In Situ Measurement of Soil Heat Flux with the Gradient Method

Douglas R. Cobos* and John M. Baker

ABSTRACT

The use of soil heat flux as a critical component of the surface energy balance is routine; however, its accurate quantification is not. The direct measurement of soil heat flux is generally accomplished with soil heat flux plates. However, the presence of heat flux plates causes perturbations in heat and fluid flow in the soil that may give rise to measurement errors. We describe here the direct measurement of soil heat flux with the gradient technique using a tri-needle instrument, where soil heat flux is the product of the soil thermal conductivity measured by transient heating of the center needle and the soil temperature gradient measured between the outer needles. Soil heat fluxes measured this way were compared with those obtained from commercially available soil heat flux plates. Laboratory trials revealed good precision and accuracy (error generally <5%) in measurements of thermal conductivity and soil heat flux with the heated needle technique in a medium-textured sand, but exposed occasional errors in the accurate determination of thermal conductivity arising from poor sensor-soil thermal contact in a coarser medium. Extended field data in a finer-textured soil showed good agreement among needle sensors and heat flux plates, and surprisingly did not reveal errors associated with fluid blockage by the heat flux plates. Our results indicate that the measurement of soil heat flux with the gradient technique with needle sensors is a viable alternative to heat flux plates, and may improve absolute accuracy of this measurement.

Soil heat flux (S) is a critical component of the surface energy balance along with net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and in some cases, canopy storage and photosynthesis. When each of these components is measured independently, the surface energy balance equation should be fulfilled or closed. With the recent increase in long-term eddy covariance measurements of soil-atmosphere CO2 exchange, the closure of the surface energy balance equation is often used as an evaluation of the accuracy of the eddy covariance technique. Residual energy is generally attributed to a variety of errors associated with the eddy covariance measurements of LE and H. One underlying assumption is that measurements of Rn and S are without error, which underscores the necessity of accurate quantification of S. These measurements are especially important when plants are sparse and a major portion of the solar radiation reaches the soil.

The most common method of measuring soil heat flux is the combination method (Fuchs and Tanner, 1968; Fuchs, 1986) where soil heat flux plates are used to measure the heat flux at a known depth, and the heat storage in the layer above the plates is derived by calorimetry, where storage is the product of the temperature change during a given time period and the specific heat of the soil above the plate. The standard design of a soil heat flux plate is a thermopile sensor embedded in a resin disk of known thermal conductivity. The heat flux by conduction through the soil is described by Fourier’s Law

\[ S = -\lambda_{soil} \frac{dT}{dz} \]  

where \( \lambda_{soil} \) is the thermal conductivity of the soil (W m\(^{-1}\) K\(^{-1}\)), and \( dT/dz \) is the vertical temperature gradient (K m\(^{-1}\)). Similarly, heat flux through the soil heat flux plate is the product of the thermal conductivity of the resin material (\( \lambda_{plate} \)) and the temperature gradient across the disk. However, unless \( \lambda_{plate} = \lambda_{soil} \), the heat flux field will either converge or diverge at the plate, so that the heat flux through the disk is not an accurate measure of the soil heat flux. This phenomenon, known as deflection error, was described by Philip (1961), who showed that deflection error could be minimized by reducing \( \lambda_{plate} \) and decreasing the thickness of the plate in proportion to the surface area of the horizontal plate surface. Philip (1961) also developed an analytical correction for deflection error based on the geometry of the plate, its thermal conductivity, and that of the soil. Since this correction requires additional measurements, it is generally ignored.

Recently, a new type of heat flux plate has become commercially available. These plates have a heating element integrated into one side of the sensor. By generating a heat pulse of known power, and measuring the proportion of it that travels through the plate relative to that traveling into the soil, the deflection error can be corrected. However, these heat flux plates are quite large (diam. = 8 cm). Because the heat flux plates are impervious to the flow of fluids in the soil, the transport of both liquid water and water vapor is prevented. This would be expected to cause differences between the thermal properties of the soil above and below the sensor after rainfall or irrigation. Additionally, since the heat flux plates physically block latent heat transport through the soil, condensation on either heat flux plate surface would result in erroneous estimates of soil heat flux by the plate (Fuchs, 1986; Buchan, 1991).

All heat flux plates are also plagued by problems associated with installation. The general installation procedure is to expose a vertical soil face, scrape out a horizontal groove into the face, and insert the heat flux plate into the groove. It is preferable to have the groove slightly thinner than the thickness of the heat flux plate so that the heat flux plate fits tightly into the groove, and is therefore in good thermal contact with the soil on both the upper and lower faces. This method requires some skill if good soil–plate contact is to be achieved without undue perturbation of the surrounding soil. Even when great care is taken in installation, good soil–


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plate contact may not be achieved until the soil has been thoroughly wetted and has reconsolidated.

An alternative to the use of soil heat flux plates is direct measurement of soil heat flux with the gradient technique, where the heat flux is computed directly from Fourier’s Law (Eq. (1)) as the product of the soil thermal conductivity and the gradient of temperature with depth. This method has been proposed a number of times (e.g., Staley and Gerhardt, 1957; Tanner, 1963; Fuchs, 1986; Sauer, 2002) and used in the laboratory to calibrate heat flux plates (van Loon et al., 1998), but the difficulty of determining $\lambda_{\text{soil}}$ accurately has limited the use of this method in the field. Kimball et al. (1976) used the gradient approach to calculate soil heat fluxes with the De-Vries (1963) method to compute $\lambda_{\text{soil}}$ from the weighted averaging of the thermal conductivities of the soil constituents. Because of uncertainty in the DeVries (1963) approach to calculate $\lambda_{\text{soil}}$, Kimball et al. (1976) recommended that the gradient technique be used at a depth of 20 cm where large uncertainties in $\lambda_{\text{soil}}$ have minimal impact on the determination of surface soil heat flux.

Recent advances in the use of transient-heated needle techniques have allowed the direct, accurate, in situ quantification of soil thermal conductivity (Bristow et al., 1994). Use of heated-needle techniques in conjunction with a concurrent, colocated measure of the soil temperature gradient permits a direct calculation of soil heat flux by the gradient technique. With the improved accuracy in the determination of $\lambda_{\text{soil}}$, the gradient technique can be employed at 5- to 10-cm depths where soil heat flux plates are commonly deployed with the combination method. Since the needles used are small in diameter (generally <2 mm), this method is much less intrusive than heat flux plates, and heat and fluid flow in soil are unaltered, preventing both deflection errors and any errors arising from the blockage of liquid water and water vapor. Furthermore, the needle-type sensors can be inserted horizontally into a vertical soil face without excavation of the soil volume directly involved in the measurement, thus minimizing soil disturbance, and promoting good soil–sensor contact. We describe here both laboratory and field evaluations of the applicability of this method for measuring soil heat flux.

**MATERIALS AND METHODS**

**Theory**

Fourier’s Law states that heat flux by conduction is the product of the thermal conductivity of the medium, in this case soil, and the temperature gradient in that medium:

$$S = -\lambda_{\text{soil}} \frac{dT}{dz} \quad \text{(1)}$$

where $S$ is the soil heat flux by conduction (W m$^{-2}$), $\lambda_{\text{soil}}$ is the thermal conductivity of the soil (W m$^{-1}$ K$^{-1}$), and $dT/dz$ is the temperature gradient (K m$^{-1}$). The temperature gradient can be approximated by measuring the soil temperature at two depths, but $\lambda_{\text{soil}}$ is more difficult to quantify.

There are two main methods for direct in situ measurement of soil thermal conductivity by transient heating of needle probes; the single- and dual-probe methods. Both methods use an electrically heated needle, which approximates an infinite line source of heat. The rate at which the heat is conducted away from the line source depends on the thermal properties of the soil, so the thermal conductivity can be determined from the temperature response across time, either adjacent to the heat source (single-needle method; e.g., De Vries, 1952; Shiozawa and Campbell, 1990), or at some finite distance from the heat source (dual-needle method; e.g., Lubimova et al., 1961; Campbell et al., 1991). We have chosen here to employ the single-needle method.

With the single-needle transient heating method, a heater and temperature sensor are mounted together in a single needle. The temperature response of the probe is measured during heating, and the thermal conductivity is derived from a simplified analytical solution of the heat conduction equation. The complete solution for the heat conduction equation as it relates to thermal conductivity measurement by transient heating probe methods is well known. For a thorough discussion of the theory behind soil thermal property measurement by both the single and dual needle methods, see Bristow et al. (1994).

Briefly, the soil thermal conductivity can be closely approximated with the single-needle method by

$$\lambda_{\text{soil}} = \frac{q}{4\pi s} \quad \text{(2)}$$

where $q$ is the energy input per unit length of heater per unit time (W m$^{-1}$) and $s$ is the slope of the linear regression between measured temperature and the natural log of time, $dT/d(ln t)$. It should be noted that during the time period immediately after the commencement of heating, the temperature data are strongly affected by the thermal characteristics of the probe and the contact resistance between the soil and the probe. As heating time increases, the temperature response is increasingly a function of the surrounding soil (Shiozawa and Campbell, 1990). Therefore, the first 5 to 10 s of temperature data should be excluded from the calculation of $s$ (Bristow et al., 1994).

**Sensors**

The sensors used here were custom fabricated by Thermal Logic Devices (Pullman, WA). They consist of three parallel stainless steel needles extending within a plane from a cylindrical epoxy body (Fig. 1). The needles have a diameter of 1.25 mm, and are 60 mm in length. All three needles contain a chromel-constantan thermocouple centered lengthwise in the needle. The center needle contains an additional 70-ohm heating element that extends the length of the needle. All nee-
sensors are installed so that the plane containing the three needles is normal to the soil surface. The center needle is used to measure $\lambda_{\text{soil}}$ with the single-probe heat pulse technique described above, and the outer two needles are used to determine $dT/dz$.

Two self-calibrating heat flux plates (HFP01SC, Huxselsex Thermal Sensors, Delft, the Netherlands) were also included in this study. The HFP01SC plates share the standard heat flux plate design, consisting of a thermopile sensor embedded in a 5 by 80 mm resin disk. The disks have a manufacturer’s stated thermal conductivity of 0.8 W m$^{-1}$ K$^{-1}$. The HFP01SC plates differ from other heat flux plates in that an electric heating element is incorporated into the upper face of the plate, which allows in situ correction for flux divergence. With this method, the heating element is used to produce a heat flux of known magnitude. Under ideal conditions (i.e., perfect soil–plate contact and $\lambda_{\text{plate}} = \lambda_{\text{soil}}$), exactly 50% of this heat flux would travel through the heat flux plate, and the other half would conduct into the soil above the plate. However, because this is not generally the case, a correction is calculated as

$$E_{\text{sen}} = \frac{(G_{\text{sen}}/2)/V_{\text{sen}}}{[3]}
$$

where $E_{\text{sen}}$ is the corrected calibration coefficient (W m$^{-2}$ V$^{-1}$), $V_{\text{sen}}$ is the measured voltage response to the heat pulse, and $G_{\text{sen}}$ is area-averaged power dissipated by the heating element (W m$^{-2}$). This method is designed to correct for errors associated with both deflection error and contact resistance between the plate and the soil (Huxselsex Thermal Sensors, 1999).

**Lab Study**

A comparison between two HFP01SC plates run with the self-calibration routine and three tri-needle probes was conducted under controlled conditions in the laboratory. We used a heat flux plate calibration chamber designed and constructed at the University of Wisconsin, and described in detail by Watts et al. (1990). This apparatus consists of a 45.7- by 50.8-cm rectangular heater plate at the bottom of a 10.2-cm deep chamber that is well insulated on three sides. The upper surface of the chamber is an aluminum heat sink, facilitating heat dissipation through the top of the chamber, thus creating a one-dimensional heat flux through the medium placed in the chamber. The total energy input to the heater plate can be easily determined, and heat losses through the insulation have been previously determined in detail, so the absolute magnitude of the heat flux through the chamber is well known (C.B. Tanner, unpublished data). The walls of the calibration chamber contain four sets of thermocouples in good thermal contact with the media in the chamber. These thermocouple pairs are oriented vertically, 2.86 cm apart, and are used to measure the $dT/dz$ in the chamber. Since $dT/dz$ and $E$ are known, the thermal conductivity of the media in the calibration chamber can be calculated.

We filled the calibration apparatus with commercial quartz sandbox sand. This sand had a medium texture with particle sizes ranging from 0.4 to 0.5 mm. To avoid possible effects from flux divergence through the sides of the calibration chamber, the five sensors were arranged approximately equidistant (11–12 cm) from the edges of the chamber, and were alternated in a circular pattern. This arrangement ensured that each sensor was at least 10 cm from adjacent sensors and chamber walls.

The heat flux plates and the center needle of the tri-needle sensors were centered vertically in the chamber.

Soil thermal conductivity was determined hourly. A constant current module (CE8, Campbell Scientific, Logan, UT) was used to supply a 50-mA current to the heating elements in the center needle of each tri-needle probe, resulting in power dissipation ($q$ from Eq. 2) of 2.917 W m$^{-1}$ from each probe. Current was supplied to the heating elements for a total of 25 s. The temperature response was measured by the thermocouple in each center needle, and recorded by a datalogger (CR21X, Campbell Scientific, Logan, UT). Preliminary analysis indicated that 5 s of excluded data was sufficient to limit the effects of probe thermal properties, and achieve excellent linearity between $\ln t$ and $T$ ($s$ in Eq. [2]). Temperature data from thermocouples in the outer two needles of each probe were recorded every 30 s and averaged across 0.5-h periods. Temperature gradient data were excluded for the first 5 min after the execution of the thermal conductivity measurement routine to minimize the effects of soil heat field perturbations caused by the probe heating.

Soil heat flux was calculated every 30 min with the 30-min averaged value of $dT/dz$, and the most recent hourly measurement of $\lambda_{\text{soil}}$.

The HFP01SC correction routine was performed every two hours, and heat flux data were recorded every 30 s by a separate datalogger. These values were averaged across 0.5-h periods. The chamber thermocouples were read every 5 s, and averaged half-hourly.

**Field Study**

A comparative study was conducted between the tri-needle probes and two HFP01SC plates during the 2002 growing season at the University of Minnesota’s Rosemount Research and Outreach Center, located 24 km south of St. Paul, MN (44°44′ N, 93°05′ W). The soil at this site is predominantly a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) with an average bulk density of 1.25 g cm$^{-3}$. This field is farmed in a conventionally tilled corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] rotation, and was planted in soybeans during this study. Three tri-needle probes (two with 6-mm needle spacing and one with 12-mm spacing) and two heat flux plates were installed on Day 128 (8 May 2002), and measurements were taken until Day 253 (10 Sept. 2002). All heat flux sensors were buried at a depth of 10 cm from the soil surface. The heat flux plates were installed with careful insertion into horizontal grooves that had been cut into a vertical soil face. The tri-needle probes were inserted into the vertical soil face with a guide to ensure that the needles remained parallel, and therefore that the spacing between the thermocouples in the outer needles remained uniform, and oriented so that the plane containing the needles was normal to the soil surface. Upon careful removal at the end of the field study, no changes in sensor spacing were apparent. However, such changes are a point of concern with this type of sensor.

The tri-needle sensors were operated in a manner identical to that described in the laboratory section. The HFP01SC correction routine was performed every 3 h, and heat flux data were recorded every 30 s. These values were averaged across 0.5-h periods. The heat storage in the soil layer above each sensor was calculated, but we have chosen to focus on sensor-based measurements, so these data have not been in-
Table 1. Intersensor measurement differences between the three tri-needle probes during a soil warming period with a medium-textured dry sand in the calibration chamber.

<table>
<thead>
<tr>
<th>Parameter†</th>
<th>Average difference</th>
<th>Maximum difference</th>
<th>Magnitude of average difference</th>
<th>Magnitude of maximum difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{\text{soil}} )</td>
<td>2.7</td>
<td>9.3</td>
<td>0.006 W m(^{-1}) K(^{-1})</td>
<td>0.025 W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( \text{dT/dz} )</td>
<td>2.4</td>
<td>22.9</td>
<td>7.82 K m(^{-1})</td>
<td>33.64 K m(^{-1})</td>
</tr>
<tr>
<td>( S )</td>
<td>5.0</td>
<td>18.6</td>
<td>4.77 W m(^{-2})</td>
<td>12.52 W m(^{-2})</td>
</tr>
</tbody>
</table>

† \( \lambda_{\text{soil}} \) = thermal conductivity of the soil, \( \text{dT/dz} \) = temperature gradient, and \( S \) = soil heat flux.
‡ Maximum % differences in \( \text{dT/dz} \) and \( S \) were the result of differing response times of individual sensors to the onset of heating, and correspond to errors of only 7.98 K m\(^{-1}\) and 1.48 W m\(^{-2}\), respectively.

RESULTS AND DISCUSSION

Lab Study

The precision and reproducibility of the single-probe measurements of \( \lambda_{\text{soil}} \) was evaluated under controlled conditions in the laboratory. When undisturbed, \( \lambda_{\text{soil}} \) measurements by individual sensors varied <3% in all cases, and generally varied <2% during the course of several days in the medium-textured sand.

In the laboratory, a uniform, homogenous media (sand) with a uniform thermal conductivity of 0.273 W m\(^{-1}\) K\(^{-1}\) was used. This allowed an evaluation of the precision of the thermal conductivity, thermal gradient, and soil heat flux measurements among the three tri-needle sensors. Table 1 shows intersensor variability between the three tri-needle sensors in the medium-textured sand during a soil warming period (Fig. 2) where \( S \) was altered from 0 to 126 W m\(^{-2}\). The performance of the tri-needle sensors was somewhat disappointing, with an average intersensor difference in soil heat flux of 5%. However, on further inspection it was determined that the majority of the error occurred as a result of differing response times of individual sensors during the period of rapid heating.

An analysis of the absolute accuracy of measurements of soil heat flux by all sensors was conducted in the laboratory (Table 2). During a 36-h calibration period with dry sand as the medium and the heater plate continuously on, the heat flux through the box varied <2%, averaging 126 W m\(^{-2}\). The two HFP01SC heat flux plates overestimated the heat flux through the chamber by an average of 22%, while the tri-needle sensors underestimated the heat flux by an average of 2% with a maximum error of 6%. Error analysis was conducted on \( \text{dT/dz} \) and \( \lambda_{\text{soil}} \) by comparing these quantities measured by the tri-needle sensors with independent measurements by the calibration chamber. Interestingly, it was found that the tri-needle probes overreported \( \lambda_{\text{soil}} \) by 3%, and underreported \( \text{dT/dz} \) by 5%. The excellent overall agreement in reference and measured \( S \), and the fact that the errors in \( \lambda_{\text{soil}} \) and \( \text{dT/dz} \) are opposite in sign suggest that edge effects and nonhomogeneity of the sand near the built-in chamber thermocouples could result in flawed reference values for \( \text{dT/dz} \) (and consequently, reference \( \lambda_{\text{soil}} \)). However, even if the errors in \( \lambda_{\text{soil}} \) and \( \text{dT/dz} \) had been additive, the magnitude of the absolute error of 8% is still far less than what was observed in the heat flux plates. The large overestimation of \( S \) by the Hukseflux plates may be the result of the very low thermal conductivity of the dry sand (0.273 W m\(^{-1}\) K\(^{-1}\)). The greater thermal conductivity of the heat flux plate material (0.8 W m\(^{-1}\) K\(^{-1}\)) will cause flux convergence through the plate, and thus artificially high heat fluxes. The self-calibration routine of the Hukseflux plates should ac-

![Fig. 2. Reference soil heat flux and soil heat flux from three tri-needle probes and two HFP01SC heat flux plates during the onset of a heating cycle in the heat flux plate calibration chamber. The short period of zero-reference heat flux on Day 54 was the result of an early morning power outage that affected the heating element in the calibration chamber but left the battery-powered sensors and dataloggers unaffected.](image-url)
Table 2. Comparison of relevant values measured with three different instruments. The values from the calibration chamber are used as reference values for error analysis.

<table>
<thead>
<tr>
<th>Parameter†</th>
<th>Chamber (reference)</th>
<th>Tri-probes</th>
<th>Heat flux plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$126 \text{ W m}^{-2}$</td>
<td>$123 \text{ W m}^{-2}$</td>
<td>$154 \text{ W m}^{-2}$</td>
</tr>
<tr>
<td>$S$ error</td>
<td>$3 \text{ W m}^{-2}$ (8 max)</td>
<td>$0.281 \text{ W m}^{-1} \text{ K}^{-1}$ (0.018 max)</td>
<td>$28 \text{ W m}^{-2}$ (33 max)</td>
</tr>
<tr>
<td>$\lambda_{\text{soil}}$ error</td>
<td>$0.008 \text{ W m}^{-2} \text{ K}^{-1}$ (0.018 max)</td>
<td>$-24 \text{ K m}^{-1}$ (39 max)</td>
<td></td>
</tr>
<tr>
<td>$\frac{dT}{dz}$</td>
<td>$462 \text{ K m}^{-1}$</td>
<td>$439 \text{ K m}^{-1}$</td>
<td>$-24 \text{ K m}^{-1}$ (39 max)</td>
</tr>
</tbody>
</table>

† The reference thermal conductivity value was determined from known values of reference $S$ and reference $dT/dz$ and was not measured directly.

Field Study

The three tri-needle probes were deployed in a field setting during the growing season of 2002 alongside two HFP01SC plates, with the intention of evaluating the overall performance of the needle sensors, isolating errors associated with fluid flow blockage by the HFP01SC plates. In the field, spatial variability in the thermal properties of the soil and the surface energy balance, especially under a partially closed plant canopy, confounds attempts to intercompare soil heat flux sensors. However, some general conclusions about sources of error can be drawn from an extended field data set.

The overall agreement among all five sensors was generally good (Fig. 3). However, the lack of a reliable reference, the effects of spatial variability on the thermal properties of the soil, and differences in heat storage above the sensors make extended analysis of agreement among the sensors impossible. Soil thermal conductivity

![Diagram](https://via.placeholder.com/150)

**Fig. 3.** Example diel cycle of soil heat flux measured in an early season soybean field by three tri-needle probes and two HFP01SC heat flux plates at 10 cm. Storage corrections have not been applied.
during the season ranged from 0.672 to 2.24 W m\(^{-1}\) K\(^{-1}\) as water content changed, with a mean of 1.26 W m\(^{-1}\) K\(^{-1}\). Agreement between the heat flux plates and tri-needle sensors was not correlated with soil thermal conductivity, indicating that the Hukseflux self-calibration routine was effective in correcting for flux divergence in the field setting, in contrast with the measurements in the calibration chamber with dry sand.

One of the main proposed benefits of tri-needle sensors relative to heat flux plates is a minimization of errors associated with the blockage of fluid flow in the soil by the heat flux plates. During the course of the field study, a total of seven major rainfall events were measured with enough precipitation to deliver a wetting front past the 10-cm depth where the heat flux plates and tri-needle sensors were buried. Subsequent to each of these rainfall events, the typical thermal shock was observed among all sensors as water came into contact with the sensors. This phenomenon was relatively short lived (0.5–2 h), and all sensors appeared to regain function shortly thereafter. After each major rainfall event, the HFP01SC calibration coefficients decreased by up to 25% when the next self-calibration was performed. Good agreement was observed between the soil heat flux measured by the plates and the tri-probes after rainfall events, indicating that water blockage during infiltration events by the HFP01SC plates did not cause significant errors despite their relatively large surface area. This is probably partially because of the self-calibration feature of the HFP01SC heat flux plates, and may not be true of all heat flux plates. Errors associated with condensational warming of the surfaces of the heat flux plates are more difficult to analyze in the field, and were not identified here. It should be noted that neither standard heat flux plates nor the tri-needle sensors account for latent heat losses below the sensor, which could give rise to significant errors in the determination of soil heat flux in some situations (Mayocchi and Bristow, 1995). Placement of the heat flux sensors relatively deep in the soil profile (10 cm) should minimize these errors under most field conditions.

**CONCLUSIONS**

The use of needle-type sensors for direct application of the gradient technique has been shown here to be a viable method for accurate quantification of soil heat flux in the field setting. The reproducibility of soil thermal conductivity measurements in a medium-textured dry sand for individual sensors was excellent. However, laboratory investigations in a coarse sand exposed errors in the determination of thermal conductivity that were attributable to poor sensor-soil thermal contact. These problems were not observed in natural soils, where the soil is generally finer textured and wetter.

A field intercomparison among the tri-needle sensors and commercially available heat flux plates yielded good agreement, with relative differences that were generally small. Expected errors associated with heat flux plates acting as barriers to fluid flow in soils were not observed in more than 100 d of field use.

**ACKNOWLEDGMENTS**

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