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CAREFUL MEASUREMENTS AND ENERGY BALANCE CLOSURE – THE CASE OF SOIL HEAT FLUX

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1. INTRODUCTION

One of the characteristics that makes John Norman a unique and special scientist is his interest in and contributions to both experimental science and simulation modeling. Some scientists familiar with his research career may be most aware of his contributions to simulation modeling including Cupid and PALMS. The second and closely coupled portion of his scientific contributions relate to his innovative approaches to making accurate, detailed biophysical measurements and, when necessary, development of instruments to make these measurements possible.

An area of persistent concern in micrometeorological measurements is the failure to close the energy balance at surface flux stations. While most attention has focused on errors and corrections associated with the eddy fluxes, none of the energy balance terms are measured without error. The flux plate method is the most commonly employed method for measuring soil heat flux (G) and, although simple to use, is also susceptible to significant errors.

A series of experiments were completed to quantify errors associated with energy and water flow distortion and thermal contact resistance of soil heat flux plates and techniques to alleviate these errors (Sauer et al., 2003; Ochsner et al., 2006; Sauer et al., 2007). These studies indicated that flux plates consistently underestimate G by as much as 70% and corrections to overcome this systematic bias were not practical. Some of the uncertainty in plate performance is associated with sensor calibration, for which there is no standard technique. The objective of the current research was to complete simultaneous calibration of several types of commercially-available soil heat flux plates. In order to eliminate possible errors due to different calibration media and especially thermal contact resistance, the measurements were completed with the plates embedded in agar-stabilized water.

2. METHODS

Four commercially-available flux plates with a range of thermal conductivity (λ), face area, and thickness were evaluated (Table 1; CN3, Carter-Scott Manu. Pty. Ltd.[†], Brunswick, Victoria, Australia; GHT-1C, Int. Thermal Instr. Co., Del Mar, CA; HFT1.1, Radiation & Energy Balance Systems, Seattle, WA; 610, C. W. Thornthwaite Assoc., Pittsgrove, NJ). All measurements were completed in a calibration

Table 1. Plate designation, dimensions and manufacturer-specified thermal conductivity of flux plates evaluated.

Plate	Area	Thickness	λ
	(cm^2)	(mm)	($W\ m^{-1}\ K^{-1}$)
CN3	13.9	7.0	0.40
GHT-1C	27.0	5.7	0.26
HFT1.1	11.3	3.9	1.0
610	4.9	2.6	0.33

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[†]Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U. S. Department of Agriculture.

box consisting of an insulated 0.46 x 0.51 x 0.089-m cavity filled with agar-stabilized water (10 g L^{-1}). A heat source plate on the bottom, a heat sink plate on top, and insulated side walls enabled one-dimensional heat flow in the cavity space. The cavity was first filled half full with agar (4.5 cm-deep). After the agar set three flux plates of each design were positioned on the agar (Fig. 1) and additional agar added to fill the cavity. Calibration runs were completed at fluxes of 21, 43, 86, and 172 W m^{-2} for several days until steady-state conditions were achieved at each flux. One day of hourly data under steady-state conditions at each flux were used for analysis (Fisher's Protected LSD) and interpretation.

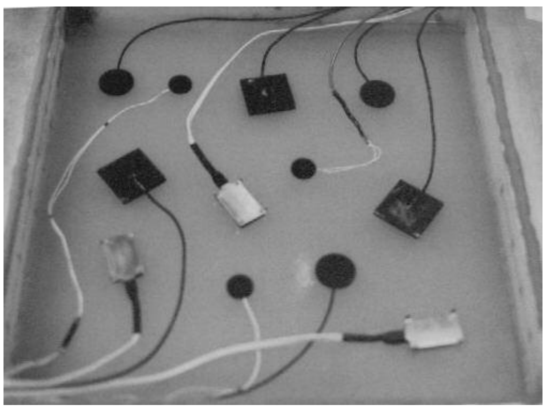

Fig. 1. Distribution of heat flux plates on agar when the cavity was half full.

Manufacturer-specified calibration factors were used for individual plates to obtain plate flux values. Philip (1961) proposed a correction for heat flow divergence around flux plates based on the dimensions of the plate and difference in λ between plate and media

$$G_m/G = 1/[1 - \alpha r(1 - \lambda/\lambda_m)] \quad (1)$$

where the subscript m refers to the flux plate, α is an empirical factor relating to plate shape and r is a dimensionless factor equal to plate thickness divided by the square root of the plate face area. The λ of the agar as measured during the plate calibration runs was 0.567±0.004 W m^{-1} K^{-1}.

3. RESULTS

Average G_m measured with the CN3, GHT-1C, and 610 flux plates were always less than the known flux through the agar (Fig. 2). The underestimates averaged across all fluxes were 20.1, 22.6, and 33.5% for the CN3, GHT-1C, and 610 plates, respectively. The HFT1.1 plates also underestimated the agar G at 21 and 43 W m^{-2} (by 31.9 and 5.9%, respectively) but overestimated the agar G at 86 and 172 W m^{-2}. The HFT1.1 G_m at 86 W m^{-2} was the only instance when the plate G_m was not significantly greater or less than the agar G. These results were not unexpected as the CN3, GHT-1C, and 610 flux plates have a manufacturer-specified λ_m from 0.17 to 0.31 W m^{-1} K^{-1} less than the agar and heat flow distortion around the plates would be expected. The HFT1.1 flux plate has a λ_m 0.43 W m^{-1} K^{-1} greater than the agar resulting in the highest G_m values at all fluxes and G_m equivalent to or greater than the agar G at 86 and 172 W m^{-2}.

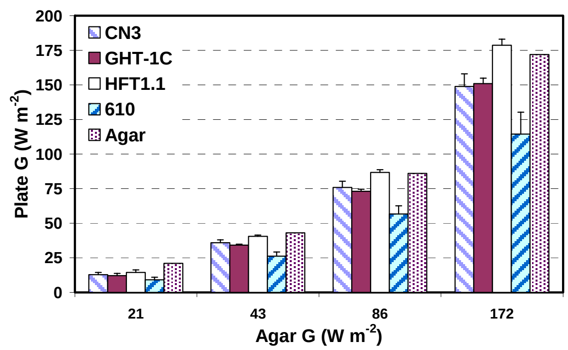

Fig. 2. Average G_m for triplicate flux plates of the models evaluated and the known agar G. Error bars represent one standard deviation.

If heat flow distortion was the primary cause for lack of agreement between the plate G_m values and the agar G then the Philip correction should bring the G_m values into agreement with the agar G. Fig. 3 shows

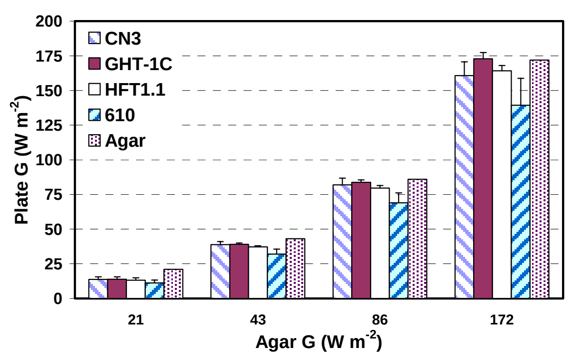

Fig. 3. Average G_m for triplicate flux plates following the Philip correction using manufacturer-specified λ_m values. Error bars represent one standard deviation.

that agreement is significantly improved following the Philip correction for all plates except the HFT1.1. agar G although it was never statistically equal to the known G.

The manufacturer-specified λ_m values (Table 1) were used to obtain the Philip corrected-values shown in Fig. 3. Sauer et al. (2007) reported measured λ_m for each of these plates, which were found to be 0.6, 0.63, 1.26, and 0.21 W m^{-1} K^{-1} for the CN3, GHT-1C, HFT1.1, and 610, respectively. Fig. 4 shows the G_m values with the Philip correction using the measured λ_m values.

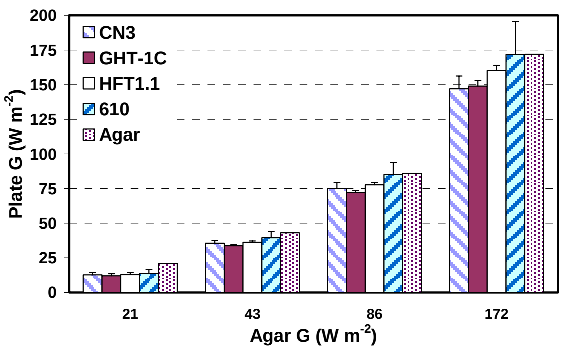

Fig. 4. Average G_m for triplicate flux plates following the Philip correction using measured (Sauer et al., 2007) λ_m values. Error bars represent one standard deviation.

Overall, use of the measured λ_m values failed to improve agreement between the G_m values and the agar G. For the CN3, GHT-1C, and HFT1.1 plates there was actually better agreement without the Philip correction than with the Philip correction using measured λ_m values. However, the best agreement of all plate-agar comparisons was achieved for the 610 plate and the Philip correction using measured λ_m, which produced G_m values statistically equal to the agar G at 86 and 172 W m^{-2}.

4. CONCLUSIONS

Results of this study and previous research indicates that systematic errors resulting in consistent underestimates of G when using flux plates is likely to occur. Efforts to avoid heat and water flow distortion and thermal contact resistance or correct for these errors have proven difficult to achieve. If more accurate G values are desired, development of new measurement approaches will be necessary. At present, advancements in heat dissipation sensor technology make the gradient method one possibility (Cobos and Baker, 2003; Ochsner et al., 2006). Another possibility is the development of a perforated flux plate that minimizes errors associated with the standard impervious plate design (Sauer et al., 2008). Improving G measurement accuracy should be a component of any comprehensive effort to improve surface energy balance closure.

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