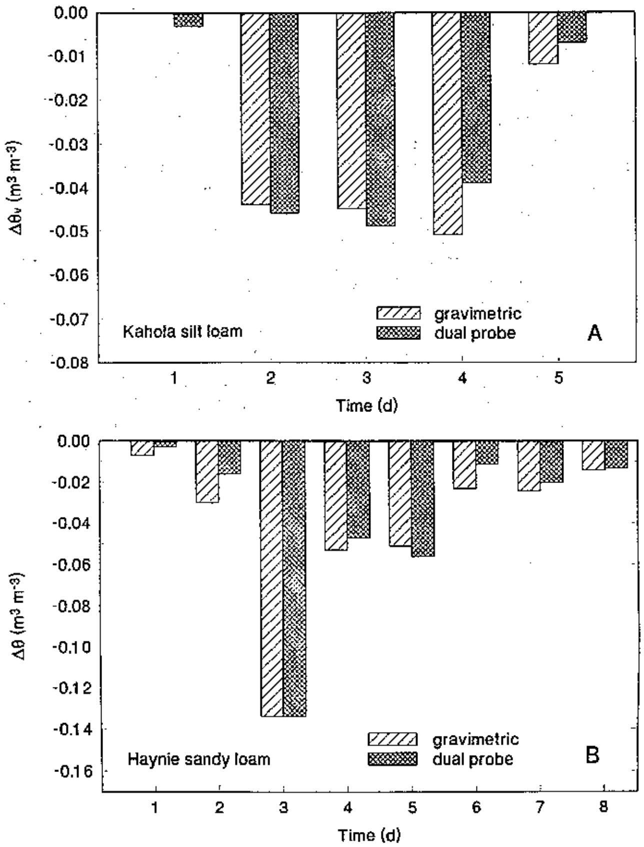

Fig. 6. Changes in water content ($\Delta\theta_v$) for (a) Kahola silt loam; (b) Haynie sandy loam, estimated by dual-probe and gravimetric methods, during soil column desorptions in Tempe pressure cells. Pressure steps ranged from 2 to 95 kPa at 24-h intervals.

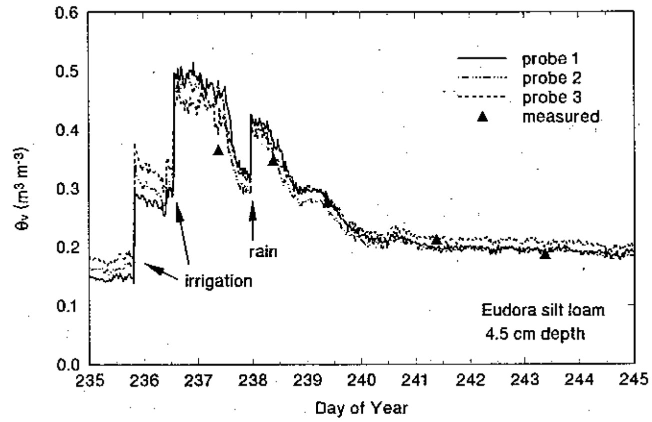

Fig. 7. Field performance of dual-probe heat capacity sensors in estimating θ_v in bare soil, compared with measurements from gamma attenuation.

Day of Year 237–238. The accuracy of, and agreement among, multiple probes at shallow depths suggest a potential application of the dual-probe technique in estimating near-surface evaporation (e.g., Baker and Spaans, 1994). Bristow et al. (1993) reported that strong temperature gradients near the soil surface affected dual-probe performance at 1 cm, but did not influence estimates of θ_v at 3- or 8-cm depths.

In 1995, improvements in probe design resulted in more robust instruments that could be installed directly into undisturbed soil beneath an established crop. The probes detected a consistent difference in θ_v of approximately 0.10 $m^3\ m^{-3}$ between mulch-covered and bare soil, under frequent irrigation (data not shown). No instruments failed during the experiment. Dual-probe measurements were not compared against an independent means of estimating θ_v because of the position of dual-probes (in the root zone) relative to that of the gamma attenuation access tubes. Local variation in θ_v caused by the adjacent root system precluded meaningful comparisons between individual dual-probes. However, from this complication one can propose a further application of dual-probe technology: determining the uptake of water by plants in the field or grown in containers. Positioning several dual-probes in or near the root zone of a potted plant or field crop would permit detailed evaluation of spatial and temporal variation in θ_v. The small sampling volume of the dual-probe ($\approx$3.5 cm^3) makes the instrument appropriate for this type of investigation but also requires attention to both the positioning of individual probes in the soil and to the probes' sampling rate.

CONCLUSIONS

Depending on one's experimental objectives, using dual-probe heat-capacity sensors to determine θ_v and $\Delta\theta_v$ in a nonswelling soil offers a number of advantages over other methods. Because the instruments are electronic, measurements can be automated to provide frequent (e.g., hourly) estimates of ρc_p and θ_v at a number of locations. In 1994, 24 instruments were used simultaneously, and in 1995, 16 dual-probes were operated successfully. The small volume of soil sampled by a dual-probe makes the technique ideal for detecting small-scale spatial and temporal variation in θ_v, especially at shallow depths. The instruments estimated θ_v to within 0.03 $m^3\ m^{-3}$ in the laboratory and to within 0.05 $m^3\ m^{-3}$ in the field. Nonetheless, the strength of the dual-probe technique is in measuring *changes* in θ_v, estimates of which are unaffected by errors in the measurement of soil bulk density, specific heat of the soil mineral fraction, and soil organic matter, if these properties do not change with time. In soil column desorptions in the laboratory, estimates of $\Delta\theta_v$ by the dual-probe method and the gravimetric method agreed to within 0.01 $m^3\ m^{-3}$. The dual-probe heat-pulse method has broad utility in soil and plant science, because values of soil temperature, heat capacity, water content, and thermal diffusivity can be determined from a single reading.

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