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Performance Of Extended Shuttleworth-Wallace Model For Estimating And Partitioning Of Evapotranspiration In A Partial Residue-Covered Subsurface Drip-Irrigated Soybean Field

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Performance of Extended Shuttleworth-Wallace Model for Estimating and Partitioning of Evapotranspiration in a Partial Residue-Covered Subsurface Drip-Irrigated Soybean Field

L. O. Odhiambo, S. Irmak

Abstract. *Estimation of actual evapotranspiration (ET), especially its partitioning into plant transpiration (T) and soil evaporation (E), in agricultural fields is important for effective soil water management and conservation and for understanding the interactions between ET, T, and E with the management practices. Direct field measurements of ET, T, and E rates are difficult and costly; hence, mathematical models are used for estimating them. The objective of this study was to evaluate the practical applicability of the Shuttleworth-Wallace (S-W) model to estimate and partition ET in a subsurface drip-irrigated soybean (*Glycine max *L. Merr.) field with partial residue cover. While its performance has been studied for various surfaces, the performance evaluation of the S-W model for such surface has not been carried out. An integrated approach of calculating bulk stomatal resistance (r_s^c) as a function of soil water content (θ_i) was incorporated into the model to allow simulation of T over a range of θ_i, and a residue decomposition function was introduced to account for surface residue decay over time to more accurately account for the actual residue cover in field conditions. The model performance was evaluated for different plant growth stages during the 2007 and 2008 growing seasons at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, Nebraska. The sum of estimated T and E was compared to the Bowen Ratio Energy Balance System (BREBS)-measured actual ET on a daily time-step. The model was able to capture the trends and magnitudes of measured ET, but its performance differed for various plant physiological growth stages. The root mean square difference (RMSD) values between the model-estimated and measured ET values for the growing season (day after emergence until physiological maturity) were 1.26 and 1.03 mm d^{-1} for 2007 and 2008, respectively. Best performance was observed during the mid-season during full canopy cover with a two-year average r^2 of 0.87, average RMSD of 0.94 mm d^{-1}, and average mean biased error (MBE) of 0.30 mm d^{-1}. Estimates for both initial and late season growth stages where E was dominant had the least agreement with BREBS measurements. The proportion of T and E in the estimated ET varied with growth stage. The S-W-estimated seasonal total ET and BREBS measurements were equal in 2007 (S-W model ET = 496 mm and BREBS ET = 498 mm), and in 2008 the model underestimated by only 8.2% (S-W model ET = 452 mm and BREBS ET = 489 mm). While, in general, the model was successful in tracking the trends and magnitude of the BREBS-measured ET, further re-parameterization of the T module of the model can improve its accuracy to estimate ET, especially T, during the initial and late season (before full canopy cover and after physiological maturity) for a subsurface drip-irrigated soybean canopy. Other enhancements needed in the model for improved estimation of the E component include accurate determination of soil surface resistance coefficients and accounting for direct evaporation of intercepted rainfall on the canopy.*

Keywords. *Bowen ratio, Evaporation, Evapotranspiration, Shuttleworth-Wallace model, Soybean, Transpiration.*

Quantification of actual crop evapotranspiration (*ET*) is essential to water balance analyses of agricultural fields, and its partitioning into crop transpiration (*T*) and soil water evaporation (*E*) components is important for developing best management strategies for agricultural water conservation and management, biophysical research, development of new technologies in precision irrigation, studies that aim to optimize crop productivity by reducing the soil evaporation losses (reduced tillage), analysis of mutual interrelationships between *T* and *E* to better understand soil-water-yield relationships, and investigating plant physiology and microclimate interactions. Continuous and direct measurements of *ET*, *T*, and *E* rates are difficult and costly; hence, integrated mathematical models are useful for estimating them over the entire range of crop development stages.

Various forms of the Penman-Monteith (Monteith, 1965) combination-based energy balance modeling approaches have been employed to estimate *ET* and its components. These approaches include the FAO-56 dual crop coefficient method (FAO-56, 1998) and its various forms and multi-layer Penman-Monteith methods (Choudhury and Monteith, 1988; Shuttleworth and Gurney, 1990; Shuttleworth and Wallace, 1985). In sparse canopies with surface residue cover, multi-

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layer models are advantageous because they are able to incorporate the effects of different canopy and soil surface characteristics in the discrete estimation of T and E. The existing multi-layer Penman-Monteith-type methods fall into three main approaches based on how energy exchange in the soil-atmosphere system is partitioned between plant canopy and soil surface, and how sensible and latent heat are routed. The first approach is the coupled multi-layer Penman-Monteith method in which the energy and vapor flux interact between plant canopy and soil surface (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990). The second approach is the uncoupled multi-layer method in which the energy and vapor flux do not interact between plant canopy and soil surface (Choudhury and Monteith, 1988; Gardiol et al., 2003; Kustas and Norman, 1999; Norman et al., 1995), and the third approach is a hybrid of the coupled and uncoupled multi-layer approaches (Guan and Wilson, 2009; Lagos et al., 2009). Among these methods, the coupled multi-layer approach developed by Shuttleworth and Wallace (1985) to partition surface energy over sparse canopies is well structured to separately estimate T and E. The Shuttleworth-Wallace (S-W) model consists of a dual layer of Penman-Monteith equations coupled through a network of controlling resistances. Farahani and Ahuja (1996) presented procedures for extending the S-W model to include the effects of surface crop residue on soil evaporation by explicitly specifying a partially covered soil area and partitioning evaporation between bare and residue-covered areas. The extended S-W model is incorporated into the widely used Root Zone Water Quality Model (RZWQM) (Farahani and DeCoursey, 2000) to estimate energy-limiting E and T rates. The parameters required in the extended S-W model include plant canopy and residue coverage, surface and aerodynamic resistances, and net radiation partitioned between plant canopy and soil surface. Microclimatic variables such as incoming shortwave radiation (R_s), wind speed (u), air temperature (T_a), relative humidity (RH), and soil water content (θ_i) are also required as inputs.

The S-W modeling approach has been used with good results in a number of evapotranspiration studies in agricultural fields (Anadranistakis et al., 2000; Brisson et al., 1998; Farahani and Bausch, 1995; Kato et al., 2004; Lafleur and Rouse, 1990; Lund and Soegaard, 2003; Sene, 1994; Stannard, 1993; Tourula and Heikinheimo, 1998; Ortega-Farias et al., 2007, 2010), but its practical application is somewhat limited by the large number of parameters and measurements required, and the lack of accurate quantitative knowledge of the resistance terms that control the latent heat fluxes at the canopy and soil surface. There is also an added difficulty that requires microclimatic variables used in the S-W model to be measured above crop canopies when available microclimatic data are normally measured at weather stations above either grass or alfalfa surfaces away from the agricultural fields for which the ET estimates are made. The bulk stomatal resistance term ($r_s{}^c$), which represents resistance to water vapor moving out from the sub-stomatal cavities within the canopy layers, and the soil surface resistance ($r_s{}^s$), which represents resistance to water vapor moving out of the soil profile, are dynamically and numerically the most important resistances of the S-W model, yet the most difficult to precisely quantify. Studies that have applied the S-W model to estimate or partition ET over field crops use a variety of empirical procedures to calculate these resistance terms. Farahani and Bausch (1995) calculated $r_s{}^c$ as a function of the mean stomatal resistance of a single leaf averaged by the effective leaf area index (LAI_{eff}) and $r_s{}^s$ from an empirical function of θ_i derived from field-measured data. LAI_{eff} is defined as the effective value of leaf area index (LAI) that accounts for illumination-induced stomatal closure deeper in the canopy. The Farahani and Bausch (1995) method is not able to accurately estimate $r_s{}^c$ under water-limiting conditions when stomatal opening is influenced by θ_i among other factors. However, under non-water limiting conditions, their method showed that the model performed satisfactorily for the entire range of canopy cover. Their estimated cumulative ET deviated by 6%, 3%, and 4% from measured cumulative ET for periods of LAI $\leq$ 2, LAI > 2, and over the entire growing season, respectively. Anadranistakis et al. (2000) incorporated into the S-W model a three-layer soil water balance module to allow quantification of $r_s{}^c$ and $r_s{}^s$ based on θ_i. They compared the results of S-W estimation with ET calculated from soil water balance and found the agreement between the two to be within 8%. Alves and Cameira (2002) found that a simple modification in the calculation of LAI_{eff} could improve ET estimates. Kato et al. (2004) calculated $r_s{}^c$ as a function of R_s and vapor pressure deficit (D), and $r_s{}^s$ as a function θ_i of the top soil layer, soil surface temperature (T_s), and molecular vapor diffusivity through the soil layer. They did not consider θ_i for calculation of $r_s{}^c$ since their experimental field was well-watered. They compared S-W model estimation with Bowen Ratio Energy Balance System (BREBS) measurements and found close agreements for both short- and long-term measurements. Ortega-Farias et al. (2010) evaluated the S-W model with variable $r_s{}^c$ calculated as a function of θ_i, T_a, R_s, and D, and variable $r_s{}^s$ calculated as a function of θ_i in the top soil layer. They compared the S-W model performance against eddy-covariance measurements over an irrigated vineyard. The S-W model was able to estimate ET with a root mean square error (RMSE) of 0.51 mm d^{-1} and mean absolute error (MAE) of 0.41 mm d^{-1}.

The S-W model with extension for residue-covered soil surface has not been thoroughly evaluated over croplands since its development by Farahani and Ahuja (1996). Furthermore, there is not sufficient knowledge of the model's performance in practical applications to estimate and partition ET for subsurface drip-irrigated soil and vegetation surfaces. Subsurface drip irrigation creates a very different environment in terms of interactions between the soil, soil moisture, and residue cover than overhead sprinkler and other surface irrigation methods. Depending on the soil texture and other factors, the drip laterals are usually buried 15 to 40 cm below the soil surface and the topsoil remains drier than the other irrigation methods because there is no surface wetting due to irrigation, minimizing the soil evaporation losses. Thus, the partitioning of ET into E and T presents different dynamics and challenges under subsurface drip irrigation as compared with other irrigation methods. The objective of this study is to evaluate the applicability of the extended Shuttleworth-Wallace (S-W) model to estimate and partition ET in a subsurface drip-irrigated soybean field with partial residue cover. An integrated approach of calculating bulk stomatal resistance ($r_s{}^c$) as a function of soil water content (θ_i) was incorporated into the model to allow simulation of T over a range of θ_i, and a residue decomposition function was introduced to account for surface residue reduction (decay) over time.

Materials and Methods

The S-W model was evaluated using microclimatic and agronomic data measured over a subsurface drip-irrigated soybean (*Glycine max* L. Merr.) field (Mutiibwa and Irmak, 2011). The sum of model-estimated *T* and *E* were compared to the BREBS-measured *ET* in initial, mid-season, and late-season growth stages for two different growing seasons.

Experimental Site and Field Measurements

Datasets used in this study were measured in a 13.5 ha subsurface drip-irrigated soybean field during the 2007 and 2008 growing seasons (May to October) (Mutiibwa and Irmak, 2011). The experimental field is located at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (40° 34 N, 98° 8′ W, elevation of 552 m above mean sea level). The average annual rainfall in the area is 680 mm, with the majority of the rainfall occurring in the early spring from late April to late June. The soil in the field is classified as Hastings silt loam, which is a well drained soil with a 0.5% slope. The particle size distribution is 15% sand, 62.5% silt, 20% clay, and 2.5% organic matter content. The soil field capacity (θ_{fc}) is 0.34 m^3 m^{-3}, the permanent wilting point (θ_{wp}) is 0.14 m^3 m^{-3}, and the saturation point (θ_{sat}) is 0.51 m^3 m^{-3}. In 2007, the field was planted with soybean (variety Pioneer 93M11) seeds on 21 May at a rate of 156,000 plants per ha with a planting depth of 0.025 m and row spacing of 0.76 m with an east-west planting direction. Plants emerged on 26 May and were harvested on 24 October 2007. In 2008, the field was again planted with the same soybean variety on 19 May, at the same planting density, planting depth, and row spacing as in 2007. Plants emerged on 24 May and were harvested on 1 October 2008. The subsurface drip irrigation (SDI) laterals were placed in the middle of every other row (1.52 m) at a depth of approximately 0.40 m below the soil surface. Irrigation was applied seven times during the 2007 crop season and four times during the 2008 growing seasons. The available soil water in the effective root zone was maintained at a maximum allowable depletion of 45% of plant-available water during the mid-season growth stage to avoid crop water stress (Irmak et al., 2008). The initial effective depth at planting (Z_{rmin} = 0.1 m) and the maximum effective depth occurring at mid-season (Z_{rmax} = 1.2 m) of soybean were taken from FAO-56 (1998). The development of the root zone was assumed to increase from initial to maximum depth in proportion to the increase in LAI.

Surface soil moisture content at 0.06 m was measured hourly using three SMP1R soil moisture probes (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.) installed along the crop line, drip row, and dry row. Daily averages of the three SMP1R readings were used. Soil moisture profile at 0.30, 0.60, 0.90, 1.20, and 1.80 m depths were measured using a model 4302 neutron probe soil moisture meter (Troxler Electronics Laboratories, Inc., Research Triangle Park, N.C.) twice a week throughout the growing seasons. LAI was measured at 7 to 10 day intervals using an LAI-2000 plant canopy analyzer (LI-COR, Inc., Lincoln, Neb.) Plant height was measured on the same days as LAI (Irmak et al., 2008; Irmak and Mutiibwa 2009a, 2009b). Figure 1 shows the date and amounts of irrigation applications and the amounts of rainfall.

Measurements of surface energy fluxes, including latent heat flux (*ET*), sensible heat flux, soil heat flux, net radiation, and other climatic variables were made in the experimental field using a deluxe version of a BREBS (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.). Air temperature and humidity were measured using two chromel-constantan thermocouple probes (REBS models THP04015 and THP04016, respectively) raised to an average height of 1 m above the canopy as the crop grew. Incoming and outgoing shortwave radiation were measured simultaneously using a REBS model THRDS7.1 double-sided total hemispherical radiometer. Net radiation was measured using a REBS Q*7.1 net radiometer. Both radiometers were installed at 4.5 m above the ground surface. Wind speed was measured at 3.0 m height using a cup anemometer (model 034B, Met One Instruments, Grant Pass, Ore.) The fetch distances were 520 m in the north-south direction and 280 m in the east-west direction. The prevailing wind direction at the site is south-southwest. The BREBS and other datasets used in this study are part of the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) (Irmak, 2010) that operates ten deluxe-version BREBS and one eddy covariance system over various vegetation surfaces. Detailed description of the microclimate measurements, including latent heat flux, sensible heat flux, soil heat flux, and other microclimatic variables (actual vapor pressure, air temperature, relative humidity, wind speed and direction, incoming and outgoing shortwave radiation, net radiation, albedo, and soil temperature) are presented by Irmak (2010).

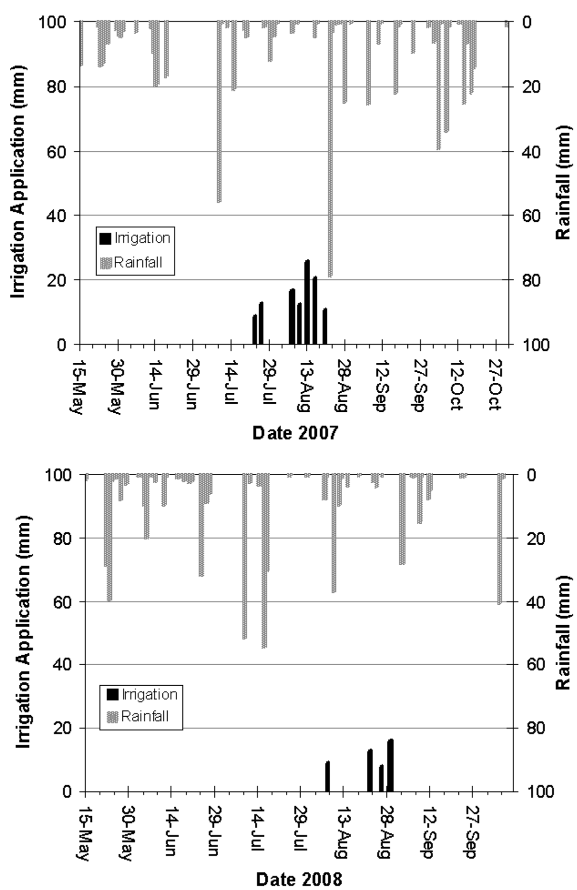

Figure 1. Amounts of irrigation applications and rainfall measured at the experimental site during the 2007 and 2008 growing seasons.

FORMULATION OF THE EXTENDED S-W MODEL

The total ET measured above the canopy at the measurement height is the sum of transpiration from the canopy (T), soil water evaporation from bare soil areas (E_s), and soil water evaporation from residue-covered soil areas (E_r) and can be written as:

$$ET = T + C_s E_s + C_r E_r \quad (1)$$

where C_s and C_r are the fractions of the soil surface area occupied by bare soil and residue, respectively. No distinction is made between the soil surface beneath and between canopies such that $C_s + Cr = 1$. In the absence of residue, $C_r = 0$ and $C_s = 1$. The components T, E_s, and E_r are estimated separately using the extended S-W model (Farahani and Ahuja, 1996; Farahani and DeCoursey, 2000), which is expressed as:

$$T = \frac{CC}{\lambda} \times \frac{\Delta(R_n - G) + \frac{\rho c_p D - \Delta r_a^c R_{nsub}}{r_a^a + r_a^c}}{\Delta + \gamma\left(1 + \frac{r_s^c}{r_a^a + r_a^c}\right)} \quad (2)$$

$$E_s = \frac{CS}{\lambda} \times \frac{\Delta(R_n - G) + \frac{\rho c_p D - \Delta r_a^s [(R_n - G) - (R_{ns} - G_s)]}{r_a^a + r_a^s}}{\Delta + \gamma\left(1 + \frac{r_s^s}{r_a^a + r_a^s}\right)} \quad (3)$$

$$E_r = \frac{CR}{\lambda} \times \frac{\Delta(R_n - G) + \frac{\rho c_p D - \Delta r_s^a [(R_n - G) - (R_{nr} - G_r)]}{r_a^a + r_a^s}}{\Delta + \gamma\left(1 + \frac{r_s^s + r_s^r}{r_a^a + r_a^r}\right)} \quad (4)$$

where T is the crop transpiration rate above the canopy at the measurement height (mm d^{-1}); E_s is soil water evaporation rate per unit area of bare soil area (mm d^{-1}); E_r is the soil water evaporation rate per unit area of residue-covered soil area (mm d^{-1}); R_n, R_{nsub}, R_{ns}, and R_{nr} are the flux of net radiation above the canopy, below the canopy, over the bare soil area, and over the residue-covered soil area, respectively (W m^{-2}); G, G_s, and G_r are soil heat flux below the canopy, on the bare soil area, and on the residue-covered soil area, respectively (W m^{-2}); ρ is the mean air density at constant pressure (kg m^{-3}); c_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}); γ is the psychrometric constant (kPa K^{-1}); Δ is slope of the saturation vapor pressure versus air temperature curve (kPa K^{-1}); D is the air vapor pressure deficit at the mean canopy height (kPa); $r_a{}^c$ is the bulk aerodynamic resistance of the canopy elements (s m^{-1}); $r_s{}^c$ is the bulk surface resistance of the canopy (s m^{-1}); $r_a{}^s$ is the aerodynamic resistance between the bare soil surface and mean canopy height (s m^{-1}); $r_s{}^s$ is the soil surface resistance (s m^{-1}); $r_a{}^r$ is the aerodynamic resistance between the residue cover and the mean canopy height (s m^{-1}); and $r_s{}^r$ is the surface resistance of the residue cover (s m^{-1}). The parameters CC, CS, and CR are resistance coefficients for canopy, bare soil area, and residue-covered area, respectively. They are expressed as:

$$CC = \left[1 + \frac{R_a R_c (C_s R_r + C_r R_s)}{R_s R_r (R_c + R_a)}\right]^{-1} \quad (5)$$

$$CS = \left[1 + \frac{R_a (C_s R_r + C_r R_s)}{R_r C_s (R_a + R_s)}\right]^{-1} \quad (6)$$

$$CR = \left[1 + \frac{R_a (C_s R_r + C_r R_s)}{R_s C_r (R_a + R_r)}\right]^{-1} \quad (7)$$

where

$$R_a = (\Delta + \gamma) r_a^a \quad (8)$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s \quad (9)$$

$$R_c = (\Delta + \gamma) r_a^c + \gamma r_s^c \quad (10)$$

$$R_r = (\Delta + \gamma) r_a^s + \gamma (r_s^s + r_s^r) \quad (11)$$

Equations 1 through 11 define the extended S-W ET model applicable for partial canopy and residue cover conditions with the asymptotic limits of closed canopy transpiration, bare soil evaporation, and completely residue-covered soil evaporation.

ESTIMATING SURFACE RESIDUE COVER

The extended S-W model takes into consideration the effects of surface residue cover on aerodynamic resistance ($r_a{}^s$) and surface resistance ($r_s{}^s$) at the soil surface that control the rate of soil evaporation. Unger and Parker (1976) compared the effects of different types of residue on soil evaporation and found that residue thickness and surface coverage, rather than residue type, were the dominant factors affecting evaporation. They reported a negative, linear relationship between soil water evaporation rate and the thickness of the residue layer. This study used the relationship between measured crop yield and crop residues produced (Wortmann et al., 2008) and tables of typical percent residue remaining after winter weathering and various field operations (Shelton et al., 2000) to estimate percent of residue from the previous crop season remaining on the field surface after planting. Approximately 1 ton of residue (at 10% moisture) is produced with 1.02 tons of maize grain and 0.82 tons of soybean (Wortmann et al., 2008). In 2007, the residue remaining on the field was from a previous maize crop harvested in October 2006. The yield of the 2006 maize crop was 11.6 tons ha^{-1}, and the amount of residue produced at harvest was estimated at 11.4 tons ha^{-1}. Maize residue is not as fragile as soybean residue and is little affected by winter weathering. About 90% of maize residue remains after winter weathering (Shelton et al., 2000). The maize residue stalks were shredded with a stalk chopper before planting the soybean crop in 2007. The field was planted using a ridge-till planter that leaves about 60% (Shelton et al., 2000) of residue remaining on the soil

surface. The final amount of surface residue remaining on the field surface at the beginning of the 2007 crop season was 6.2 tons ha^{-1}, estimated by multiplying the amount of residue after harvest by the percent residue remaining after winter weathering and the percent residue remaining after planting operations. The 2007 soybean crop was harvested in October 2007, and the combine-measured yield and estimated amount of residue produced were 4.7 and 5.7 tons ha^{-1}, respectively. Soybean residues are fragile and are reduced by winter weathering to about 75% (Shelton et al., 2000). The field was ridge-planted with soybean in May 2008 and resulted in little or no change in surface residue remaining. The final amount of residue remaining at the beginning of the 2008 crop season was 4.3 tons ha^{-1}, estimated by multiplying the amount of residue after harvest by the percent residue remaining after winter weathering.

The amount of residue remaining at the field surface was evenly distributed and continued to decrease during the crop growing season due to residue decomposition. Residue decomposition is controlled by environmental factors, mainly temperature and moisture content (Gregory et al., 1985; Roper, 1985), carbon/nitrogen (C/N) ratio of the residue (Meentemeyer, 1978; Parr and Papendick, 1978; Aber and Melillo, 1982; Reinertsen et al., 1984), solar radiation, and humidity. The daily amount of residue remaining on the soil surface was estimated using a first-order exponential decomposition function (Steiner et al., 1999):

$$\frac{M_t}{M_o} = \exp^{-k_d(DCD)} \tag{12}$$

where M_t is the total residue mass at time t (tons ha^{-1}), M_o is the initial mass at the beginning of the crop season (tons ha^{-1}), k_d is a crop-specific decomposition coefficient (ton ton^{-1} d^{-1}), and DCD is decomposition days. The coefficient k_d accounts for the differences in C/N ratio and physical properties of the residues, and reported values for legume residues are significantly higher than those of cereal residues. Steiner et al. (1999) and Quemada (2004) reported k_d values ranging from 0.015 to 0.042 for cereal residues; van Donk et al. (2008) reported k_d values ranging from 0.02 to 0.03 for legume residues and 0.013 to 0.015 for cereal residues. A larger k_d value implies a faster residue decay rate. Sensitivity analysis of the k_d parameter showed that a 10% increase in its value can result in 0.0 to 0.14 mm d^{-1} increase in E. The values k_d = 0.030 for soybean residue and k_d = 0.015 for maize residue were used in this study. DCD is calculated as a function of daily air temperature and residue moisture coefficients. Daily temperature and moisture coefficients (TC and MC, respectively) are calculated and constrained from 0 to 1, with 1 indicating conditions for maximum decomposition and 0 indicating no decomposition. Based on the principle of most limiting factor, the DCD for a given day is equal to the minimum of TC or MC and is expressed as:

$$DCD = \min(TC, MC) \tag{13}$$

The coefficient TC is calculated using the procedures proposed by Steiner et al. (1994):

$$TC = \frac{2T_a{}^2 (T_{opt})^2 - T_a{}^4}{(T_{opt})^4} \tag{14}$$

where T_a is the daily average air temperature (°C), and T_{opt} is the optimum air temperature for residue decomposition (T_{opt} = 32°C). In calculating MC, it is assumed that 4 mm of precipitation is enough to fully wet a layer of residue (Steiner et al., 1994). If precipitation for a given day is more than 4 mm, the precipitation coefficient (PC) is set to 1. For precipitation below 4 mm, PC is equal to precipitation divided by 4. MC was calculated (Steiner et al., 1994) as:

$$MC_t = 0.5MC_{t-1} + PC_t$$

$$(MC_t = 1.0 \text{ when } MC_t > 1.0) \tag{15}$$

$$PC_t = 1.0 \text{ when } P_t \geq 4.0 \text{ mm} \tag{16}$$

$$PC_t = P_t/4 \text{ when } P_t < 4.0 \text{ mm} \tag{17}$$

where P_t is the current days precipitation (mm), PC_t is the precipitation coefficient for the current day, and MC_t and MC_{t-1} are the moisture coefficients for the current and previous days. The fraction of soil surface covered with crop residue (C_r) was estimated as a function of the mass of residue (Gregory, 1982) expressed as:

$$C_r = 1 - \exp(-A_m M_i) \tag{18}$$

where A_m is an empirical parameter that converts mass to an equivalent area and varies with residue characteristics and randomness of distribution. Reported values of A_m for maize and soybean are 0.32 and 0.20, respectively (Gregory, 1982). The estimated fractions of residue cover during the crop growing season in 2007 and 2008 are presented in figure 2. In 2007, the fraction of residue cover decreased from about 87% in early season to about 55% at the end of the season, whereas it was about 60% in early season and 27% in late season in 2008. The larger percentage in residue cover in 2007 was due to the presence of maize residue from the previous year.

Residue thickness (h_r) is needed to compute the residue aerodynamic and surface resistance coefficients. The thickness of the residue is estimated from knowledge of residue specific density (ρ_{sr}), mass (M), fraction cover (C_r), and porosity (ϕ_r):

$$h_r = \frac{0.1M}{C_r(1-\phi_r)\rho_{sr}} \tag{19}$$

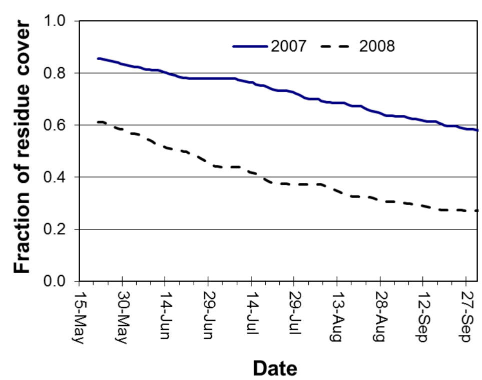

Figure 2. Estimated fraction of residue cover during the crop growing season in 2007 and 2008.

Values of ρ_{sr} = 298 kg m^{-3} (maize), ρ_{sr} = 180 kg m^{-3} (soybean), and a mean ϕ_r value of 0.85 (Farahani and DeCoursey, 2000) were used in this study for analysis of residue height. The lager the ϕ_r value, the lesser the diffusive resistance to water vapor transport from the soil to the atmosphere. Sensitivity analysis of the ϕ_r parameter showed that a 10% increase in its value can result in 0.01 to 0.50 mm d^{-1} increase in E.

Partitioning Net Radiation and Soil Heat Flux

The net radiation (R_n) measured or estimated above the field reflects the effect of the composite albedo of canopy, bare soil, and residue cover on incoming solar radiation (R_s). The S-W model computation requires the partitioning of R_n into net radiation intercepted by the canopy surface (R_{nc}), bare soil area (R_{ns}), and residue-covered area (R_{nr}). The fraction of R_n penetrating the canopy to the ground surface is estimated by Beer's law expressed as:

$$R_{nsub} = R_n \exp(-C_{ext}\text{LAI}) \tag{20}$$

where R_{nsub} is R_n reaching the ground surface, C_{ext} is the canopy extinction coefficient for R_n, and LAI is leaf area index. A third-order polynomial function derived from measured LAI data was used to estimate daily LAI, as shown in figure 3. The value of C_{ext} is affected by crop row spacing, stage of crop development, and time of the day. Ritchie (1972) reported a mean C_{ext} value of 0.398 by regressing above and below canopy R_n data for maize, cotton, snap beans, sorghum, and soybean crops. In a field experiment, Flenet et al. (1996) found a weighted mean C_{ext} value of 0.525 for soybean, which took into account row spacing, stage of crop growth, and time of day. Brisson et al. (1998) estimated a C_{ext} value of 0.25 for soybean, which is less than the values generally reported. In the RZWQM (Farahani and DeCoursey, 2000), a mean C_{ext} value of 0.594 is used for maize and soybean. The R_{nc} is calculated as:

$$R_{nc} = R_n - R_{nsub} \tag{21}$$

and R_{nsub} is partitioned into R_{ns} and R_{nr} by the principle of superposition, which considers the fraction of the ground surface that is under residue cover (C_r) as follows:

$$R_{ns} = (1 - C_r)R_{nsub} \tag{22}$$

$$R_{nr} = C_r R_{nsub} \tag{23}$$

For daily periods, the soil heat flux below the canopy (G), on the bare soil area (G_s), and on the residue-covered soil area (G_r) are relatively small as compared to R_n and their net daily values were assumed to be negligible in this model.

Calculation of Surface Resistances

The canopy surface (bulk stomatal) resistance (r_s^c) and the soil surface resistance (r_s^s) affect water vapor transport from plant stomatal cavities to leaf surface and from soil profile to soil surface, respectively. The r_s^c is influenced by the degree of stomatal opening. Several environmental factors including carbon dioxide (CO_2) concentration, solar radiation (R_s), air vapor pressure deficit (D), air temperature (T_a), soil moisture content (θ_i), and plant conditions have been found to affect stomatal opening (Hsiao et al. 1973; Jarvis and Morison, 1981). In this study, r_s^c was modeled as a function of R_s, T, D, and θ_i. The CO_2 concentration was not considered. The simplified approach developed by Jarvis (1976) and extended by Noilhan and Planton (1989) for use in mesoscale atmospheric models was used and is expressed as:

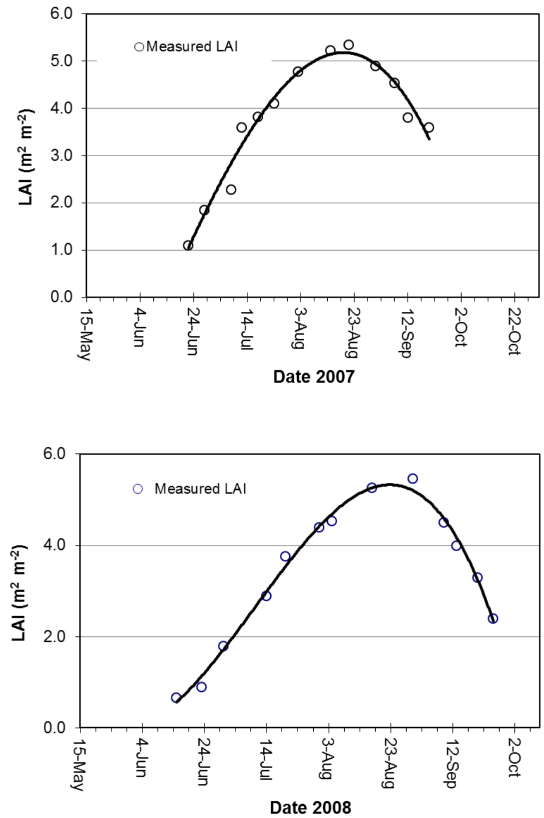

Figure 3. Measured leaf area index (LAI) in 2007 and 2008 seasons. Each data point represents and average of 15 measurements.

$$r_s^c = \frac{r_{s\,min}^c}{\text{LAI}} \frac{F_1}{F_2 F_3 F_4} \tag{24}$$

The factor F_1 accounts for the influence of solar radiation flux density (R_s) on r_s^c and is estimated as follows:

$$F_1 = \frac{1 + f}{f + \left(r_{s\,min}^c / r_{s\,max}^c\right)} \tag{25}$$

$$f = \frac{0.55 R_s}{R_{sl}} \frac{2}{\text{LAI}} \tag{26}$$

where $r_s^c{}_{max}$ is the maximum stomatal resistance, $r_s^c{}_{min}$ is the minimum stomatal resistance, R_s is the solar radiation flux (Wm^{-2}) reaching the canopy, R_{sl} is the threshold radiation value above which the stomata is assumed to open. The term 2/LAI expresses the shading between leaves, while the factor 0.55 represents the photosynthetic active radiation (PAR) portion of the solar radiation flux. Actual values of r_{smin}, r_{smax}, and R_{sl} for soybean are not known, and typical values found in the literature were used for computing F_1 (table 1).

The factor F_2 in equation 24 accounts for the effect of soil moisture content (θ_i) on r_s^c. It varies between 0 and 1 when θ_i varies between moisture content at permanent wilting

Table 1. Typical values of parameters and coefficients used in the simulations.

Symbol	Variable/Parameter	Value	Unit	Source
A_m	Residue specific mass to equivalent area conversion coefficient	0.32 (soybean) 0.20 (maize)	Dimensionless	Gregory (1982)
ϕ_r	Mean residue porosity	0.85	Dimensionless	Farahani and Ahuja (1996)
K_d	Crop specific residue decomposition coefficient	0.300 (soybean) 0.015 (maize)	Dimensionless	Van Donk et al. (2008)
ρ_{sr}	Residue specific density	180 (soybean) 298 (maize)	kg m^{-3}	Farahani and Ahuja (1996)
C_{ext}	Canopy extinction coefficient	0.525	Dimensionless	Flenet et al. (1996)
$r_s{}^c{}_{min}$	Minimum stomatal resistance	25	s m^{-1}	Soiniti and Kramer (1976)
$r_s{}^c{}_{max}$	Maximum stomatal resistance	3000	s m^{-1}	Norman (1979)
R_{sl}	Threshold radiation value for stomatal opening	100	W m^{-2}	Noilhan and Planton (1989)
r_b	Mean boundary layer resistance	25	s m^{-1}	Shuttleworth and Wallace (1985)
n	Eddy diffusivity decay constant	2.5	Dimensionless	Shuttleworth and Wallace (1985)
z_{os}	Roughness length of soil surface	0.01	m	Van Bavel and Hillel (1976)
k	Von Karman's constant	0.41	Dimensionless	Shuttleworth and Wallace (1985)
C_d	Mean drag coefficient for individual leaves	0.07	Dimensionless	Shuttleworth and Gurney (1990)

point (θ_{wp}) and a critical moisture content value (θ_{cr}) at which plants begin to experience the effects of water stress. Factor F_2 was estimated as follows (Noilhan and Planton, 1989):

$$F_2 = 1 \text{ when } \theta_i > \theta_{cr} \quad (27)$$

$$F_2 = \frac{\theta_i - \theta_{wp}}{\theta_{cr} - \theta_{wp}} \text{ when } \theta_{wp} \le \theta_i \le \theta_{cr} \quad (28)$$

$$F_2 = 0 \text{ when } \theta_i < \theta_{wp} \quad (29)$$

where all values of moisture content are expressed as a fraction volumetric moisture content in the root zone. Some applications of this approach assume that the process of stomatal closure begins as soon as the available water falls below field capacity (θ_{fc}) and hence $\theta_{cr} = \theta_{fc}$ (Ortega-Farias et al., 2010). The value of θ_{cr} varies with atmospheric evaporative demand, crop characteristics, and soil type. Doorenbos et al. (1986) suggested θ_{cr} values for different crops ranging between 0.125 and 0.7 for an atmospheric evaporative demand varying from 2 to 10 mm d^{-1}. Raes et al. (2009) suggested θ_{cr} values ranging from 0.1 to 0.9 based on crop sensitivity to water stress. Several authors have shown that the θ_{cr} value for soybean is between 0.4 and 0.6 (Doorenbos et al., 1986; Rosadi et al., 2007; Raes et al., 2009). An average of θ_{cr} = 0.5 as suggested for the FAO AquaCrop model (Raes et al., 2009) was used in this study.

The functions F_3 and F_4 represent the effects of D and air temperature (T_a), respectively, and were estimated as follows (Noilhan and Platon, 1989):

$$F_3 = 1 - 0.0025D \quad (30)$$

$$F_4 = 1 - 0.0016(298 - T_a)^2 \quad (31)$$

Due to the lack of a developed function for estimating $r_s{}^s$ for silt loam soils, an empirical function (eq. 32) developed by Ortega-Farias et al. (2010) for clay loam soils was used as the closest approximation to estimate $r_s{}^s$:

$$r_s^s(\theta_i) = 19\left(\frac{\theta_s}{\theta_i}\right)^{3.5} \quad (32)$$

A sensitivity analysis of the $r_s{}^s$ parameter show that a 10% increase in its value can result in 0.01 to 0.21 mm d^{-1} increase in E.

Calculation of Aerodynamic Resistances

The aerodynamic resistances affect water vapor transport from the evaporating surface to the atmospheric air stream. The surface aerodynamic resistances consist of the aerodynamic resistances above the canopy ($r_a{}^c$), above the bare soil surface ($r_a{}^s$), above the residue-covered surface ($r_a{}^r$), and above the mean canopy height ($r_a{}^a$). The $r_a{}^c$ represents resistance to water vapor on the leaf surface joining the canopy air stream and is influenced by the boundary layer conditions around the leaves and is calculated as an inverse function of LAI as follows:

$$r_a^c = \frac{r_b}{2\text{LAI}} \quad (33)$$

where r_b is mean boundary layer resistance. Shuttleworth and Wallace (1985) suggested typical r_b values of 25 s m^{-1}, and Farahani and Bausch (1995) recommended a mean seasonal r_b value of 10 s m^{-1} for the RZWQM. Both studies showed that model results are only slightly sensitive to this parameter. Mathematical functions for the calculation of $r_a{}^s$, $r_a{}^r$, and $r_a{}^a$ were presented by Farahani and Ahuja (1996) as follows:

$$r_a^s = \frac{h_c \exp(n)}{nK_h}\left[\exp\left(\frac{-nz_o^s}{h_c}\right) - \exp\left\{\frac{-n(Z_o^c + d_p)}{h_c}\right\}\right] \quad (34)$$

$$r_a^r = \frac{h_c \exp(n)}{nK_h}\left[\exp\left(\frac{-nz_o^r}{h_c}\right) - \exp\left\{\frac{-n(Z_o^c + d_p)}{h_c}\right\}\right] \quad (35)$$

$$r_a^a = \frac{1}{ku_*}\ln\left[\frac{z - d_c}{h_c - d_c}\right] + \frac{h_c}{nK_h}\left[\exp\left\{\frac{n[1 - (Z_o^c + d_p)]}{h_c}\right\} - 1\right] \quad (36)$$

where h_c is the crop height, n is the eddy diffusivity decay constant (2.5), z is the wind measurement height (m), k is von Karman's constant (0.41), d_c is the crop displacement height, $Z_o{}^c$ is the preferred value of crop roughness length calculated as $Z_o{}^c = 0.13h_c$, d_p is the preferred displacement height calculated as $d_p = 0.63h_c$, $z_o{}^s$ is the roughness length of bare soil surface with a value of 0.01 m (van Bavel and Hillel, 1976), $z_o{}^r$ is the roughness of residue-covered surface ($z_o{}^r = 0.13h_r$, where h_r = residue height calculated in eq. 19), K_h is the eddy diffusion coefficient at the top of the crop, and $u*$ is the friction velocity. The daily crop heights (h_c) were estimated from a third-order polynomial function derived from measured plant height data, as shown in figure 4. The parameters K_h, $u*$, and d_c are calculated as:

$$K_h = ku_*(h_c - d_c) \tag{37}$$

$$u* = \frac{ku}{\ln\left(\frac{z - d_c}{z_o}\right)} \tag{38}$$

$$d_c = 1.1 h_c \ln\left(1 + \beta^{1/4}\right) \tag{39}$$

where $\beta = c_d$(LAI), and c_d is the mean drag coefficient for individual leaves.

Equation 34 is used when the ground surface is completely bare, and equation 35 is used when the ground is completely covered with residue. For partially residue-covered fields, it is not clear how aerodynamic properties are affected by the spatially varying surface roughness conditions. In such conditions, Farahani and Ahuja (1996) recommended a composite aerodynamic resistance ($r_a{}^{sr}$) to replace $r_a{}^s$ and $r_a{}^r$ in equations 3, 4, 9, and 11. The $r_a{}^{sr}$ is calculated using an area-weighted roughness height $z_o{}^{sr}$ ($z_o{}^{sr} = C_r z_o{}^r + C_s z_o{}^s$) in place of $z_o{}^r$ in equation 35. During the initial growth stage when $h_c = 0$, $r_a{}^{sr}$ and $r_a{}^a$ are estimated from the aerodynamic resistance between the surface and the measurement height ($r_a{}^z$). The $r_a{}^z$ is partitioned between $r_a{}^{sr}$ and $r_a{}^a$ such that $r_a{}^z = r_a{}^{sr} + r_a{}^a$. The $r_a{}^z$ is computed as:

$$r_a^z = \frac{[\ln(z / z_o^{sr})]^2}{k^2 u} \tag{40}$$

The fractions of $r_a{}^z$ assigned to $r_a{}^{sr}$ and $r_a{}^a$ have no numerical consequence in the simulated ET rates.

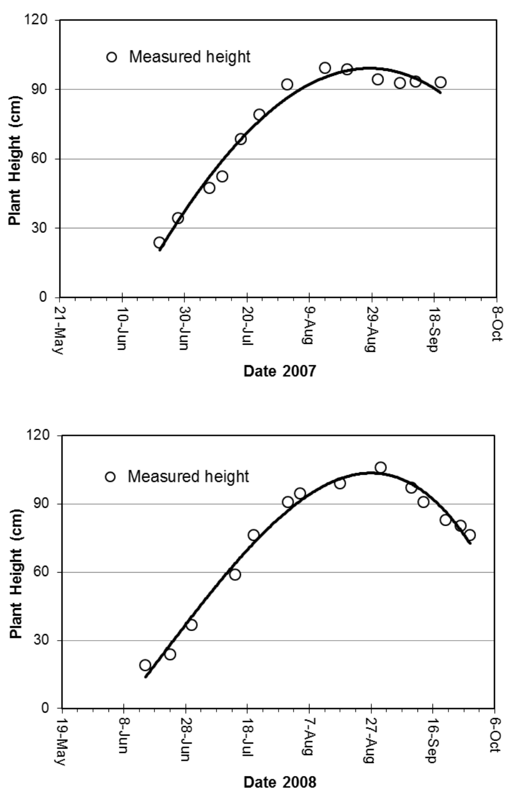

Figure 4. Measured plant height (h_c) in 2007 and 2008 seasons. Each data point represents and average of 15 measurements.

Parameters and Coefficients Used in the Simulations

As presented in the preceding sections, simulation of ET, T, and E using the S-W model requires quantification of several variables, including surface residue cover, net radiation partition between the plant canopy and soil surface, and surface resistance and aerodynamic resistance terms. The empirical functions used to quantify these variables require several parameters and coefficients whose precise values for soybean are not known and/or difficult to estimate. Typical values of these parameters and coefficients found in the literature were used in the simulations and are presented in table 1.

Results and Discussion

Variation of Resistance Terms during the Growing Season

The bulk stomatal resistance ($r_s{}^c$) and soil surface resistance ($r_s{}^s$) are dynamically and numerically critical resistances of the S-W model, and hence the reliability of their estimated values influences the accuracy of the S-W-estimated ET. The $r_s{}^c$ was calculated as a function of LAI, θ_i, and microclimatic factors (R_s, T_a, and D). Figure 5 presents average measured volumetric soil water content at 0.06, 0.30 and 0.90 m depths over time. Seasonal variations of $r_s{}^c$ during the growing seasons in 2007 and 2008 are presented in figures 6a and 6b. During both growing seasons, there was sufficient soil moisture from rainfall and irrigation, and hence θ_i had little impact on the estimated $r_s{}^c$ values. The fluctuations of $r_s{}^c$ values due to daily fluctuations in microclimatic factors were minimal, but $r_s{}^c$ decreased gradually and significantly with the increase in LAI. At very low LAI (i.e., <2.0), the values of $r_s{}^c$ was over 800 s m^{-1} in both 2007 and 2008, and at full canopy cover it typically ranged from 12 to 20 s m^{-1}. There were a few days during full canopy cover when the values $r_s{}^c$ peaked above 20 s m^{-1}, and those values were associated with lower R_s, T_a, and D. The $r_s{}^s$ values were calculated as a function of θ_i in the top layer of soil measured at 6 cm depth. The variation of $r_s{}^s$ during the growing seasons in 2007 and 2008 are shown in figures 6c and 6d. The values of $r_s{}^s$ varied inversely with θ_i at the topsoil layer and were not related to plant factors. In both years, the surface resistance fluctuated as a function of change in soil water status of the topsoil. The value of $r_s{}^s$ ranged between about 200 and 1400 s m^{-1} in 2007, whereas it ranged between about 200 and 1100 s m^{-1} in 2008. From the data in both years, the lowest $r_s{}^s$ of the soil under the

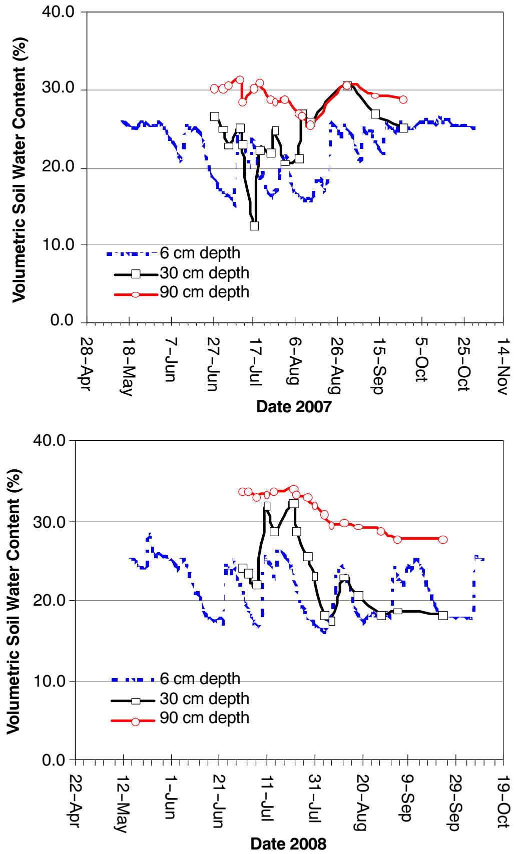

Figure 5. Measured average volumetric soil water content at 0.30 and 0.90 m soil depths during the growing seasons in 2007 and 2008.

subsurface drip irrigation method in these experimental conditions is about 200 s m^{-1}.

Comparison of S-W Model-Estimated *ET* against BREBS-Measured *ET*

The BREBS may be considered as an indirect method of measuring local water vapor flux above the vegetation surface, while the S-W model estimates *ET* from microclimatic data measured above the crop canopy. In addition to microclimatic variables, parameters describing surface and aerodynamic resistances are also required for the S-W model simulation. These resistance terms are influenced by the amount of crop canopy cover, crop height, residue cover, and soil moisture content at the top layer and the effective root zone.

The S-W model simulations were conducted for the period from 15 May to 31 October in 2007 and from 15 May to 10 October in 2008. The S-W model estimated *ET* and the BREBS-measured *ET* above soybean are presented in figures 7a and 7b for 2007 and 2008, respectively. Regression plots of the S-W model estimated *ET* against the BREBS-measured *ET* for the active crop growing period are presented in figures 8a and 8b. Although the S-W model estimates did not always match exactly with the BREBS-measurements, they did capture the major trends exhibited by the measured data during the active crop growing period. The growing period of soybean was divided into four distinct growth stages: initial, crop development, mid-season, and late season. The model exhibited different performances for the various growth stages, as shown by the regression plots of the S-W model estimates versus the BREBS-measurements for the various growth stages in figures 9 and 10. The initial stage

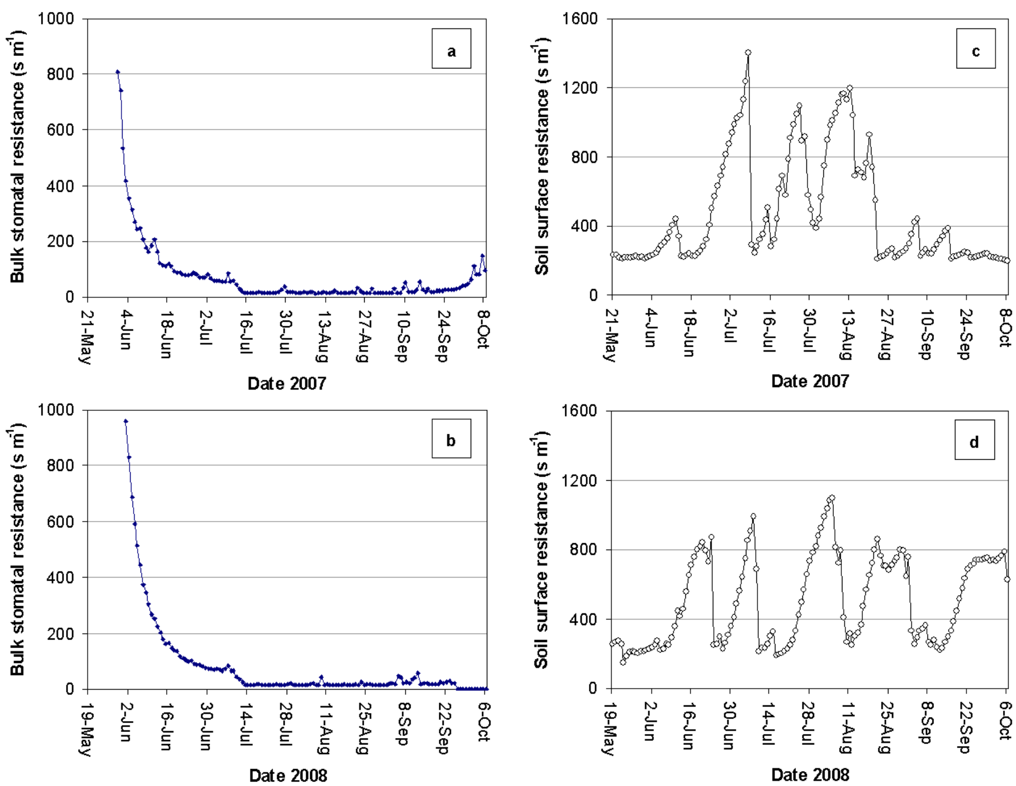

Figure 6. (a-b) Seasonal variations of bulk stomatal resistance during the growing season, and (c-d) variations of soil surface resistance during the growing season.

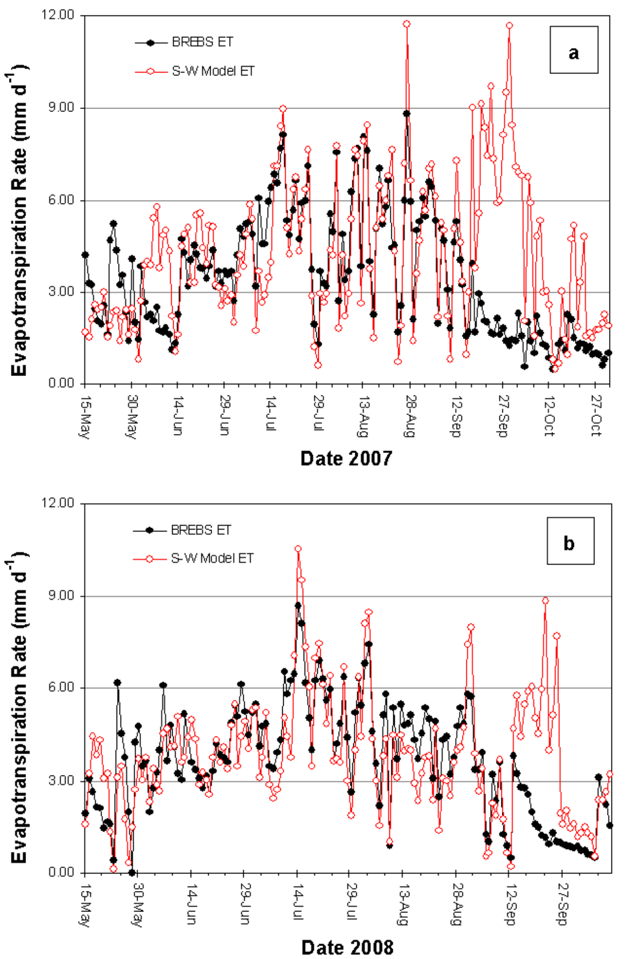

Figure 7. Measured average volumetric soil water content at 0.30 and 0.90 m soil depths during the growing seasons in (a) 2007 and (b) 2008.

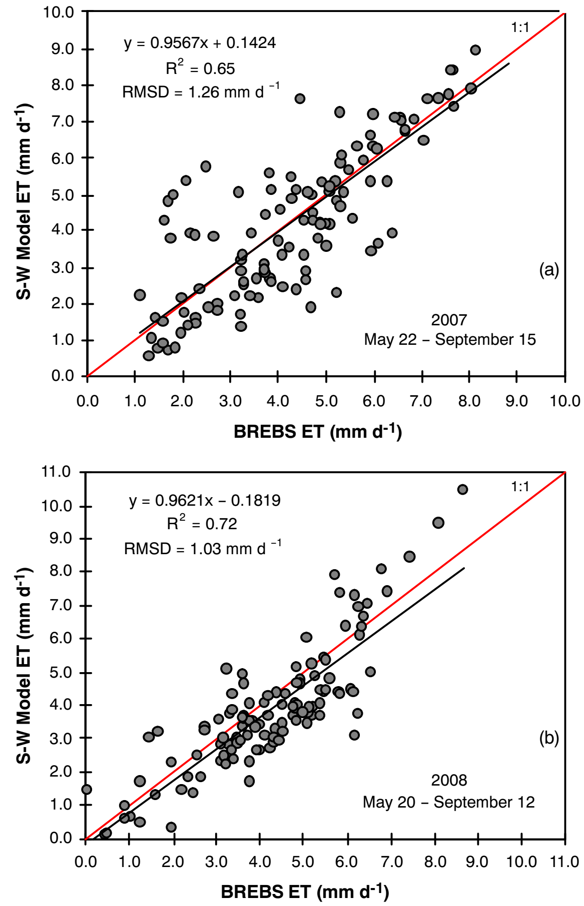

Figure 8. Performance of the S-W model daily evapotranspiration estimates in comparison to the Bowen Ratio Energy Balance System (BREBS) measurements in the (a) 2007 and (b) 2008 growing seasons.

runs from planting date to approximately 10% ground cover (0 < LAI < 0.21) (21 May to 10 June in 2007, and 19 May to 8 June in 2008). During this stage, the leaf area is small, and *ET* is predominately in the form of *E*. Model performance during the initial stage was poorly correlated to the BREBS measurements. The coefficients of determinant (r^2) for this stage were 0.06 and 0.353 for 2007 and 2008, respectively. The root mean square difference (RMSD) and the mean bias error (MBE) were 2.0 and -0.28 mm d^{-1}, respectively, for 2007 and 1.38 and 0.29 mm d^{-1}, respectively, for 2008. The poor performance of the model during this stage could be attributed to several factors, including the simplifying assumptions in the model that ignore the lateral transfer of heat between bare and residue-covered soil areas and inability of the model to adequately quantify the controlling soil surface resistance term from the input data. The initial stage also had large amounts of residue cover and frequent rainfall events. The S-W model overestimated the BREBS measurements during this period when there was no rainfall and underestimated following rainfall events. For example, in 2007 the S-W model overestimated BREBS measurements during the period of 18 to 22 May, when there was no rainfall. However, following rainfall events of 13.6 and 12.6 mm on 23 and 24 May, respectively, the BREBS measurements were higher than the S-W model-estimated *ET* for the next three days (BREBS measurements were 4.7, 5.2, and 4.3 mm for 23, 24, and 25 May, respectively; and S-W model estimates were 1.9, 2.3, and 2.39 mm for 23, 24, and 25 May, respectively) as shown in figure 11a. Similar trends were observed for the 2008 crop season (fig. 11b). An empirical function (eq. 32) developed by Ortega-Farias et al. (2010) for clay loam soils was used as the closest approximation to estimate $r_s^{\ s}$ for the study field's silt loam soil. Lack of accurate $r_s^{\ s}$ values may have contributed to overestimation by the model during periods of no rainfall when *ET* is predominantly from soil evaporation. Higher values of the BREBS measurements following rainfalls could be explained by the fact that BREBS was able to measure total water vapor flux above the surface, including the evaporative from soil surface, evaporation of intercepted rainfall from crop canopy and surface residue, and plant transpiration. The SW model only estimated water vapor flux from soil water evaporation and crop transpiration without considering direct evaporation from the intercepted rainfall on the canopy.

The crop development stage runs from 10% ground cover to full canopy cover (0.21 < LAI < 3.5) (11 June to 15 July in 2007, and 9 June to 13 July in 2008). As the crop develops and shades more soil surface, soil evaporation decreases and transpiration gradually becomes the major process. The S-W model estimation at the crop development stage was slightly better than its poor performance at the initial stage for both the 2007 and 2008 data. The r^2 for the crop development stage

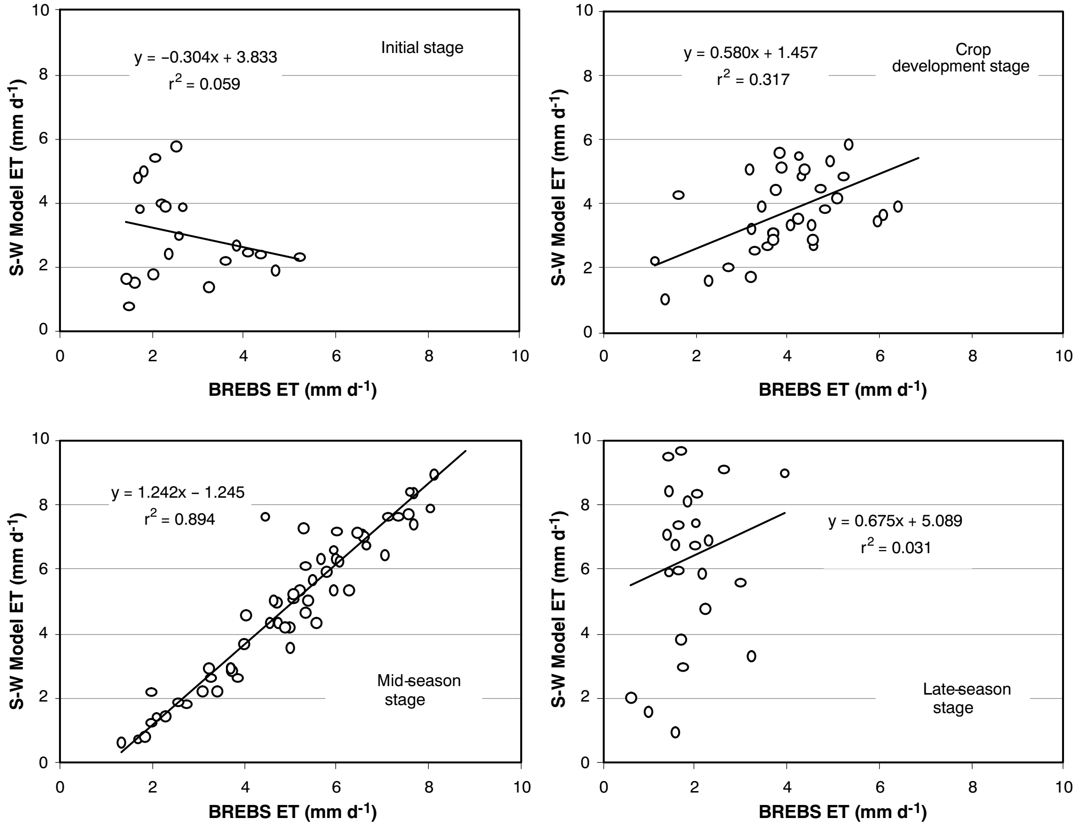

Figure 9. Regression plots of S-W model *ET* estimates against BREBS *ET* measurements for the various growth stages in 2007.

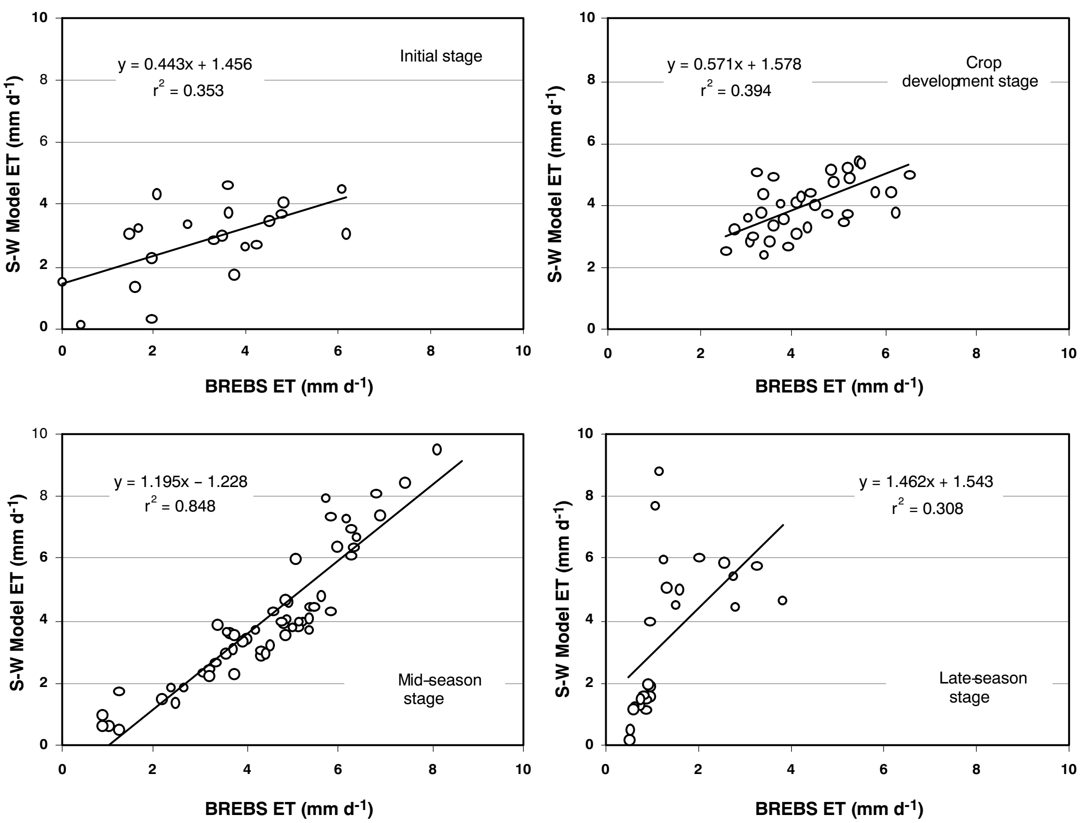

Figure 10. Regression plots of S-W model *ET* estimates against BREBS *ET* measurements for the various growth stages in 2008.

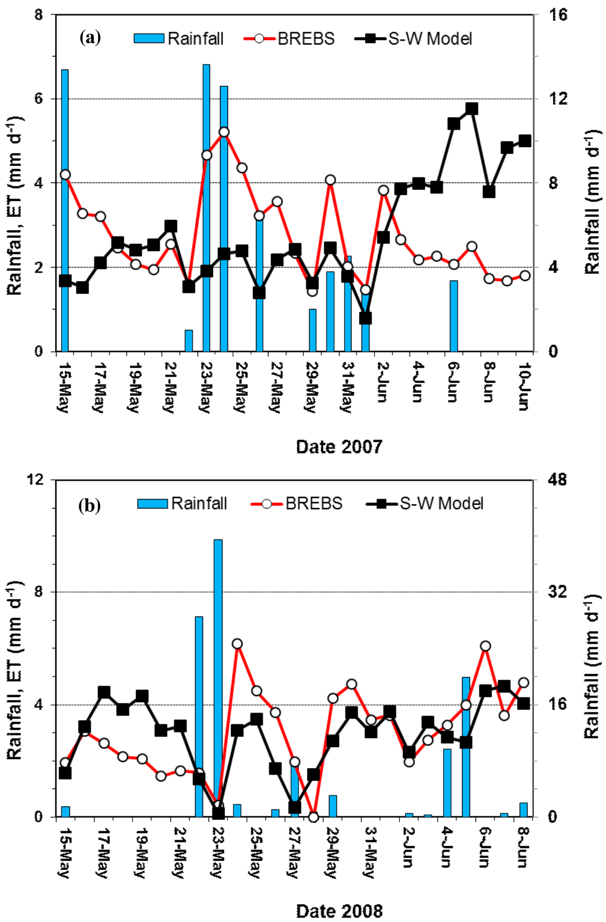

Figure 11. S-W model overestimation of BREBS measurements during periods when there was no rainfall and underestimation of BREBS measurements following rainfall events.

was 0.317 for 2007 and 0.394 for 2008. The RMSD and MBE were 1.25 and 0.24 mm d^{-1}, respectively, for 2007 and 0.95 and 0.29 mm d^{-1}, respectively, for 2008. The mid-season stage is the longest growth period and runs from full canopy cover to the start of maturity (3.5 < LAI < 5.3) (16 July to 13 September in 2007, and 14 July to 11 September in 2008). The S-W model performed very well during the mid-season stage compared to other growth stages with the exception of one day in 2007 (27 August) and a couple of days in 2008 (14 and 15 July). The *ET* estimated by the S-W model ranged from 0.6 to 11.7 mm d^{-1} in 2007 and from 0.2 to 10.5 mm d^{-1} in 2008. The BREBS-measured *ET* ranged from 0.6 to 8.8 mm d^{-1} in 2007 and from 0.41 to 8.7 mm d^{-1} in 2008. Seasonal average S-W model estimated *ET* was 4.7 and 3.8 mm for 2007 and 2008, respectively, whereas seasonal average BREBS-measured *ET* was 3.9 and 3.7 mm for 2007 and 2008, respectively. Since *T* is the dominant component of *ET* during the mid-season stage, the good performance of the model at this stage points to well-defined resistance terms that control latent heat fluxes from the fully closed canopy. Daily maximum difference between S-W model estimated and BREBS-measured *ET* during the mid-season in 2007 occurred on 27 August. The BREBS-measured *ET* was 8.8 mm d^{-1}, and the model estimate was 11.7 mm d^{-1}. There were rainfall events for the previous five days, with a very large rain event (78 mm d^{-1}) on 22 August. Extremely wet soil conditions and ponding of rain water on the soil surface (visual observation) may be responsible for the 2.9 mm d^{-1} difference between the measured and modeled *ET*. The S-W model may have overestimated soil evaporation components due to extremely high soil moisture content due to rain events by assigning a very low soil resistance value that caused increased evaporation estimates. Other considerable over–estimations of the model during the mid-season occurred on 14 and 15 July in 2008 (fig. 7b). These two days were also rainy days, and the S-W model overestimated measured *ET* by about 2 mm d^{-1} on 14 July and by 1.4 mm d^{-1} on 15 July 2008. The r^2 of the S-W *ET* estimate was 0.894 for 2007 and 0.848 for 2008. The RMSD and MBE were 0.90 and 0.27 mm d^{-1}, respectively, for 2007 and 0.98 and 0.34 mm d^{-1}, respectively for 2008.

The late-season stage runs from the start of maturity to harvest or full senescence (14 September to 8 October in 2007, and 12 September to 6 October in 2008). It is usually associated with less efficient stomatal conductance of leaf surface due to physiological maturity, leaf aging, and senescence, thereby causing a reduction or cessation of crop transpiration. The S-W model simulation presumed *T* until the end of the season. The r^2 was 0.031 for 2007 and 0.308 for 2008. The RMSD and MBE were 5.20 and -4.47 mm d^{-1}, respectively, for 2007 and 2.98 and -2.18 mm d^{-1}, respectively, for 2008. The low model performance at the late-season stage may be attributed to lack of accounting for the reduction of *T* with leaf age, senescence, and leaf drop. There are also changes soil residue cover from leaf senescence, which may affect soil water evaporation and are not accounted for in the model.

Some of the observed poor performance of the S-W model in the crop development and mid-season stages can be the result of a combination of several factors. One reason might be the use of a constant light extinction coefficient (C_{ext}). Randomly oriented canopy structure and light interception and distribution within the canopy are continuously and dynamically influenced by many factors such as wind speed; time of day and time of year as solar latitude changes; solar zenith angle (Θ) of incoming radiation; leaf size, shape, and age; variability in crop growth rate; LAI; canopy height; and other management and microclimatic factors (Irmak and Mutiibwa, 2008). For instance, for maize canopy, Irmak and Mutiibwa (2008) showed that the extinction coefficient not only changes during the season, but also shows significant fluctuations due to changes in the sun angle and other factors. They reported that the daily maximum coefficient varied from near zero to as high as 1.8 with a seasonal average of 0.73. The daily average coefficient ranged from 0.12 to 1.14 with a seasonal average of 0.44. Diurnal fluctuations and seasonal attenuation in the daily average coefficient were influenced significantly by Θ. Thus, using a constant extinction coefficient may not be able to fully and accurately account for the partitioning of the R_n into canopy and soil surface interception because the extinction coefficient shows considerable fluctuations in different growth stages, impacting the portioning of available energy. This can impact the accuracy of *T* and *E* estimates by the model. Other reasons may include spatial variation of microclimatic factors in the canopy profile, light distribution above and within the canopy, spatial variation of soil water content and disease and nitrogen stresses among plants, variability in aging and senescence of plant parts, variability in wind pattern and

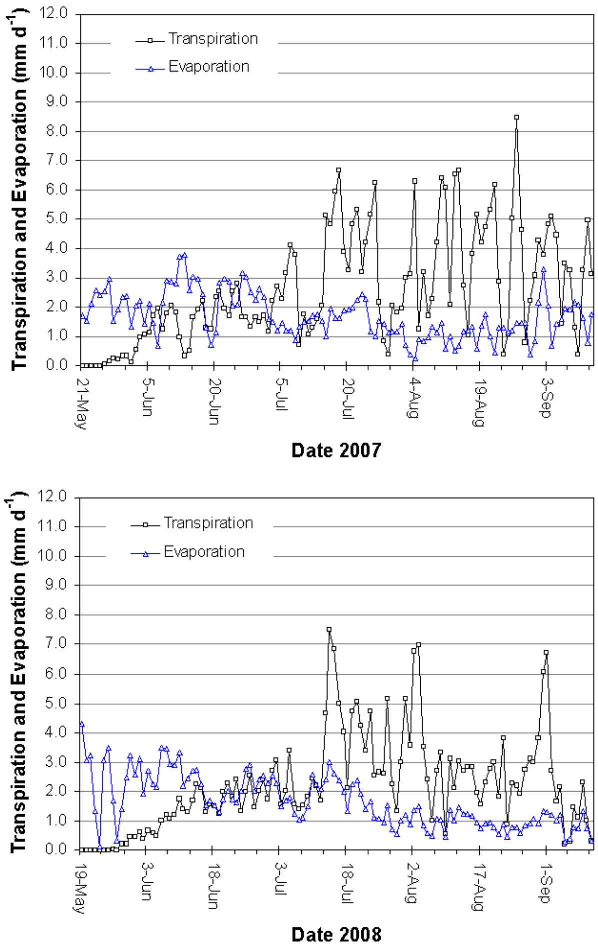

Figure 12. Estimated daily rates of transpiration and soil evaporation during the 2007 and 2008 seasons.

distribution above and within the canopy, and other factors (Irmak and Mutiibwa, 2009a). Another reason might be associated with the inability of the model to effectively estimate late-season stomatal resistance of physiologically matured and aged leaves.

Partitioning *ET* into Transpiration and Soil Evaporation

The S-W model discretely estimates *T* and *E* in a coupled approach (*T* and *E* are not independent), where *E* is the sum of soil water evaporation from bare soil surface (E_s) and from residue-covered soil surface (E_r) ($E = E_s + E_r$). The estimated *T* and *E* components during the 2007 and 2008 crop growing periods are presented in figure 12, and the portions of *T* and *E* in the estimated *ET* at different growth stages are given in table 2. In 2007, *T* was at its maxima from mid-July to late August and ranged from 2 to 8.5 mm d^{-1}. In 2008, *T* had a smaller magnitude due to more precipitation and increased numbers of days associated with lower available energy; *T* was at its maximum range from mid-July to early September and ranged from 2 to 7.5 mm d^{-1}. As shown in the results in table 2, during the initial growth stage, *ET* was predominantly in the form of *E* (*T* = 22% and *E* = 78% in 2007; *T* = 12% and *E* = 88% in 2008). As the crop developed and more leaves contributed to transpiration, the portion of *T* increased and equaled *E* during the crop development stage (*T* = 51% and *E* = 49% in 2007; *T* = 49% and *E* = 51% in 2008). At the mid-season stage, most of the ground was shaded from solar radiation, and *T* was the dominant process (*T* = 74% and *E* = 26% in 2007; *T* = 73% and *E* = 27% in 2008). Even under subsurface drip irrigation conditions where topsoil was not wetted due to irrigation events, *E* remained a significant portion of the seasonal total *ET* in both years. This was mainly due to surface soil wetting from precipitation, which was high in both years. In both years, the high *T* and low *E* rates were associated with the LAI value of approximately 3.5 to 4.0 and plant height of approximately 70 to 80 cm, which occurred around 20 to 25 July in 2007 and 2008. Improvements needed in the estimation *E* include accurate determination of soil surface resistance and consideration of direct evaporation of intercepted rainfall.

Comparison of Estimated Cumulative *ET*, *T*, and *E* against BREBS Measurements

Seasonal trends of cumulative *ET*, *T*, and *E* estimated by the S-W model in comparison with the BREBS-measured cumulative *ET* are presented in figure 13. There was a very good agreement between the cumulative *ET* from the S-W model estimates and the BREBS-measurements for the period from planting until the end of mid-season, basically physiological maturity, in both years. In 2007, after

Table 2. Portion of transpiration (*T*) and evaporation (*E*) in the S-W model-simulated evapotranspiration (*ET*) for the 2007 and 2008 growing seasons.

Growing Season	Growth Stage	BREBS Measured *ET* (mm)	S-W Model Estimated *ET* (mm)	Portion of *T* (%) in S-W Model Estimated *ET*	Portion of *E* (%) in S-W Model Estimated *ET*
2007	Initial stage	54.7	63.1	22	78
	Crop development stage	141.4	133.1	51	49
	Mid-season stage	301.8	300.2	74	26
	Late-season stage	47.4	159.2	62	38
	Seasonal total	545.3	655.6	61	39
	Seasonal average	3.9	4.7	54	46
2008	Initial stage	66.0	59.8	12	88
	Crop development stage	152.5	142.3	49	51
	Mid-season stage	270.9	250.2	73	27
	Late-season stage	34.5	89.1	61	39
	Seasonal total	523.9	541.4	58	42
	Seasonal average	3.7	3.8	50.6	49.4

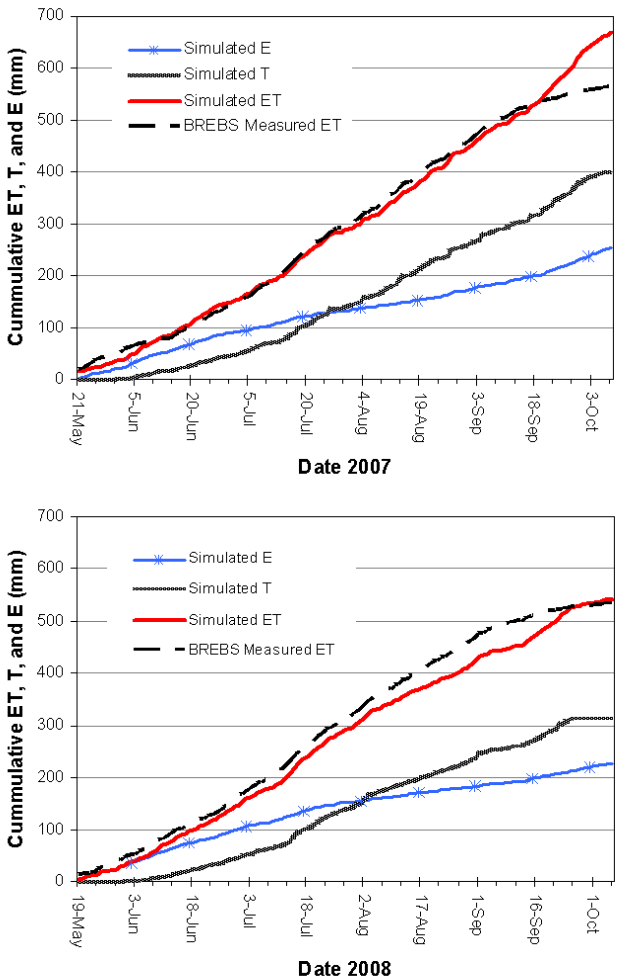

Figure 13. Cumulative *ET*, *T*, and *E* estimated by the S-W model and BREBS-measured cumulative *ET* for the 2007 and 2008 growing seasons.

physiological maturity (end of September), there was an overestimation by the S-W model, most likely due to overestimation of *T*, which led to cumulative *ET* overestimation. In 2008, *ET* was slightly underestimated by the model during the active growth period. The values for cumulative *ET* from planting to end of the mid-season growth stage were similar in 2007 (496 mm for S-W model and 498 mm for BREBS). In 2008, the model underestimated cumulative *ET* by 8.2% during the same period (452 mm for S-W model and 489 mm for BREBS). The seasonal total *ET* was larger in 2007 than in 2008 due to a longer growing season (21 May to 24 October in 2007, and 24 May to 1 October in 2008). The difference between the cumulative *ET* simulated by the S-W model and the BREBS measurements increased during the end of the late-season stage. At the end of crop growth period, cumulative *ET* was 656 mm for the S-W model and 545 mm for the BREBS measurements in 2007 and 541 mm for the S-W model and 524 mm for the BREBS measurements in 2008. The increase in difference in cumulative *ET* at the end of the crop season was mainly due to the model's overestimation of *T* during the late season growth stage. If the *T* component is ignored in the S-W model during the late season stage, then the difference in cumulative *ET* between the model and the BREBS measurements at the end of the crop season would be within 2% (overestimation) in 2007 and within -7% (under-estimation) in 2008. Overall, the S-W model was able to track BREBS-measured *ET* very well. However, re-parameterization of the *T* module of the extended S-W model can further improve its ability to estimate *ET*, especially *T*, during the late season after physiological maturity.

Conclusions

The extended Shuttleworth-Wallace (S-W) model performance was evaluated for estimating evaporative losses for a subsurface drip-irrigated soybean canopy at different plant growth stages during two growing seasons. The sum of estimated transpiration (*T*) and evaporation (*E*) was compared to the Bowen Ratio Energy Balance System (BREBS) measured actual evapotranspiration (*ET*) on a daily time-step. The model was able to successfully track the trends in measured *ET*, and its performance during the mid-season had a two-year average r^2 = 0.87, average root mean square difference (RMSD) = 0.94 mm d^{-1}, and average mean biased error (MBE) = 0.30 mm d^{-1}. Both the initial and late-season growth stages, where *E* is predominant, had poor agreement with the BREBS measurements. When cumulative measured and estimated daily *ET* values were compared, the differences in the performance of the model between the growth stages did not seem so obvious. This is because the overestimations were cancelled by the under-estimations, but not precisely because of the accuracy of the model. While the model estimates were very virtuous in terms of tracking the trends and magnitude of the BREBS-measured *ET*, further re-parameterization of the *T* module of the extended S-W model can improve its ability to estimate *ET*, especially *T*, during the late season after physiological maturity for a subsurface drip-irrigated soybean canopy. The simulations in this study had the following drawbacks, which may have affected the model performance:

- The simulations used existing empirical functions developed under different conditions to estimate the resistance terms that control energy fluxes at the canopy and soil surface.
- The simulations used typical values of several parameters and coefficients found in the literature. Some of these parameters or coefficients may be site or crop specific, and there are no methods of recalibration.
- The simulations used a constant light extinction coefficient value to partition net radiation between the canopy and soil surface. This may not fully take into account the daily and hourly variation in available energy. Net radiation is the main driving force of *ET*, and hence inaccurate partitioning may have led to discrepancies between estimated *T* and *E*, especially around sunrise and sunset. The impact of the extinction coefficient would be expected to impact the portioning of net radiation more so during the initial and late growth stages.
- The effects of rainfall interception and evaporation from the canopy and residue cover were not accounted for in the S-W model, which can impact the *E* estimates.
- The leaf aging and senescence effects on leaves in controlling transpiration during the late season were not accounted for.

- The effects of leaf senescence and accumulation of the leaves on the residue cover and soil water evaporation during the late-season growth period was not taken into consideration.

These drawbacks need to be considered in future studies to improve the accuracy of the S-W model estimates of evaporative losses for a subsurface drip-irrigated vegetation surface.

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