ESTIMATION OF SPATIAL EVAPOTRANSPIRATION OVER NON-IRRIGATED AGRICULTURAL AREAS USING A TWO-SOURCE ENERGY BALANCE MODEL

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ABSTRACT

Spatial estimation of evapotranspiration (ET) from satellite imagery is important in agricultural studies because it provides information about the spatial variability of crop growing patterns and health, as well as for crop water requirements.

The two-source energy balance model is one of the techniques used successfully in estimating ET spatially, through the estimation of surface energy fluxes such as sensible heat flux H, soil heat flux G, net radiation Rn, and latent heat flux LE, the latter being extrapolated to daily ET.

The current study applies the two-source model to rain fed agricultural field located in the Walnut Creek watershed south of Ames, Iowa. Landsat TM images used to perform the analysis with the support of ground based data were acquired during the SMACEX project conducted in the summer of 2002. A visual basic interface called SETMI was programmed to interact with ArcGIS and perform the analysis spatially.

A footprint model was used to compare the estimates of the different fluxes with measurements from eddy covariance flux towers. Two different closure methods were used to overcome the lack of closure problem in the eddy covariance measurements. Generally, the results show good agreements between the measurements and the estimates. The results show an underestimation of sensible heat flux with RMSE of 30 (Wm^{-2}) and latent heat flux with RMSE of 45 (Wm^{-2}). The net radiation and the soil heat flux shows RMSE of 17 (Wm^{-2}) and 29 (Wm^{-2}), respectively. The daily ET resulted in a RMSE of 0.71 (mm/day) and BIAS of -0.29 (mm/day).

INTRODUCTION

Evapotranspiration (ET) is an important component in hydrology, climatology, and water resource management. The spatial estimation of ET is required because of the inherent spatial variability of different factors affecting ET, such as soil and weather factors. It also provides information about the variability of the growing pattern of crops in the agricultural studies. Spatial ET over large areas can be estimated using satellite imagery.

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In irrigated agriculture, reliable estimates of spatially distributed ET can aid in the detection of water stress in cropped fields as well as seasonal ET, providing improved crop water demand estimates.

The following study applies the two source energy balance model (TSM) originally developed by Norman et al. (1995) with the consideration of the series resistance formulation approach in estimating the sensible heat flux over the surface. It is proved to have a better description of the interaction between the surface and the near-surface atmosphere (Anderson et al. 1997, Li et al., 2005). It deals with the surface energy fluxes over the bare soil and the vegetation canopy separately and then combines them at a level above the ground surface called air-canopy interface. The TSM with its recent modifications (Anderson et al. 1997, Li et al., 2005) has been used to provide estimates of different surface energy fluxes over a wide range of land surface covers. In order to perform the analysis, the TSM was programmed using ArcGIS as the modeling interface and Visual Basic 6 as a programming language to estimate ET spatially within a larger framework called Spatial EvapoTranspiration Modeling Interface (SETMI).

The model was tested over rain fed fields of corn and soybean crops located in the Walnut Creek watershed south of Ames, Iowa. Landsat TM5 and TM7 satellite images were the main sources of the remotely sensed data. SETMI requires only three spectral bands RED, NIR, and thermal IR for the analysis. The ground flux data were acquired through the Soil Moisture Atmosphere Coupling Experiment SMACEX project during the summer of 2002 (Kustas et al., 2005, Prueger et al., 2005). The required ground data for analysis and verification were wind speed, surface temperature, incident solar radiation, reference ET, height of flux measurements, net radiation (Rn), soil heat flux (G), and sensible heat flux (H) and latent heat flux (LE).

In addition to the output of the spatial LE image, the model can also produces spatial estimates of the net radiation Rn (Wm^{-2}), the soil heat flux G (Wm^{-2}), and the sensible heat flux H (Wm^{-2}). All the output images are instantaneous estimates for the energy fluxes and the LE was then converted to daily ET (mm/day). For verification purposes, a footprint model was used to obtain the flux source area and integrate the spatial fluxes to compare the estimated spatial surface energy fluxes with the ground based measurements of the different fluxes from eddy covariance.

METHODOLOGY

Description of the Two-Source Model

The two source energy balance model used in this study was originally developed by Norman et al. (1995) with the considerations of the series resistance formulation in the estimation of the sensible heat flux. General description of the model formulation is shown in Figure 1. The energy balance equation is described in Equation1.

$$Rn = H + LE + G \quad (1)$$

where Rn is the net radiation (W m^{-2}) which represents the available energy on surface to do work, H the sensible heat flux (W m^{-2}), LE the latent heat flux (W m^{-2}), and G the soil heat flux (W m^{-2}).

The two source model in its series formulation treats the bare soil and the vegetation surfaces separately and combines the effects at the canopy-air interface. For the estimation of the sensible heat flux it assumes that

$$H = H_c + H_s \tag{2}$$

where H_c and H_s are the canopy and soil components of sensible heat flux, respectively. These components can be estimated using Equations 3 to 5.

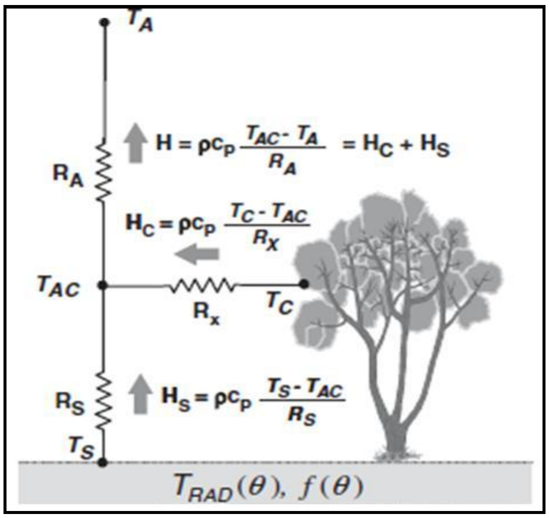

Figure 1. Schematic diagram describing the two-source model TSM approach, (from Anderson et al., 2007).

$$H = \rho C_p \frac{T_{ac} - T_a}{R_a} \tag{3}$$

$$H_c = \rho C_p \frac{T_c - T_{ac}}{R_x} \tag{4}$$

$$H_s = \rho C_p \frac{T_s - T_a}{R_s} \tag{5}$$

where R_a is the aerodynamic resistance to heat transfer and can be estimated using Equation (6), ρ the air density taken as 1.24 (kg m-3), C_p the specific heat of air taken as 1005 (J kg^{-1} K^{-1})and T_s, T_a, and T_{ac} the surface, air, and air-canopy interface temperatures, respectively.

$$R_a = \frac{\left[\ln\left(\frac{z_u - d_o}{z_{om}}\right) - \psi_M\right]\left[\ln\left(\frac{z_t - d_o}{z_{om}}\right) - \psi_H\right]}{k^2 u} \qquad (6)$$

where z_u and z_t are the measurement heights for wind speed and air temperature, respectively, d_o the displacement height estimated as a fraction of canopy height h_c , d_o = (2/3)×h_c , and z_{om} the roughness length for momentum taken as a fraction of canopy height, z_{om} = (1/8)×h_c (Garratt and Hicks, 1973). The stability correction factor for atmospheric heat and momentum transfer are ψ_H and ψ_M, respectively (Brutsaet, 1982).

The total boundary layer resistance of the complete canopy leaves R_x is estimated using the equation described by Norman et al. (1995). The resistance to heat flow in the boundary layer immediately above the soil surface R_s is estimated using Equation 7.

$$R_s = \frac{1}{a + bu_s} \qquad (7)$$

where *a* and *b* are constants equals to 0.004 and 0.012, respectively. The parameter u_s represents the wind speed at height above the soil surface where the effect of soil surface roughness is minimal and estimated by the equation described by Norman et al. (1995). Recent modification to Equation 7 shows that R_s can be updated by the knowledge of T_s and T_c, in which it replaces the constant *a* by c×$(T_s\text{-}T_c)^{(1/3)}$, where c = 0.0025, (Li et al, 2005), (Norman et al, 1995), (Kustas and Norman, 1999a, 2000).

For the estimation of the soil and canopy components of the latent heat flux estimates the TSM assumes that

$$LE = LE_c + LE_s \qquad (8)$$

where LE_c and LE_s are the canopy and soil components of the latent heat flux, respectively. LE_c is estimated using Priestly-Taylor formulation described in Equation 9 (Norman et al, 1995).

$$LE_c = \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} Rn_c \qquad (9)$$

where α_{PT} is Priestly-Taylor constant taken as 1.26, f_G the fraction of the LAI that is green (f_g =1), Δ the slope of the saturation vapor pressure versus temperature curve, and γ the psychrometric constant (0.066kPaC^{-1}), and Rn_c the canopy component of the net radiation.

For the estimation of the soil heat flux the TSM assumes that

$$G = C_g \times Rn_s \qquad (10)$$

where Rn_s is the soil component of the net radiation and C_g constant taken as 0.35 (Santanello and Friedl, 2003).

The net radiation can be estimated using the recently revised version of the two-source model as described by Li et al. (2005), which is based on the model developed by Campbell and Norman (1998) and can be described as

$$Rn = Rn_c + Rn_s \quad (11)$$

$$Rn_c = Ln_c + (1-\tau_s)(1-\alpha_c)S \quad (12)$$

$$Rn_s = Ln_s + \tau_s(1-\alpha_s)S \quad (13)$$

where Ln_c and Ln_s are the canopy and soil components of the long wave radiation estimated using Equations 14 and 15, respectively, α_s the soil albedo, α_c the canopy albedo, τ_s the solar transmittance , and S the solar radiation.

$$Ln_c = [1-\exp(-k_L \Omega LAI)][L_{sky} + L_c + L_s] \quad (14)$$

$$Ln_c = \exp(-k_L \Omega LAI)L_{sky} + [1-\exp(-k_L \Omega LAI)]L_c + L_s \quad (15)$$

where k_L is an extinction coefficient, L_{sky}, L_c, and L_s the long wave radiation from the sky, canopy, and soil, which can be calculated from air, canopy, and soil temperatures, respectively, and Ω is the clumping factor as function of the sun zenith angle.

To estimate the T_c and T_s, the TSM assumes that they are related to the radiometric surface temperature T_R through Equation 18.

$$T_R(\phi) = \left[f_c(\phi)T_c^4 + (1 - f_c(\phi))T_s^4 \right]^{1/4} \quad (16)$$

where $f_c(\phi)$ is the fraction of vegetation cover as function of the view zenith angle ϕ , estimated using Equations 17 and 18.

$$f_c(\phi) = 1 - \exp\left(\frac{-0.5\Omega LAI}{\cos(\phi)}\right) \quad (17)$$

$$\Omega(\phi) = \frac{\Omega(0)\Omega(90)}{\Omega(0) + [\Omega(90) - \Omega(0)]\exp(k\phi^P)} \quad (18)$$

where Ω is the clumping factor at the view zenith angle, k and p empirical coefficients estimated using the procedure described by Li et al. (2005).

To have spatial estimate for the crop height h_c and the leaf area index LAI the formulation developed by Anderson et al. (2004) are used as described by Equations 19 and 20 and for Corn and Soybean, respectively, and Equation 21 for the leaf area index.

$$h_{c\_corn} = (1.2 \times NDWI + 0.6) \times (1 + 0.04 \times \exp(5.3 \times NDWI)) \tag{19}$$

$$h_{c\_soybean} = (0.5 \times NDWI + 0.26) \times (1 + 0.005 \times \exp(4.5 \times NDWI)) \tag{20}$$

$$LAI = (2.88 \times NDWI + 1.14) \times (1 + 0.104 \times \exp(4.1 \times NDWI)) \tag{21}$$

where NDWI is the normalized difference water index,

Both the estimated and measured instantaneous latent heat fluxes were converted to daily ET values in order to be compared against each other. The ratio between the instantaneous actual ET from the energy balance to instantaneous reference evapotranspiration ET_o is calculated and multiplied by the daily reference ET_o to extrapolate to daily actual ET values, assuming that the ratio is constant throughout the specific DOY. The ET_o values were obtained from a reference ET weather station within the project area.

Modeling Tool

In order to perform the spatial analysis, a Visual Basic code was developed and designed to run within ArcGIS platform. The code written to apply the TSM is part of a framework called Spatial EvapoTranspiration Modeling Interface or (SETMI) which consists of different user friendly windows that allows the user to select the required images for the analysis, their spectral band arrangement, to enter weather data, and to select the crop types. The output layer options allows for the selection of intermediate layers such as LAI and final output layers such as Rn, H, G, and LE. A snapshot of the SETMI main window is shown in Figure 2.

Model Verification

The comparison between surface energy balance flux measurements obtained using the eddy covariance systems and the TSM spatial estimates was conducted by integrating the spatial fluxes using the footprint model called Flux Source Area Model FSAM developed by Schmid (1995). In order to obtain the footprints for each field, the FSAM approach requires the friction velocity, roughness length for momentum, Monin-Obukhov stability length, height of zero plane displacements, and standard deviation of wind direction. The FSAM provides the weights of contribution to the upwind source area to the total area from which flux measurements are obtained. The FSAM provides 90 % of the total source area that contributes to the measured energy heat fluxes. With the assistance of the wind direction, the footprints for each satellite overpass date and time and were geo-referenced to the specified field and tower, to be using in the integration of the spatial fluxes.

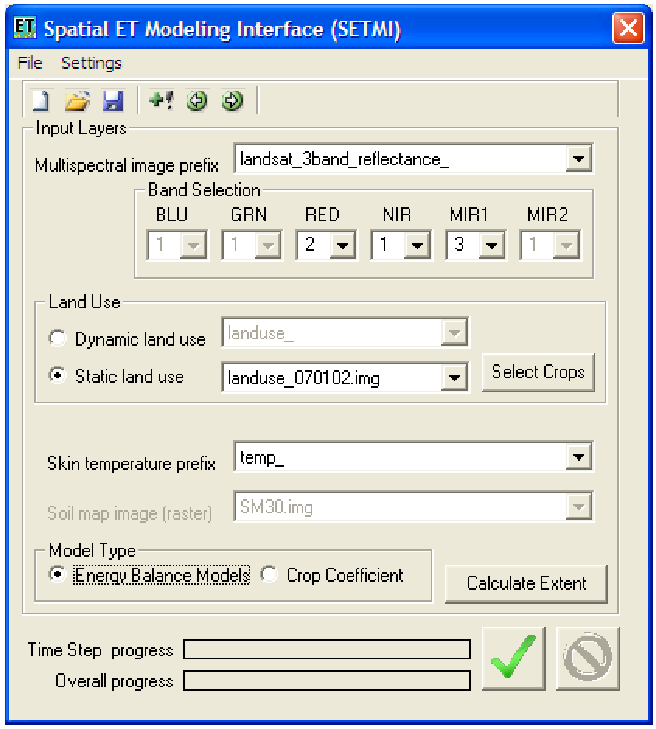

Figure 2. Snapshot for SETMI main window.

The statistical measurements used to compare the estimates with the measurements are the root mean square error RMSE, the mean absolute error MAE and the BIAS described in Equations 23, 24, and 25, respectively.

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(P_i - O_i)^2} \tag{23}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} abs(P_i - O_i) \tag{24}$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{25}$$

where P_i and O_i are the estimated and measured values for each value i and total number of measurements n.

The estimated surface energy fluxes were compared to adjusted measured fluxes due to the problem of lack of closure of the energy balance in typical eddy covariance systems measurements. The first method used for estimating closure was the residual method which assumes that all the error in closure should be added to LE. The second method uses the Bowen ratio to proportionally distribute the error between LE and H. The error in closure is reported for each day and crop.

DATA

Study Site

The study site consisted of mostly rain fed corn and soybean fields covering an area of approximately 12×22 kilometers located south of Ames, Iowa. The crop season starts in late April/early May and lasts until late September/early October. The average annual precipitation is 835 mm.

Remote Sensing Data

The remote sensing data used consisted of Landsat TM5 and TM7 images acquired during the summer of 2002 to match the period of SMACEX project intensive field campaign. The images used in this paper were taken on day of years DOY 174, 182, and 189. These images were atmospherically corrected using MODTRAN (Berk et al., 1989) to obtain at-surface reflectance for the short bands and the radiometric surface temperature with the longwave band. Only the four bands namely red (R), near infrared (NIR), mid infrared1 (MIDIR1), and the thermal infrared of the Landsat images were required for the analysis. Another data set necessary to complete the analysis was the land use image, which identifies the crop types and locations during the study period.

Ground Based Data

The ground based data consisted of air temperature, wind speed, height of measurements, vapor pressure, and incoming solar radiation. Also eddy covariance measurements of surface energy fluxes of Rn, H, LE, and G were acquired in order to be compared with the estimated fluxes. Addition measurements also necessary for model verification were friction velocity, wind direction, and standard deviation of wind direction.

The data from only 8 of the 12 available eddy covariance systems are processed for the purpose of the analysis. The selected corn fields were 6, 24, 33, 151, and 152, while the soybean fields were 3, 13, 23, 161, and 162. The locations of these systems are shown in Figure 3.

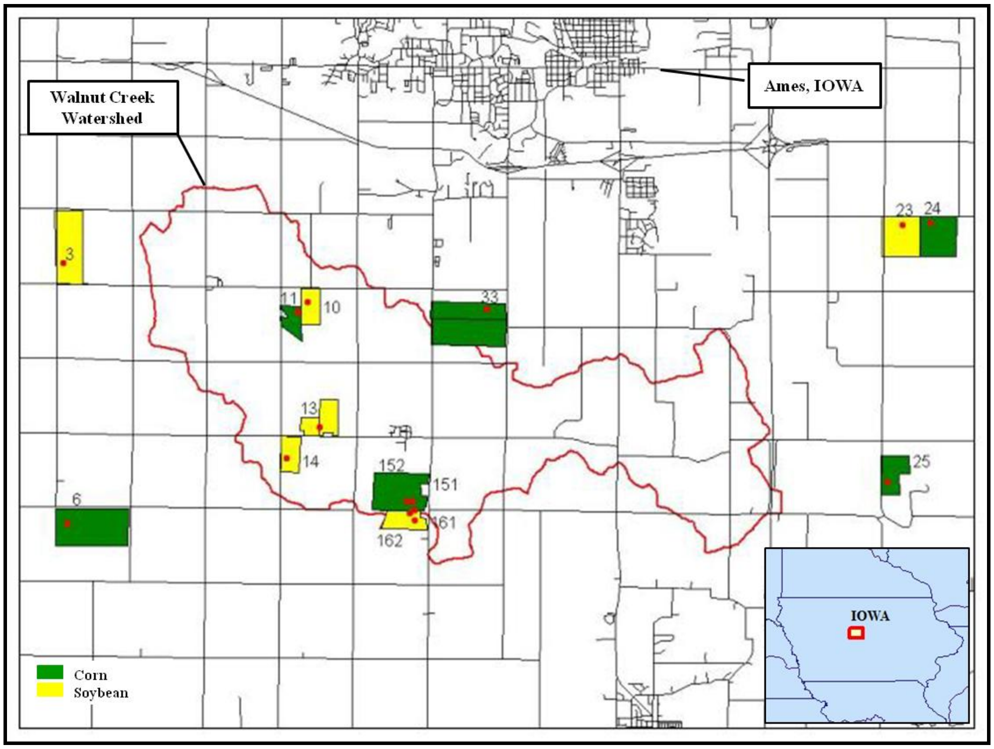

Figure 3. Schematic diagram for the study area, the locations of the eddy covariance systems, and the crop type in the fields.

RESULTS AND DISCUSSION

The latent heat flux LE for DOY 174 (June 23, 2002) clipped to the area around fields 151 and 152 (corn) and fields 161 and 162 (soybean) is shown in Figure 4. The result shows the spatial variability of LE over both corn and soybean fields. The LE for corn field is relatively higher than for soybean which should be the case because of the crop physiological differences.

The source area footprint for DOY 189 for tower 151 in corn field 15 is shown in Figure 5. It shows that the source area extends up to 257 meter from the eddy covariance system in the direction 210º from north based on the wind direction measurements and with a width of about 90 meters perpendicular to the wind direction.

The results obtained for the estimated and measured H_{Re} adjusted with the residual method are shown in Figure 6 and for those H_{BR} adjusted to the Bowen ratio are shown in Figure 7. Generally the results show that for both H_{Re} and H_{BR}, the model underestimates the sensible heat flux with relatively better estimates for H_{Re}. The corn fields show lower sensible heat flux values than the soybean fields as expected because it was at higher green cover, therefore most of the energy was used for LE as the results indicate later in the this section. Comparing measurements adjusted by the two closure methods with the estimated sensible heat flux the RMSE for H_{Re} is 30 (Wm^{-2}) lower than that for H_{BR} 49 (Wm^{-2}), the MAE for H_{Re} is 21 (Wm^{-2}) while it is 37 (Wm^{-2}) for H_{BR}, and the BIAS is -9 (Wm^{-2}) for H_{Re} while it is -31 (Wm^{-2}) for H_{BR}.

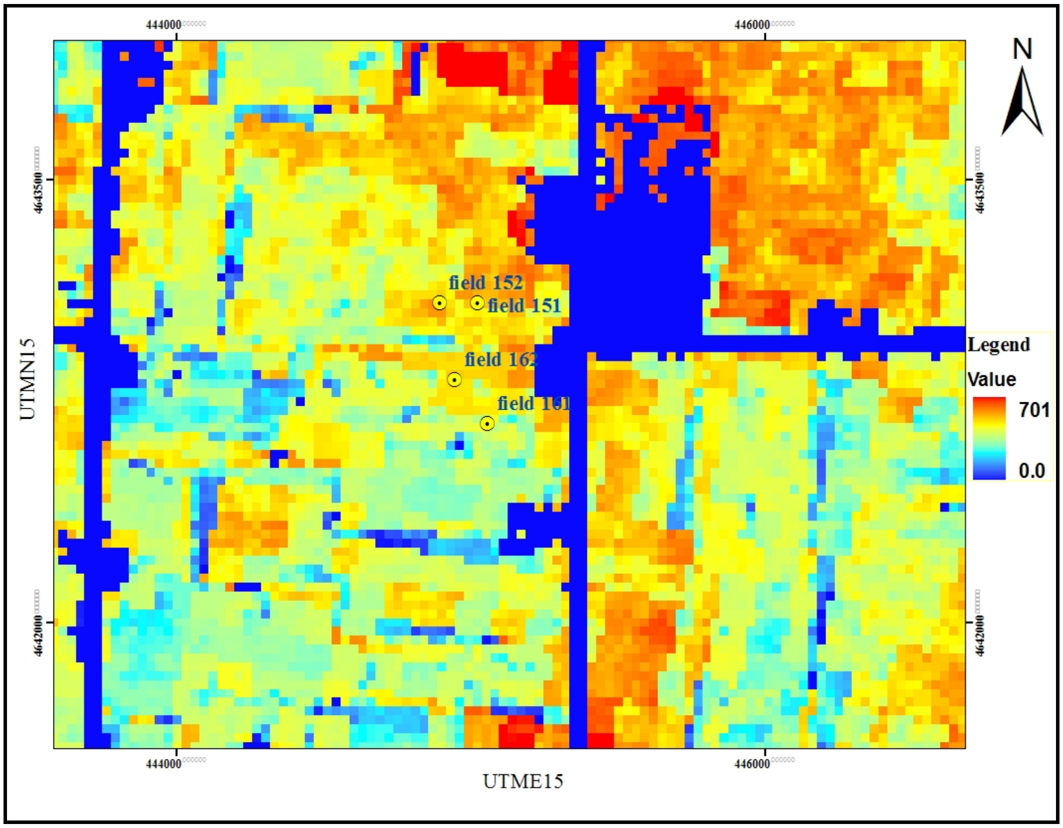

Figure 4. Snapshot of the latent heat flux LE on DOY 174 (June 23, 2002) clipped around the fields 151, 152, 161, and 162.

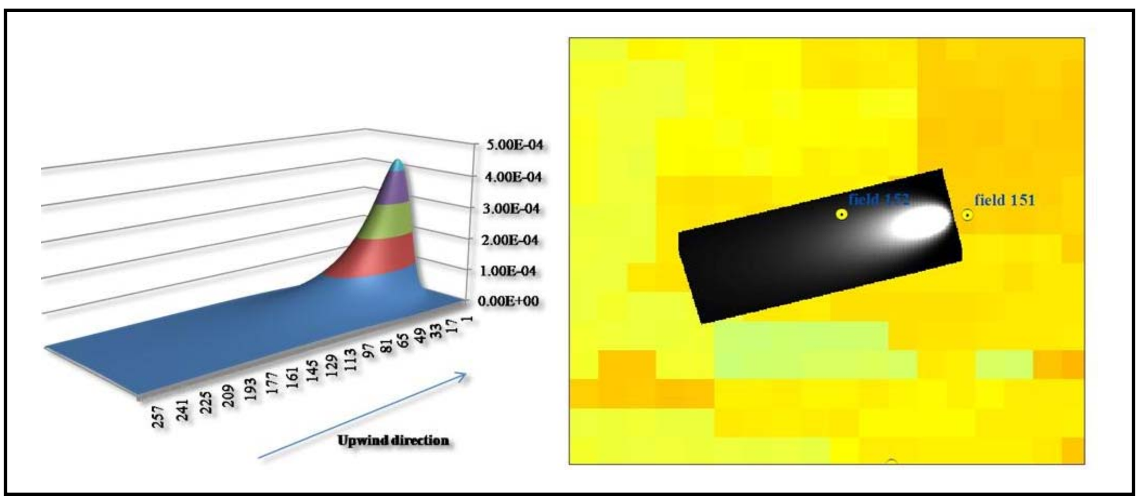

Figure 5. Source area footprint for tower 151 in corn for field on DOY 189.

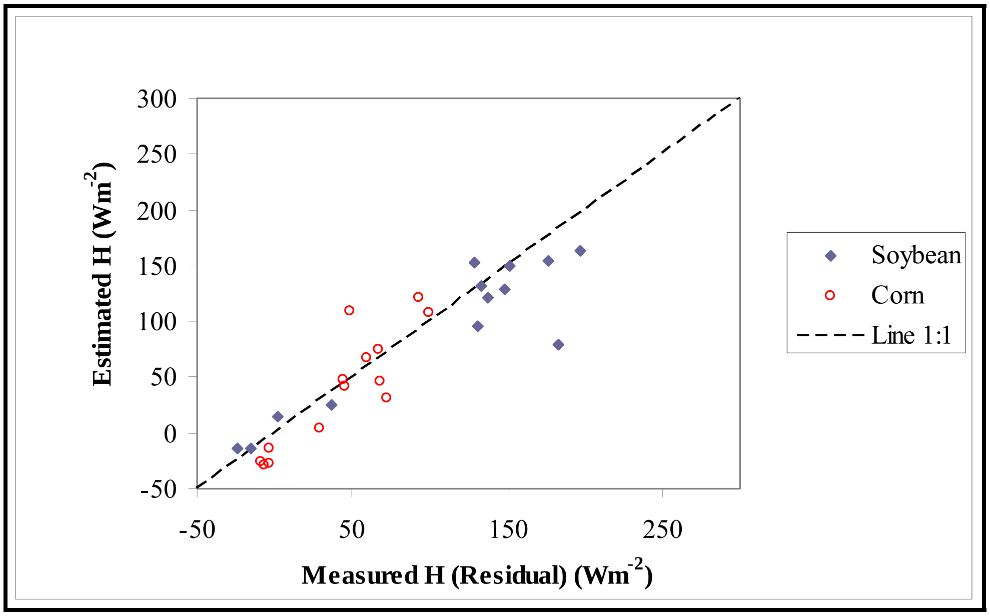

Figure 6. Plot of adjusted H_{Re} (Residual) versus estimated sensible heat flux H.

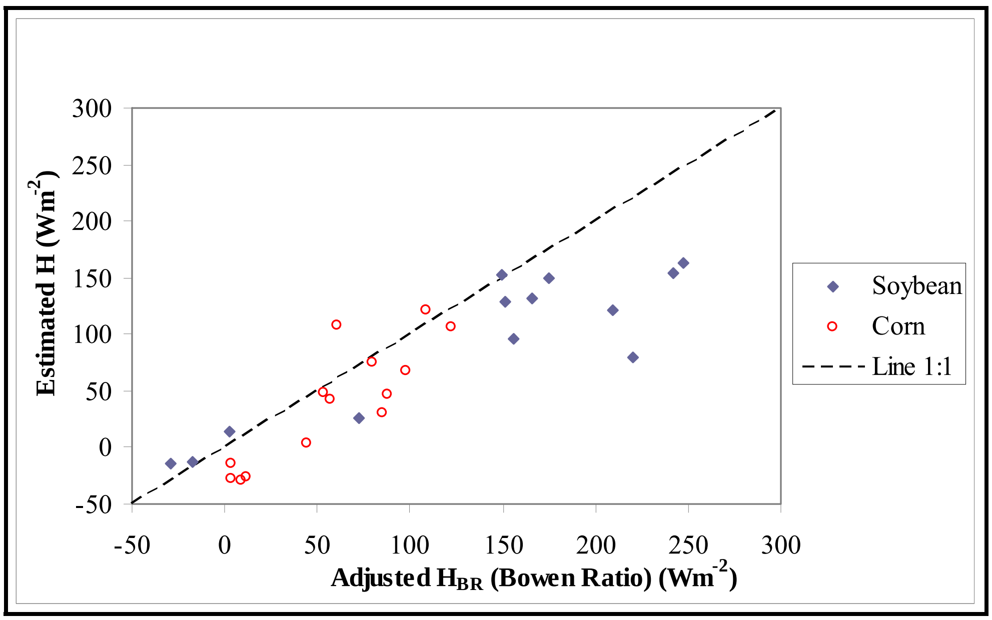

Figure 7. Plot of adjusted H_{BR} (Bowen Ratio) versus estimated sensible heat flux H.

The comparison between the estimated and measured LE_{Re} adjusted using the residual method are shown in Figure 8, and for those LE_{BR} adjusted with Bowen ratio are shown in Figure 9. Generally, both plots show good agreement between measured and estimated latent heat fluxes. However, when comparing the closure methods, LE_{Re} resulted in an underestimation of the LE fluxes compared with LE_{BR}. The LE fluxes in the corn fields were higher than those for soybean fields. From Table 1, the RMSE for LE_{Re} is 45 (Wm^{-2}) while it is 46 (Wm^{-2}) for LE_{BR}, the MAE is 34 (Wm^{-2}) for LE_{Re} and 38 (Wm^{-2}) for LE_{BR}, and the BIAS is -19 (Wm^{-2}) for LE_{Re} and 3 (Wm^{-2}) for LE_{BR}.

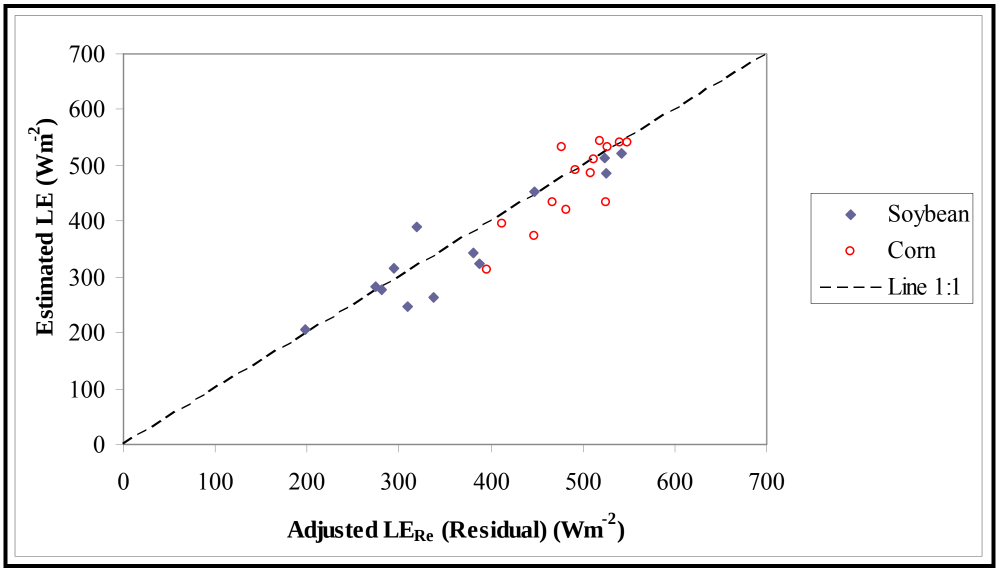

Figure 8. Plot of adjusted LE_{Re} (Residual) versus estimated latent heat flux LE.

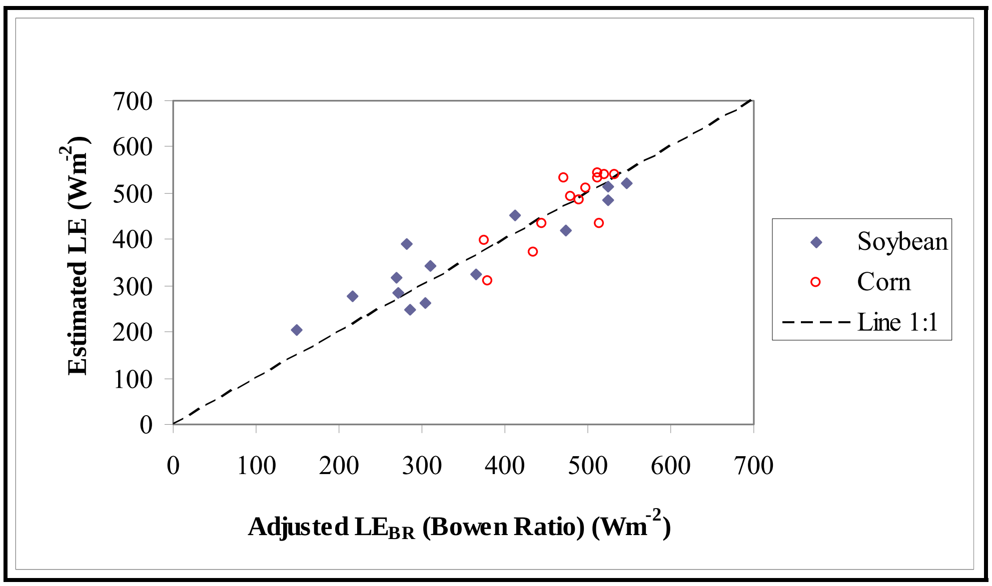

Figure 9. Plot of adjusted LE_{BR} (Bowen Ratio) versus estimated latent heat flux LE.

A comparison of the estimated and measured G is shown in Figure 10. The result shows an overestimation of G. The soil heat fluxes in the corn fields were relatively lower than those in the soybean fields since it had a higher green cover and LAI than the soybean fields. Table 1 shows that the RMSE is 29 (Wm^{-2}), the MAE 23 (Wm^{-2}), and the BIAS 22 (Wm^{-2}).

The net radiation results are shown in Figure 11. The corn fields showed relatively higher values of net radiation but with less agreement with measurements compared to the soybean fields. From Table 1 the RMSE is 17 (Wm^{-2}), and the MAE 13 (Wm^{-2}). The estimated model BIAS is -7 (Wm^{-2}) which indicates that the model underestimates the Rn.

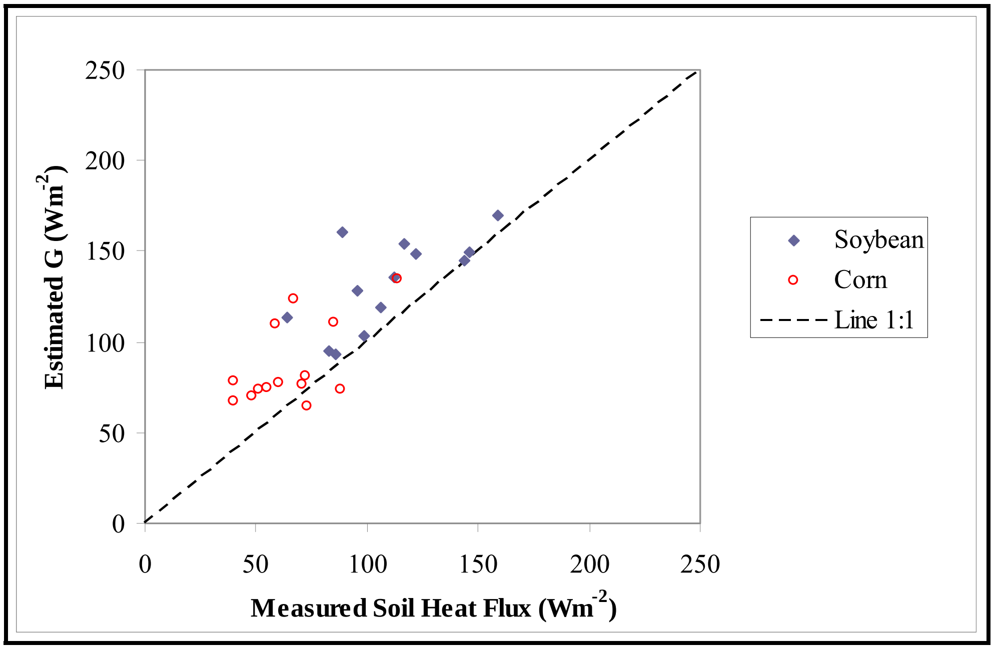

Figure 10. Plot of measured versus estimated soil heat fluxes.

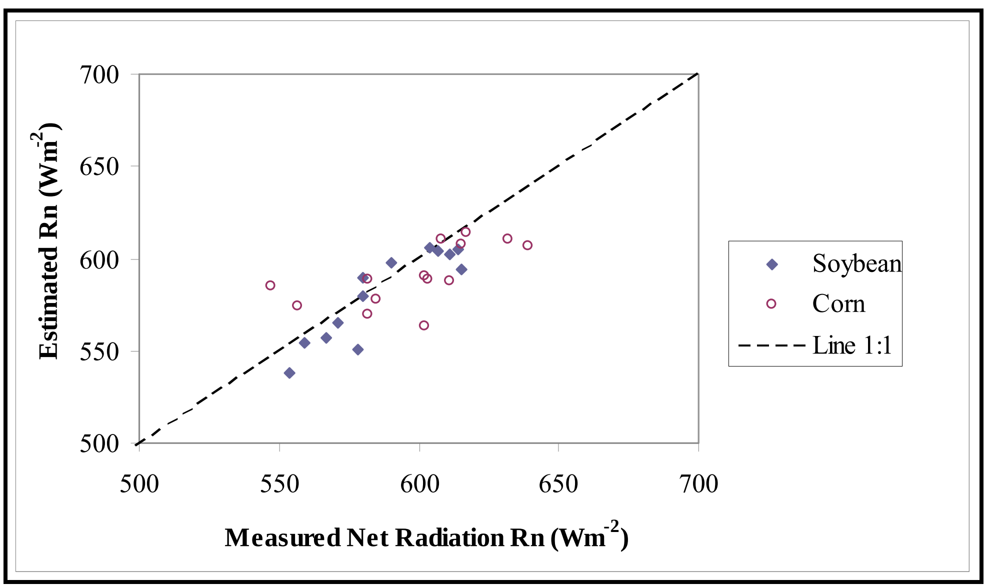

Figure 11. Plot of measured versus estimated net radiation.

Daily ET estimates are compared for the residual ET_{Re} (mm/day) and Bowen ratio ET_{BR} methods of closure in Figures 12 and 13, respectively, and a summary of the statistical results is shown in Table 1.The results show good agreement between measurements and estimates with slight underestimation in both cases.

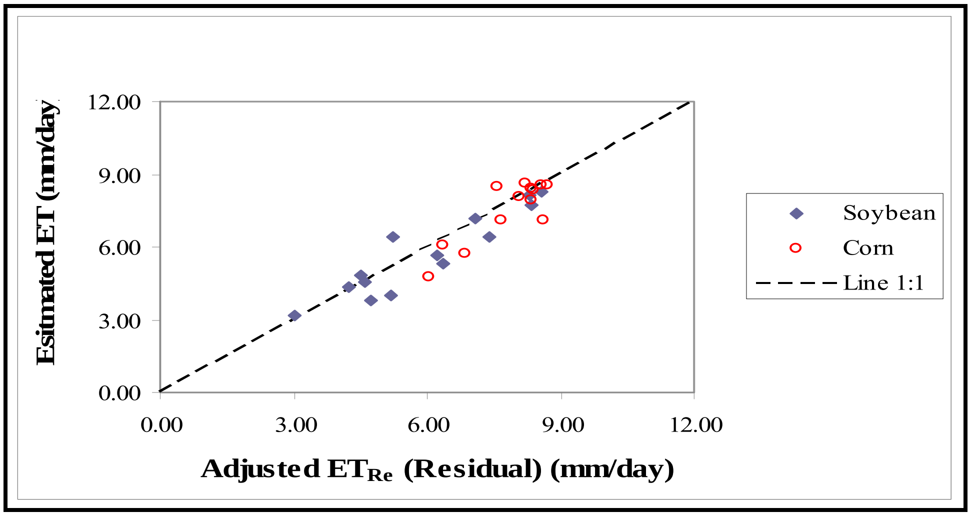

Figure 12. Plot of adjusted ET_{Re} (Residual) versus estimated ET.

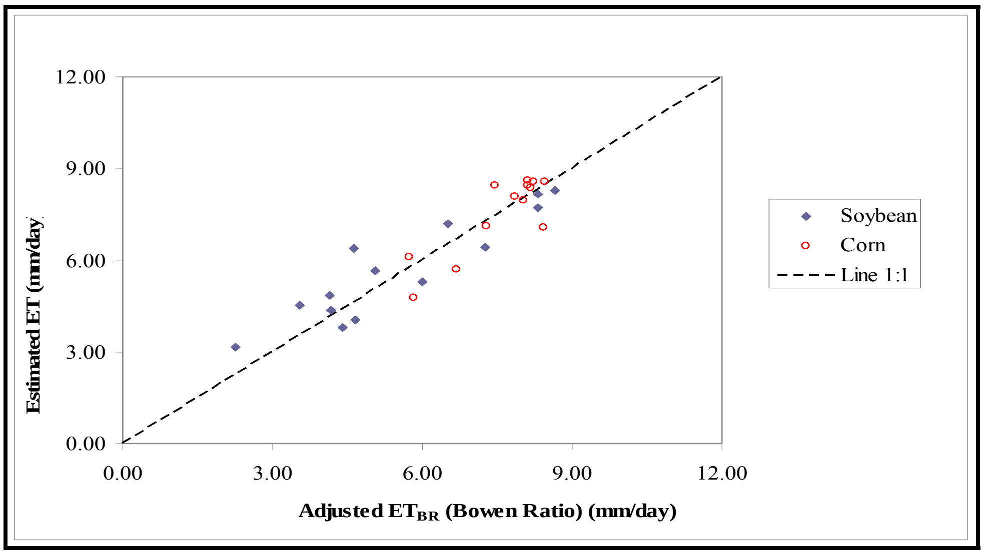

Figure 13. Plot of adjusted ET_{BR} (Bowen Ratio) versus estimated ET.

Table 1. Summary of statistical comparison between estimated and measured of the surface energy fluxes.

	RMSE	MAE	BIAS
H_{Re} (Wm^{-2})	30	21	-9
H_{BR} (Wm^{-2})	49	37	-31
LE_{Re} (Wm^{-2})	45	34	-19
LE_{BR} (Wm^{-2})	46	38	3
G (Wm^{-2})	29	23	22
R_n (Wm^{-2})	17	13	-7
ET_{Re} (mm/day)	0.71	0.53	-0.29
ET_{BR} (mm/day)	0.72	0.60	-0.05

CONCLUSIONS

The current study applied the two-source energy balance model to rain fed corn and soybean cropped fields located in Ames, Iowa. The version of the TSM used is the series resistance formulation for the estimation of the sensible heat flux. A visual basic interface was developed called SETMI that uses the ArcGIS as a platform to perform the analysis.

Landsat TM images were used as the remotely sensed inputs supported with ground based data acquired during the SMACEX project. Two different methods of forcing closure in the eddy covariance flux measurements were tested; the residual and the Bowen ratio methods. The footprint FSAM was used to integrate the source area spatially distributed fluxes in order to be compared with the measured fluxes.

The results indicate that this version of the TSM, when considering the overall performance, slightly underestimates H and LE with BIAS of -9 (Wm^{-2}) and -19 (Wm^{-2}) for H_{Re} and LE_{Re}, respectively. The error in the estimates described by the RMSE are 30 (Wm^{-2}) and 45 (Wm^{-2}) for H_{Re} and LE_{Re}, respectively. There might be a room to improve the model performance by exploring recent modifications for the TSM in decomposing Rn (Anderson et al., 2007). Also the accumulated uncertainty from estimating the different biophysical parameters (e.g. LAI and h_c) could have reduced the model performance and can be improved by exploring different methods. The daily ET_{Re} results showed an underestimation as indicated by the BIAS of -0.29 (mm/day).

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