Agricultural and Forest Meteorology 216 (2016) 129–140

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Soil heat flux calculation for sunlit and shaded surfaces under row crops: 2. Model test☆

Paul D. Colaizzi[a,*], Steven R. Evett[a], Nurit Agam[b], Robert C. Schwartz[a], William P. Kustas[c], Michael H. Cosh[c], Lynn McKee[c]

[a] USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, USA
[b] Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede-Boqer Campus, 84990, Israel
[c] USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD, USA

ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form 5 August 2015
Accepted 11 October 2015

Keywords:
Calorimetric method
Cotton
Energy balance model
Irrigation
Model sensitivity
Texas

ABSTRACT

A method to calculate surface soil heat flux (G_0) as a function of net radiation to the soil ($R_{N,S}$) was developed that accounts for positional variability across a row crop interrow. The method divides the interrow into separate sections, which may be shaded, partially sunlit, or fully sunlit, and calculates $R_{N,S}$ for each interrow section using a relatively simple geometric approach. Normalized $R_{N,S}$ is then related to normalized G_0 for 24 h time steps through a single empirical parameter. The method was tested against G_0 determined using the calorimetric method for upland cotton (*Gossypium hirsutum* L.) with north–south (NS) and east–west (EW) row orientations from sparse to full canopy cover at Bushland, Texas, USA. Data were grouped by canopy cover for three periods in the growing season, including sparse (BEG), medium (MID), and full (END). For each row orientation, measurements used for calorimetric G_0 were located at five interrow positions in two replicates; one position was used for model calibration, and four positions were used for the model test. For NS, soil temperature and volumetric soil water content at 0.02 and 0.06 m depths and soil heat flux at the 0.08 m depth below the surface were measured. For EW, soil temperature and soil heat flux were measured at the same depths and positions as for NS, but volumetric water content was obtained only at a single depth (0.05 m) and in the interrow center in three replicates. Discrepancy between calculated and calorimetric G_0 was larger for EW compared with NS rows for BEG and MID periods (partial canopy cover), but nearly the same during the END period (full canopy cover). During BEG and MID, the greater discrepancy of calorimetric G_0 vs. calculated G_0 for EW rows compared with NS may have been related to measurement of volumetric soil water at only a single depth and interrow position, as well as lower sensor accuracy, compared with those used in NS rows. For NS, the Nash–Sutcliffe modified Index of Agreement was 0.81–0.84; for EW, it was 0.69–0.78 throughout the growing season. The method provided a straightforward way to account for positional variability of G_0 across a row crop interrow, which was most important for NS rows during sparse to medium canopy cover.

Published by Elsevier B.V.

1. Introduction

Surface soil heat flux (G_0) is an important component of the soil–plant–atmosphere energy balance. For bare soil, G_0 can be up to 50% of net radiation (R_N); for partial vegetation cover, particularly row crops, G_0 and soil net radiation ($R_{N,S}$) can have substantial positional variation as related to soil illumination by direct beam solar irradiance (Ham and Kluitenberg, 1993; Heilman et al., 1994;

Abbreviations: a, empirical constant used in surface soil heat flux model (no units); BEG, beginning period of the study during sparse canopy cover; END, end period of the study during full or nearly full canopy cover; EW, east–west crop row orientation; f_{SIS}, fraction of shading of an interrow section (no units); G_0, soil heat flux at the soil surface (W m^{-2}); $G_{0,MAX}$, maximum G_0 over 24 h (midnight to midnight) (W m^{-2}); $G_{0,MIN}$, minimum G_0 over 24 h (midnight to midnight) (W m^{-2}); MID, middle period of the study during intermediate canopy cover; NS, north–south crop row orientation; R_N, total net radiation (W m^{-2}); $R_{N,S}$, soil net radiation (W m^{-2}); $R_{N,S,MAX}$, maximum $R_{N,S}$ over 24 h (midnight to midnight) (W m^{-2}); $R_{N,S,MIN}$, minimum $R_{N,S}$ over 24 h (midnight to midnight) (W m^{-2}).

☆ Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

* Corresponding author.
E-mail address: paul.colaizzi@ars.usda.gov (P.D. Colaizzi).

http://dx.doi.org/10.1016/j.agrformet.2015.10.009
0168-1923/Published by Elsevier B.V.

Kustas et al., 2000; Agam et al., 2012a,b; Evett et al., 2012a). In situ estimates of G_0 can be made using the calorimetric or temperature gradient methods, which require measurements of soil heat flux (calorimetric only), soil temperature, and volumetric soil water content at depths down to 0.1–0.2 m below the surface (Sauer and Horton, 2005).

Estimates of G_0 by the calorimetric, temperature gradient, or other methods are limited by the number of in situ measurements that can be practically obtained. Because G_0 is primarily related to R_N or $R_{N,S}$, for practical applications it is typically calculated as a function of these (e.g., Santanello and Friedl, 2003) and sometimes other parameters in order to account for changes in vegetation cover (e.g., Kustas and Daughtry, 1990; Kustas et al., 1993). Most applications consider spatial scales larger than the substrate (soil) and vegetation, and hence do not account for the spatial variation that is known to occur at smaller scales (Maes and Steppe, 2012). Furthermore, the small-scale spatial variability of some energy flux components may tend to cancel out at longer (i.e., daily or 24 h) time steps for row crops even with partial cover; these components include G_0 (Agam et al., 2012a) and soil evaporation (Agam et al., 2012b). On the other hand, many energy balance models are designed to be driven by remotely sensed measurements of surface reflectance and brightness temperature. These applications often rely on one-time-of-day measurements, and therefore must be temporally scaled to daily or longer time steps (Peters and Evett, 2004; Colaizzi et al., 2006; Van Niel et al., 2011, 2012). Errors in any one-time-of-day calculated energy balance component, such as G_0, can potentially lead to larger errors following temporal scaling (Colaizzi et al., 2014). For row crops with partial cover, sources of error might include changes in the proportion of sunlit and shaded soil impacting the overall surface energy balance. Our hypothesis is that soil–plant–atmosphere energy balance models, particularly those designed for remote sensing applications, might be improved by accounting for the positional variation of sunlit and shaded soil beneath a row crop.

Calculation of $R_{N,S}$ to differentiate between shaded, partially sunlit, and fully sunlit soil beneath a row crop is straightforward using a geometric approach. Therefore, Colaizzi et al. (2015) described such a procedure to calculate $R_{N,S}$, and a new approach was also developed to calculate G_0 as a function of $R_{N,S}$ that required only one empirical parameter. The objective of this paper is to test this procedure by comparing calculated G_0 to calorimetric G_0 at different positions across a row crop interrow and for two row orientations.

2. Methods

2.1. Calorimetric and calculated G_0

Brief reviews of calorimetric and calculated (i.e., modeled) G_0 are presented here; additional details are in Colaizzi et al. (2015). The sign convention is positive toward the soil surface, and all fluxes have W m^{-2} units unless otherwise stated. In the calorimetric method, G_0 is the sum of measured heat flux (i.e., by heat flux plates) at depth Zp below the soil surface (G_{Zp}) and divergent heat flux in soil layers between the surface and the plates ($\Delta G_{0,Zp}$):

$$G_0 = G_{Zp} + \Delta G_{0,Zp}, \quad (1)$$

where

$$\Delta G_{0,Zp} = \frac{\sum_{j=1}^{N}(T_{s,zj,i+1} - T_{s,zj,i})\Delta z_j C_{zj}}{(t_{i+1} - t_i)} \quad (2)$$

where j is the soil layer, z_j is the depth of the midpoint of layer j, N is the total number of layers, $T_{s,z}$ is the soil temperature (K) at depth z at successive time steps t_{i+1} and t_i (s), Δz_j is the thickness of soil layer j (m), and C_{zj} is the volumetric heat capacity of the soil in layer j (J m^{-3} K^{-1}), calculated as:

$$C_{zj} = \rho_{M,zj}c_{M,zj}\theta_{M,zj} + \rho_{W,zj}c_{W,zj}\theta_{W,zj} + \rho_{O,zj}c_{O,zj}\theta_{O,zj} \quad (3)$$

where ρ is the density (Mg m^{-3}), c is the specific heat (J kg^{-1} K^{-1}), and θ is the volumetric content (m^3 m^{-3}), and subscripts M, W, and O, stand for minerals, water, and organic constituents, respectively. Volumetric heat capacities were calculated as $\rho_{M,zj}c_{M,zj} = 2.0 \times 10^6$ J m^{-3} K^{-1} and $\rho_{W,zj}c_{W,zj} = 4.2 \times 10^6$ J m^{-3} K^{-1} and assumed constant for each soil layer, and $\theta_{O,zj}$ was negligible (Evett et al., 2012a). Also for each soil layer, $\theta_{M,zj}$ was calculated as $\rho_{b,zj}/\rho_{M,zj}$, where $\rho_{b,zj}$ is soil bulk density and $\rho_{M,zj} = 2.65$ Mg m^{-3}, and $\theta_{W,zj}$ was measured (described in the next section).

A G_0 model based primarily on calculated $R_{N,S}$ was developed by Colaizzi et al. (2015) as:

$$G_0 = \frac{R_{N,S} - R_{N,S,MIN}}{R_{N,S,MAX} - R_{N,S,MIN}}\left(aR_{N,S,MAX} + R_{N,S,MIN}\right) - R_{N,S,MIN} \quad (4)$$

where $R_{N,S,MIN}$ and $R_{N,S,MAX}$ are, respectively, the minimum and maximum $R_{N,S}$ during a 24 h period, and $a = -0.31$. Calculation procedures for $R_{N,S}$ and related terms are in Colaizzi et al. (2012, 2015). It should be noted that measurements were available for R_N but not for $R_{N,S}$. However, Colaizzi et al. (2015) showed that calorimetric G_0 was poorly correlated to R_N but better correlated to $R_{N,S}$ during midday for mid to full canopy cover, which gave stronger justification to develop the model using $R_{N,S}$. This nonetheless imposed a limitation to this study where calculated vs. measured $R_{N,S}$ could not be compared; therefore, the relative impacts of calculated $R_{N,S}$ and assumptions of Eq. (4) could not be assessed in explaining discrepancies between calorimetric and calculated G_0. Although $R_{N,S}$ is inherently more difficult to measure compared to R_N for vegetated surfaces due to numerous factors, future studies should nonetheless strive to improve measurements of this and other relevant variables near the soil surface (Pieri, 2010).

2.2. Field measurements

All field measurements used to evaluate the model were obtained at the USDA Agricultural Research Service Conservation and Production Research Laboratory, Bushland, Texas, USA (35°11′ N lat., −102°06′ W long., 1170 m elevation M.S.L.). The soil is a Pullman clay loam (fine, mixed, super active, thermic torrertic Paleustolls) with slow permeability (USDA-NRCS, 2015), having a dense Bt layer from about 0.3–1.3-m depth and a calcic horizon that begins at approximately the 1.3-m depth. Field measurements were obtained during the Bushland Evapotranspiration and Agricultural Remote sensing EXperiment 2008 (BEAREX08) (Evett et al., 2012b). Details of the field experiment, including measurements of micrometeorology variables (solar irradiance, air temperature, relative humidity, wind speed) and plant samples (width, height, and leaf area) are given in Colaizzi et al. (2015) and in Evett et al. (2012b), but are briefly reviewed here.

Cotton (*Gossypium hirsutum* L.) was seeded on May 17, 2008 on raised beds in four 4.7 ha fields that contain large monolythic weighing lysimeters located in the field centers. The fields are arranged in a square pattern; the east two fields were irrigated by a lateral move sprinkler system, and the west two fields were not irrigated (dryland production). The seed rate in the irrigated fields was 15.8 seeds m^{-2}, and fields were designated northeast (NE) and southeast (SE). The crop was planted in row orientations of north–south (NS) for the NE field, and east–west (EW) for the SE field. Following crop establishment, furrow dikes were installed in the interrows to control run on and runoff of rain and irrigation water (Schneider and Howell, 2000). Micrometeorology variables were measured at the weighing lysimeter site and at a grass reference site immediately east of the SE field, where grass was fully