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Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes

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Abstract

Soil thermal property data, especially as a function of water content, are currently not readily available. Demand for these data is, however, on the increase because of improvements in and wider applications of soil heat and water transport models. Small dual-probe sensors have been developed that will assist to overcome this shortage in soil thermal property data, and in this paper, we demonstrate their capability through discussion of measurements carried out on unsaturated sandy soil which was subjected to a wetting and drying cycle. The dual-probes employ heat-pulse methodology and yield the soil thermal diffusivity, heat capacity and conductivity from a single heat-pulse measurement. Thermal properties measured in this study are compared with independent estimates made using standard procedures from the literature. These standard procedures require knowledge of the soil mineralogy, and our dual-probe measurements highlight the fact that we cannot always rely on particle size data for accurate mineralogical information. The consequences of using inappropriate mineralogical data and hence, incorrect thermal properties in soil physical analyses, are illustrated. We also show how volumetric water content can be determined from dual-probe heat capacity measurements and other basic soil data (bulk density and specific heat). These data showed the presence of strong hysteresis in the water retention of the material used in this study, and highlight the fact that the dual-probes have an important role to play in monitoring soil water content as well as providing soil thermal property data. © 1998 Elsevier Science B.V.

Keywords: Heat-pulse probes; Soil thermal properties; Soil mineralogy; Soil water content

1. Introduction

Recent advances in heat-pulse theory have lead to the development of small dual-probe sensors that have the ability to improve our routine measurement of soil thermal properties and soil water content (Campbell et al., 1991; Bristow et al., 1993, 1994a,b; Kluitenberg et al., 1995; Tarara and Ham, 1997). These sensors consist of two stainless steel needles mounted in parallel and separated by a distance r. One needle contains a line-source heater (heater probe) and the other a temperature sensor (sensor probe). With the dual-probe device inserted in soil, a heat pulse is applied to the heater and the temperature at the sensor probe recorded as a function of time. The soil thermal diffusivity and volumetric heat capacity are then determined from the measured temperature response with time ($\Delta T(t)$) at the sensor

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probe (Bristow et al., 1994a,b, 1995; Welch et al., 1996). Thermal conductivity is calculated as the product of the diffusivity and heat capacity. The heat capacity measured with the dual-probes can also be used together with other basic soil data to calculate the soil's volumetric water content (Bristow et al., 1993; Bilskie, 1994; Tarara and Ham, 1997). This attribute of the dual-probe is one of the main attractions in pursuing development of this heat-pulse methodology.

In this paper, we demonstrate the capability of the dual-probe heat-pulse sensors by describing measurements of thermal properties and volumetric water content made on sandy soil which was subjected to a drying and wetting cycle. The measured thermal properties are compared with independent estimates made using standard procedures based on soil bulk density, specific heat and volume fraction of the soil constituents (de Vries, 1963; Campbell, 1985). Discrepancies between the dual-probe measurements and standard estimates are discussed and the need for reliable data on soil mineralogy highlighted.

2. Theory

The heat-pulse methodology used with the dual-probes in this study is based on a solution of the radial heat conduction equation for an infinite line heat source in a homogeneous and isotropic medium at a uniform initial temperature. For a heat pulse of duration t_0 (s) the solution is (de Vries, 1952; Kluitenberg et al., 1993; Bristow et al., 1994a)

$$\Delta T(r,t) = \frac{q'}{4\pi(\rho c)\kappa}\left[Ei\left(\frac{-r^2}{4\kappa(t-t_0)}\right) - Ei\left(\frac{-r^2}{4\kappa t}\right)\right] \quad t > t_0 \qquad (1)$$

Here, ΔT is the change in temperature (°C), r is radial distance from the line source (m), t is time (s), q' is the energy input per unit length of heater per unit time (W m^{-1}), ρc and κ are the volumetric heat capacity (J m^{-3} $°C^{-1}$) and thermal diffusivity (m^2 s^{-1}), respectively, of the material surrounding the line source, and $-Ei(-x)$ is the Exponential integral. The Exponential integral can be evaluated using formula 5.1.53 of Abramowitz and Stegun (1972) for $0 \le x \le 1$ and formula 5.1.56 of Abramowitz and Stegun (1972) for $1 \le x < \infty$. The thermal properties can be determined from heat-pulse measurements using the single-point method which uses only the peak of the $\Delta T(t)$ data (Bristow et al., 1994a) or a nonlinear model fit of Eq. (1) to the measured $\Delta T(t)$. This can be achieved using the method of Marquardt (1963) described by Bristow et al. (1995) or the maximum likelihood optimisation procedure described by Welch et al. (1996).

Independent estimates of the soil thermal properties for comparison with the dual-probe measurements were obtained using the standard procedures of de Vries (1963) and Campbell (1985) and here, we summarise the theory on which these procedures are based. Volumetric heat capacity ρc is calculated as the sum of the heat capacities of the individual constituents. Separating the mineral fraction into just two components allows us to write

$$\rho_c = (\rho c)_q\phi_q + (\rho c)_{rm}\phi_{rm} + (\rho c)_w\theta_v + (\rho c)_a\phi_a + (\rho c)_o\phi_o \qquad (2)$$

where ρ is density, c specific heat, ϕ volume fraction, θ_v volumetric water content, and the subscripts q, rm, w, a and o indicate quartz, remaining minerals (i.e., minerals other than quartz), water, air and organic matter, respectively. If the mineral fractions are not separated and contributions of air and organic matter are ignored, Eq. (2) can be rewritten as (Campbell, 1985)

$$\rho c = (\rho c)_m(1-P) + (\rho c)_w\theta_v \qquad (3)$$

where the subscript m now indicates that one is dealing with the 'average' properties of the minerals (i.e., solids), P is total porosity ($P = 1 - \phi_s$) and ϕ_s is the volume fraction of solids. Since $P = 1 - \rho_b/\rho_m$, where ρ_b is soil bulk density, Eq. (2) can also be expressed as

$$\rho c = \rho_b c_m + (\rho c)_w\theta_v \qquad (4)$$

Thermal conductivity λ can be calculated as (McInnes, 1981; Campbell, 1985)

$$\lambda = A + B\theta_v - (A - D)\exp\left[-(C\theta_v)^E\right] \qquad (5)$$

where A, B, C, D and E are soil dependent coefficients which have been related to soil properties by Campbell (1985). These relationships are

$$A = (0.57 + 1.73\phi_q + 0.93\phi_{rm}) / (1 - 0.74\phi_q - 0.49\phi_{rm}) - 2.8\phi_s(1 - \phi_s) \quad (6)$$

$$B = 2.8\phi_s \quad (7)$$

$$C = 1 + 2.6/(m_c^{0.5}) \quad (8)$$

$$D = 0.03 + 0.7\phi_s^2 \quad (9)$$

$$E = 4 \quad (10)$$

where subscripts q, rm and s indicate quartz, minerals other than quatrz, and total solids, and m_c is the clay fraction.

Campbell (1985) indicates that for many mineral soils, the quartz fraction can be taken as zero, and Eqs. (6), (7) and (9) simplified to give

$$A = 0.65 - 0.78\rho_b + 0.60\rho_b^2 \quad (11)$$

$$B = 1.06\rho_b \quad (12)$$

$$D = 0.03 + 0.1\rho_b^2 \quad (13)$$

When using the above approach to predict soil thermal properties it is usual to use Eqs. (4), (5), (11)–(13) in place of Eqs. (2), (5)–(7) and (9). Once ρc and λ have been determined, thermal diffusivity κ can be calculated by definition as

$$\kappa = \lambda / \rho c \quad (14)$$

3. Materials and methods

The dual-probe heat-pulse probes used to make measurements reported here consisted of parallel heater and sensor needle probes made from thin-wall stainless steel tubing, 0.813 mm outer diameter, and 28 mm in length (see Bristow et al., 1993 for details). The heater element was made from 75-μm diameter enamelled Evanohm wire (Wilbur B. Driver, Newark, NJ) which was pulled into the heater needle. Copper–Constantan thermocouples were pulled into and centred in the sensor needles. The needles were then filled with high thermal conductivity epoxy glue to provide water-resistant, electrically-insulated probes. The resistance of the completed heaters was 1141 Ω m^{-1}. The heat-pulse was generated by applying voltage from a direct current supply to the heater for a fixed period. A 21X data logger (Campbell Scientific, Logan, UT) was used to control the application of the heat-pulse, monitor the current through the heater, and measure temperatures at the sensor probe. The instrumentation and wiring of thermocouples in this study enabled temperature measurements with a resolution of 0.0167°C.

The measurements for this study were made in a rectangular soil box in which we packed Sandfly Creek sand (98% sand, 1% silt, 1% clay) to a bulk density of 1.52 Mg m^{-3}. This soil, which has been used extensively by local turf and sporting clubs, was obtained from a deposit just south of Townsville (146°47′E, 19°19′S). The soil box had a porous ceramic base which was connected to a hanging water column that allowed control of soil suction (matric potential) within the box. Two heat-pulse probes were installed at the same depth on opposite sides of the soil box. The dual-probes were installed horizontally into the soil through slots in the wall once the soil had been packed into the box. Initial measurements were made on the dry soil and the soil was then wetted by capillarity. The soil was then taken through a drying and wetting cycle (0–500 mm suction range) by adjusting the hanging water column. Dual-probe readings were made once the system had reached equilibrium following each change in soil suction. A microtensiometer (Ross et al., 1992) installed in the soil box at the same depth as the dual-probes was used to ensure that equilibrium had been reached prior to making the heat-pulse measurements. The heat-pulse measurements were made using an 8 s heat pulse ($t_0 = 8$ s) to provide a power input of 63.5 W m^{-1}. The actual measurement period was 75 s during which time $\Delta T(t)$ data were collected at the sensor probe every 0.5 s. These $\Delta T(t)$ data were analysed using the HPC.EXE code of Welch et al. (1996) to obtain the soil thermal properties. Soil water content was calculated from the measured volumetric heat capacity ρc using Eq. (4) rearranged as

$$\theta_v = \frac{\rho c - \rho_b c_m}{(\rho c)_w} \quad (15)$$

Independent estimates of soil thermal properties were also made using the procedures of de Vries

(1963) and Campbell (1985) which are described in detail in Section 2.

4. Results and discussion

Soil thermal properties measured using the dual-probes are shown in Figs. 1–3 as a function of soil water content θ_v. The thermal diffusivity κ which is small at low water contents, increases as water content increases, reaches a maximum, and then slowly decreases as water content continues to increase towards saturation (Fig. 1) (Hillel, 1980). This is typical of most soils. The relationship between volumetric heat capacity ρc and θ_v is linear (Fig. 2) and is typical of rigid soils in which bulk density does not change with water content. The thermal conductivity λ as a function of θ_v is presented in Fig. 3. Here, we also see the typically low λ for dry soil, a rapid increase in λ as the soil water increases and there is better connectivity between soil particles, and then a further slow increase in λ as θ_v continues to increase towards saturation. In general, there is very close agreement between data from the two dual-probes.

It is important to note that our first attempt at using the procedures of de Vries (1963) and Campbell (1985) (Eqs. (2), (5)–(10) and (14)) to predict the soil thermal properties from basic soil data (see Section 2 for details) did not appear very successful. Because our particle size data showed that we had 98% sand, 1% silt and 1% clay, we assumed that the soil mineralogy would be dominated by quartz. We therefore set $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (i.e., 100% quartz mineralogy). This resulted in a large overprediction in κ and λ, and an underprediction in ρc as indicated by the curve labelled Pred-1 in Figs. 1–3. We then investigated the effect of changes in soil mineralogy on the soil thermal property estimates and these estimates are shown in Figs. 1–3 by the curves identified as Pred-2 and Pred-3. In Pred-2, $\phi_q = 0.2857$, $\phi_{rm} = 0.2868$ (i.e., 50% quartz mineralogy, 50% clay mineralogy), and in Pred-3 $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (i.e., 100% clay mineralogy). The complete set of soil thermal and physical properties for the Sandfly Creek sand used in the calculations are given in Table 1.

The thermal properties determined using the de Vries and Campbell methods are obviously sensitive to the choice of mineralogy (Figs. 1–3). Comparison with our dual-probe measured thermal properties suggested that the soil mineralogy should be roughly 50% quartz and 50% clay, which was somewhat at odds with what we had assumed given the particle

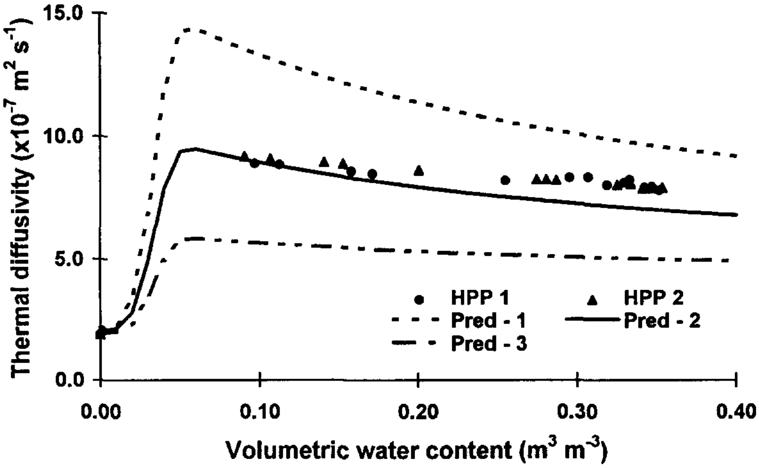

Fig. 1. Comparison of measured and predicted soil thermal diffusivity as a function of water content. The curves labelled Pred-1, Pred-2 and Pred-3 where determined as described in the text using $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (100% quartz mineralogy), $\phi_q = 0.2857$, $\phi_{rm} = 0.2868$ (50% quartz mineralogy, 50% clay mineralogy), and $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (100% clay mineralogy), respectively.

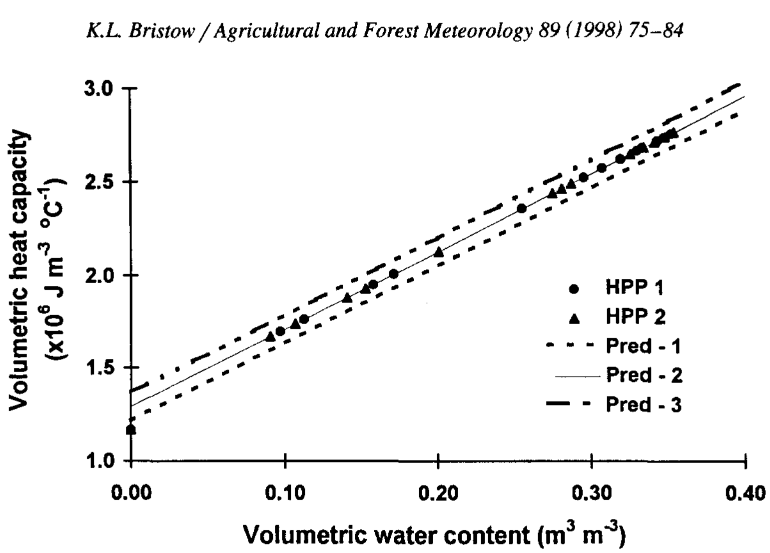

Fig. 2. Comparison of measured and predicted soil volumetric heat capacity as a function of water content. The curves labelled Pred-1, Pred-2 and Pred-3 where determined as described in the text using $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (100% quartz mineralogy), $\phi_q = 0.2857$, $\phi_{rm} = 0.2868$ (50% quartz mineralogy, 50% clay mineralogy), and $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (100% clay mineralogy), respectively.

size data. We therefore had the soil analysed using X-Ray Diffraction (XRD) at the James Cook University Advanced Analytical Centre (Townsville, QLD, Australia), and the results of these analyses showed that our soil consisted of 49% quartz with Albite, K feldspar, amphibole, mica/illite and smectite/smectite based mixed layers making up the remaining 51% of the sample. These results agreed almost exactly with what our thermal property measurements indicated the soil mineralogy should be, and confirmed the ability of the dual-probe technique to provide high quality thermal property data. The results also warned against relying exclusively on particle size data to determine the soil mineralogy.

It is obvious from the predicted curves given in Figs. 1–3 that incorrect mineralogy can lead to quite

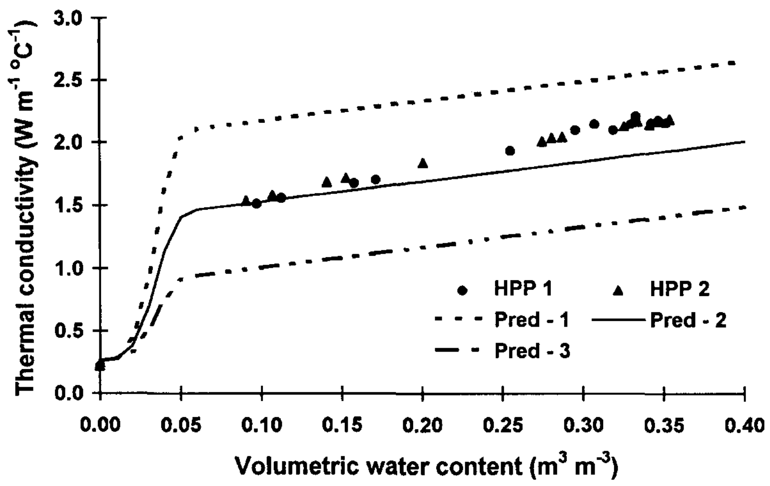

Fig. 3. Comparison of measured and predicted soil thermal conductivity as a function of water content. The curves labelled Pred-1, Pred-2 and Pred-3 where determined as described in the text using $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (100% quartz mineralogy), $\phi_q = 0.2857$, $\phi_{rm} = 0.2868$ (50% quartz mineralogy, 50% clay mineralogy), and $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (100% clay mineralogy), respectively.

Table 1

Thermal properties of soil materials (based after Campbell, 1985) and soil physical properties of the Sandfly Creek sand. Pred-1, Pred-2 and Pred-3 refer to 100% quartz mineralogy, 50% quartz and 50% clay mineralogy, and 100% clay mineralogy, respectively

Property		Values			Units
Specific heat (quartz)		0.8			J g^{-1}°C^{-1}
Specific heat (other minerals ≅ clay)		0.9			J g^{-1}°C^{-1}
Particle density (quartz)		2.66			Mg m^{-3}
Particle density (other minerals ≅ clay)		2.65			Mg m^{-3}
Vol. heat capacity (quartz)		2.13			MJ m^{-3}°C^{-1}
Vol. heat capacity (other minerals ≅ clay)		2.39			MJ m^{-3}°C^{-1}
Sandfly Creek sand		Pred-1	Pred-2	Pred-3	
Measured	clay fraction	0.01			n/a
Measured	silt fraction	0.01			n/a
Measured	sand fraction	0.98			n/a
Measured	bulk density	1.52			Mg m^{-3}
Calculated	ϕ (quartz)	0.5714	0.2857	0	n/a
Calculated	ϕ (other minerals)	0	0.2868	0.5736	n/a
Calculated	ϕ (f) = porosity	0.4286	0.4275	0.4264	n/a

misleading thermal properties. For this soil, use of incorrect mineralogy can cause thermal diffusivity and conductivity to be too large by a factor greater than 2 over a large part of the water content range (Figs. 1 and 3). The error in volumetric heat capacity is not as great, and is constant over the full water content range (0.147 MJ m^{-3} °C^{-1} for our soil) (Fig. 2). While the error in ρc may not seem large, one needs to consider its effect on estimates of soil water content made using Eq. (15), and this is discussed below. It is clear that accurate mineralogical data are needed to ensure good quality results.

In Fig. 4, we show the soil water retention data determined using $c_m = 850$ J kg^{-1}°C^{-1} (i.e., 50% quartz, 50% clay), $\rho_b = 1520$ kg m^{-3}, and the dual-probe measured ρc in Eq. (15). There is, in general, good agreement between measurements obtained with the two probes, and the strongly hysteretic behaviour

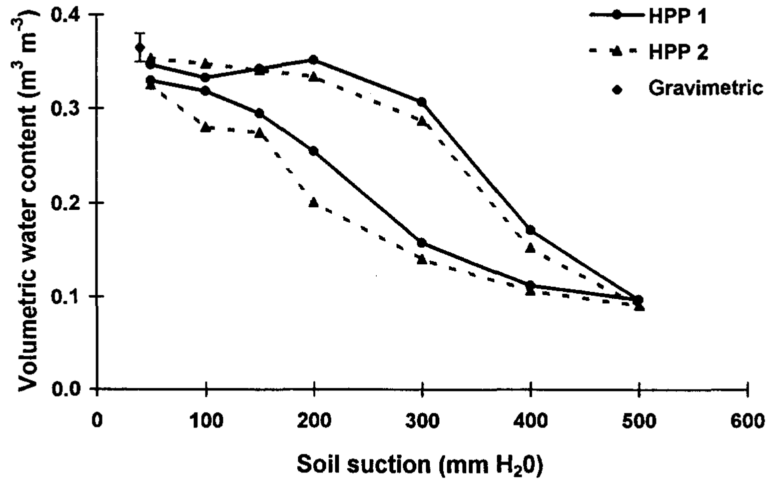

Fig. 4. Volumetric water content measured with dual-probes 1 and 2 as a function of soil suction. Note the strongly hysteretic nature of the soil water retention data. Gravimetrically determined water content at the wet end is included for comparative purposes.

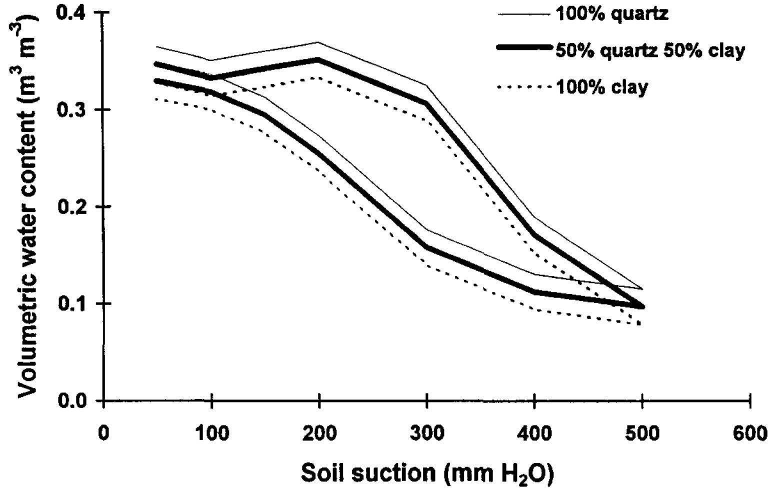

Fig. 5. Data showing the sensitivity to choice of mineralogy (and hence, differences in c_m) when using Eq. (15) together with dual-probe measured soil heat capacities (ρc) to calculate volumetric water contents. These data are for Probe 1.

of the system which was subjected to a drying and wetting cycle is obvious. Reasons for the poor agreement between probes at the 100 and 200 mm suctions on the wetting curve are unclear. Soil water content measured at the wet end by taking several small cores from the soil box agreed well with the dual-probe measurements. Good agreement between water content measurements made with the dual-probe and with independent gamma attenuation methods have been shown previously by Bristow et al. (1993) and Tarara and Ham (1997).

Use of thermal capacity measured with the dual-probe and Eq. (15) to obtain soil water content is dependent on knowledge of the soil specific heat c_m, and hence soil mineralogy. The effect on estimated water contents for probe 1 when mineralogy is

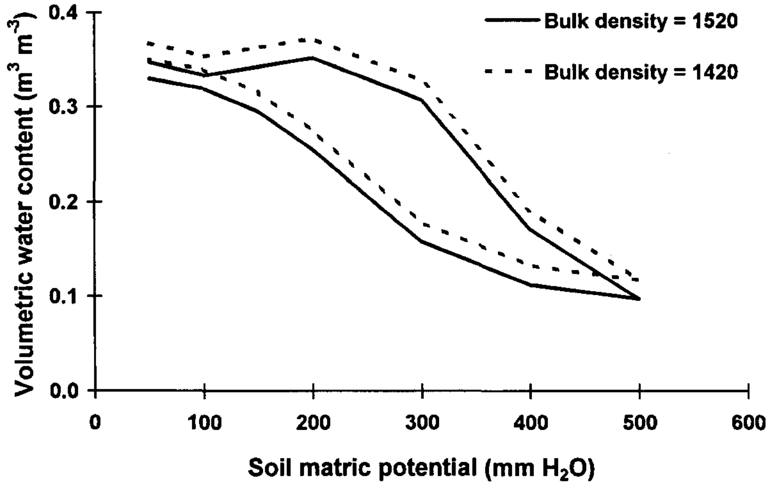

Fig. 6. Data showing the sensitivity to choice of bulk density when using Eq. (15) together with dual-probe measured soil heat capacities (ρc) to calculate volumetric water contents. These data are for Probe 1.

changed from 100% quartz to 100% clay is shown in Fig. 5. For this particular soil, the water contents changed by 0.036 m^3 m^{-3}, which represents an error > 10% at the wet end and a considerably larger error at the dry end. The potential for errors of this magnitude does reinforce the need for care in determining soil mineralogy when using these thermal methods to estimate soil water content.

Eq. (15) is also dependent on knowledge of the soil bulk density ρ_b, and Fig. 6 shows the effect on estimated water contents for probe 1 when ρ_b is changed from 1520 kg m^{-3} to 1420 kg m^{-3}. For this particular soil, the water contents changed by 0.02 m^3 m^{-3}, which represents an error of roughly 5% at the wet end and which increases as one moves into the drier part of the water content range. Although bulk densities can usually be obtained with an accuracy greater than 100 kg m^{-3} care should be taken to avoid the cumulative effect of errors in ρ_b and soil mineralogy.

4.1. Indicative sensitivity in simulated soil heat conduction to use of 'incorrect' mineralogy and hence 'incorrect' thermal properties

Thermal properties dictate the storage and movement of heat in soils and as such determine the temperature and heat flux in soils as a function of time and depth. In Section 4, we showed that thermal properties obtained using soil bulk density, specific heat and the volume fraction of the soil constituents (de Vries, 1963; Campbell, 1985) are sensitive to the choice of mineralogy (Figs. 1–3). Here we use a closed-form solution of the governing equation for heat flow in soils to demonstrate the importance of using the 'correct' mineralogy, and hence the 'correct' soil thermal properties, when calculating soil temperature. The closed form solution for a uniform, infinitely deep soil subjected to a sinusoidally varying surface temperature with a maximum at midday and a minimum at midnight can be expressed as

$$\begin{aligned} T(z,t) &= T_{\text{ave}} \\ &\quad + A_0 \exp(-z/D_d) \\ &\quad \times \sin(2\pi t/\tau - \pi/2 - z/D_d) \qquad (16) \end{aligned}$$

where T_{ave} is the mean soil temperature, A_0 is the amplitude of the temperature wave at the soil surface, τ is the period, and D_d is the damping depth, given by

$$D_d = [\lambda\tau/(\rho c \pi)]^{0.5} = (\kappa\tau/\pi)^{0.5} \qquad (17)$$

We used Eqs. (16) and (17) with thermal properties ρc and λ taken from Figs. 2 and 3 to simulate soil temperature as a function of time and depth. T_{ave} and A_0 were set at 25°C and 10°C, respectively. The midday and midnight temperature profiles are shown in Fig. 7 for a dry($\theta_v = 0$), moist ($\theta_v = 0.06$) and wet soil profile ($\theta_v = 0.3$). The solid lines show results

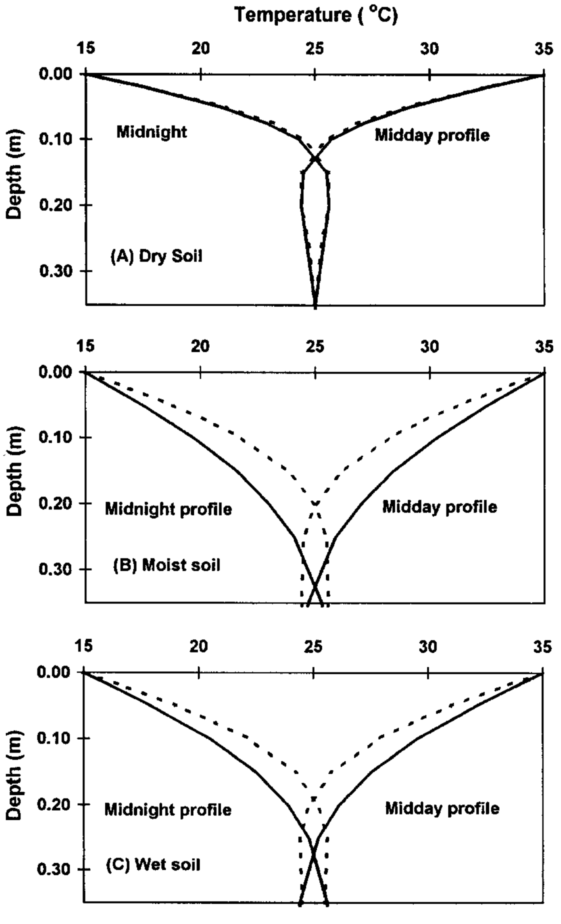

Fig. 7. Midday and midnight temperature profiles for (A) dry (B) moist and (C) wet soil as calculated using Eqs. (16) and (17). The solid lines show results for simulations using Pred-1 thermal properties with $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (100% quartz mineralogy), and the dashed lines show results obtained using Pred-3 thermal properties with $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (100% clay mineralogy).

for simulations using Pred-1 thermal properties with $\phi_q = 0.5714$ and $\phi_{rm} = 0$ (100% quartz mineralogy), and the dashed lines show results obtained using Pred-3 thermal properties with $\phi_q = 0$ and $\phi_{rm} = 0.5736$ (100% clay mineralogy). Under dry conditions the errors due to use of 'incorrect' mineralogy are negligible. Under wet conditions, however, the situation can be quite different with the temperature waves for the quartz mineralogy penetrating much deeper into the profile than those for the clay mineralogy (Fig. 7).

The above differences in behaviour under wet and dry conditions are explainable given the shape of the $\lambda(\theta)$ relationship (Fig. 3) and the form of Fourier's Law ($G = -\lambda \partial T / \partial z$) which describes the soil heat flux G. We see from Fourier's law that λ and G are linearly related, so that a 20% error in λ will translate into a 20% error in G, provided the temperature gradient remains constant. In dry soil the mineralogy has little or no effect on λ (Fig. 3), and hence little effect on G. As soil water content increases however, mineralogy becomes important, and λ, and hence G, can be in error by more than 100% if the mineralogy is assumed to be quartz rather than clay. The resultant differences in the temperature range at a given depth, up to 4.4°C for moist soil and 3.4°C for wet soil at a depth of 0.15 m for our example (Fig. 7), cannot be ignored when addressing temperature dependent processes in the chemically and biologically active near surface zone. Although the situation is somewhat more complex under field situations where heat and water flow interact, these results highlight the need for good quality soil mineralogical data, and for simple, practical methods for making in situ measurements of soil thermal properties.

5. Conclusions

Results of this study have demonstrated the ability of small dual probes to provide reliable measurements of soil thermal properties as a function of water content. It is also clear from the findings reported here that particle size distribution is not always a good predictor of soil mineralogy, and that substantial errors can occur when estimating soil thermal properties if the incorrect mineralogy is used. When used in simulation studies these errors in thermal properties can translate into substantial errors in predicted soil temperature, particularly under moist soil water conditions. The value of measurements such as those made possible by these dual-probes should therefore not be underestimated, and their use will hopefully help provide more comprehensive data sets of soil thermal properties, especially as a function of soil water content.

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