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Abstract — A surface energy balance model (SEB) was extended by Lagos et al. *Irrig Sci* 28:51–64 (2009) to estimate evapotranspiration (ET) from variable canopy cover and evaporation from residue-covered or bare soil systems. The model estimates latent, sensible, and soil heat fluxes and provides a method to partition evapotranspiration into soil/residue evaporation and plant transpiration. The objective of this work was to perform a sensitivity analysis of model parameters and evaluate the performance of the proposed model to estimate ET during the growing and non-growing season of maize (*Zea Mays L.*) and soybeans (*Glycine max*) in eastern Nebraska. Results were compared with measured data from three eddy covariance systems under irrigated and rainfed conditions. Sensitivity analysis of model parameters showed that simulated ET was most sensitive to changes in surface canopy resistance, soil surface resistance, and residue surface resistance. Comparison between hourly estimated ET and measurements made in soybean and maize fields provided support for the validity of the surface energy balance model. For growing season's estimates, Nash–Sutcliffe coefficients ranged from 0.81 to 0.92 and the root mean square error (RMSE) varied from 33.0 to 48.3 W m^{-2}. After canopy closure (i.e., after leaf area index (LAI = 4) until harvest), Nash–Sutcliffe coefficients ranged from 0.86 to 0.95 and RMSE varied from 22.6 to 40.5 W m^{-2}. Performance prior to canopy closure was less accurate. Overall, the evaluation of the SEB model during this study was satisfactory.

Introduction

Evapotranspiration (ET) is the total amount of water lost via transpiration and evaporation from plant surfaces and the soil in an area where vegetation is growing. Traditionally, ET from agricultural fields has been estimated using the two-step approach by multiplying the weather-based reference ET (Jensen et al. 1971; Allen et al. 1998; ASCE 2002) by crop coefficients (Kc) to make approximate allowance for crop differences. Crop coefficients are determined according to the crop type and the crop growth stage (Allen et al. 1998). However, there is typically some question regarding whether the crops grown compare with the conditions represented by the idealized Kc values (Parkes et al. 2005; Rana et al. 2005; Katerji and Rana 2006; Flores 2007). In addition, it is difficult to accurately predict the crop growth stage dates for many crops (Allen et al. 2007).

A second method is to make a one-step estimate of ET based on the Penman–Monteith (P–M) equation (Monteith 1965), with crop-to-crop differences represented by the use of crop-specific values of surface and aerodynamic resistances (Shuttleworth 2006). ET estimations using the one-step approach with the P–M model has been studied by several authors (e.g., Stannard 1993; Farahani and Bausch 1995; Rana et al. 1997; Alves and Pereira 2000; Kjelgaard and Stockle 2001; Ortega-Farias et al. 2004; Shuttleworth 2006; Katerji and Rana 2006; Flores 2007; Irmak et al. 2008). Although different degrees of success have been achieved, the model has generally performed more satisfactorily when the leaf area index (LAI) is large (LAI>2 $m^2 m^{-2}$). Results show that the "*big leaf*" assumption used by the P–M model is not satisfied for sparse vegetation and crops with partial canopy cover (Stannard 1993; Farahani and Bausch 1995).

A third approach consists of extending the P–M single-layer model to a multiple-layer model (i.e., two layers in the Shuttleworth–Wallace model (Shuttleworth and Wallace 1985) and four layers in the Choudhury–Monteith model (Choudhury and Monteith 1988)). These extended approaches provide the potential for modeling ET for the entire range of plant cover and the ability of partitioning ET between crop transpiration and soil evaporation. The advantage of these models has been recognized by several authors (e.g., Shuttleworth and Gurney 1990; Farahani and Ahuja 1996; Stannard 1993; Massman 1992; Gardiol et al. 2003; Iritz et al. 2001; Tourula and Heikinheimo 1998; Ortega-Farias et al. 2007; Anadranistakis et al. 2000; Alves and Cameira 2002; Lafleur and Rouse 1990). Results from using multiple-layer models are encouraging, in general, and these models performed satisfactorily for a large range of canopy cover than single-layer models.

Recognizing the potential of multiple-layer models to estimate ET, a modified surface energy balance model (SEB), was developed by Lagos et al. (2009) to include the effect of crop residue on evapotranspiration. The model relies mainly on the Schuttleworth–Wallace (1985) and Choudhury and Monteith (1988) approaches and has the potential to predict evapotranspiration for varying soil cover ranging from partially residue-covered soil to closed-canopy surfaces. Background information and procedures of the SEB model were described in the previous paper, and only a brief summary is included here. The objective of this work was to perform a sensitivity analysis of model parameters and evaluate the performance of the proposed model to estimate ET during the growing and non-growing season of maize (*Zea Mays L.*) and soybeans (*Glycine max*). Results were compared with measured data from eddy covariance flux systems.

Materials and methods

Study sites

Three sites located at the University of Nebraska Agricultural Research and Development Center (ARDC) near Mead, NE, were used for model evaluation. Field area ranges from 49 to 65 ha, providing sufficient fetch of uniform cover required for adequately measuring mass and energy fluxes using eddy covariance systems (Verma et al. 2005). **Site 1** is an irrigated (center pivot) continuous maize system of 48.7 ha (41°17′N, 96°48′W); **site 2** is an irrigated (center pivot) maize–soybean rotation system of 52.4 ha (41°16′N, 96°47′W); and **site 3** is a rain-fed maize–soybean rotation system of 65.4 ha (41°18′N, 96°44′W) (Figure 1). Maize was grown at sites 2 and 3 during 2003 and 2005, while soybeans were grown in 2002 and 2004. The soil at the ARDC is a deep silty clay loam, typical of eastern Nebraska (Suyker and Verma 2008). The fields have been farmed in no-tillage system since 2001. Information about planting densities and grain yield is provided in Table 1. Information on other crop management practices is given by Verma et al. (2005), and Suyker and Verma (2008).

During this study, mean annual air temperature ranges from 9.9°C (2003, site 2) to 11.2°C (2005, site 1) and annual rainfall ranges between 541 mm (2002) and 670 mm (2004) at all sites. During most of the growing seasons (May–October), mean air temperature was within 18.6°C (2003, site 2) and 20.1°C (2005, site 1), and growing season rainfall ranges between 386 mm (2005) and 448 mm (2004) (Table 1). Annual average wind speed measured at 3 m ranged from 2.96 m s^{-1} (2005, site 2) to 3.56 m s^{-1} (2002, site 2). During May to October, average wind speed was between 2.18 m s^{-1} (2003, site 2) and 3.34 m s^{-1} (2002, site 3), and predominant wind direction during this period were mostly from south and southeast directions for all years.

At all sites, soil water content in the root zone was measured continuously at four depths (0.10, 0.25, 0.5, and 1.0 m) by employing Theta probes (Delta-T Device, Cambridge, UK). Green leaf area index and biomass measurements were made approximately bimonthly during the growing season. Air temperature and humidity were measured at 3 m and 6 m (Humitter 50Y, Vaisala, Helsinki, Finland), net radiation at 5.5 m (CNR1, Kipp and Zonen, Delft, NLD), and soil heat flux at 0.06 m depth (Radiation and Energy Balance Systems Inc., Seattle, WA). Soil temperature was measured at 0.06, 0.1, 0.2, and 0.5 m depths (Platinum RTD, Omega Engineering, Stamford, CT). At the three sites, eddy covariance measurements of latent heat, sensible heat, and momentum fluxes were made using an omnidirectional three-dimensional sonic anemometer (Model R3, Gill Instruments Ltd., Lymington, UK) and an open-path infrared CO_2/H_2O gas analyzer system (Model LI7500, Li-Cor Inc., Lincoln, NE). The eddy covariance sensors were mounted 3 m above the ground when the canopy was shorter than 1 m and later moved to 6 m until harvest (maize only). Fluxes were corrected for inadequate sensor frequency response (Suyker and Verma 1993) and adjusted for the variation in air density due to the transfer of water vapor and sensible heat. More details of flux measurements, data filling, and flux corrections are given in Verma et al. (2005) and Suyker and Verma (2009). At all sites, footprint

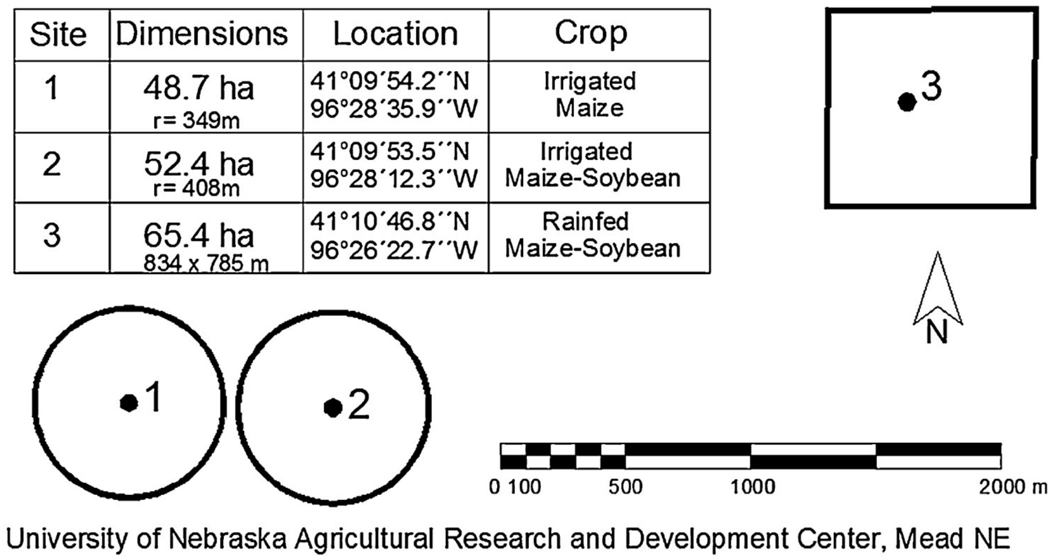

Figure 1. Size and location of sites (*black dots* represent eddy covariance system location)

analyses for all seasons were performed to test the proportion of the measured fluxes originating from the crop within a specified upwind distance (Gash 1986; Schuepp et al. 1990). The footprint model shows 85–90% of the fetch to an extent of 350 m from eddy covariance systems. Three-dimensional flux footprints were plotted using wind direction. Figure 2a shows the daily footprint during the day of year (DOY) 198 of 2003 at site 2; Figure 2b, daytime during the growing season; Figure 2c, footprint weights DOY 205 at 12:30 pm; and Figure 2d, cumulative footprint weights DOY 205 at 12:30 pm. In general, the point of maximum influence was located at 50 m from the eddy covariance systems, and most of the fluxes were originated within an upwind distance of 300–350 m. Due to that wind speed, wind direction and other environmental conditions were very similar at all sites, three-dimensional flux footprints were similar; this confirms that most of latent and sensible heat fluxes measured by eddy covariance systems came from the experimental fields.

The surface energy balance model for evapotranspiration (SEB)

The modified surface energy balance (SEB) model developed by Lagos et al. (2009) has four layers (Figure 3a). The first extended from the reference height above the vegetation and the sink for momentum within the canopy, a second layer between the canopy level and the soil surface, a third layer corresponding to the top soil layer, and the fourth, a lower soil layer where the soil atmosphere is saturated with water vapor. The soil temperature at the bottom of the lower level was held constant at least for a 24-h period. The SEB model distributes net radiation (Rn), sensible heat (H), latent heat (λE) and soil heat fluxes (G) through the soil/residue/canopy system. Horizontal gradients of the potentials are assumed to be small enough for lateral fluxes to be ignored, and physical and biochemical energy storage terms in the canopy/residue/soil system are assumed to be negligible. The evaporation of water on plant leaves due to rain, irrigation, or dew is also ignored.

Total latent heat flux from the canopy/residue/soil system (λE) (Wm^{-2}) is the sum of the latent heat from the canopy (transpiration) λE_c (W m^{-2}), latent heat from the soil λE_s (W m^{-2}), and latent heat from the residue-covered soil (evaporation) λE_r (W m^{-2}), calculated as:

$$\lambda E = \lambda E_c + (1 - f_r) \cdot \lambda E_s + f_r \cdot \lambda E_r \quad (1)$$

where f_r is the fraction of the soil affected by residue (0–1)

By analogy with Ohm's law, the differences in vapor pressure between two levels can be written in terms of resistance and latent heat flux as illustrated in Figure 3b (Shuttleworth and Wallace 1985).

The latent heat flux from the canopy (λE_c), the latent heat flux from the bare soil surface (λE_s), and the latent heat fluxes from the soil affected by residue (λE_r) can be expressed by:

(a) Canopy: Latent heat flux from the canopy is given by:

$$\lambda E_c = \frac{\Delta \cdot r_1 \cdot \mathrm{Rn}_c + \rho \cdot C_p \cdot (e_b^* - e_b)}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} \quad (2)$$

(b) Bare soil: Latent heat flux from bare soil surfaces λE_s can be estimated by:

$$\lambda E_s = \frac{\mathrm{Rn}_s \cdot \Delta \cdot r_2 \cdot r_L + \rho \cdot C_p \cdot [(e_b^* - e_b) \cdot (r_u + r_L + r_2) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_2)]}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} \quad (3)$$

(c) Residue-covered soil: Similarly to bare soil latent heat flux from the residue-covered soil, λE_r can be estimated by:

$$\lambda E_r = \frac{\text{Rns} \cdot \Delta \cdot (r_2 + r_{rh}) \cdot r_L + \rho \cdot C_p \cdot [e_b^* - e_b) \cdot (r_u + r_L + r_2 + r_{rh}) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_2 + r_r)]}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})} \quad (4)$$

Table 1. Crop management details, rainfall, and air temperature at all sites

	Site 1	Site 2	Site 3
2002 — Crop	Maize	Soybean	Soybean
Planting date	May 9	May 20	May 20
Harvest date	November 4	October 7	October 9
Grain yield (kg ha^{-1})	12,970	3,990	3,320
Plant density (pl ha^{-1})	81,000	370,644	370,644
Annual rainfall (mm)	541*		
Mean annual air temperature (°C)	10.7	10.5	10.6
May–October rainfall (mm)	429*		
May–October air temperature (°C)	19.3	19.2	19.4
2003 — Crop	Maize	Maize	Maize
Planting date	May 15	May 14	May 13
Harvest date	October 27	October 23	October 11
Grain yield (kg ha^{-1})	12,120	14,000	7,720
Plant density (pl ha^{-1})	77,000	84,329	64,292
Annual rainfall (mm)	572*		
Mean annual air temperature (°C)	10.3	9.9	10.0
May–October rainfall (mm)	389*		
May–October air temperature (°C)	19.1	18.6	18.8
2004 — Crop	Maize	Soybean	Soybean
Planting date	May 7	June 2	June 3
Harvest date	October 14	October 19	October 11
Grain yield (kg ha^{-1})	12,120	3,730	3,140
Plant density (pl ha^{-1})	84,012	370,644	370,644
Annual rainfall (mm)	670*		
Mean annual air temperature (°C)	10.7	10.3	10.3
May–October rainfall (mm)	448*		
May–October air temperature (°C)	19.2	18.8	18.9
2005 — Crop	Maize	Maize	Maize
Planting date	May 5	May 2	April 26
Harvest date	October 12	October 17	October 18
Grain yield (kg ha^{-1})	12,050	13,180	9,100
Plant density (pl ha^{-1})	82,374	83,200	60,358
Annual rainfall (mm)	600*		
Mean annual air temperature (°C)	11.2	10.9	10.8
May–October rainfall (mm)	386*		
May–October air temperature (°C)	20.14	20.02	19.9

* Annual and May–October rainfall same for all sites

where Rn_c is the net radiation absorbed by the canopy (W m^{-2}) and Rn_s is the net radiation absorbed by the soil (W m^{-2}), ρ is the density of moist air (kg m^{-3}), Cp is the specific heat of air (J Kg^{-1}°C^{-1}), and γ is the psychrometric constant (mb°C^{-1}). Variable Δ is the mean rate of change of saturated vapor pressure with temperature between two levels (mb°C^{-1}); Choudhury and Monteith (1988) found that Δ evaluated at the air temperature (T_a) located at the reference height usually gave the components of the heat balance with acceptable accuracy. Therefore, Δ evaluated at T_a is used here. Variable e_b is the vapor pressure of the atmosphere at the canopy level (mb), and $e^{\cdot}_{b}$ is the saturation vapor pressure of the atmosphere at the canopy level (mb). Variable T_b represents the air temperature at the sink of momentum in the canopy (°C), and T_m is the temperature at the bottom of the lower layer (°C). In Figure 3b) e_1* is the saturation vapor pressure at the canopy (mb) and e_L* is the saturation vapor pressure at the top of the wet layer (mb).

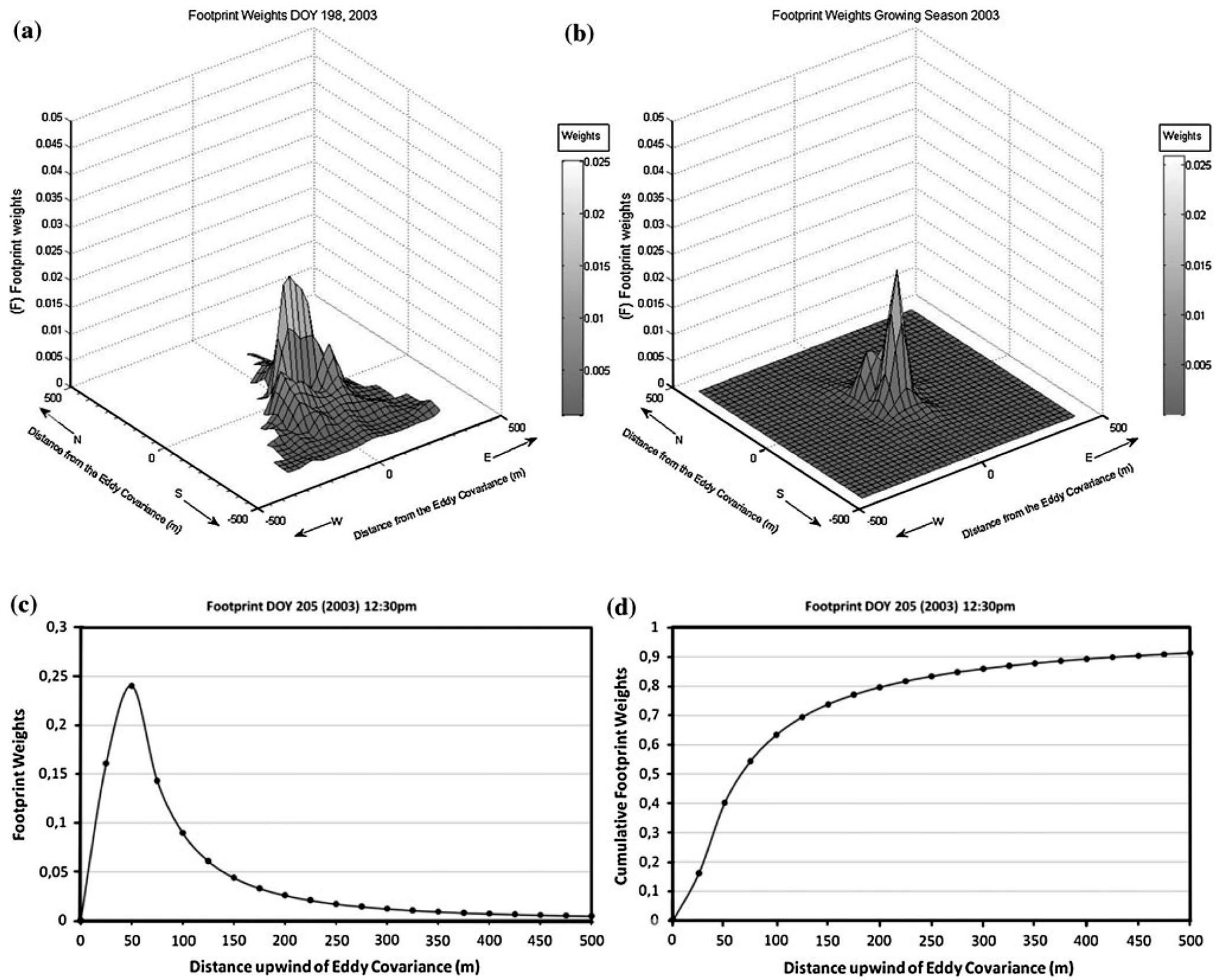

Figure 2. Footprint representation at site 2 during 2003, **a)** daytime day of the year (DOY) 198, **b)** daytime during the growing season, **c)** footprint weights DOY 205 at 12:30 pm and **d)** cumulative footprint weights DOY 205 at 12:30 pm

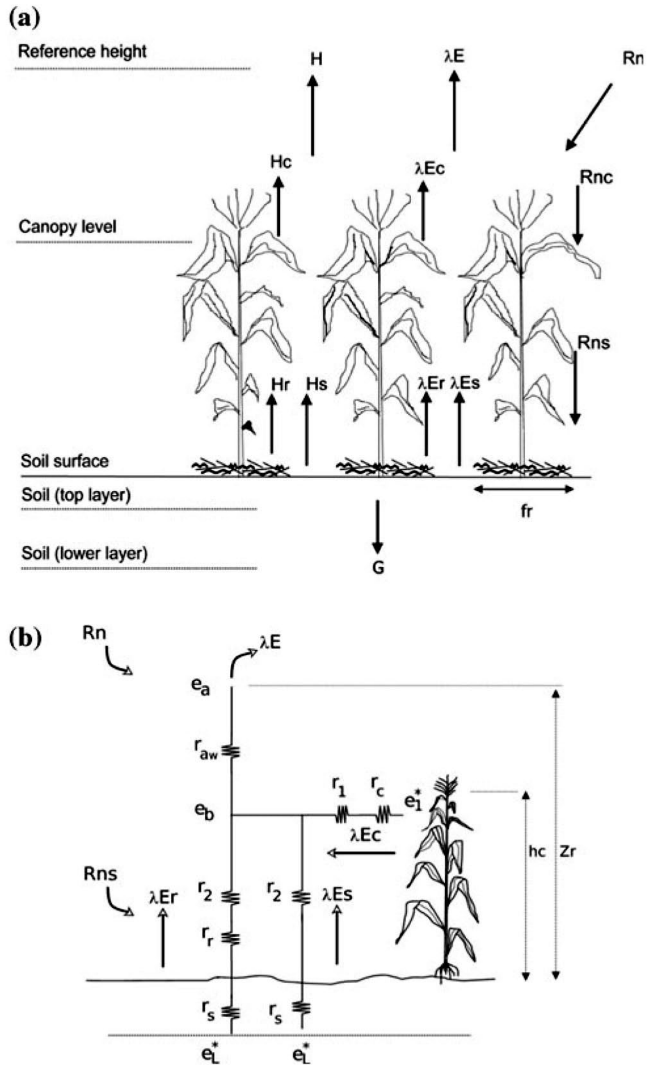

Figure 3. a) Fluxes of the surface energy balance (SEB) model and **b)** a schematic resistance network of the SEB model for latent heat flux. (*Rn* net radiation, Rn_c net radiation absorbed by the canopy, Rn_s net radiation absorbed by the soil, *H* sensible heat, H_c sensible heat from the canopy, H_r sensible heat from the residue-covered soil, H_s sensible heat from the bare soil, λE evapotranspiration, λE_c latent heat flux from the canopy, λE_r latent heat flux from the residue-covered soil, λE_s, latent heat flux from the bare soil, *G* soil heat flux, f_r fraction of the soil covered by residue, e_a vapor pressure deficit of the air, e_b vapor pressure deficit of the air at the canopy level; e_1*, saturated vapor pressure at the canopy; e_L*, saturated vapor pressure at the top of the wet layer; r_{aw}, aerodynamic resistance for water vapor; r_c, surface canopy resistance; r_1, aerodynamic resistance between the canopy and the air at the canopy level; r_2, aerodynamic resistance between the soil and the air at the canopy level; r_r, residue resistance for water flux; r_s, soil resistance for water flux; *hc*, crop height; *Zr*, reference height)

Parameter r_1 is an aerodynamic resistance between the canopy and the air within the canopy (s m^{-1}), r_c is the surface canopy resistance (s m^{-1}), r_2 is the aerodynamic resistance between the soil and the canopy (s m^{-1}), r_s is the resistance to the diffusion of water vapor through the soil at the top soil layer (s m^{-1}), and r_{rh} and r_r are the residue resistance to transfer of heat and vapor flux, respectively (s m^{-1}). Variables r_u and r_L are resistances to the transport of heat for the upper and lower soil layers, respectively. In Figure 3b), r_{aw} represents the aerodynamic resistance to the transfer of water flux.

The modified SEB model is applicable to conditions ranging from fully closed canopies to surface with bare soil partially covered with residue. Values for T_b and e_b are necessary to estimate latent heat and sensible heat fluxes in Equations (2) through (4). The detailed expressions for these parameters were described in the previous paper (Lagos et al. 2009).

Sensitivity analysis

A sensitivity analysis was performed to evaluate the response of the SEB model to changes in resistances and model parameters. Meteorological conditions, crop characteristics and soil/residue characteristics used in these calculations are given in Table 2. Such conditions are typical for midday during the growing season of maize in southeastern Nebraska. The sensitivity of total latent heat from the system was explored when model resistances and model parameters were changed under different LAI conditions. The effect of the changes in model parameters and resistances was expressed as changes in total ET (λE) and changes in the crop transpiration ratio. The transpiration ratio is the ratio of crop transpiration (λE_c) to total ET (transpiration ratio = $\lambda E_c/\lambda E$).

Model performance

There are several statistical techniques used to evaluate the performance of physical models (Legates and McCabe 1999; Krause et al. 2005; Moriasi et al. 2007; Coffey et al. 2004). In this work, the coefficient of determination (r^2), the Nash–Sutcliffe coefficient (E), the index of agreement (d), the root mean square error (RMSE), and the mean absolute error (MAE) are used for model evaluation.

Results and discussion

Sensitivity analysis

The response of the SEB model was evaluated for three values of the extinction coefficient (Cext = 0.4, 0.6, and 0.8), three conditions of vapor pressure deficit (VPDa = 0.5 kPa, 0.1 kPa, and 0.25 kPa), three soil temperatures (T_m = 21°C, 0.8 × T_m = 16.8°C, and 1.2 × T_m = 25.2°C), changes in the parameterization of aerodynamic resistances (the attenuation coefficient, α (α = 1, 2.5, and 3.5), the mean boundary layer resistance, r_b (±40%), and the crop height *h* (±30%), selected

Table 2. Predefined conditions for the sensitivity analysis

Variable	Symbols	Value	Unit
Net radiation	Rn	500	W m^{-2}
Air temperature	T_a	25	°C
Relative humidity	RH	68	%
Wind speed	u	2	m s^{-1}
Soil temperature at 0.5 m	T_m	21	°C
Solar radiation	Rad	700	W m^{-2}
Canopy resistance coefficients	C1, C2, C3	5, 0.005, 300	
Maximum leaf area index	LAImax	6	m^2 m^{-2}
Soil water content	Θ	0.25	m^3 m^{-3}
Saturation soil water content	Θ*s*	0.5	m^3 m^{-3}
Soil porosity	*φ*	0.5	m^3 m^{-3}
Soil tortuosity	*τs*	1.5	
Residue fraction	f_r	0.5	
Thickness of the residue layer	Lr	0.02	m
Residue tortuosity	sr	1	
Residue porosity	*φr*	1	
Upper layer thickness	Lt	0.05	m
Lower layer depth	Lm	0.5	m
Soil roughness length	Zo′	0.01	m
Drag coefficient	Cd	0.07	
Reference height	*z*	3	m
Attenuation coefficient	*α*	2.5	
Maximum solar radiation	Radmax	1,000	W m^{-2}
Extinction coefficient	Cext	0.6	
Mean leaf width	*w*	0.08	m
Water vapor diffusion coefficient	Dv	2.56×10^{-5}	m^2 s^{-1}
Fitting parameter	*β*	6.5	
Soil thermal conductivity, upper layer	*K*	2.8	W m^{-1} °C^{-1}
Soil thermal conductivity, lower layer	*K′*	3.8	W m^{-1} °C^{-1}

conditions for the soil surface resistance, r_s (0.227 and 1,500 s m^{-1}), four values for residue resistance, r_r (0, 400, 1,000, and 2,500 s m^{-1}), changes of ±30% in surface canopy resistance, r_c, and changes of ±30 of r_u.

Results showed that the response of total ET to changes on Cext was small, generally less than 1% for all values of LAI. For a VPDa = 0.1 kPa, total ET was 3–28% larger than total ET for a VPDa = 0.5 kPa, with the larger difference when LAI = 0. Soil temperature, T_m, is required for the SEB model. Measurements of soil temperature are common for 0.1 m below the soil surface and are becoming more popular for 0.2 and 0.5 m in current weather station networks. However, partial canopy cover shading, variation in soil thermal properties, and/or different moisture content may amplify the variation of T_m. The response of total ET to changes in T_m (±4.2°C) was generally less than 7% (Figure 4a). Similarly, the effects on transpiration ratio ($\lambda E_c/\lambda E$) for different LAI conditions were minimal with differences of less than 3% (Figure 4a). On the parameterization of aerodynamic resistances, the effect on total ET to changes in the attenuation coefficient in general was small, with differences generally less than 2%. Changes in mean boundary layer resistance, r_b, of ±40% had minimum effects on total ET, and similarly, changes in ±30% of crop height produced differences of less than 2% in total ET. In contrast, significant effects on total ET and the transpiration ratio were observed for changes in the soil surface resistance, r_s. The $r_s = 0$ corresponds to a substrate of wet soil or free water, a value of 227 s m^{-1} represents an intermediate value for a 0.05-m soil layer, and the third value of 1,500 s m^{-1} corresponds to a fairly dry soil with volumetric soil water content Θ = 0.1 (m^3 m^{-3}). Results show that total evapotranspiration is significantly altered by the condition of the soil, with the largest impact for small LAI values (Figure 4b). Differences in total ET ranged from 2–3% for a LAI of 5–6 to a value of 50% for LAI = 0. The effect on transpiration ratio was also significant with a minimum difference of 3% (LAI = 6) and a maximum of 30% for a LAI of 0.5 (Figure 4b).

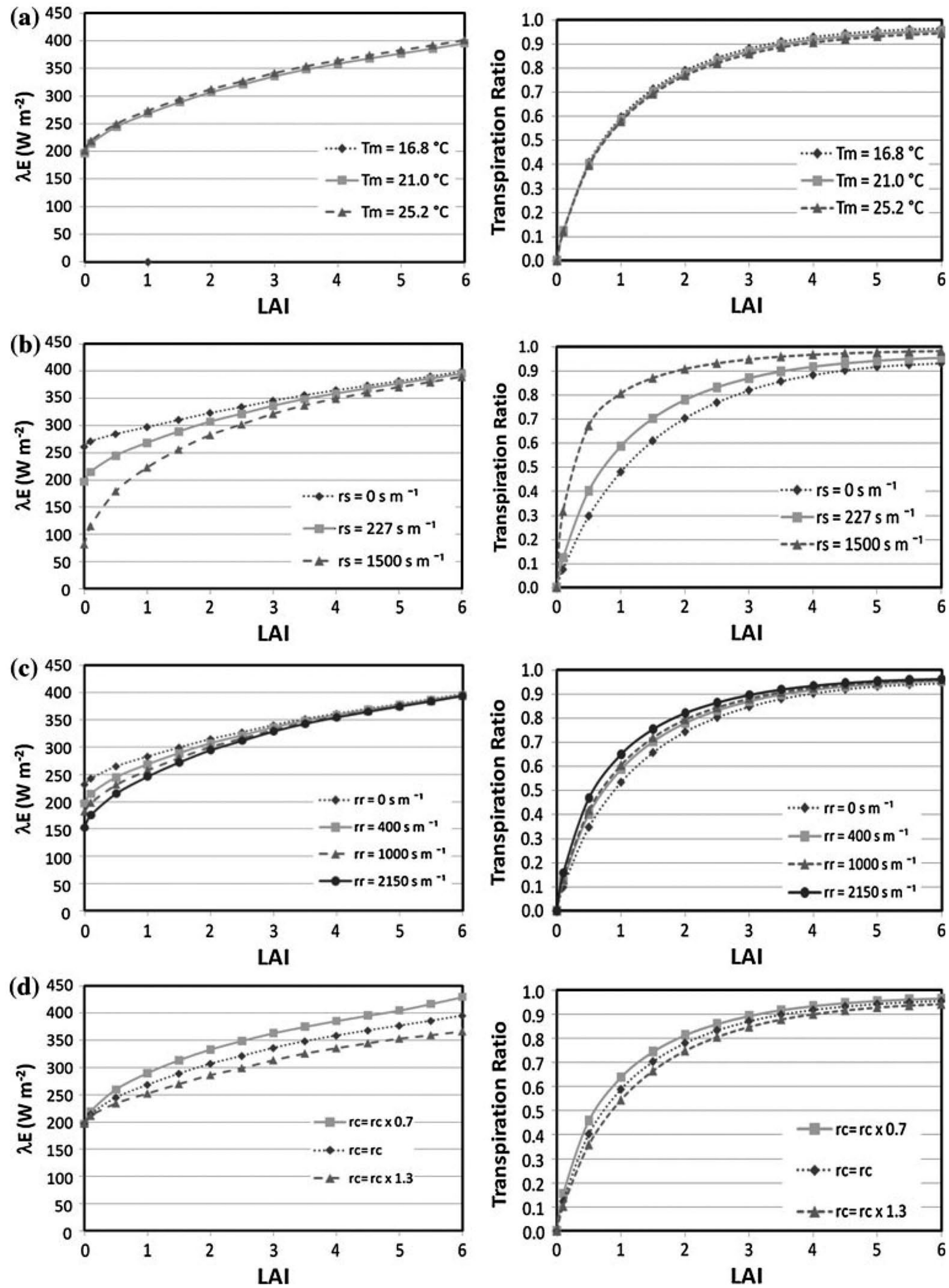

Figure 4. Sensitivity analysis for **a)** soil temperature (T_m), **b)** soil resistance (r_s), **c)** residue resistance (r_r), and **d)** canopy resistance (r_c) under variable leaf area index (LAI) conditions

Total ET and transpiration ratio calculated by changes in the residue resistance, r_r, are illustrated in Figure 4c. The r_r = 0 condition represents a lack of any residue, a value of 400 s m^{-1} represents an intermediate value for a 0.02-m residue layer with residue characteristics presented in Table 1 and wind speed of 2 m s^{-1}at 2 m height from the ground surface. The third value of r_r = 1,000 s m^{-1} corresponds to a second intermediate value calculated for a 0.055-m residue layer and wind speed of 2 m s^{-1} measured at 2 m. The last value of r_r = 2,500 s m^{-1} corresponds to an extreme value calculated for a 0.055-m residue layer and wind speed of 0 m s^{-1} measured at 2 m. Results showed that larger residue resistance values produced a reduction in total ET. For residue resistances less than 1,000 s m^{-1}, differences in total ET ranged from 0 to 23%, with the highest differences for small LAI values (Figure 4c). A residue resistance of 2,500 s m^{-1} significantly reduced ET, with differences of 1–25% when compared with total ET calculated with r_r = 400 m s^{-1}. A residue resistance of 2,500 s m^{-1} produced a maximum difference in the transpiration ratio of 7% (LAI = 1.5) when compared with the transpiration ratio calculated with $r_r = 400$ m s^{-1}. Changes of ±30% in surface canopy resistance were used to test the effects of r_c on total evapotranspiration. Total ET was reduced for higher values of r_c. No effects of r_c on total ET was found for LAI = 0; however, a difference of 6% was found when LAI = 0.5 up to 10% when LAI = 6 (Figure 4d). The effect on the transpiration ratio due to changes in r_c is shown in Figure 4d, and differences in the transpiration ratio for ±30% of change in canopy resistance ranged between 1 and 10%, with the largest impact for 0.5 < LAI < 1.5.

For the soil heat flux resistance, r_u, result shows that changes in ±30% of r_u had minimum effects on total ET, differences ranged between 0 and 2% with the largest value for LAI = 0, but less than 1% when LAI > 1. Differences in the transpiration ratio for ±30% change in r_u were less than 1% for the LAI range.

In general, the sensitivity analysis of model resistances showed that simulated ET was most sensitive to changes in surface canopy resistance for LAI > 0.5 values, and soil surface resistance and residue surface resistance for small LAI values (LAI < ~3). The model was less sensitive to changes in the others parameters evaluated.

Model evaluation

Model evaluation is a two-step process that includes model calibration and model validation. However, prior to calibration, the energy balance closure of the measurements from the eddy covariance systems was evaluated. Measured net radiation, Rn, was compared against the sum of measured latent heat flux (λE), sensible heat flux (H), soil heat flux (G), and storage terms (S). Combination of soil and canopy heat storage and the energy used in photosynthesis was considered for an accurate estimation of the energy balance closure (Verma et al. 2005; Meyers and Hollinger 2004). The storage term, S, was the sum of soil heat storage, canopy heat storage, heat stored in the residue, and energy used in photosynthesis. These terms were estimated by Verma et al. (2005) following Meyers and Hollinger (2004). Linear regressions between hourly values of Rn and $H + \lambda E + G + S$ for the three study sites were calculated during the 4 years of measurements (2002– 2005) (Table 3). The regression slopes ranged from 0.82 to 0.93 (generally bigger than 0.87), and the intercepts ranged between –3.3 and 4.6 W m^{-2} with r^2 of 0.96–0.97, giving a fairly good closure of the energy balance at all study sites. Similar results were found under large and small LAI values (Table 3).

Model calibration

Measurements made at site 2 (soybean and maize under irrigated conditions) were used to calibrate the SEB model during the growing and non-growing seasons of 2002 and 2003. As a result of the sensitivity analysis, parameters affecting canopy resistance were used to adjust model ET estimations to eddy covariance measurements under large LAI conditions (LAI > 2). Accordingly, parameters affecting soil and residue resistance were calibrated for low LAI conditions. The slopes of the regression between measured and estimated ET, the coefficient of correlation, r^2, and the Nash–Sutcliffe coefficient, E, were used to calibrate the model. Model parameters after calibration are presented in Table 4, and initial range of calibrated values is presented in parenthesis.

After calibration, agreement between measured and estimated evapotranspiration was very good. During the growing season of soybean (2002), the RMSE of the model was 38.2 W m^{-2}, the MAE was 25.7 W m^{-2}, the E was 0.91, and the index of agreement (d) was 0.99. During the period from planting until the LAI reached a value of two, the RMSE of the model was 45.6 W m^{-2}, the MAE was 30.0 W m^{-2}, the E was 0.68, and the index of agreement (d) was 0.99. For the period of the growing season where 2 < LAI < 4, the RMSE of the model was 35.5 W m^{-2}, the MAE was 24.4 W m^{-2}, the E was 0.96, and the index (d) was 0.99. At the end of the growing season between the time the crop LAI was 4 and harvest, the RMSE of the model was 32.6 W m^{-2}, the MAE was 23.0 W m^{-2}, the E was 0.95, and the index d was 0.99.

Similarly, for maize (2003) during the growing season, the RMSE of the model calculated with all data was 33.7 W m^{-2}, the MAE was 20.3 W m^{-2}, the E was 0.89, and the index of agreement (d) was 0.97. During the period from planting until the LAI reached a value of two, the RMSE of the model was 45.5 W m^{-2}, the MAE was 30.3 W m^{-2}, the E was 0.71, and the index of agreement (d) was 0.92. For the period of the growing season where 2 < LAI < 4, the RMSE of the model was 58.7 W m^{-2}, the MAE was 40.6 W m^{-2}, the E was 0.82, and the index (d) was 0.97. At the end of the growing season between the time the crop LAI was 4 and harvest, the RMSE of the model was 39.4 W m^{-2}, the MAE was 25.7 W m^{-2}, the E was 0.93, and the index d was 0.98. The ratio of annual ET calculated with the SEB model and the annual ET measured with the eddy covariance was 1.00 during 2002 and 0.95 during 2003.

Model validation

SEB model inputs included net radiation, air temperature, relative humidity, soil temperature at 0.5 m, wind speed, incoming shortwave solar radiation, soil water content, residue amount covering the soil by hectare, and calibrated parameters given in Table 4.

Table 3. Energy balance closure during 2002–2005 at all sites and for large (LAI > 2) and small (LAI < 2) canopy conditions

Site	2002		2003		2004		2005		LAI > 2		LAI < 2	
	y	r^2	*y*	r^2	*y*	r^2	*y*	r^2	*y*	r^2	*y*	r^2
1	0.82*X* + 2	0.96	0.90*X* + 1.0	0.96	0.88*X* + 1.2	0.97	0.89*X* – 1.1	0.97	0.91*X* – 0.46	0.98	0.90*X* – 0.26	0.98
2	0.87*X* – 2.5	0.96	0.89*X* – 1.7	0.97	0.87*X* – 1.4	0.97	0.92*X* – 3.3	0.97	0.88*X* – 0.52	0.98	0.94*X* – 0.96	0.98
3	0.87*X* + 4.6	0.96	0.92*X* + 1.6	0.96	0.89*X* + 3.0	0.97	0.93*X* – 0.3	0.97	0.93*X* – 0.10	0.99	0.96*X* – 0.50	0.98

y = H + λE + G + S (W m^{-2}) ; *X* = Rn (W m^{-2})

Site 1 Evapotranspiration predicted by the SEB model was compared with eddy covariance measurements made for an irrigated maize field during the growing and nongrowing seasons of 2002 through 2005. Linear regressions between hourly values of *λE* estimated with the model and measured by the eddy covariance system were calculated during the 4 years of measurements (2002–2005). The regression slopes for the entire year ranged from 1.02 (2004) to 1.09 (2002). The coefficients of determination, r^2, were 0.92 (2002), 0.92 (2003), 0.91 (2004), and 0.90 (2005), giving a fairly good agreement between measure and estimated ET for all years of study at site 1. During the growing seasons, regression slopes range from 1.04 (2005) to 1.11 (2002), with r^2 ranges between 0.93 and 0.95 (Figure 5).

The ratios of annual ET calculated with the SEB model to the annual ET measured with the eddy covariance system were 1.06 during 2002, 1.01 during 2003, 0.94 during 2004, and 0.98 during 2005, resulting in annual *λE* differences of less than 6%. The SEB model has the capability to separate total evapotranspiration in canopy transpiration and soil evaporation. The ratio of annual canopy transpiration over total ET was 0.70 for 2002, 0.74 for 2003, 0.67 for 2004, and 0.64 for 2005.

The statistics indices of agreements, *E*, *d*, RMSE, and MAE were used to evaluate the performance of the model. Calculations were made for complete years, growing seasons (planting to harvest), early growing seasons where LAI < 2, growing seasons where 2 < LAI < 4, and growing seasons where LAI > 4. Results are given in Table 5. The Nash–Sutcliffe coefficient, *E*, ranges from 0.88 to 0.90 for the complete year analysis and from 0.89 to 0.91 during the growing season. For the growing season when LAI < 2, *E* ranged from 0.54 to 0.68, 0.73–0.91 for 2 < LAI < 4, and 0.92 to 0.95 for growing season where LAI > 4, showing a better model performance for large LAI values. In the same way, the index of agreement, *d*, ranges from 0.97 to 0.98 during the whole year, 0.98 for the

Table 4. Model parameters after calibration. (In parenthesis, initial range of calibrated parameters)

Variable	Symbol	Value after calibration	Unit
Canopy			
Canopy resistance coefficients	C_1	5 (4–6)	
For maize and soybeans	C_4	0.005 (0.002–0.007)	
	C_3	300 (200–500)	
Maximum leaf area index, maize	LAImax	6 (5–6.5)	$m^2\ m^{-2}$
Maximum leaf area index, soybeans	LAImax	5 (4–6.5)	$m^2\ m^{-2}$
Attenuation coefficient	α	2.5 (1–3.5)	
Extinction coefficient	Cext	0.6 (0.4–0.7)	
Soil			
Upper layer thickness	Lt	0.05 (0.025–0.1)	m
Saturation soil water content	Θ*s*	0.5 (0.4–0.55)	$m^3\ m^{-3}$
Soil porosity	*φ*	0.5 (0.4–0.6)	$m^3\ m^{-3}$
Soil tortuosity	τ*s*	1.5 (1.1–2.0)	
Fitting parameter	*β*	6.5 (5–7)	
Soil thermal conductivity, upper layer	*K*	0.5 (0.3–2.5)	W m^{-1} °C^{-1}
Soil thermal conductivity, lower layer	*K′*	2.5 (1–2.5)	W m^{-1} °C^{-1}
Residue			
Residue tortuosity	*τr*	1.0 (1.0–1.2)	
Residue porosity	*φr*	0.99 (0.5–0.99)	
Residue thermal conductivity	Kr	0.2 (0.05–0.4)	W m^{-1} °C^{-1}

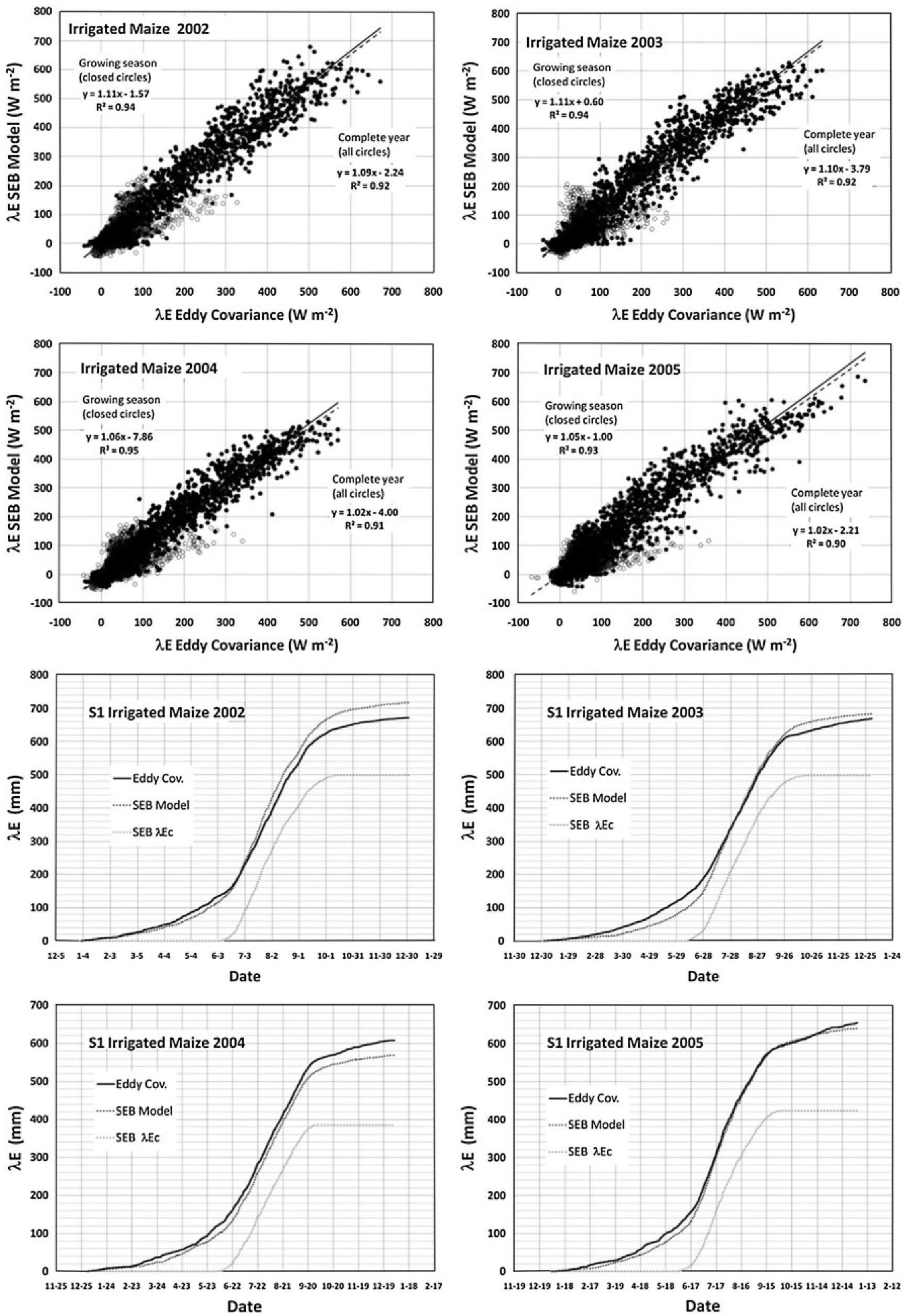

Figure 5. Measured versus estimated hourly evapotranspiration (λE) (*above*), and cumulative λE (*below*) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration (λE_c) estimated with the SEB model. Site 1 during 2002, 2003, 2004, and 2005 seasons

growing season, 0.89–0.92 growing season where LAI < 2, 0.92–0.98 for 2 < LAI < 4, and 0.98–0.99 for growing season where LAI > 4. The RMSE ranges from 27.9 to 33.3 W m^{-2} during the whole year, 35.0–43.5 W m^{-2} for the growing season, 39.4–46.6 W m^{-2} growing season where LAI < 2, 46.8–70.3 W m^{-2} for 2 < LAI < 4, and 30.6–39.8 W m^{-2} for growing season where LAI > 4, and these ranges agree with those found by others evaluations of multiple source evapotranspiration models (Domingo et al. 1999; Poblete-Echeverría and Ortega-Farias 2009; Odhiambo and Irmak 2011).

In general for all years of analysis at site 1, the model performed best during the growing season where LAI > 4. On the contrary, poor model performance was found when the LAI < 2 during the early growing season, showing that at site 1 the model has more difficulties estimating ET for sparse-canopy than closed-canopy surfaces.

Site 2 The SEB model was evaluated during 2004 for irrigated soybean and irrigated maize during 2005. Similar to site 1, linear regressions between hourly values of λE estimated with the model and measured by the eddy covariance system were calculated during the 2 years of measurements (2004–2005). The regression slopes were 0.94 (2004) and 1.01 (2005). The coefficient of determination, r^2, was 0.9 for 2004 and 2005. During the growing seasons, regression slopes were 0.98 (2004) and 1.04 (2005) with r^2 of 0.93 and 0.92 for 2004 and 2005, respectively (Figure 6). The ratios of annual ET calculated with the SEB model and the annual ET measured with the eddy covariance were 0.85 (2004) and 0.97 (2005). The ratio of annual canopy transpiration to total ET was 0.59 for 2004 and 0.68 for 2005.

Statistics indices *E*, *d*, RMSE, and MAE are given in Table 5. The Nash–Sutcliffe coefficient, *E*, ranged from 0.88 to 0.89 for the annual analysis, 0.9–0.92 for the growing season, 0.62–0.79 growing season where LAI < 2, 0.88–0.96 for 2 < LAI < 4, and 0.94–0.95 for growing season where LAI > 4. In the same way, the index of agreement, *d*, was 0.97 during the annual analysis and 0.98 for the growing season. The RMSE ranges from 29.6 to 32.9 W m^{-2} during the whole year and 34.5–41.2 W m^{-2} for the growing season.

In general at site 2, similar to site 1, the best performance of the model was found during the growing season where LAI > 4. Poorer model performance was found when the LAI < 2 during the early growing season.

Table 5. Statistic indices for hourly ET estimations using the SEB model at sites 1, 2, and 3

Year	Period	Site 1				Site 2				Site 3			
		E	*d*	RMSE (W m^{-2})	MAE (W m^{-2})	*E*	*d*	RMSE (W m^{-2})	MAE (W m^{-2})	*E*	*d*	RMSE (W m^{-2})	MAE (W m^{-2})
2002	Annual	0.88	0.97	33.3	19.7					0.88	0.97	28.7	17.5
	Growing season	0.89	0.98	43.5	28.6					0.88	0.97	38.9	26.0
	Planting < LAI < 2	0.54	0.90	46.6	32.0					0.77	0.95	39.6	26.4
	2 < LAI < 4	0.76	0.96	70.3	49.7					0.92	0.98	41.8	29.1
	4 < LAI < harvest	0.92	0.98	39.8	26.0					0.90	0.97	24.6	10.8
2003	Annual	0.89	0.98	32.5	19.5					0.85	0.97	32.0	19.4
	Growing season	0.89	0.98	43.3	28.1					0.87	0.97	40.8	26.8
	Planting < LAI < 2	0.64	0.92	43.4	28.6					0.71	0.92	41.8	27.1
	2 < LAI < 4	0.73	0.95	68.8	45.7					0.91	0.98	46.4	32.4
	4 < LAI < harvest	0.92	0.98	40.5	26.5					0.88	0.98	30.9	15.9
2004	Annual	0.90	0.98	27.9	17.6	0.88	0.97	29.6	18.6	0.90	0.97	26.4	16.8
	Growing season	0.91	0.98	35.0	24.5	0.92	0.98	34.5	24.0	0.92	0.98	33.0	22.3
	Planting < LAI < 2	0.68	0.92	39.4	28.3	0.79	0.94	41.2	28.5	0.85	0.96	35.9	24.0
	2 < LAI < 4	0.85	0.97	48.1	33.1	0.96	0.99	28.8	21.0	0.96	0.99	28.1	21.2
	4 < LAI < harvest	0.95	0.99	30.6	21.6	0.95	0.99	30.2	21.4	0.94	0.98	22.6	10.7
2005	Annual	0.89	0.97	32.9	20.3	0.89	0.97	32.9	19.9	0.82	0.96	37.1	21.2
	Growing season	0.90	0.98	41.5	28.0	0.90	0.98	41.2	27.2	0.81	0.96	48.3	30.9
	Planting < LAI < 2	0.54	0.89	46.8	30.9	0.62	0.90	48.7	32.5	0.57	0.89	45.8	29.7
	2 < LAI < 4	0.91	0.98	46.8	33.0	0.88	0.97	52.4	36.0	0.72	0.95	68.5	46.8
	4 < LAI < harvest t	0.93	0.98	38.2	26.0	0.94	0.99	35.8	23.9	0.86	0.97	34.7	17.0

ET evapotranspiration, *E* Nash–Sutcliffe coefficient, *d* index of agreement, RMSE root mean square error, MAE mean absolute error, LAI leaf area index

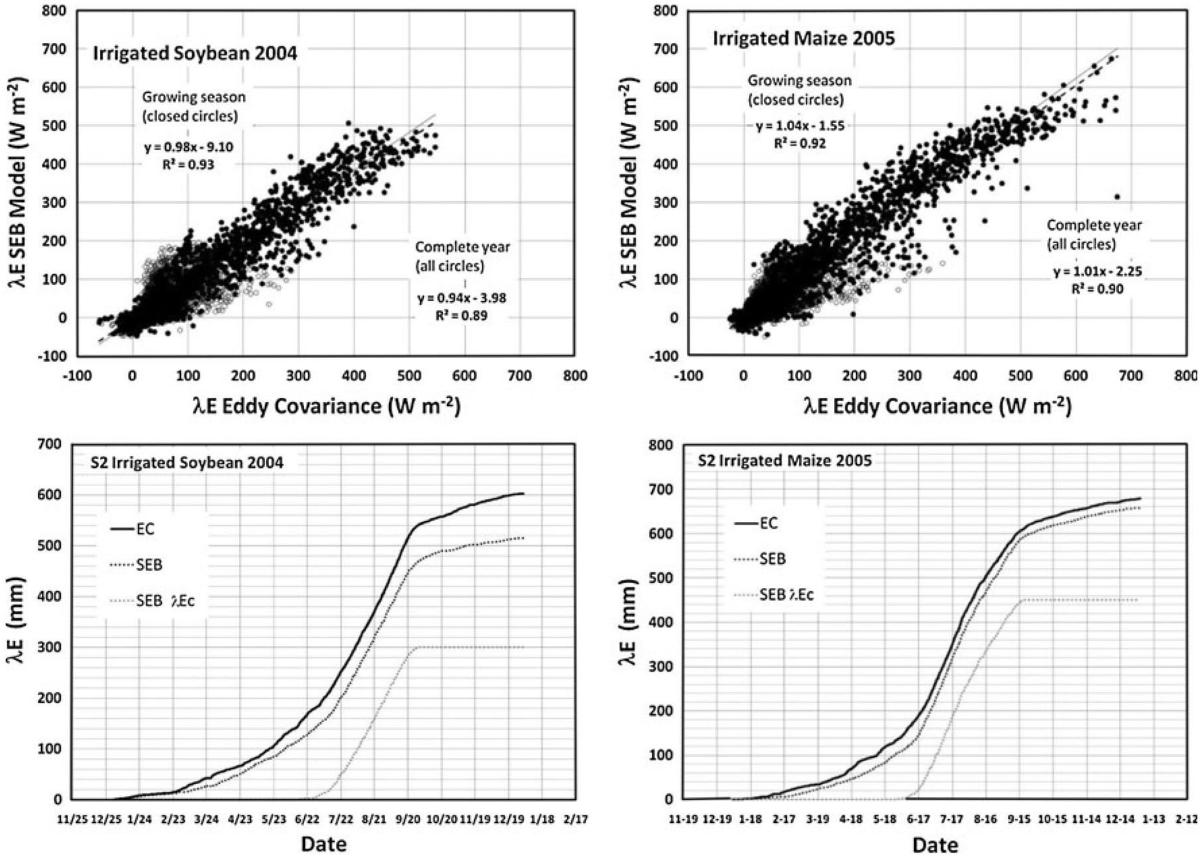

Figure 6. Measured versus estimated hourly evapotranspiration (λE) (*above*), and cumulative λE (*below*) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration (λE_c) estimated with the SEB model. Site 2 during 2004 and 2005 seasons

Site 3 In this site, data from rain-fed maize and soybeans rotation system were used to evaluate model performance during 2002 through 2005 (Figure 7). Linear regressions between hourly values of λE estimated with the model and measured by the eddy covariance system were calculated during the 4 years of measurements (2002–2005). The regression slopes ranged from 0.94 (2004) to 1.15 (2005), giving a fairly good agreement between measure and estimated ET for all years of study. The coefficients of determination, r^2, were 0.90 (2002), 0.89 (2003), 0.90 (2004), and 0.89 (2005). During the growing seasons, regression slopes range from 0.96 (2004) to 1.17 (2005), with r^2 ranges between 0.91 and 0.93.

The ratios of annual ET calculated with the SEB model and the annual ET measured with the eddy covariance system were 0.98 during 2002, 0.97 during 2003, 0.88 during 2004, and 1.14 during 2005, giving a good agreement between measure and estimated annual ET. At site 3, the ratio of annual canopy transpiration to total ET was 0.53 for 2002, 0.61 for 2003, 0.55 for 2004, and 0.64 for 2005.

The statistics indices of agreements, E, d, RMSE, and MAE are given in Table 5. The Nash–Sutcliffe coefficient, E, ranges from 0.82 to 0.9 for the complete year analysis and 0.81 to 0.92 for growing seasons. In the same way, the index of agreement, d, ranged from 0.96 to 0.97 during the whole year and 0.96 to 0.98 during the growing season. The RMSE ranges from 26.4 to 37.1 W m^{-2} during the whole year and 33.0 to 48.3 W m^{-2} for the growing season.

Conclusions

A sensitivity analysis of model parameters and an evaluation of the SEB model to estimate ET were performed during the growing and non-growing season of maize and soybean grown in eastern Nebraska. Results were compared against measurements made employing eddy covariance flux systems. In general, simulated hourly ET was most sensitive to changes in surface canopy resistance, soil surface resistance, and residue surface resistance. The model was less sensitive to changes in the extinction coefficient, soil temperature, the attenuation coefficient, the surface boundary layer, errors in the crop height, and soil heat flux resistances. Comparison between estimated ET and measurements provided support for the validity of the surface energy balance model. For annual estimations, the coefficient of determination, r^2, ranged from 0.88 to 0.92, with linear regression slopes in the range of 0.93–1.14. The Nash–Sutcliffe coefficients were in the range

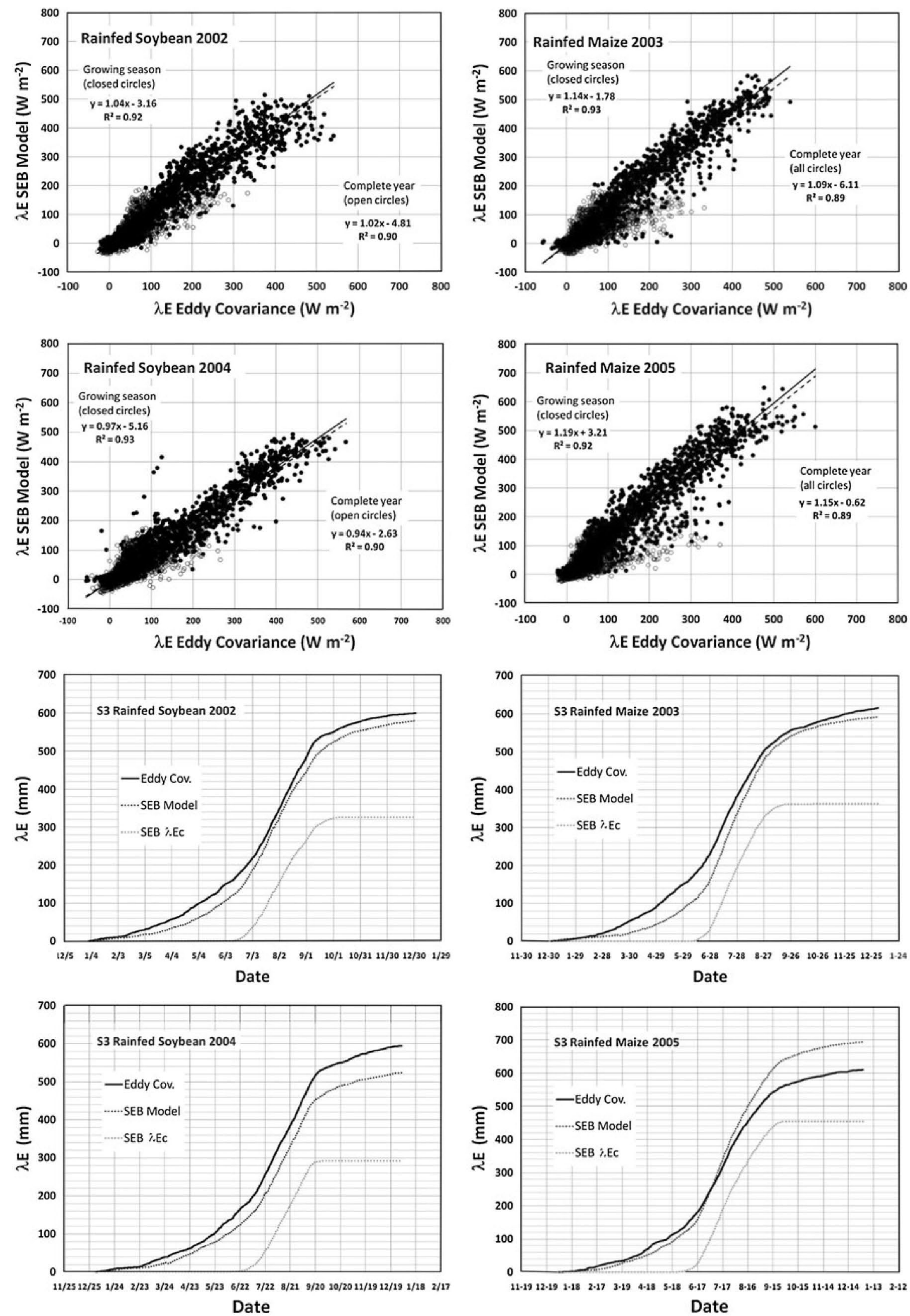

Figure 7. Measured versus estimated hourly evapotranspiration (λE) (*above*), and cumulative λE (*below*) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration (λE_c) estimated with the SEB model. Site 3 during 2002, 2003, 2004, and 2005 seasons

0.82–0.90, and the RMSE of the model was 26.4–37.1 W m^{-2}. Estimates of hourly ET during the growing seasons resulted in an r^2 range of 0.91–0.95, and linear regression slopes in the range of 0.96–1.17. The Nash–Sutcliffe coefficients ranged from 0.81 to 0.92 for growing season estimates. The RMSE varied from 33.0 to 48.3 W m^{-2}. During the growing season, the model predicted ET more accurately after canopy closure (i.e., after LAI = 4 until harvest) and performs similar to one source models where effect of soil evaporation is minimum. Prior to canopy closure, the model was less accurate, showing the needs of further improvements under low LAI conditions and sparse canopy. Predicted ET values were more accurately under irrigated conditions than for dry land agriculture. The ratio of annual ET calculated with the SEB model to the annual ET measured with the eddy covariance system ranged between 0.94 and 1.06 for irrigated maize, resulting in annual λE differences of less than 6%. For maize fields, crop transpiration estimated with the SEB model was 64–74% of the annual evapotranspiration under irrigated conditions and 61–64% under rain-fed conditions. For soybeans fields, crop transpiration was 59% of the annual ET under irrigated conditions and 53–55% under dry land. Overall, the performance of the SEB model in estimating evapotranspiration was reasonably satisfactory.

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References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop requirement, irrigation and drainage paper no. 56. Irrigation and drainage paper no 56. FAO, Rome

Allen RG, Tasumi M, Trezza R (2007) Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-model. J Irrig Drain Eng 133(4):380–394

Alves I, Cameira M (2002) Evapotranspiration estimation performance of root zone water quality model: evaluation and improvement. Agric Water Manag 57:61–73

Alves I, Pereira LS (2000) Modeling surface resistance from climatic variables? Agric Water Manag 42:371–385

Anadranistakis M, Liakatas A, Kerkides P, Rizos S, Gavanosis J, Poulovassilis A (2000) Crop water requirements model tested for crops grown in Greece. Agric Water Manag 45:297–316

ASCE (2002) The ASCE standardized equation for calculating reference evapotranspiration, task committee report. Environment and Water Resources Institute of ASCE, New York

Choudhury BJ, Monteith JL (1988) A four layer model for the heat budget of homogeneous land surfaces. Q J R Meteorol Soc 114:373–398

Coffey ME, Workman SR, Taraba JL, Fogle AW (2004) Statistical procedures for evaluating daily and monthly hydrologic model predictions. Trans ASAE 47:59–68

Domingo F, Villagarcía L, Brenner AJ, Puigdefábregas J (1999) Evapotranspiration model for semi-arid shrub-lands tested against data from Spain. Agric For Meteorol 95:67–84

Farahani HJ, Ahuja LR (1996) Evapotranspiration modeling of partial canopy/residue covered fields. Trans ASAE 39:2051–2064

Farahani HJ, Bausch W (1995) Performance of evapotranspiration models for Maize—bare soil to closed canopy. Trans ASAE 38:1049–1059

Flores H (2007) Penman–Monteith formulation for direct estimation of maize evapotranspiration in well watered conditions with full canopy. PhD dissertation, University of Nebraska–Lincoln

Gardiol JM, Serio LA, Della Maggiora AI (2003) Modelling evapotranspiration of corn (Zea mays) under different plant densities. J Hydrol 271:188–196

Gash JHC (1986) A note on estimating the effect of a limited fetch on micrometeorological evaporation measurements. Bound Lay Meteorol 35:409–413

Iritz Z, Tourula T, Lindroth A, Heikinheimo M (2001) Simulation of willow short-rotation forest evaporation using a modified Shuttleworth-Wallace approach. Hydrol Process 15:97–113

Irmak S, Mutiibwa D, Irmak A, Arkebauer T, Weiss A, Martin D, Eisenhauer D (2008) On the scaling up leaf stomatal resistance to canopy resistance using photosynthetic photon flux density. Agric For Meteorol 148:1034–1044

Jensen JM, Wright JL, Pratt BJ (1971) Estimating soil moisture depletion from climate, crop and soil data. Trans ASAE 14: 954–959

Katerji N, Rana G (2006) Modeling evapotranspiration of six irrigated crops under Mediterranean climate conditions. Agric For Meteorol 138:142–155

Kjelgaard JF, Stockle CO (2001) Evaluating surface resistance for estimating corn and potato evapotranspiration with the Penman- Monteith model. Trans ASAE 44:797–805

Krause P, Boyle DP, Base F (2005) Comparison of different efficiency criteria for hydrological model assessment. Adv Geosci 5:89–97

Lafleur P, Rouse W (1990) Application of an energy combination model for evaporation from sparse canopies. Agric For Meteorol 49:135–153

Lagos LO, Martin D, Verma S, Suyker A, Irmak S (2009) Surface energy balance model of transpiration from variable canopy cover and evaporation from residue-covered or bare-soil systems. Irrig Sci 28:51–64

Legates DR, McCabe GJ (1999) Evaluating the use of "goodness of fit" measures in hydrologic and hydro climatic model validation. Water Resour Res 35:233–241

Massman WJ (1992) A surface energy balance method to partitioning evapotranspiration data into plant and soil components for a surface with partial canopy cover. Water Resour Res 28:1723– 1732

Meyers TP, Hollinger SE (2004) An assessment of storage terms in the surface energy balance of maize and soybean. Agric For Meteorol 125:105–115

Monteith JL (1965) Evaporation and the environment. Proc Symp Soc Expl Biol 19:205–234

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASAE 50:885–900

Odhiambo LO, Irmak S (2011) Performance of extended Shuttleworth-Wallace model for estimating and partitioning of evapotranspiration in a partial residue-covered subsurface drip-irrigated Soybean field. Trans ASABE 54:915–930

Ortega-Farias S, Olioso A, Antonioletti R (2004) Evaluation of the Penman-Monteith model for estimating soybean evapotranspiration. Irrig Sci 23:1–9

Ortega-Farias S, Carrasco M, Olioso A (2007) Latent heat flux over Cabernet Sauvignon vineyard using the Shuttleworth and Wallace model. Irrig Sci 25:161–170

Parkes M, Jiang W, Knowles R (2005) Peak crop coefficient values for Shaanxi north-west China. Agric Water Manag 73:149–168

Poblete-Echeverría C, Ortega-Farias S (2009) Estimation of actual evapotranspiration for a drip-irrigated Merlot vineyard using a three-source model. Irri Sci 28:65–78

Rana G, Katerji N, Mastrorilli M, El Moujabber M, Brisson N (1997) Validation of a model of actual evapotranspiration for water stressed soybeans. Agric For Meteorol 86:215–224

Rana G, Katerji N, De Lorenzi F (2005) Measurement and modelling of evapotranspiration of irrigated citrus orchard under Mediterranean conditions. Agric For Meteorol 128:199–209

Schuepp PH, Leclerc MY, Macpherson JI, Desjardins RL (1990) Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Bound Lay Meteorol 50:355–373

Shuttleworth WJ (2006) Towards one-step estimation of crop water requirements. Trans ASAE 49:925–935

Shuttleworth WJ, Gurney R (1990) The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q J R Meteorol Soc 116:497–519

Shuttleworth WJ, Wallace JS (1985) Evaporation from sparse crops—An energy combination theory. Q J R Meteorol Soc 111:839–855

Stannard DI (1993) Comparison of Penman-Monteith, Shuttleworth-Wallace, and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. Water Resour Res 29:1379–1392

Suyker A, Verma S (1993) Eddy correlation measurements of CO2 flux using closed path sensor: theory and field test against open path sensor. Bound Lay Meteorol 64:391–407

Suyker A, Verma S (2008) Interannual water vapor and energy exchange in an irrigated Maize-based agroecosystem. Agric For Meteorol 148:417–427

Suyker A, Verma S (2009) Evapotranspiration of irrigated and rain fed maize-soybean cropping systems. Agric For Meteorol 149:443–452

Tourula T, Heikinheimo M (1998) Modeling evapotranspiration from a barley field over the growing season. Agric For Meteorol 91:237–250

Verma S, Dobermann A, Cassman KG, Walters DT, Knops JM, Arkebauer TJ, Suyker A, Burba G, Amos B, Yang HS, Ginting D, Hubbard KG, Gitelson AA, Walter-Shea EA (2005) Annual Carbon dioxide exchange in irrigated and rain fed maize-based agroecosystems. Agric Forest Meteorol 131:77–96 150 Irrig Sci (2013) 31:135–150