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Spectral Data-Based Estimation of Soil Heat Flux

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SPECTRAL DATA-BASED ESTIMATION OF SOIL HEAT FLUX

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ABSTRACT. *Numerous existing spectral-based soil heat flux (G) models have shown wide variation in performance for maize and soybean cropping systems in Nebraska, indicating the need for localized calibration and model development. The objectives of this article are to develop a semi-empirical model to estimate G from a normalized difference vegetation index (NDVI) and net radiation (R_n) for maize (*Zea mays *L.) and soybean (*Glycine max *L.) fields in the Great Plains, and present the suitability of the developed model to estimate G under similar and different soil and management conditions. Soil heat fluxes measured in both irrigated and rainfed fields in eastern and south-central Nebraska were used for model development and validation. An exponential model that uses NDVI and R_n was found to be the best to estimate G based on r^2 values. The effect of geographic location, crop, and water management practices were used to develop semi-empirical models under four case studies. Each case study has the same exponential model structure but a different set of coefficients and exponents to represent the crop, soil, and management practices. Results showed that the semi-empirical models can be used effectively for G estimation for nearby fields with similar soil properties for independent years, regardless of differences in crop type, crop rotation, and irrigation practices, provided that the crop residue from the previous year is more than 4000 kg ha^{-1}. The coefficients calibrated from particular fields can be used at nearby fields in order to capture temporal variation in G. However, there is a need for further investigation of the models to account for the interaction effects of crop rotation and irrigation. Validation at an independent site having different soil and crop management practices showed the limitation of the semi-empirical model in estimating G under different soil and environment conditions.*

***Keywords.** Energy balance, NDVI, Net radiation, Remote sensing, Soil heat flux.*

Over the last two decades, land surface energy models have been used in research worldwide to estimate evapotranspiration (ET) using satellite imagery. Efforts are now being made to incorporate these models into decision-support systems for farmers and managers to advance water resource management applications. For instance, METRIC (Mapping Evapotranspiration at high Resolution using Internalized Calibration) has been successfully used for water management in the western U.S. (Allen et al., 2007a, 2007b; Irmak et al., 2011a). These models require accurate estimation of soil heat flux (*G*) over large heterogeneous terrains composed of different soil and vegetation types in order to partition available energy (net radiation, R_n - *G*) between sensible heat flux (*H*) and latent heat flux (*LE*). Soil heat flux plates offer a powerful way to estimate *G* on uniform soil surfaces at a point scale. For instance, *G* values were estimated fairly reliably with three sensors on a uniform, well-drained silt loam soils planted with maize and soybean crops (Irmak et al., 2011a). Kustas et al. (2000) found that there should be at least three soil heat flux plates to determine *G* for sparse clumped vegetation, with one out in the open or interspaced area, one underneath the representative vegetation, and one in a partial cover condition. However, use of soil heat flux plates to measure *G* over large areas is difficult, challenging, and sometimes impractical due to the number of measurements and sites needed and the operational expense and maintenance of such a dense network. Furthermore, *in situ* measurements of *G* may be valid only for a very small area around the point of measurement (Verhoef, 2004). Therefore, extrapolation of ground-based point measurements over large heterogeneous areas will be difficult and erroneous. Stannard et al. (1994) showed the standard errors in area-averaged *G* fluxes to be on the order of 30 to 40 W m^{-2} using three soil heat flux plates among three micrometeorological stations located in a sparse vegetative canopy cover site in a semi-arid rangeland ecosystem. Methods are needed to estimate *G* accurately for large heterogeneous land surfaces from easily and commonly collected data.

Early studies demonstrated that *G* is strongly correlated with R_n and it could account for significant portion of net radiation. In sparse canopy ecosystems in semi-arid or arid regions, *G* was up to 40% of R_n, which could be equal to or higher than *LE* (Verhoef et al., 1996). In forests, *G* usually accounts for 5% of R_n (Chen et al., 2002; Beringer et al., 2005), while in grasslands, *G* can account for 25% of R_n, or about 180 W m^{-2} (Wilson et al., 2002). Initial modeling efforts involved simple empirical relationships to estimate *G* as a fraction (0.20 to 0.50) of R_n (Choudhury et al., 1987; Norman et al., 1995). Some researchers incorporated reflectance-based vegetation indices in their models in order to account for spatial variability in *G* due to variability in soil, topography, and

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Table 1. Cropping details at Mead sites, Nebraska.

Mead Site	Year	Crop/Cultivar	Plant Population (per ha)	Planting Date	Harvest Date	Irrig. Depth (mm)	Rainfall[a] (mm)
1: Irrigated continuous maize	2003	Maize/Pioneer 33B51	77,000	May 15	October 27	378	370
	2004	Maize/Pioneer 33B51	79,800	May 3	October 13	260	409
	2005	Maize/DeKalb 63-75	69,200	May 4	October 12	324	330
2: Irrigated maize-soybean rotation	2003	Maize/Pioneer 33B51	78,000	May 14	October 23	350	370
	2004	Soybean/Pioneer 93B09	296,000	June 2	October 18	184	409
	2005	Maize/Pioneer 33B51	76,300	May 2	October 17	309	330
3: Rainfed maize-soybean rotation	2003	Maize/Pioneer 33B51	57,600	May 13	October 13	0	370
	2004	Soybean/Pioneer 93B09	264,700	June 2	October 11	0	409
	2005	Maize/Pioneer 33G66	53,700	April 26	October 17	0	330

[a] Rainfall amount shown is for the growing season from May 1 to October 31.

vegetation over heterogeneous land surfaces (Clothier et al., 1986; Kustas and Daughtry, 1990; Bastiaanssen et al., 1998; Melesse and Nangia, 2005). The aforementioned models suggest a G/R_n relationship by fitting measured and estimated G with very limited spectral data, and the coefficients describing G were locally developed. Application of these simple models has shown the inadequacy of the empirical relationship in different locations and years (Jacob et al., 2002).

In our work (Irmak et al., 2011b), application of these models has shown wide variation in performance for maize and soybean cropping systems in Nebraska. Statistical analyses of model performance against measured data showed a wide range of variation in the ability of these models to estimate G not only between sites but also between years. Therefore, coefficients describing G cannot be readily used in different agro-meteorological conditions. In many cases, these models need to be recalibrated for local soil, climate, and vegetation cover to achieve a realistic estimation of G.

The main objective of this study was to develop a simple, locally calibrated G model from routinely collected remote sensing data for the application of land surface energy balance modeling. The specific objectives were to: (1) develop a semi-empirical model to estimate G from normalized difference vegetation index (NDVI) and R_n for maize (*Zea mays* L.) and soybean (*Glycine max* L.) fields in the Great Plains, and (2) present the validation of the developed model to estimate G for nearby fields and at an independent field with different management practices and environmental settings.

Materials and Methods

Description of Sites and Data

Data used in this study were collected at the two research centers of the University of Nebraska-Lincoln, namely the Agricultural Research and Development Center (ARDC) near Mead, Nebraska, and the South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska. Field data at ARDC Mead were collected from three sites:

- Site 1: Center-pivot irrigated, continuous maize (41° 9′ 54.2″ N, 96° 28′ 35.9″ W; 361 m above mean sea level).
- Site 2: Center-pivot irrigated, maize-soybean rotation (41° 9′ 53.5″ N, 96° 28′ 12.3″ W; 362 m above mean sea level).
- Site 3: Rainfed, maize-soybean rotation (41° 10′ 46.8” N, 96° 26′ 22.7″ W; 362 m above mean sea level).

Net radiation was measured using a Kipp & Zonen CNR1 net radiometer (Campbell Scientific, Inc., Logan, Utah), and

Table 2. Crop residue (leaves, stalks, cobs) at the end of harvesting (kg ha^{-1}).

Year	Mead Site 1	Mead Site 2	Mead Site 3
2002	9817	5968	4001
2003	9585	9996	6572
2004	8437	3637	3077
2005	9887	9290	9065

G was measured using two soil heat flux plates (Radiation and Energy Balance Systems, Inc., Seattle, Wash.). The NDVI was computed based on spectral reflectance in the red and near-infrared bands measured using an SKR 1850 Series four-channel radiometer (Skye Instruments, Ltd., Powys, U.K.). The soil at these sites is deep silty clay loam (13% sand, 57% silt, 27.5% clay, and 2.5% organic matter). Table 1 provides the cropping information at the ARDC Mead sites. All three sites at ARDC are under no-till condition. The aboveground crop residue at the end of the harvesting at these sites was measured. The quantities of crop residue (leaves, stalks, and cobs) excluding the harvested grain are provided in table 2.

Field data at SCAL near Clay Center, Nebraska, were collected from subsurface drip irrigated field (40° 34′ N, 98° 8′ W; 552 m above mean sea level). Net radiation was measured using a REBS Q*7.1 net radiometer (Radiation and Energy Balance Systems, Inc., Bellevue, Wash.), and G was measured using three REBS HFT3.1 plates (Radiation and Energy Balance Systems, Inc., Bellevue, Wash.). The NDVI was computed using Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images. The soil at this site is Hastings silt loam (15% sand, 62.5% silt, 20% clay, and 2.5% organic matter).

Details of these sites and the meteorological conditions for the experimental years are provided by Irmak et al. (2011b). Further details about the ARDC sites can be found in Verma et al. (2005) and Suyker et al. (2005), and details about the SCAL site can be obtained from Irmak and Mutiibwa (2010).

Hypothesis and Model Development for Each Case Study

We developed four case studies using different combinations of datasets from the ARDC Mead sites in Nebraska to determine whether semi-empirical equations describing G can be used at the fields with similar soil properties in order to capture temporal variation in G. We also tested whether these equations can be used to estimate G at an independent site having different soil and crop management conditions.

An exponential form (Choudhury et al., 1987; Murray and Verhoef, 2007) was used for all models:

$$G = a\ \exp^{b\,NDVI} R_n \quad (1)$$

where a and b are the site-specific coefficients for any particular condition. We tried to answer a specific question for each case study. Detailed descriptions of each case study are given below.

Case 1: Can coefficients calibrated in an irrigated continuous maize field be used in fields with similar soil properties but different cropping and irrigation practices?

Case 1 uses data from the irrigated continuous maize site (Mead site 1) to calibrate the coefficients in equation 1. Three years of data (2003, 2004, and 2005) from Mead site 1 were used to develop a semi-empirical G equation that captures temporal variation in the G/R_n ratio due to the variation in field conditions.

We hypothesized that coefficients describing G can be used at another field with similar soil properties and climate conditions. Thus, the performance of case 1 is evaluated for estimating G at Mead sites 2 and 3 regardless of differences in cropping system and management practices (i.e., irrigation and crop rotation). The calibrated equation was validated at Mead site 2 (irrigated maize-soybean rotation) and Mead site 3 (rainfed maize-soybean rotation) for 2003, 2004, and 2005 to test the hypothesis that an accurate estimation of G could be achieved in nearby fields with similar soil properties.

Case 2: Can coefficients calibrated in maize fields be used for other cropping systems in the same fields?

Case 2 was evaluated to determine the effect of crop type on G estimation. It was assumed that the seasonal progression of land cover conditions, particularly percentage of vegetation cover, can be characterized with NDVI. Therefore, the coefficients describing G can be used for other cropping systems. For this purpose, we included data from Mead site 1 (2003, 2004, and 2005), site 2 (2003 and 2005), and site 3 (2003 and 2005) for model development. The calibrated model was validated for 2004 for irrigated soybean at Mead site 2 and for rainfed soybean at Mead site 3. It was hypothesized that the calibrated G model could be applied to other conditions independent of the cropping system.

Case 3: Can coefficients calibrated in irrigated crop fields be used in rainfed fields?

Case 3 included data from irrigated experiments at Mead sites 1 and 2 for model development. The combined data included three years of data (2003, 2004, and 2005) from site 1 and two years of data (2003 and 2005) from site 2. The equation developed from case 3 was tested at Mead site 3 (rainfed maize-soybean rotation) for rainfed maize (2003 and 2005). It was hypothesized that the total magnitude of G would be different in the rainfed field than in the irrigated fields because of the differences in water content and residue cover density, and that this would, in turn, impact the volumetric heat capacity of the soil. The thermal conductivity and volumetric specific heat of soil change with soil water content (Campbell, 1977; Brutsaert 1982). It was hypothesized that there may be a model bias when coefficients calibrated with data from irrigated fields are used in rainfed cropping systems.

Case 4: Can coefficients calibrated in particular fields be used in the same fields for another year?

Case 4 uses data from irrigated and rainfed maize and soybean fields at the Mead sites and tests the performance of the model for the same sites in an independent year. The model calibration was carried out using data from Mead sites 1, 2, and 3 for 2003 and 2004. The model was validated at Mead sites 1, 2, and 3 for 2005. The calibration and validation in this case included data from rainfed and irrigated fields. It was hypothesized that the calibrated model can be used to estimate G accurately in independent years.

Statistical Analyses

The performance of each case study at the validation sites was evaluated on the basis of mean absolute error (MAE), root mean square error (RMSE), coefficient of determination (r^2), and Nash-Sutcliffe coefficient of efficiency (E). Statistically significant differences among the four cases were determined using Student's t-test on the estimated data from each model. The p-values were computed based on statistical significance level (0.05) to test the null hypothesis.

Results and Discussion

Evaluation of Case 1 for Estimating G in Nearby Fields

A total of three years of data (2003, 2004, and 2005) from Mead site 1 (irrigated continuous maize) were used to calibrate the coefficients for case 1 (fig. 1). The equation developed for case 1 is:

$$G = 0.3118\, e^{(-1.4122 NDVI)} R_n \quad (2)$$

The coefficient describing the impact of NDVI on G was -1.4122, which indicates that G decreases with increasing canopy cover (i.e., a 10% increase in NDVI results in a 13% reduction in G). There was a good relationship (r^2 = 0.70) between G/R_n and NDVI for the calibration dataset (n = 219).

Equation 2 was used to estimate G for Mead site 2 (irrigated maize-soybean rotation) and site 3 (rainfed maize-soybean rotation) to evaluate the performance of the model for estimating G in nearby fields (fig. 2; table 3). The model performed well at site 2, with relatively low RMSE of 15 and 19 W m^{-2} for 2003 and 2005, respectively. Maize was planted at site 2 in both 2003 and 2005, but the G estimations were better during 2003 ($y = 0.993x$) than 2005 ($y = 0.825x$). Underestimation at site 2 during 2005 can be explained by considering the low amount (<4000 kg ha^{-1}) of crop residue at this site in 2004 (table 2). Since the field was under no-till

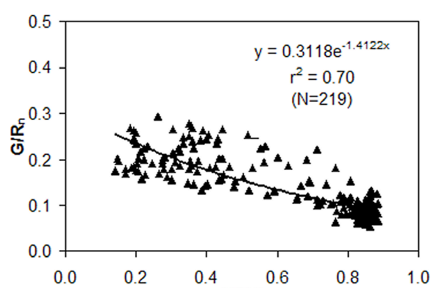

Figure 1. Relationship between G/R_n and NDVI for case 1 using data from site 1 (irrigated continuous maize) at Mead, Nebraska.

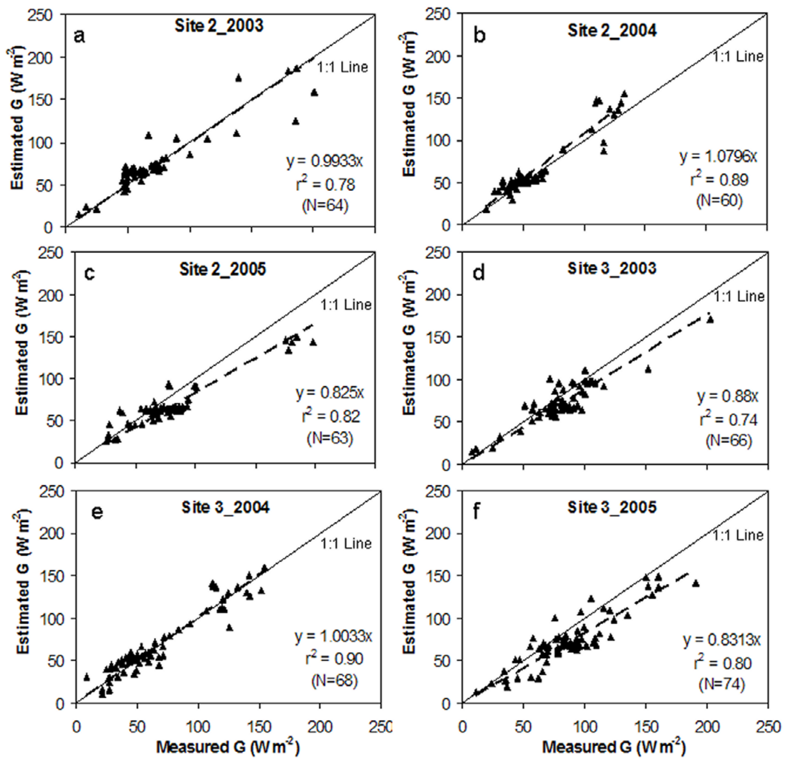

Figure 2. Comparison of measured and estimated *G* using semi-empirical equation for case 1 at (a) Mead site 2 (irrigated maize-soybean rotation) in 2003 (b) Mead site 2 in 2004, (c) Mead site 2 in 2005, (d) Mead site 3 with rainfed maize-soybean rotation in 2003, (e) Mead site 3 in 2004, and (f) Mead site 3 in 2005. The solid line indicates a 1:1 line, and the dashed line represents the regression equation.

Table 3. Evaluation of each case study for estimating *G* for three sites at Mead, Nebraska. Statistics include mean absolute error (MAE, W m^{-2}), root mean square error (RMSE, W m^{-2}), coefficient of determination (r^2), and Nash-Sutcliffe coefficient of efficiency (*E*).

		Validation Site Details			Validation Statistics					
Case	Model Equation	Site	Year	Crop	*N*	Slope	MAE (W m^{-2})	RMSE (W m^{-2})	r^2	*E*
1	$G = 0.3118\ e^{(-1.4122\ NDVI)}\ R_n$ (location effect)	Mead Site 2	2003	Irrigated maize	64	0.99	10	15	0.78	0.84
		Mead Site 2	2004	Irrigated soybean	60	1.08	9	13	0.89	0.83
		Mead Site 2	2005	Irrigated maize	63	0.83	15	19	0.82	0.73
		Mead Site 3	2003	Rainfed maize	66	0.88	13	16	0.74	0.67
		Mead Site 3	2004	Rainfed soybean	68	1.00	9	12	0.9	0.9
		Mead Site 3	2005	Rainfed maize	74	0.83	17	21	0.8	0.62
2	$G = 0.3105\ e^{(-1.3326\ NDVI)}\ R_n$ (crop effect)	Mead Site 2	2004	Irrigated soybean	60	1.12	11	14	0.88	0.79
		Mead Site 3	2004	Rainfed soybean	68	1.03	10	13	0.89	0.89
3	$G = 0.3139\ e^{(-1.4091\ NDVI)}\ R_n$ (irrigation effect)	Mead Site 3	2003	Rainfed maize	66	0.89	13	15	0.74	0.68
		Mead Site 3	2005	Rainfed maize	74	0.84	17	20	0.8	0.63
4	$G = 0.3172\ e^{(-1.4582\ NDVI)}\ R_n$ (annual effect)	Mead Site 1	2005	Irrigated maize	68	0.95	16	23	0.59	0.62
		Mead Site 2	2005	Irrigated maize	63	0.82	16	19	0.83	0.72
		Mead Site 3	2005	Rainfed maize	74	0.83	18	22	0.79	0.60

condition, the type and amount of residue cover from the previous year might impact *G* significantly, especially during partial canopy cover. Maize and soybean were planted at site 2 during 2003 and 2004, respectively. Maize following soybean is likely to have higher *G* early in the growing season due to the lesser amount of soybean residue from the previous year (table 2). In addition, early in the season, the G/R_n ratio at site 2 (validation site) was larger than at site 1 (calibration site) (Irmak et al., 2011b). The maximum G/R_n among the three years of data at site 1 was about 0.25, while it was as high as 0.45 in 2005 at site 2. Equation 2 was calibrated with the dataset from site 1 (continuous maize) in which inter-annual variability in *G* due to differences in crop rotations did not exist. As a result, the coefficients describing equation 2 did not capture temporal variation (high values) in G/R_n due to low crop residue, and the results showed variation from year to year when case 1 was tested.

A good correlation was observed between estimated and measured *G* from the irrigated soybean field at site 2 in 2004 (fig. 2b). On the average, case 1 overestimated *G* at site 2 by only 8% in the irrigated soybean field in 2004 and underestimated *G* in irrigated maize by about 17% in 2005.

Case 1 underestimated *G* in the rainfed maize field during 2003 and 2005 at site 3, particularly at higher *G* values. Site 3 was a rainfed field under a maize-soybean crop rotation having maize in both 2003 and 2005. Better estimation of *G* was obtained during 2004 (r^2 = 0.90, RMSE = 12 W m^{-2}) as compared to 2003 (r^2 = 0.74, RMSE = 16 W m^{-2}) and 2005 (r^2 = 0.80, RMSE = 21 W m^{-2}) (table 3, figs. 2d to 2f). For instance, the estimated *G* was within 1% of the measured *G* for 2004, indicating the model's ability to estimate *G* quite well under a rainfed soybean cropping system.

Overall, the results from site 3 were similar to those from site 2 when case 1 was tested. The estimations were reasonably good for rainfed and irrigated soybean, indicating that the model captured the major patterns of temporal *G* variability for soybean fields if nearby fields were planted with maize in the previous year. However, the model underestimated *G* for irrigated and rainfed maize fields, especially during partial canopy cover, if the crop residue was less than 4000 kg ha^{-1}.

Evaluation of Case 2 for Estimating *G* for Soybean Cropping Systems

Case 2 was evaluated to test the hypothesis that *G* can be estimated independently of the cropping system. Equation 1 was calibrated using data collected from the maize growing seasons, and it was validated in soybean growing seasons. Hence, the data from maize at Mead site 1 (2003, 2004, and 2005), site 2 (2003 and 2005), and site 3 (2003 and 2005) were used for the calibration of the model (fig. 3). The resulting exponential relationship for case 2 is:

$$G = 0.3105\, e^{(-1.3326 NDVI)} R_n \qquad (3)$$

The model validation was carried out for Mead sites 2 and 3 for the soybean growing season in 2004. The model overestimated *G* by 12% at site 2 (table 3, fig. 4a). This overestimation was slightly higher as compared to the overestimation of case 1 (eq. 2) at site 2 in 2004. This is because the calibration of equation 3 included data from site 2 and site 3. The same crop rotation was followed at both sites. Thus, the maize crops at these two sites had soybean crops in the previous year. Due to the lower amount of crop residue from soybean as compared with maize, the G/R_n ratio was higher for maize at sites 2 and 3 as compared to that for site 1. Hence, case 2 (eq. 3) produces a slightly higher *G* as compared with case 1 (eq. 2) for the same NDVI and R_n.

The model estimated *G* at site 3 very well (y = 1.034x) in 2004 with an r^2 of 0.89 (n = 68) (fig. 4b). Better model performance at site 3 as compared to site 2 in 2004 can be explained by the presence of a lower plant population at site 3, since this might have resulted in higher *G*. Thus, slight overestimation of case 2 was compensated for by a higher measured value of *G* at site 3. Site 2 was irrigated, whereas site 3 was under rainfed cultivation. Hence, the effect of irrigation was investigated as discussed below.

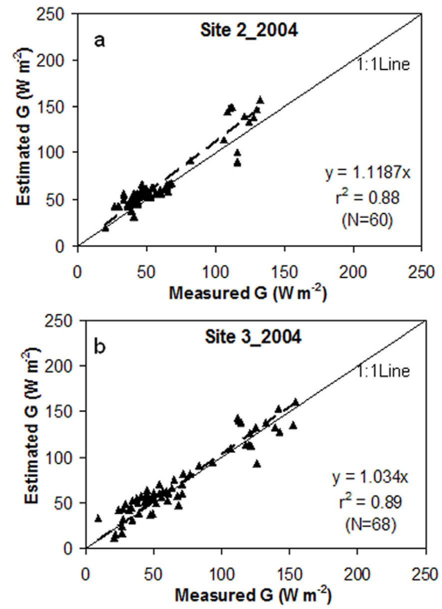

Figure 4. Comparison of measured and estimated *G* for soybean using semi-empirical equation for case 2 at (a) Mead site 2 (irrigated maize-soybean rotation) in 2004 and (b) Mead site 3 (rainfed maize-soybean rotation) in 2004. The solid line indicates a 1:1 line, and the dashed line represents the regression equation.

Evaluation of Case 3 for Estimating *G* for Rainfed Maize

The NDVI, *G*, and R_n data collected from the maize field at Mead site 1 (2003, 2004, 2005) and site 2 (2003 and 2005) were used for the calibration (fig. 5). The equation developed for case 3 is:

$$G = 0.3139\, e^{(-1.4091 NDVI)} R_n \qquad (4)$$

Equation 4 was used to estimate *G* for Mead site 3 (rainfed maize-soybean rotation) during the maize growing years of 2003 and 2005 (figs. 6a and 6b). A good correlation was observed for the year 2003 (table 3). The RMSE was 15 W m^{-2}, and the model efficiency was 0.68. The irrigation details at Mead sites 1 and 2 are shown in table 1. Model validation at site 3 resulted in slightly higher RMSE (20 W m^{-2}) for 2005. Although 2005 had better correlation as compared to 2003 (r^2 = 0.74), the underestimation of the model was slightly

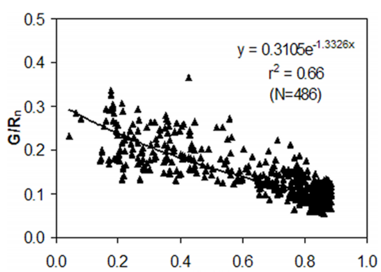

Figure 3. G/R_n and NDVI relationship for case 2 using 2003, 2004, and 2005 data from Mead site 1 (irrigated continuous maize) and 2003 and 2005 data from Mead site 2 (irrigated maize-soybean rotation) and Mead site 3 (rainfed maize-soybean rotation).

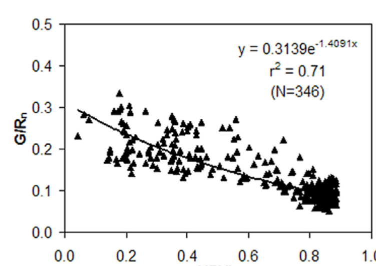

Figure 5. Relationship between G/R_n and NDVI for case 3 using three years (2003, 2004, and 2005) of data from site 1 (irrigated continuous maize) and two years (2003 and 2005) of data from site 2 (irrigated maize-soybean rotation) at Mead, Nebraska.

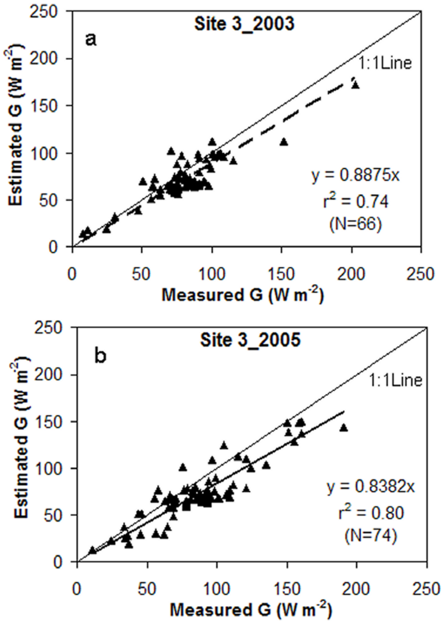

Figure 6. Comparison of measured and estimated *G* for rainfed maize using semi-empirical equation for case 3 at (a) Mead site 3 (rainfed maize-soybean rotation) in 2003 and (b) Mead site 3 in 2005. The solid line indicates a 1:1 line, and the dashed line represents the regression equation.

higher in 2005 (~16%) than in 2003 (~11%) due to the crop residue factor.

Results showed that the case 3 results from both years were very similar to those obtained for case 1 (figs. 2d and 2f) at these sites. The coefficients in equations 2 and 4 were very similar. Nevertheless, it is difficult to judge whether the model performance was affected by the change in crop rotation or irrigation effect. It should be noted that all *G* measurements were corrected for the soil moisture content, as discussed by Irmak et al. (2011b). Due to limitation of our sites and data-

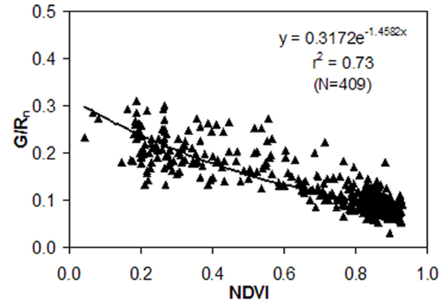

Figure 7. Case 4 relationship between G/R_n and NDVI using 2003 and 2004 data from Mead site 1 (irrigated continuous maize), Mead site 2 (irrigated maize-soybean rotation), and Mead site 3 (rainfed maize-soybean rotation).

sets, we were unable to determine the interaction effect of crop rotation and irrigation.

In both cases 1 and 3, the overall variation was higher in 2005 as compared to 2003. Case 4 was formulated and further investigated to determine the interannual variation in model estimates.

Evaluation of Case 4 for Estimating *G* in the Same Fields for Independent Years

Case 4 was evaluated to understand the interannual variation in *G* using data from Mead sites 1, 2, and 3 for the years 2003 and 2004 (fig. 7). A good correlation ($r^2 = 0.73$) was obtained from the calibration datasets ($n = 409$) with the following equation:

$$G = 0.3172\, e^{(-1.4582 NDVI)} R_n \qquad (5)$$

The model validation for case 4 was carried out at Mead sites 1, 2, and 3 for 2005 (figs. 8a to 8c). The MAE and RMSE at site 1 (irrigated continuous maize) were 16 and 23 W m^{-2}, respectively (table 3). The model estimated *G* within 5% ($y = 0.9538x$) of the measured *G* ($n = 68$). This model performed well considering the spatiotemporal variability in *G*. It also

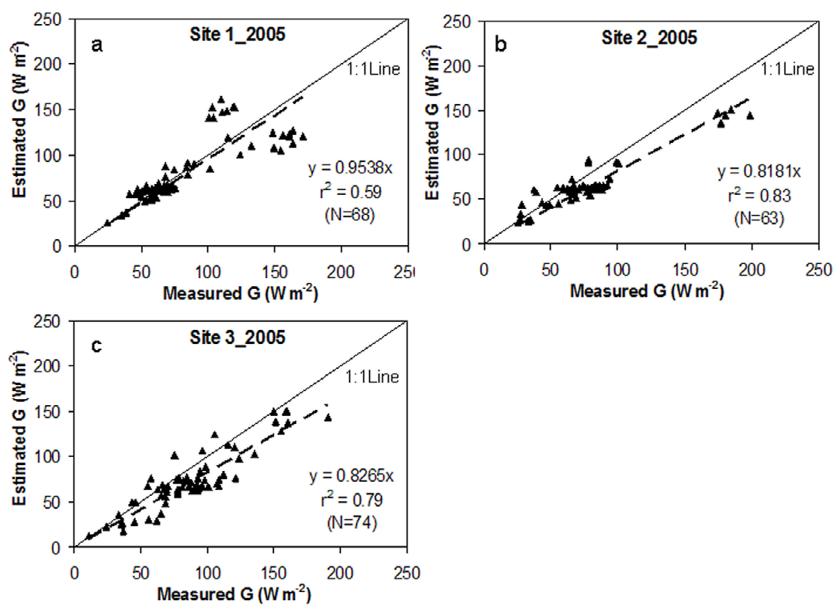

Figure 8. Comparison of measured and estimated *G* in 2005 using semi-empirical equation for case 4 at (a) Mead site 1 (irrigated continuous maize), (b) Mead site 2 (irrigated maize-soybean rotation), and (c) Mead site 3 (rainfed maize-soybean rotation). The solid line indicates a 1:1 line, and the dashed line represents the regression equation

Table 4. Matrix table showing the statistical significance difference between four cases.[a]

	Case 1	Case 2	Case 3	Case 4
Case 1	--	SG	SG	NS
Case 2	SG	--	SG	SG
Case 3	SG	SG	--	SG
Case 4	NS	SG	SG	--

[a] SG = significant difference ($p < 0.05$).
NS = no significant difference ($p > 0.05$).

indicated that G can be estimated for the same fields in an independent year.

Overall, the validation results at Mead site 2 (irrigated maize-soybean rotation) showed a good fit between measured and estimated G values in spite of 18% underestimation in 2005 ($y = 0.8181x$; fig. 8b). This underestimation is again due to the effect of low crop residue from the previous crop. As this site is under no-till condition with crop rotation, the crop residue on the land surface from the previous crop (soybean) is less (table 2), resulting in higher G measurements. Studies have shown that lower crop residue results in higher G (Azooz et al., 1997).

The validation of case 4 at Mead site 3 (rainfed maize-soybean rotation) showed similar results as at site 2. The values of MAE and RMSE at site 3 were 18 and 21 W m^{-2}, respectively. The model underestimated G at this site (fig. 8c), which can be explained by similar conditions as discussed above for site 2. The underestimation at site 3 was also due to the reduced crop residue from the previous year (2004). For case 4, the best correlation was found at site 2 ($r^2 = 0.83$) as compared with site 1 and site 3. In general, the model underestimated G at all three sites in 2005 due to low crop residue from previous crops.

Overall, the RMSE of G from all four cases ranged within 10 to 25 W m^{-2}, much less than the RMSE range of 30 to 45 W m^{-2} obtained in many previous studies (Daughtry et al., 1990; Norman et al., 1995; Jacob et al., 2002), indicating that the simple empirical models need to be calibrated for local soil, climate, and vegetation cover in order to achieve a realistic estimation of G. The coefficients a and b in the four cases (table 3) were very similar. We conducted Student's t-test on the estimated data from each case to determine statistically significance differences among the four cases. The results based on p-values are presented in table 4. Only cases 1 and 4 were not significantly different, while other combinations (cases 1 and 2, cases 1 and 3, cases 2 and 3, cases 2 and 4, and cases 3 and 4) were significantly different. As the calibration of case 4 (eq. 5) included irrigated and rainfed sites with both maize and soybean crops under two different growing seasons (2003 and 2004), this equation can be used as a generalized model for G estimation in similar soil and management conditions.

Evaluation of Case 4 for Estimating *G* at an Independent Site

The four cases (cases 1 to 4) discussed above were calibrated and validated at the three Mead sites. We performed the validation of the generalized model from case 4 (eq. 5) at an independent site at SCAL near Clay Center, Nebraska, during the 2005, 2006, and 2007 growing seasons. All three sites at Mead were located very close to each other (within 1.6 km), but the distance between the SCAL and Mead sites was about 230 km. It should be noted that maize was planted

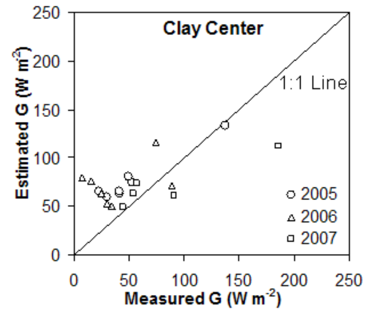

Figure 9. Evaluation of equation 9 (case 4) for estimating *G* at Clay Center, Nebraska. The solid line indicates a 1:1 line.

at SCAL during the 2005 and 2006 crop growing seasons, and soybean in 2007. The relationship of estimated and measured G for three years at SCAL is shown in figure 9. A summary of the performance statistics is presented in table 5. The MAE and RMSE in 2005 were 24.8 and 26.9 W m^{-2}, respectively. Similarly, the r^2 was 0.96 and E was 0.43 during 2005. Similar results were found in 2007. However, the model did not work satisfactorily for the 2006 growing season. The RMSE was 43.3 W m^{-2} with an r^2 of 0.15 during 2006 growing season. Overall, the model performance at the independent site resulted in twice the error observed at the Mead sites.

There are many reasons for the differences in model performance at the two locations. First of all, the soil at the Mead sites is silty clay loam, while the soil at Clay Center is silt loam. Soil composition (e.g., particle size, organic matter content, bulk density) plays an important role in thermal conductivity, thus affecting G measurement. Secondly, NDVI at the Mead sites was computed based on field measurement using a Skye radiometer, while NDVI at Clay Center was based on Landsat images. The channel bandwidth of the Skye radiometer (red band: 665-676 nm; near-infrared band: 862-874 nm) is different from the Landsat bands (red band: 630-690 nm; near-infrared band: 750/760-900 nm), a potential source of differences in NDVI. Brown et al. (2006) compared NDVI time series derived from different satellite sensors and found large differences between NDVI datasets, but the NDVI anomalies exhibited similar variances. Finally, the Mead sites are either rainfed or center-pivot irrigated, while the Clay Center site is subsurface drip irrigated. Possibly, all these factors contributed to large discrepancies between measured and modeled G at the independent SCAL site.

In general, the MAE for all validation sites at Mead, Nebraska, was less than 20% of the measured G values (table 6). These results are encouraging and indicate the suitability of this approach for modeling G in similar soil and management conditions. However, the higher percentage error (>100%) in estimation of G at the independent SCAL site in a particular year indicates the potential limitation of using a specific

Table 5. Evaluation of semi-empirical equation (eq. 5, case 4) for estimating *G* for 2005, 2006, and 2007 in an independent subsurface drip irrigated field at Clay Center, Nebraska.

Year	MAE (W m^{-2})	RMSE (W m^{-2})	r^2	E
2005	24.8	26.9	0.96	0.43
2006	38.4	43.3	0.15	-1.35
2007	27.0	36.5	0.82	0.51

Table 6. Percentage error in validation statistics (MAE) for each case study based on mean measured G values for each year at Mead and Clay Center, Nebraska.

	Mead Site 1			Mead Site 2			Mead Site 3			Clay Center		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2005	2006	2007
Measured G[a]	89.9	62.2	75.7	72.3	61.2	97.4	99.5	70.8	102.0	39.4	30.2	52.5
N[b]	128	130	122	122	129	114	131	131	128	184	184	152
Case 1	--	--	--	13.8	14.7	15.4	13.1	12.7	16.7	--	--	--
Case 2	--	--	--	--	18.0	--	--	14.1	--	--	--	--
Case 3	--	--	--	--	--	--	13.1	--	16.7	--	--	--
Case 4	--	--	--	--	--	16.4	--	--	17.6	--	--	--
Independent site	--	--	--	--	--	--	--	--	--	62.9	127.2	51.4

[a] G values represent the seasonal average from May through end of October for a given site and year.
[b] N = number of measurements for each site and year during growing season (May through end of October).

equation for different soil and agro-meteorological conditions.

Conclusions

Estimation of soil heat flux is important in studies involving the surface energy balance. The amount of energy available for sensible and latent heat fluxes is influenced by the heat transfer into or away from the soil. Quantification of G is also important in biophysical and plant physiological studies to understand the behavior and interactions of the vegetation surface with the soil and microclimate interface. Four case studies with similar model structures were developed for estimation of soil heat flux using R_n and NDVI measurements from maize and soybean fields in Great Plains environmental settings. The model performance was evaluated under different soil and cropping management practices (crop rotation, crop residue, irrigation, and rainfed) to test the case hypotheses.

The case 1 scenario was developed to test the hypothesis that an accurate estimation of G could be achieved in fields with similar soil properties. The model captured the major patterns of temporal G variability for nearby soybean fields if they were planted with maize in previous year. This indicated that the model can be used for estimating G in nearby fields with similar soil properties and crop rotation practices. However, the model underestimated G for irrigated (site 2) and rainfed (site 3) maize fields, especially during partial canopy cover and when crop residue from the previous crop was less than 4000 kg ha^{-1}. Overall, the MAE was less than 18% of mean measured G for all validated sites and years.

The case 2 hypothesis was tested to determine if the coefficients calibrated from maize fields can be used in soybean fields. The inclusion of NDVI in the model worked well in accounting for the canopy effect on heat transfer in soil, and the estimations of G were within an acceptable range. Results from irrigation effect (case 3) validation showed that the error associated with estimating G was of similar order as obtained from cases 1 and 2. However, there is a need for further investigation to understand conclusively the interaction effect of crop rotation and irrigation. The model validation for temporal effect in case 4 indicated that the model can be used effectively for G estimation in an independent year.

Based on validation of all four case studies, it is suggested that the calibrated model from case 4 (eq. 5) should be used as a generalized model for G estimation in areas having similar soil and crop management practices as in Mead, Nebraska.

Finally, the validation at an independent site at SCAL showed the limitation of the semi-empirical model for application in different soil and environmental conditions. It was concluded that caution must be taken when using the model in locations that have different soil and management practices compared to the calibrated locations. Application of a locally calibrated model should be encouraged in energy balance studies to improve the energy balance closure and provide better estimation of available energy.

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References

Allen, R. G., M. Tasumi, and R. Trezza. 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC): Model. *J. Irrig. Drain. Eng.* 133(4): 380-394.

Allen, R. G., M. Tasumi, A. T. Morse, R. Trezza, J. L. Wright, W. Bastiaanssen, W. Kramber, I. Lorite, and C. W. Robison. 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC): Applications. *J. Irrig. Drain. Eng.* 133(4): 395-406.

Azooz, R. H., B. Lowery, T. C. Daniel, and M. A. Arshad. 1997. Impact of tillage and residue management on soil heat flux. *Agric. Forest Meteorol.* 84(3-4): 207-222.

Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, and A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL):1. Formulation. *J. Hydrology* 212-213: 198-212.

Beringer, J., F. S. Chapin, C. C. Thompson, and A. D. McGuire. 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. *Agric. Forest Meteorol.* 131(3-4): 143-161.

Brown, M. E., J. E. Pinzon, K. Didan, J. T. Morisette, and C. J. Tucker. 2006. Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-Vegetation, SeaWiFS, MODIS, and Landsat ETM+ sensors. *IEEE Trans. Geosci. and Remote Sensing* 44(7): 1787-1793.

Brutsaert, W. 1982. *Evaporation into the Atmosphere*. Dordrecht, The Netherlands: D. Reidel Publishing.

Campbell, G. S. 1977. *An Introduction to Environmental Biophysics.* New York, N.Y.: Springer-Verlag.

Chen, J., M. Falk, E. Euskirchen, K. T. U, T. H. Suchanek, S. L. Ustin, B. J. Bond, K. D. Brosofske, N. Phillips, and R. Bi. 2002.

Biophysical controls of carbon flows in three successional Douglas fir stands based on eddy covariance measurements. *Tree Physiol.* 22(2-3): 169-177.

Choudhury, B. J., S. B. Idso, and R. J. Reginato. 1987. Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infrared temperature based energy balance equation. *Agric. Forest Meteorol.* 39(4): 283-297.

Clothier, B. E., K. L. Clawson, P. J. Pinter, M. S. Moran, R. J. Reginato, and R. D. Jackson. 1986. Estimation of soil heat flux from net radiation during the growth of alfalfa. *Agric. Forest Meteorol.* 37(4): 319-329.

Daughtry, C. S. T., W. P. Kustas, M. S. Moran, P. J. Pinter Jr., R. D. Jackson, P. W. Brown, W. D. Nichols, and L. W. Gay. 1990. Spectral estimates of net radiation and soil heat flux. *Remote Sensing Environ.* 32(2-3): 111-124.

Irmak, A., I. Ratcliffe, P. Ranade, K. G. Hubbard, R. K. Singh, B. Kamble, R. G. Allen, and J. Kjaersgaard. 2011a. Estimation of land surface evapotranspiration with a satellite remote sensing procedure. *Great Plains Research* 21(1): 73-88.

Irmak, A., R. K. Singh, E. A. Walter-Shea, S. B. Verma, and A. E. Suyker. 2011b. Comparison and analysis of empirical equations for soil heat flux for different cropping systems and irrigation methods. *Trans. ASABE* 54(1): 67-80.

Irmak, S., and D. Mutiibwa. 2010. On the dynamics of canopy resistance: Generalized linear estimation and relationships with primary micrometeorological variables. *Water Resources Res.* 46, W08526, doi:10.1029/2009WR008484.

Jacob, F., A. Olioso, X. F. Gu, Z. Su, and B. Seguin. 2002. Mapping surface fluxes using airborne visible, near-infrared, thermal infrared remote sensing data and a spatialized surface energy balance model. *Agronomie* 22(6): 669-680.

Kustas, W. P., and C. S. T. Daughtry. 1990. Estimation of the soil heat flux/net radiation ratio from spectral data. *Agric. Forest Meteorol.* 49(3): 205-223.

Kustas, W. P., J. H. Prueger, J. L. Hatfield, K. Ramalingam, and L. E. Hipps. 2000. Variability in soil heat flux from a mesquite dune site. *Agric. Forest Meteorol.* 103(3): 249-264.

Melesse, A. M., and V. Nangia. 2005. Estimation of spatially distributed surface energy fluxes using remotely sensed data for agricultural fields. *Hydrol. Proc.* 19(14): 2653-2670.

Murray, T., and A. Verhoef. 2007. Moving towards a more mechanistic approach in the determination of soil heat flux from remote measurements: I. A universal approach to calculate thermal inertia. *Agric. Forest Meteorol.* 147(1-2): 80-87.

Norman, J. M., W. P. Kustas, and K. S. Humes. 1995. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. *Agric. Forest Meteorol.* 77(3-4): 263-293.

Stannard, D., J. Blanford, W. Kustas, W. Nichols, S. Amer, T. Schmugge, and M. Weltz. 1994. Interpretation of surface flux measurements in heterogeneous terrain during the Monsoon ’90 experiment. *Water Resources Res.* 30(5): 1227-1239.

Suyker, A. E., S. B. Verma, G. G. Burba, and T. J. Arkebauer. 2005. Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. *Agric. Forest Meteorol.* 131(3-4): 180-190.

Verhoef, A. 2004. Remote estimation of thermal inertia and soil heat flux for bare soil. *Agric. Forest Meteorol.* 123(3-4): 221-236.

Verhoef, A., B. J. J. M. vandenHurk, A. F. G. Jacobs, and B. G. Heusinkveld. 1996. Thermal soil properties for vineyard (EFEDA-I) and savanna (HAPEX-Sahel) sites. *Agric. Forest Meteorol.* 78(1-2): 1-18.

Verma, S. B., A. Dobermann, K. G. Cassman, D. T. Walters, J. M. Knops, T. J. Arkebauer, A. E. Suyker, G. G. Burba, B. Amos, H. Yang, D. Ginting, K. G. Hubbard, A. A. Gitelson, and E. A. Walter-Shea. 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agric. Forest Meteorol.* 131(1-2): 77-96.

Wilson, K. B., A. Goldstein, E. Falge, M. Aubinet, D. Baldocchi, P. Berbigier, C. Bernhofer, R. Ceulemans, H. Dolman, C. Field, A. Grelle, A. Ibrom, B. E. Law, A. Kowalski, T. Meyers, J. Moncrieff, R. Monson, W. Oechel, J. Tenhunen, R. Valentini, and S. Verma. 2002. Energy balance closure at FLUXNET sites. *Agric. Forest Meteorol.* 113(1): 223-243.