13

Evapotranspiration of Partially Vegetated Surfaces

L.O. Lagos[1,2], G. Merino[1], D. Martin[2], S. Verma[2] and A. Suyker[2]
[1]*Universidad de Concepción Chile*
[2]*University of Nebraska-Lincoln*
[1]*Chile*
[2]*USA*

1. Introduction

Latent heat flux equivalent to Evapotranspiration (ET) is the total amount of water lost via transpiration and evaporation from plant surfaces and the soil in an area where a crop is growing. Since 80-90% of precipitation received in semiarid and subhumid climates is commonly used in evapotranspiration, accurate estimations of ET are very important for hydrologic studies and crop water requirements. ET determination and modelling is not straightforward due to the natural heterogeneity and complexity of agricultural and natural land surfaces. In evapotranspiration modelling it is very common to represent vegetation assuming a single source of energy flux at an effective height within the canopy. However, when crops are sparse, the single source/sink of energy assumption in such models is not entirely satisfied. Improvements using multiple source models have been developed to estimate ET from crop transpiration and soil evaporation. Soil evaporation on partially vegetated surfaces over natural vegetation and orchards includes not only the soil under the canopy but also areas of bare soil between vegetation that contribute to ET. Soil evaporation can account for 25-45% of annual ET in agricultural systems. In irrigated agriculture, partially vegetated surfaces include fruit orchards (i.e. apples, oranges, vineyards, avocados, blueberries, and lemons among others), which cover a significant portion of the total area under irrigation.

In semiarid regions, direct soil evaporation from sparse barley or millet crops can account for 30% to 60% of rainfall (Wallace et al., 1999). On a seasonal basis, sparse canopy soil evaporation can account for half of total rainfall (Lund & Soegaard, 2003). Allen (1990) estimated the soil evaporation under a sparse barley crop in northern Syria and found that about 70% of the total evaporation originated from the soil. Lagos (2008) estimated that under irrigated maize conditions soil evaporation accounted for around 26-36% of annual evapotranspiration. Under rain-fed maize conditions annual evaporation accounted for 36-39% of total ET. Under irrigated soybean the percentage was 41%, and under rainfed soybean conditions annual evaporation accounted for 45-47% of annual ET. Massman (1992) estimated that the soil contribution to total ET was about 30% for a short grass steppe measurement site in northeast Colorado. In a sparse canopy at the middle of the growing season, and after a rain event, more than 50% of the daily ET corresponds to directly soil evaporation (Lund & Soegaard, 2003). Soil evaporation can be maximized under frequent rainfall or irrigation events, common conditions in agricultural systems for orchard with drip or micro sprinklers systems. If some of this unproductive loss of water could be retained in the soil and used as transpiration, yields could be increased without increased rainfall or the use of supplemental irrigation (Wallace et al., 1999). The measurement and modelling of soil evaporation on partially vegetated surfaces is crucial to estimate how much water is lost to the atmosphere via soil evaporation. Consequently, better water management can be proposed for water savings.

Partially vegetated surface accounts for a significant portion of land surface. It occurs seasonally in all agricultural areas and throughout the year in or chard and natural land covers. Predictions of ET for these conditions have not been thoroughly researched. In Chile, agricultural orchards with partially vegetated surfaces include apples, oranges, avocados, cherries, vineyards, blueberries, and berries, among others. According to the agricultural census (INE, 2007) the national orchard surface covers more than 324,000 ha, representing 30% of the total surface under irrigation.

Similar to the Shuttleworth and Wallace (1985), Choudhury and Monteith (1988) and Lagos (2008) models, the modelling of evapotranspiration for partially vegetated surfaces can be accomplished using explicit solutions of the equations that define the conservation of heat and water vapor fluxes for partially vegetated surfaces and soil. Multiple-layer models offer the possibility to represent these conditions to solve the surface energy balance and consequently, estimate evapotranspiration. Modelling is essential to predict long-term trends and to quantify expected outcomes. Since ET is such a large component of the hydrologic cycle in areas with partially vegetated surfaces, small changes in the calculation of ET can result in significant changes in simulated water budgets. Thus, good data and accurate modelling of ET is essential for predicting not only water requirements for agricultural crops but also to predict the significance of irrigation management decisions and land use changes to the entire hydrologic cycle.

Currently, several methods and models exist to predict natural environments under different conditions. More complex models have been developed to account for more variables affecting model performance. However, the applicability of these models has been limited by the difficulties and tedious algorithms needed to complete estimations. Mathematical algorithms used by multiple-layer models can be programmed in a software package to facilitate and optimize ET estimation by any user. User-friendly software facilitates the use of these improved methods; users (i.e. students) can use the computer model to study the behaviour of the system from a set of parameters and initial conditions.

Accordingly, in this chapter, a review of models that estimate ET for partially covered surfaces that occur normally in agricultural systems (i.e. orchards or vineyards) is presented, and the needs for further research are assessed.

2. ET modelling review

Evapotranspiration (ET) is the total amount of water lost via transpiration and evaporation from plant surfaces and the soil in an area where a crop 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 and ASCE, 2002) by crop coefficients (Kc) to make an 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 & Rana, 2006; Flores, 2007). In addition, it is difficult to predict the correct crop growth stage dates for large populations of crops and fields (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 have been studied by several authors (Stannard, 1993; Farahani & Bausch, 1995; Rana et al., 1997; Alves & Pereira, 2000; Kjelgaard & Stockle, 2001; Ortega-Farias et al., 2004; Shuttleworth, 2006; Katerji & 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). Results shows that the "big leaf" assumption used by the P-M model is not satisfied for sparse vegetation and crops with partial canopy cover.
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 (S-W) model (Shuttleworth-Wallace, 1985) and four layers in the Choudhury-Monteith (C-M) model (Choudhury & Monteith, 1988). Shuttleworth and Wallace (1985) combined a one-dimensional model of crop transpiration and a one-dimensional model of soil evaporation. Surface resistances regulate the heat and mass transfer in plant and soil surfaces, and aerodynamic resistances regulate fluxes between the surface and the atmospheric boundary layer. Several studies have evaluated the performance of the S-W model to estimate evapotranspiration (Farahani & Baush,1995; Stannard, 1993; Lafleur & Rouse, 1990; Farahani & Ahuja, 1996; Iritz et al. 2001; Tourula & Heikinheimo, 1998; Anadranistakis et al., 2000; Ortega-Farias et al., 2007). Field tests of the model have shown promising results for a wide range of both agricultural and non-agricultural vegetation.
Farahani and Baush (1995) evaluated the performance of the P-M model and the S-W model for irrigated maize. Their main conclusion was that the Penman-Monteith model performed poorly when the leaf area index was less than 2 because soil evaporation was neglected in calculating surface resistance. Results of the S-W model were encouraging as it performed satisfactorily for the entire range of canopy cover. Stannard (1993) compared the P-M, S-W and Priestley-Taylor ET models for sparsely vegetated, semiarid rangeland. The P-M model was not sufficiently accurate (hourly r^2 =0.56, daily r^2=0.60); however, the S-W model performs significantly better for hourly (r^2=0.78) and daily data (r^2=0.85). Lafleur and Rouse (1990) compared the S-W model with evapotranspiration calculated from the Bowen Ratio Energy Balance technique over a range of LAI from non-vegetated to fully vegetated conditions. The results showed that the S-W model was in excellent agreement with the measured evapotranspiration for hourly and day-time totals for all values of LAI. Using the potential of the S-W model to partition transpiration and evaporation, Farahani and Ahuja (1996) extended the model to include the effects of crop residues on soil evaporation by the inclusion of a partially covered soil area and partitioning evaporation between the bare and residue-covered areas. Iritz et al. (2001) applied a modified version of the S-W model to estimate evapotranspiration for a forest. The main modification consisted of a two-layer soil module, which enabled soil surface resistance to be calculated as a function of the wetness of the top soil. They found that the general seasonal dynamics of evaporation were fairly well simulated with the model. Tourula and Heikinheimo (1998) evaluated a modified version of the S-W model in a barley field. A modification of soil surface resistance and aerodynamic resistance, over two growing seasons, produced daily and hourly ET estimates in good agreement with the measured evapotranspiration. The performance of the S-W model was evaluated against two eddy covariance systems by Ortega-Farias et al. (2007) over a Cabernet

Sauvignon vineyard. Model performance was good under arid atmospheric conditions with a correlation coefficient (r^2) of 0.77 and a root mean square error (RMSE) of 29 Wm^{-2}.

Although good results have been found using the Shuttleworth-Wallace approach, the model still needs an estimation or measurement of soil heat flux (G) to estimate ET. Commonly, G is calculated as a fixed percentage of net radiation (Rn). Shuttleworth and Wallace (1985) estimated G as 20% of the net radiation reaching the soil surface. In the FAO56 method, Allen et al. (1998) estimated daily reference ET (ETr and ETo), assuming that the soil heat flux beneath a fully vegetated grass or alfalfa reference surface is small in comparison with Rn (i.e. G=0). For hourly estimations, soil heat flux was estimated as one tenth of the Rn during the daytime and as half of the Rn for the night time when grass was used as the reference surface. Similarly, G was assumed to be 0.04xRn for the daytime and 0.2xRn during the night time for an alfalfa reference surface. A more complete surface energy balance was presented by Choudhury and Monteith (1988). The proposed method developed a four-layer model for the heat budget of homogeneous land surfaces. The model is an explicit solution of the equations which define the conservation of heat and water vapor in a system consisting of uniform vegetation and soil. An important feature was the interaction of evaporation from the soil and transpiration from the canopy expressed by changes in the vapor pressure deficit of the air in the canopy. A second feature was the ability of the model to partition the available energy into sensible heat, latent heat, and soil heat flux for the canopy/soil system.

Similar to Shuttleworth-Wallace (1985), the Choudhury-Monteith model included a soil surface resistance to regulate the heat and mass transfer at the soil surface. However, residue effects on the surface energy balance are not included in the model. Crop residue generally increases infiltration and reduces soil evaporation. Surface residue affects many of the variables that determine the evaporation rate. These variables include Rn, G, aerodynamic resistance and surface resistances to transport of heat and water vapor fluxes (Steiner, 1994; Horton et al., 1996; Steiner et al., 2000).

Caprio et al. (1985) compared evaporation from three mini-lysimeters installed in bare soil and in a 14 and 28 cm tall standing wheat stubble. After nine days of measurements, evaporation from the lysimeter with stubble was 60% of the evaporation measured from bare soil. Enz et al. (1988) evaluated daily evaporation for bare soil and stubble-covered soil surfaces. Evaporation was always greater from the bare soil surface until it was dry, then evaporation was greater from the stubble covered-surface because more water was available. Evaporation from a bare soil surface has been described in three stages. An initial, energy-limited stage occurs when enough soil water is available to satisfy the potential evaporation rates. A second, falling rate stage is limited by water flow to the soil surface, while the third stage has a very low, nearly constant evaporative rate from very dry soil (Jalota & Prihar, 1998). Steiner (1989) evaluated the effect of residue (from cotton, sorghum and wheat) on the initial, energy-limited rate of evaporation. The evaporation rate relative to bare soil evaporation was described by a logarithmic relationship. Increasing the amount of residue on the soil surface reduced the relative evaporation rate during the initial stage. Bristow et al. (1986) developed a model to predict soil heat and water budgets in a soil-residue-atmosphere system. Results from application of the model indicate that surface residues decreased evaporation by roughly 36% compared with simulations from bare soil.

With the recognition of the potential of multiple-layer models to estimate ET, a modified surface energy balance model (SEB) was developed by Lagos (2008) and 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. Improvements to aerodynamic resistance, surface canopy resistance and soil resistances for the transport of heat and water vapor were also suggested.

2.1 The SEB model

The modified surface energy balance (SEB) model has four layers (Figure 1), 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 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 for at least a 24h 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.

The SEB model distributes net radiation (Rn) into sensible heat (H), latent heat (λE), and soil heat fluxes (G) through the soil-canopy system (Figure 2). Total latent heat (λE) is the sum of latent heat from the canopy (λEc), latent heat from the soil (λEs) and latent heat from the residue-covered soil (λEr). Similarly, sensible heat is calculated as the sum of sensible heat from the canopy (Hc), sensible heat from the soil (Hs) and sensible heat from the residue covered soil (Hr).

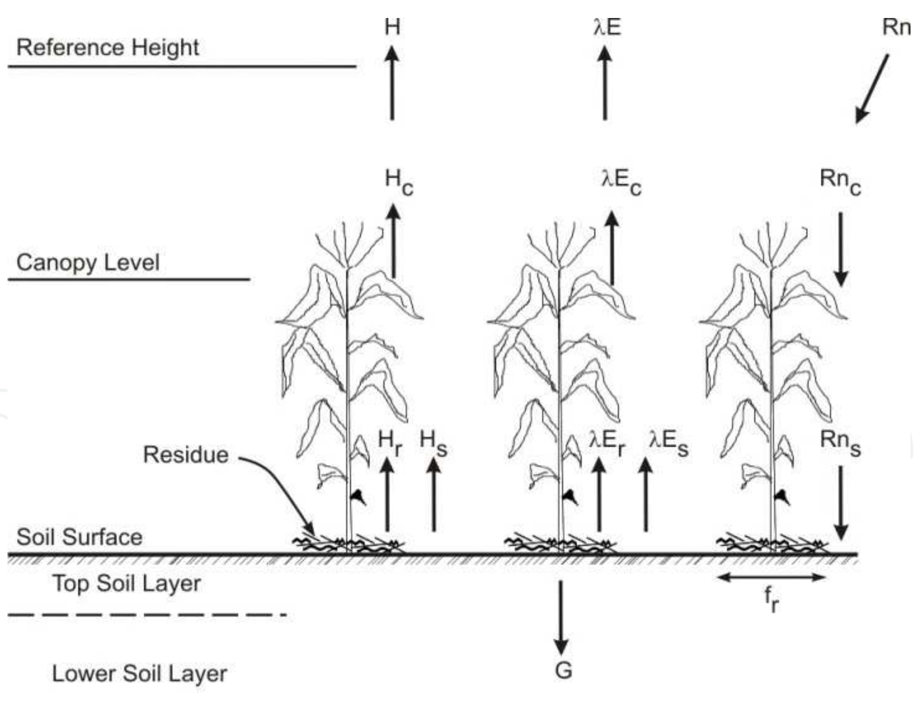


Fig. 1. Fluxes of the surface energy balance model (SEB).

The total net radiation is divided into that absorbed by the canopy (Rnc) and the soil (Rns) and is given by Rn = Rnc + Rns. The net radiation absorbed by the canopy is divided into latent heat and sensible heat fluxes as Rnc = λEc +Hc. Similarly, for the soil Rns = Gos + Hs,

where Gos is a conduction term downwards from the soil surface and is expressed as Gos = λEs + Gs, where Gs is the soil heat flux for bare soil. Similarly, for the residue-covered soil Rns = Gor + Hr where Gor is the conduction downwards from the soil covered by residue. The conduction is given by Gor = λEr + Gr where Gr is the soil heat flux for residue-covered soil.
Total latent heat flux from the canopy/residue/soil system is the sum of the latent heat from the canopy (transpiration), latent heat from the soil and latent heat from the residue-covered soil (evaporation), calculated as:

$$\lambda E = \lambda E_c + (1 - fr) \cdot \lambda E_s + fr \cdot \lambda E_r \tag{1}$$

where fr is the fraction of the soil affected by residue. Similarly, the total sensible heat is given by:

$$H = H_c + (1 - fr) \cdot H_s + fr \cdot H_r \tag{2}$$

The differences in vapor pressure and temperature between levels can be expressed with an Ohm's law analogy using appropriate resistance and flux terms (Figure 2). The sensible and latent heat fluxes from the canopy, from bare soil and soil covered by residue are expressed by (Shuttleworth & Wallace, 1985):

$$H_c = \frac{\rho \cdot c_p \cdot (T_1 - T_b)}{r_1} \quad \text{and} \quad \lambda E_c = \frac{\rho \cdot C_p \cdot (e_1^* - e_b)}{\gamma \cdot (r_1 + r_c)} \tag{3}$$

$$H_s = \frac{\rho \cdot C_p \cdot (T_2 - T_b)}{r_2} \quad \text{and} \quad \lambda E_s = \frac{\rho \cdot C_p \cdot (e_L^* - e_b)}{\gamma \cdot (r_2 + r_s)} \tag{4}$$

$$H_r = \frac{\rho \cdot C_p \cdot (T_{2r} - T_b)}{r_2 + r_{rh}} \quad \text{and} \quad \lambda E_r = \frac{\rho \cdot C_p \cdot (e_{Lr}^* - e_b)}{\gamma \cdot (r_2 + r_s + r_r)} \tag{5}$$

where, ρ is the density of moist air, C_p is the specific heat of air, γ is the psychrometric constant, T_1 is the mean canopy temperature, T_2 is the temperature at the soil surface, T_b is the air temperature within the canopy, T_{2r} is the temperature of the soil covered by residue, r_1 is an aerodynamic resistance between the canopy and the air, r_c is the surface canopy resistance, r_2 is the aerodynamic resistance between the soil and the canopy, r_s is the resistance to the diffusion of water vapor at the top soil layer, r_{rh} is the residue resistance to transfer of heat, r_r is the residue resistance to the transfer of vapor acting in series with the soil resistance r_s, e_b is the vapor pressure of the atmosphere at the canopy level, e_1^* is the saturation vapor pressure in the canopy, e_L^* is the saturation vapor pressure at the top of the wet layer, and e_{Lr}^* is the saturation vapor pressure at the top of the wet layer for the soil covered by residue.
Conduction of heat for the bare-soil and residue-covered surfaces are given by:

$$G_{os} = \frac{\rho \cdot C_p \cdot (T_2 - T_L)}{r_u} \quad \text{and} \quad G_s = \frac{\rho \cdot C_p \cdot (T_L - T_m)}{r_L} \tag{6}$$

$$G_{or} = \frac{\rho \cdot C_p \cdot (T_{2r} - T_{Lr})}{r_u} \quad \text{and} \quad G_r = \frac{\rho \cdot C_p \cdot (T_{Lr} - T_m)}{r_L} \tag{7}$$

where; r_u and r_L are resistance to the transport of heat for the upper and lower soil layers, respectively, T_L and T_{Lr} are the temperatures at the interface between the upper and lower layers for the bare soil and the residue-covered soil, and T_m is the temperature at the bottom of the lower layer which was assumed to be constant on a daily basis.

Choudhury and Monteith (1988) expressed differences in saturation vapor pressure between points in the system as linear functions of the corresponding temperature differences. They found that a single value of the slope of the saturation vapor pressure, Δ, when evaluated at the air temperature, T_a, gave acceptable results for the components of the heat balance. The vapor pressure differences were given by:

$$e_1^* - e_b^* = \Delta \cdot (T_1 - T_b) e_L^* - e_b^* = \Delta \cdot (T_L - T_b) e_b^* - e_a^* = \Delta \cdot (T_b - T_a) \quad \text{and} \quad e_{Lr}^* - e_b^* = \Delta \cdot (T_{Lr} - T_b) \tag{8}$$

The above equations were combined and solved to estimate fluxes. Details are provided by Lagos (2008). The solution gives the latent and sensible heat fluxes from the canopy as:

$$\lambda E_c = \frac{\Delta \cdot r_1 \cdot Rn_c + \rho \cdot C_p \cdot (e_b^* - e_b)}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} \quad \text{and} \quad H_c = \frac{\gamma \cdot (r_1 - r_c) \cdot Rn_c - \rho \cdot C_p \cdot (e_b^* - e_b)}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} \tag{9}$$

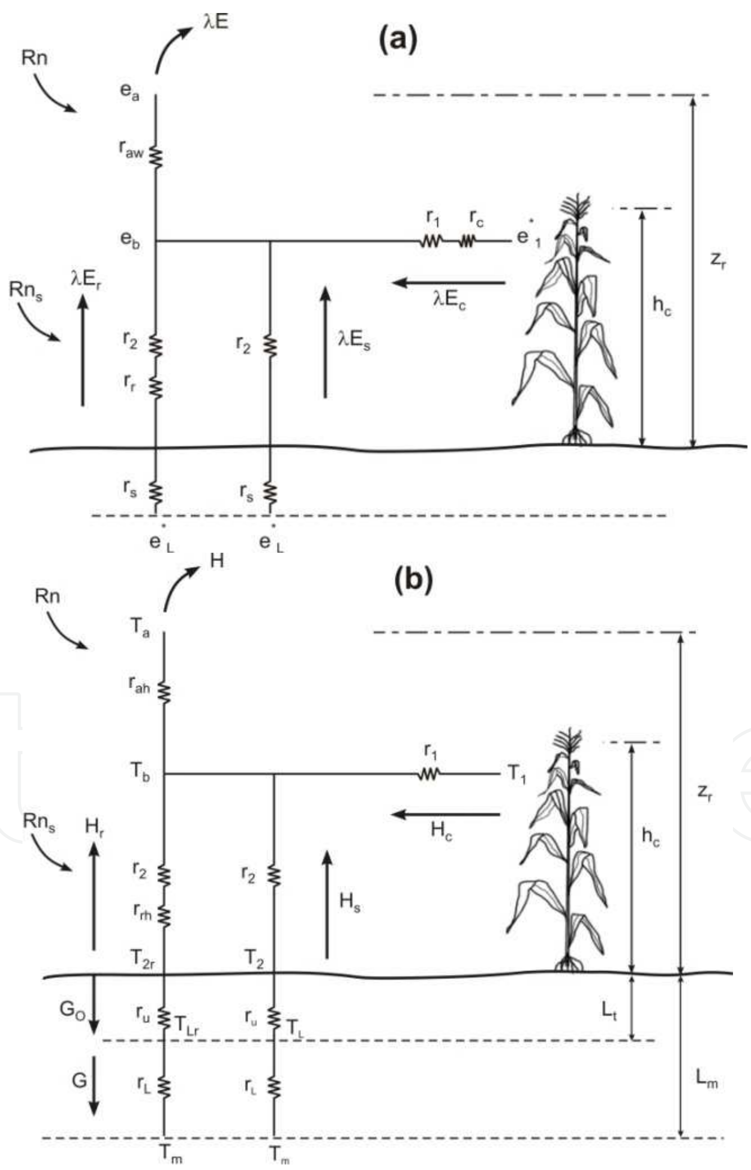


Fig. 2. Schematic resistance network of the Surface Energy Balance (SEB) model a) Latent heat flux and b) Sensible heat flux.

Similarly, latent and sensible heat fluxes from bare soil surfaces are estimated by:

$$\lambda E_s = \frac{Rn_s \cdot \Delta \cdot r_2 \cdot r_L + \rho \cdot C_p \cdot [(e_b^* - e_b) \cdot (r_u + r_L + r_2) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_2)]}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} \tag{10}$$

$$H_s = \frac{Rn_s \cdot r_L \cdot \Delta - \lambda E_s \cdot [r_L \cdot \Delta + \gamma \cdot (r_2 + r_s)] + \rho \cdot C_p \cdot (e_b^* - e_b) - \rho \cdot C_p \cdot \Delta \cdot (T_b - T_m)}{r_L \cdot \Delta} \tag{11}$$

The latent and sensible heat fluxes from the residue-covered soil are simulated with:

$$\lambda E_r = \frac{Rn_s \cdot \Delta \cdot (r_2 + r_{rh}) \cdot r_L + \rho \cdot C_p \cdot [(e_b^* - e_b) \cdot (r_u + r_L + r_2 + r_{rh}) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_2 + r_r)]}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})} \tag{12}$$

$$H_r = \frac{Rn_s \cdot r_L \cdot \Delta - \lambda E_r \cdot \left[r_L \cdot \Delta + \gamma \cdot (r_2 + r_s + r_r)\right] + \rho \cdot C_p \cdot (e_b^* - e_b) - \rho \cdot C_p \cdot \Delta \cdot (T_b - T_m)}{r_L \cdot \Delta} \tag{13}$$

Values for T_b and e_b are necessary to estimate latent heat and sensible heat fluxes. The values of the parameters can be expressed as:

$$e_b = \left(T_b \cdot (\Delta \cdot A_2 - A_3) + \frac{A_1}{\rho \cdot C_p} - \Delta \cdot A_2 \cdot T_a + A_2 \cdot e_a^* + T_m \cdot A_3 + \frac{e_a}{\gamma \cdot r_{aw}}\right) \cdot \left(\frac{\gamma \cdot r_{aw}}{1 + A_2 \cdot \gamma \cdot r_{aw}}\right) \tag{14}$$

$$T_b = \left[\frac{B_1}{\rho \cdot C_p} + T_a \cdot \left(\frac{1}{r_{ah}} - \Delta \cdot B_2\right) + (e_a^* - e_b) \cdot B_2 + T_m \cdot B_3\right] \cdot \left(\frac{r_{ah}}{1 - \Delta \cdot B_2 \cdot r_{ah} + B_3 \cdot r_{ah}}\right) \tag{15}$$

where, r_{ah} is the aerodynamic resistance for heat transport, r_{aw} is the aerodynamic resistance for water vapor transport, e_a is the vapor pressure at the reference height, and e_a^* is the saturated vapor pressure at the reference height. Six coefficients (A_1, A_2, A_3 and B_1, B_2 and B_3) are involved in these expressions. These coefficients depend on environmental conditions and other parameters. The expressions to compute the coefficients are given by (Lagos, 2008):

$$A_1 = \frac{\Delta \cdot r_1 \cdot Rn_c}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} + (1 - f_r) \cdot \frac{Rn_s \cdot \Delta \cdot r_2 \cdot r_L}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} + f_r \cdot \frac{Rn_s \cdot \Delta \cdot (r_2 + r_{rh}) \cdot r_L}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})} \tag{16}$$

$$A_2 = \frac{1}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} + (1 - f_r) \cdot \frac{(r_u + r_L + r_2)}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} + f_r \cdot \frac{(r_u + r_L + r_2 + r_{rh})}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})} \tag{17}$$

$$A_3 = \left[(1 - f_r) \cdot \frac{\Delta \cdot (r_u + r_2)}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} + f_r \frac{\Delta \cdot (r_u + r_2 + r_{rh})}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})}\right] \tag{18}$$

$$B_1 = \left[Rn_c \cdot \frac{\gamma \cdot (r_1 + r_c)}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} + Rn_s \cdot \begin{pmatrix} (1 - f_r) \cdot (1 - \Delta \cdot r_2 \cdot r_L \cdot X_s) + \\ f_r \cdot (1 - \Delta \cdot (r_2 + r_{rh}) \cdot r_L \cdot X_r) \end{pmatrix} \right] \tag{19}$$

$$B_2 = \frac{-1}{\Delta \cdot r_1 + \gamma \cdot (r_1 + r_c)} + (1 - f_r) \cdot \left(\frac{1}{r_L \Delta} - (r_u + r_L + r_2) \cdot X_s \right) + f_r \cdot \left(\frac{1}{r_L \Delta} - (r_u + r_L + r_2 + r_{rh}) \cdot X_r \right) \tag{20}$$

$$B_3 = \left[(1 - f_r) \cdot \left(\frac{1}{r_L} - \Delta \cdot (r_u + r_2) \cdot X_s \right) + f_r \cdot \left(\frac{1}{r_L} - \Delta \cdot (r_u + r_2 + r_{rh}) \cdot X_r \right) \right] \tag{21}$$

$$X_s = \left(\frac{1}{\gamma \cdot (r_2 + r_s) \cdot (r_u + r_L + r_2) + \Delta \cdot r_L \cdot (r_u + r_2)} \right) \left(\frac{(r_L \cdot \Delta + \gamma \cdot (r_2 + r_s))}{r_L \cdot \Delta} \right) \text{ and}$$
$$X_r = \left(\frac{1}{\gamma \cdot (r_2 + r_s + r_r) \cdot (r_u + r_L + r_2 + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_2 + r_{rh})} \right) \left(\frac{(r_L \cdot \Delta + \gamma \cdot (r_2 + r_s + r_r))}{r_L \cdot \Delta} \right) \tag{22}$$

These relationships define the surface energy balance model which is applicable to conditions ranging from closed canopies to surfaces with bare soil or those partially covered with residue. Without residue, the model is similar to that by Choudhury and Monteith (1988).

2.1.1 Determination of the SEB model parameters

In the following sections, the procedures to compute parameter values for the model are detailed. The parameters are as important as the formulation of the energy balance equations.

2.1.1.1 Aerodynamic resistances

Thom (1972) stated that heat and mass transfer encounter greater aerodynamic resistance than the transfer of momentum. Accordingly, aerodynamic resistances to heat (r_{ah}) and water vapor transfer (r_{aw}) can be estimated as:

$$r_{ah} = r_{am} + r_{bh} \quad \text{and} \quad r_{aw} = r_{am} + r_{bw} \tag{23}$$

where r_{am} is the aerodynamic resistance to momentum transfer, and r_{bh} and r_{bw} are excess resistance terms for heat and water vapor transfer.

Shuttleworth and Gurney (1990) built on the work of Choudhury and Monteith (1988) to estimate r_{am} by integrating the eddy diffusion coefficient over the sink of momentum in the canopy to a reference height z_r above the canopy, giving the following relationship for r_{am}:

$$r_{am} = \frac{1}{k \cdot u^*} \cdot \text{Ln}\left(\frac{z_r - d}{h - d} \right) + \frac{h}{\alpha \cdot K_h} \cdot \left[\exp\left(\alpha \cdot \left(1 - \frac{z_o + d}{h} \right) \right) - 1 \right] \tag{24}$$

where k is the von Karman constant, u* is the friction velocity, z_o is the surface roughness, d is the zero-plane displacement height, K_h is the value of eddy diffusion coefficient at the top of the canopy, h is the height of vegetation, and α is the attenuation coefficient. A value of α = 2.5, which is typical for agricultural crops, was recommended by Shuttleworth and Wallace (1985) and Shuttleworth and Gurney (1990).

Verma (1989) expressed the excess resistance for heat transfer as:

$$r_{bh} = \frac{k \cdot B^{-1}}{k \cdot u^*} \tag{25}$$

where B^{-1} represents a dimensionless bulk parameter. Thom (1972) suggests that the product kB^{-1} equal approximately 2 for most arable crops.
Excess resistance was derived primarily from heat transfer observations (Weseley & Hicks 1977). Aerodynamic resistance to water vapor was modified by the ratio of thermal and water vapor diffusivity:

$$r_{bw} = \frac{k \cdot B^{-1}}{k \cdot u^*}\left(\frac{k_1}{D_v}\right)^{2/3} \tag{26}$$

where, k_1 is the thermal diffusivity and D_v is the molecular diffusivity of water vapor in air.
Similarly, Shuttleworth and Gurney (1990) expressed the aerodynamic resistance (r_2) by integrating the eddy diffusion coefficient between the soil surface and the sink of momentum in the canopy to yield:

$$r_2 = \frac{h \cdot \exp(\alpha)}{\alpha \cdot K_h} \cdot \left[\exp\left(\frac{-\alpha \cdot z_o'}{h}\right) - \exp\left(\frac{-\alpha \cdot (d + z_o)}{h}\right)\right] \tag{27}$$

where z_o' is the roughness length of the soil surface. Values of surface roughness (z_o) and displacement height (d) are functions of leaf area index (LAI) and can be estimated using the expressions given by Shaw and Pereira (1982).
The diffusion coefficients between the soil surface and the canopy, and therefore the resistance for momentum, heat, and vapor transport are assumed equal although it is recognized that this is a weakness in the use of the K theory to describe through-canopy transfer (Shuttleworth & Gurney, 1990). Stability is not considered.

2.1.1.2 Canopy resistances

The mean boundary layer resistance of the canopy r_1, for latent and sensible heat flux, is influenced by the surface area of vegetation (Shuttleworth & Wallace, 1985):

$$r_1 = \frac{r_b}{2 \cdot LAI} \tag{28}$$

where r_b is the resistance of the leaf boundary layer, which is proportional to the temperature difference between the leaf and surrounding air divided by the associated flux (Choudhury & Monteith, 1988). Shuttleworth and Wallace (1985) noted that resistance r_b exhibits some dependence on in-canopy wind speed, with typical values of 25 s m^{-1}. Shuttleworth and Gurney (1990) represented r_b as:

$$r_b = \frac{100}{\alpha} \cdot \left(\frac{w}{u_h}\right)^{1/2} \cdot \left(1 - \exp\left(\frac{-\alpha}{2}\right)\right)^{-1} \tag{29}$$

where w is the representative leaf width and u_h is the wind speed at the top of the canopy. This resistance is only significant when acting in combination with a much larger canopy surface resistance, and Shuttleworth and Gurney (1990) suggest that r_1 could be neglected

for foliage completely covering the ground. Using r_b = 25 s m^{-1} with an LAI = 4, the corresponding canopy boundary layer resistance is r_1 = 3 s m^{-1}.
Canopy surface resistance, r_c, can be calculated by dividing the minimum surface resistance for a single leaf (r_l) by the effective canopy leaf area index (LAI). Five environmental factors have been found to affect stomata resistance: solar radiation, air temperature, humidity, CO_2 concentration and soil water potential (Yu et al., 2004). Several models have been developed to estimate stomata conductance and canopy resistance. Stannard (1993) estimated r_c as a function of vapor pressure deficit, leaf area index, and solar radiation as:

$$r_c = \left[C_1 \cdot \frac{LAI}{LAI_{max}} \cdot \frac{C_2}{C_2 + VPD_a} \cdot \frac{Rad \cdot (Rad_{max} + C_3)}{Rad_{max} \cdot (Rad + C_3)}\right]^{-1} \tag{30}$$

where LAI_{max} is the maximum value of leaf area index, VPD_a is vapor pressure deficit, Rad is solar radiation, Rad_{max} is the maximum value of solar radiation (estimated at 1000 W m^{-2}) and C_1, C_2 and C_3 are regression coefficients. Canopy resistance does not account for soil water stress effects.

2.1.1.3 Soil resistances

Farahani and Bausch (1995), Anadranistakis et al. (2000) and Lindburg (2002) found that soil resistance (r_s) can be related to volumetric soil water content in the top soil layer. Farahani and Ahuja (1996) found that the ratio of soil resistance when the surface layer is wet relative to its upper limit depends on the degree of saturation (θ/θ_s) and can be described by an exponential function as:

$$r_s = r_{so} \cdot \exp\left(-\beta \cdot \frac{\theta}{\theta_s}\right) \qquad \text{and} \qquad r_{so} = \frac{L_t \cdot \tau_s}{D_v \cdot \emptyset} \tag{31}$$

where L_t is the thickness of the surface soil layer, τ_s is a soil tortuosity factor, D_v is the water vapor diffusion coefficient and $\emptyset$ is soil porosity, θ is the average volumetric water content in the surface layer, θ_s is the saturation water content, and β is a fitting parameter. Measurements of θ from the top 0.05 m soil layer were more effective in modeling r_s than θ for thinner layers.
Choudhury and Monteith (1988) expressed the soil resistance for heat flux (r_L) in the soil layer extending from depth L_t to L_m as:

$$r_L = \frac{\rho \cdot C_p \cdot (L_m - L_t)}{K} \tag{32}$$

where K is the thermal conductivity of the soil. Similarly, the corresponding resistance for the upper layer (r_u) of depth L_t and conductivity K' as:

$$r_u = \frac{\rho \cdot C_p \cdot L_t}{K'} \tag{33}$$

2.1.1.4 Residue resistances

Surface residue is an integral part of many cropping systems. Bristow and Horton (1996) showed that partial surface mulch cover can have dramatic effects on the soil physical environment. The vapor conductance through residue has been described as a linear function of wind speed. Farahani and Ahuja (1996) used results from Tanner and Shen (1990) to develop the resistance of surface residue (r_r) as:

$$r_r = \frac{L_r \cdot \tau_r}{D_v \cdot \emptyset_r}(1 + 0.7 \cdot u_2)^{-1} \quad (34)$$

where L_r is residue thickness, τ_r is residue tortuosity, D_v is vapor diffusivity in still air, $\emptyset_r$ is residue porosity and u_2 is wind speed measured two meters above the surface. Due to the porous nature of field crop residue layers, the ratio $\tau_r/\emptyset_r$ is about one (Farahani & Ahuja, 1996).

Similar to the soil resistance, Bristow and Horton (1996) and Horton et al. (1996) expressed the resistance of residue for heat transfer, r_{rh}, as:

$$r_{rh} = \frac{\rho \cdot C_p \cdot L_r}{K_r} \quad (35)$$

where K_r is the residue thermal conductivity.

The fraction of the soil covered by residue (f_r) can be estimated using the amount and type of residue (Steiner et al., 2000). The soil covered by residue and the residue thickness are estimated using the expressions developed by Gregory (1982).

2.1.2 SEB model inputs

Inputs required to solve multiple layer models (i.e. Shuttleworth and Wallace (1985), Choudhury and Monteith (1988) and Lagos (2008) models) are net radiation, solar radiation, air temperature, relative humidity, wind speed, LAI, crop height, soil texture, soil temperature, soil water content, residue type, and residue amount. In particular, net radiation, leaf area index, soil temperatures and residue amount are variables rarely measured in the field, other than at research sites. Net radiation and soil temperature models can be incorporated into surface energy balance models to predict evapotranspiration from environmental variables typically measured by automatic weather stations.

Similar to the Shuttleworth and Wallace (1985) and Choudhury and Monteith (1988) models, measurements of net radiation and estimations of net radiation absorbed by the canopy are necessary for the SEB model. Beer's law is used to estimate the penetration of radiation through the canopy and estimates the net radiation reaching the surface (Rn_s) as:

$$Rn_s = Rn \cdot \exp(-C_{ext} \cdot LAI) \quad (36)$$

where Cext is the extinction coefficient of the crop for net radiation. Consequently, net radiation absorbed by the canopy (Rnc) can be estimated as $Rnc = Rn - Rn_s$.

2.1.3 SEB model evaluation

An irrigated maize field site located at the University of Nebraska Agricultural Research and Development Center near Mead, NE (41°09′53.5″N, 96°28′12.3″W, elevation 362 m) was used for model evaluation. This site is a 49 ha production field that provides sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using eddy covariance systems. The area has a humid continental climate and the soil corresponds to a deep silty clay loam (Suyker & Verma, 2009). The field has not been tilled since 2001. Detailed information about planting densities and crop management is provided by Verma et al. (2005) and Suyker and Verma (2009).

Soil water content was measured continuously at four depths (0.10, 0.25, 0.5 and 1.0 m) with Theta probes (Delta-T Device, Cambridge, UK). Destructive green leaf area index and biomass measurements were taken bi-monthly during the growing season. The 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). Fluxes were corrected for sensor frequency response and variations in air density. More details of measurements and calculations are given in Verma et al. (2005). Air temperature and humidity were measured at 3 and 6 meters (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 (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). More details are given in Verma et al. (2005) and Suyker and Verma (2009).

Evapotranspiration predictions from the SEB model were compared with eddy covariance flux measurements during 2003 for an irrigated maize field. To evaluate the energy balance closure of eddy covariance measurements, net radiation was compared against the sum of latent heat, sensible heat, soil heat flux and storage terms. Storage terms include soil heat storage, canopy heat storage, and energy used in photosynthesis. Storage terms were calculated by Suyker and Verma (2009) following Meyers and Hollinger (2004). During these days, the regression slope for energy balance closure was 0.89 with a correlation coefficient of $r^2 = 0.98$.

For model evaluation, 15 days under different LAI conditions were selected to initially test the model, however further work is needed to test the model for entire growing seasons and during longer periods. Hourly data for three 5-day periods with varying LAI conditions (LAI = 0, 1.5 and 5.4) were used to compare measured ET to model predictions. Input data of the model included hourly values for: net radiation, air temperature, relative humidity, soil temperature at 50 cm, wind speed, solar radiation and soil water content. During the first 5-day period, which was prior to germination, the maximum net radiation ranged from 240 to 720 W m^{-2}, air temperature ranged from 10 to 30°C, soil temperature was fairly constant at 16°C and wind speed ranged from 1 to 9 m s^{-1} but was generally less than 6 m s^{-1} (Figure 3). Soil water content in the evaporation zone averaged 0.34 m^3 $m^{-3}$and the residue density was 12.5 ton/ha on June 6, 2003. Precipitation occurred on the second and fifth days, totaling 17 mm.

Evapotranspiration estimated with the SEB model and measured using the eddy covariance system is given in Figure 4. ET fluxes were the highest at midday on June 6, reaching approximately 350 W m^{-2}. The lowest ET rates occurred on the second day. Estimated ET tracked measured latent heat fluxes reasonably well. Estimates were better for days without precipitation than for days when rainfall occurred. The effect of crop residue on evaporation from the soil is shown in Figure 4 for this period. Residue reduced cumulative evaporation by approximately 17% during this five-day period. Evaporation estimated with the SEB model on June 6 and 9 was approximately 3.5 mm/day, totaling approximately half of the total evaporation for the five days.

During the second five-day period, when plants partially shaded the soil surface (LAI = 1.5), the maximum net radiation ranged from 350 to 720 W m^{-2} and air temperature ranged from 10 to 33°C (Figure 5). The soil temperature was nearly constant at 20°C. Wind speed ranged from 0.3 to 8 m s^{-1} but was generally less than 6 m s^{-1}. The soil water content was about 0.31

$m^3\ m^{-3}$ and the residue density was 12.2 ton/ha on June 24, 2003. Precipitation totaling 3mm occurred on the fifth day. The predicted rate of ET estimated with the SEB model was close to the observed data (Figure 6). Estimates were smaller than measured values for June 24, which was the hottest and windiest day of the period. The ability of the model to partition ET into evaporation and transpiration for partial canopy conditions is also illustrated in Figure 6. Evaporation from the soil represented the majority of the water used during the night, and early or late in the day. During the middle of the day transpiration represented approximately half of the hourly ET flux.

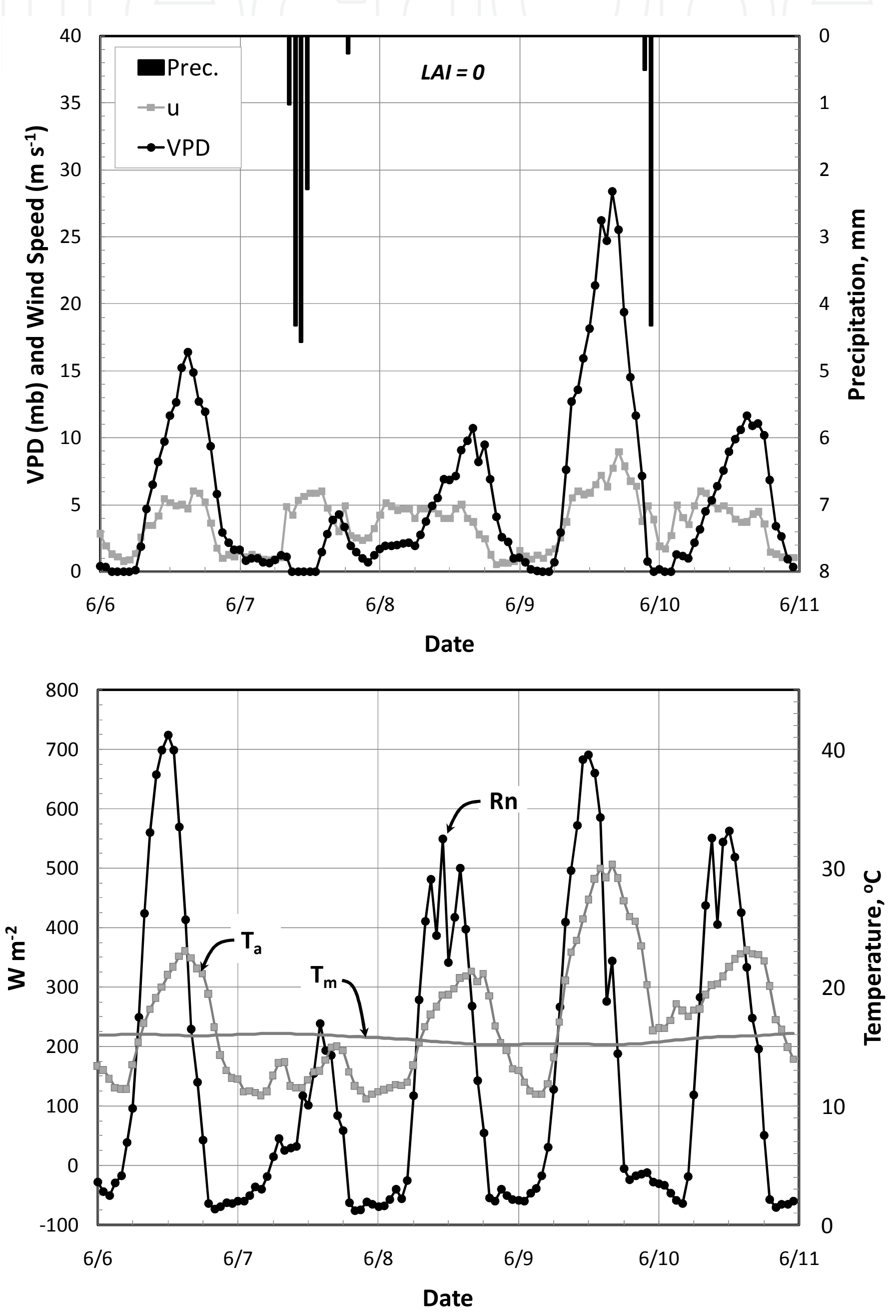


Fig. 3. Environmental conditions during a five-day period without canopy cover for net radiation (Rn), air temperature (T_a), soil temperature (T_m), precipitation (Prec.), vapor pressure deficit (VPD), and wind speed (u).

The last period represents a fully developed maize canopy that completely shaded the soil surface. The crop height was 2.3 m and the LAI was 5.4. Environmental conditions for the period are given in Figure 7. The maximum net radiation ranged from 700 to 740 W m^{-2} and air temperature ranged from 15 to 36 ºC during the period. Soil temperature was fairly constant during the five days at 21.5°C and wind speed ranged from 0.3 to 4 m s^{-1}. The soil water content was about 0.25 m^3 m^{-3} and the residue density was 11.8 ton/ha on July 16, 2003. Precipitation totaling 29 mm occurred on the third day. Observed and predicted ET fluxes agreed for most days with some differences early in the morning during the first day and during the middle of several days (Figure 8). Transpiration simulated with the SEB model was nearly equal to the simulated ET for the period as evaporation rates from the soil was very small.

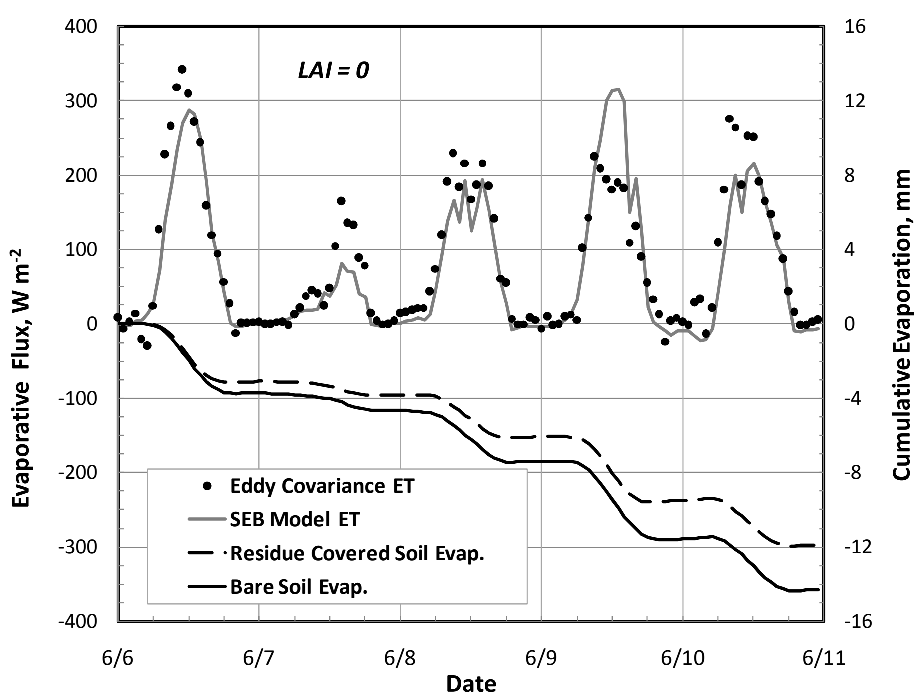


Fig. 4. Evapotranspiration estimated by the Surface Energy Balance (SEB) model and measured by an eddy covariance system and simulated cumulative evaporation from bare and residue-covered soil for a period without plant canopy cover.

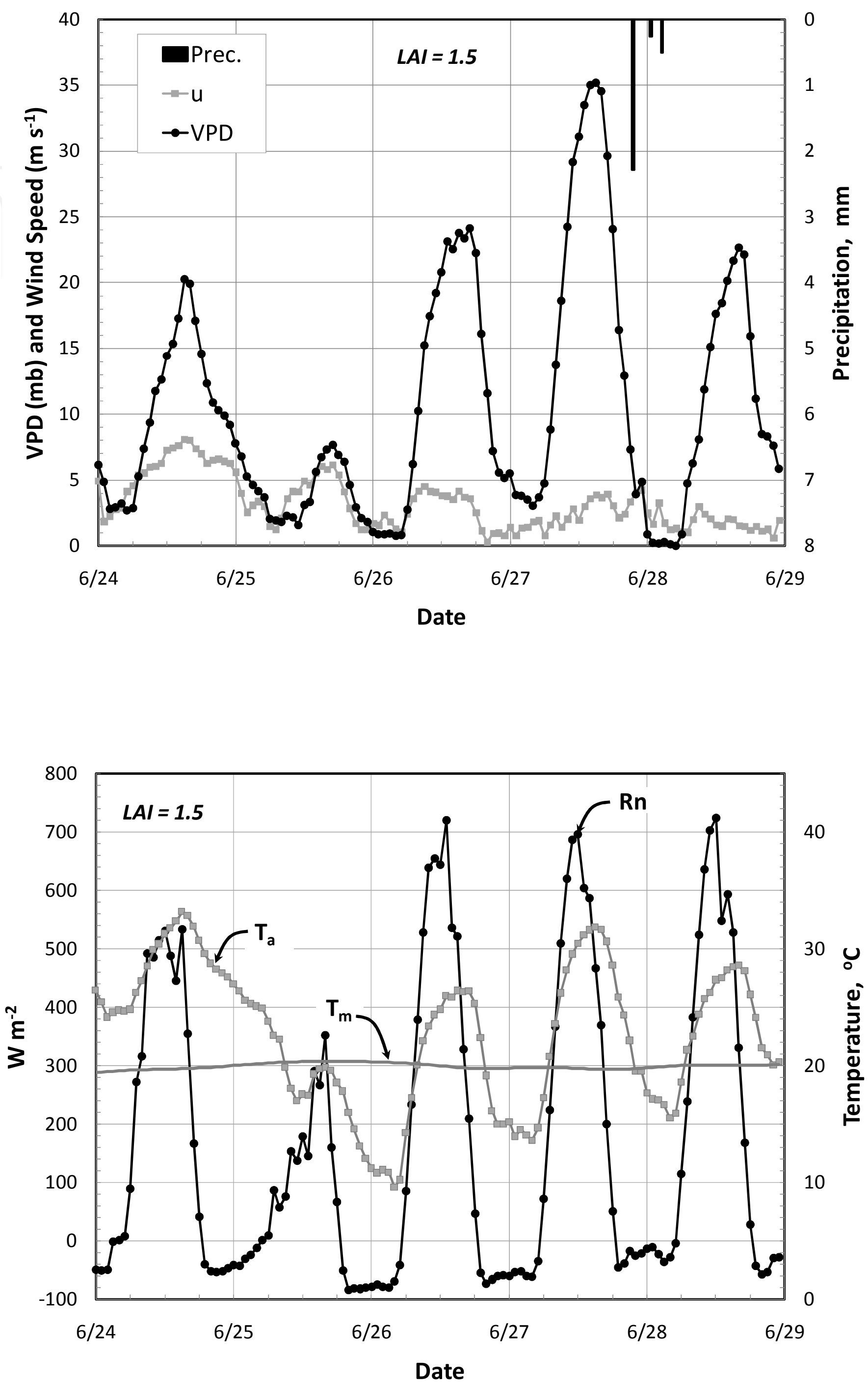


Fig. 5. Environmental conditions for a five-day period with partial crop cover for net radiation (Rn), air temperature (Ta), soil temperature (Tm), precipitation (Prec), vapor pressure deficit (VPD), and wind speed (u).

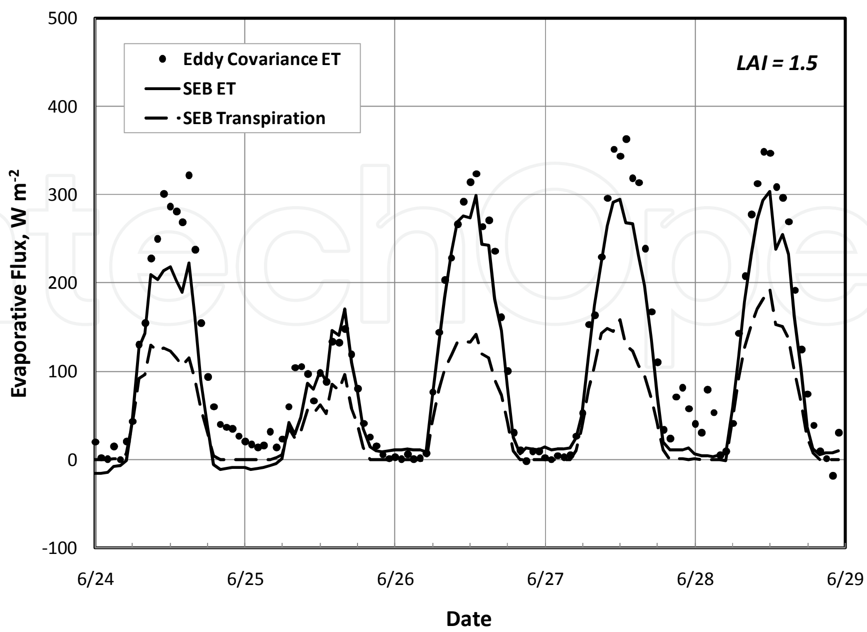
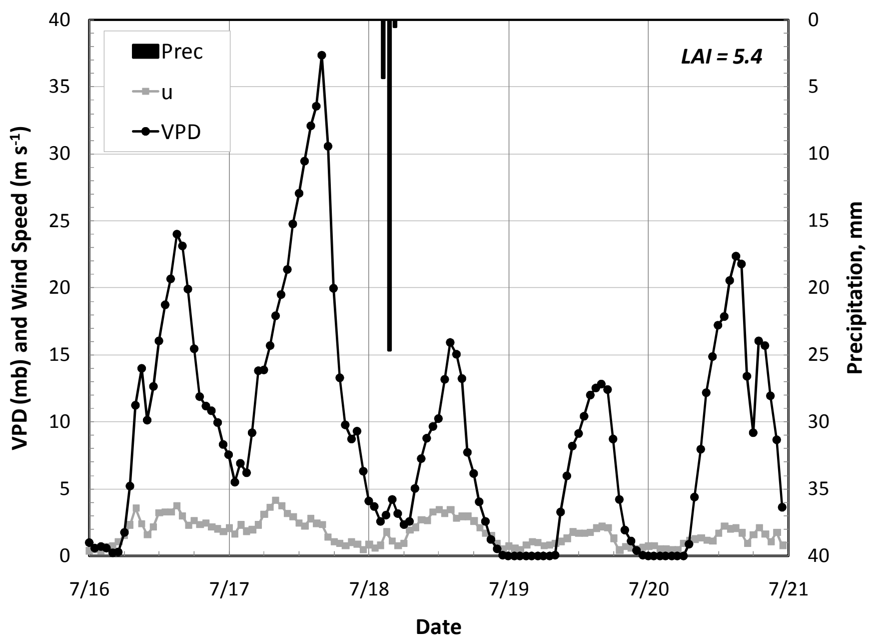


Fig. 6. Evapotranspiration and transpiration estimated by the Surface Energy Balance (SEB) model and ET measured by an eddy covariance system for a 5-day period with partial canopy cover.

Hourly measurements and SEB predictions for the three five-day periods were combined to evaluate the overall performance of the model (Figure 9). Results show variation about the 1:1 line; however, there is a strong correlation and the data are reasonably well distributed about the line. Modeled ET is less than measured for latent heat fluxes above 450 W m^{-2}. The model underestimates ET during hours with high values of vapor pressure deficit (Figure 6 and 8), this suggests that the linear effect of vapor pressure deficit in canopy resistance estimated with equation (30) produce a reduction on ET estimations. Further work is required to evaluate and explore if different canopy resistance models improve the performance of ET predictions under these conditions. Various statistical techniques were used to evaluate the performance of the model. The coefficient of determination, Nash-Sutcliffe coefficient, index of agreement, root mean square error and the mean absolute error were used for model evaluation (Legates & McCabe 1999; Krause et al., 2005; Moriasi et al., 2007; Coffey et al. 2004). The coefficient of determination was 0.92 with a slope of 0.90 over the range of hourly ET values. The root mean square error was 41.4 W m^{-2}, the mean absolute error was 29.9 W m^{-2}, the Nash-Sutcliffe coefficient was 0.92 and the index of agreement was 0.97. The statistical parameters show that the model represents field measurements reasonably well. Similar performance was obtained for daily ET estimations (Table 1). Analysis is underway to evaluate the model for more conditions and longer periods. Simulations reported here relied on literature-reported parameter values. We are also exploring calibration methods to improve model performance.



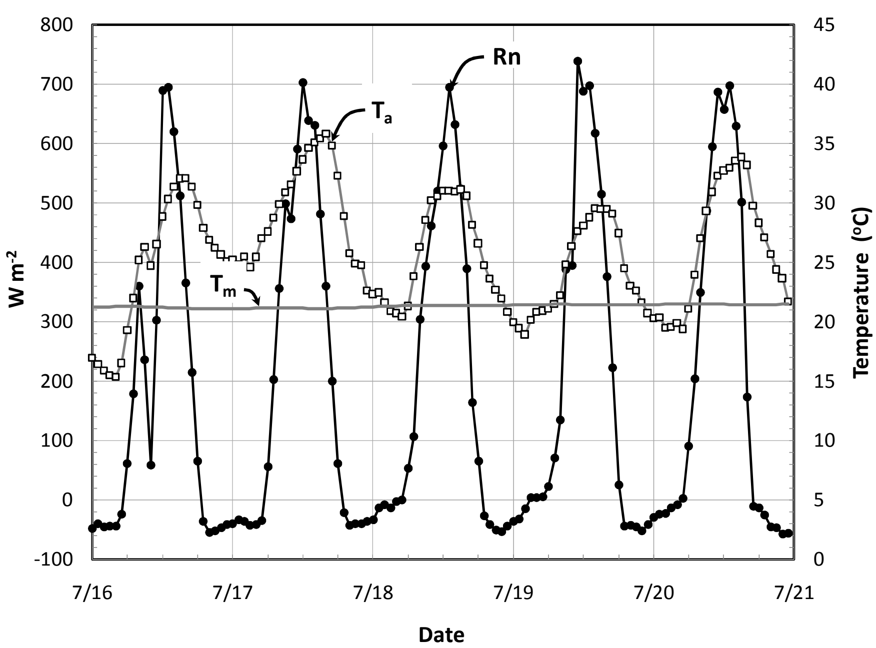


Fig. 7. Environmental conditions for 5-day period with full canopy cover for net radiation (Rn), air temperature (Ta), soil temperature (Tm), precipitation (Prec), vapor pressure deficit (VPD) and wind speed (u).

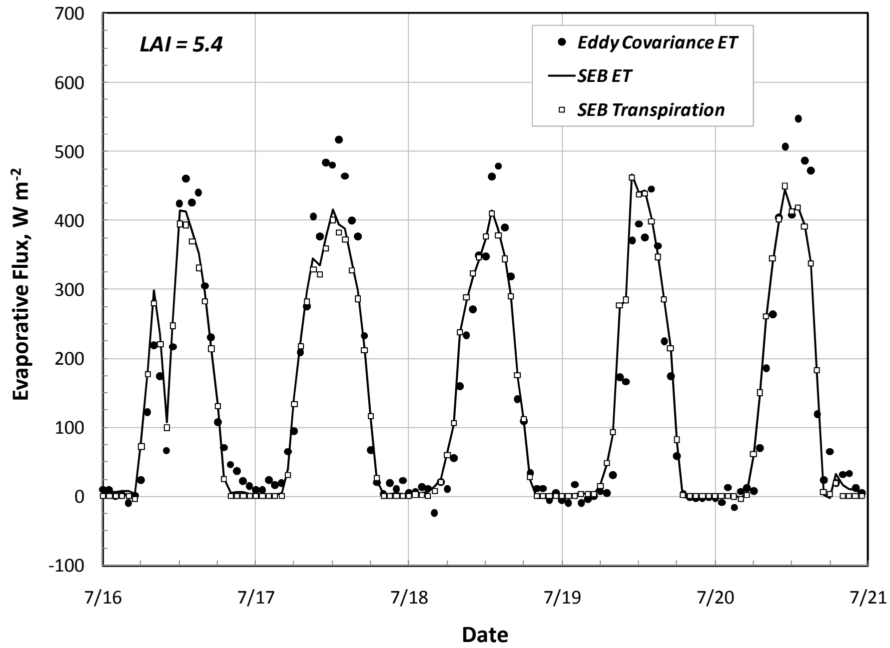


Fig. 8. Evapotranspiration and transpiration estimated by the Surface Energy Balance (SEB) model and ET measured by an eddy covariance system during a period with full canopy cover.

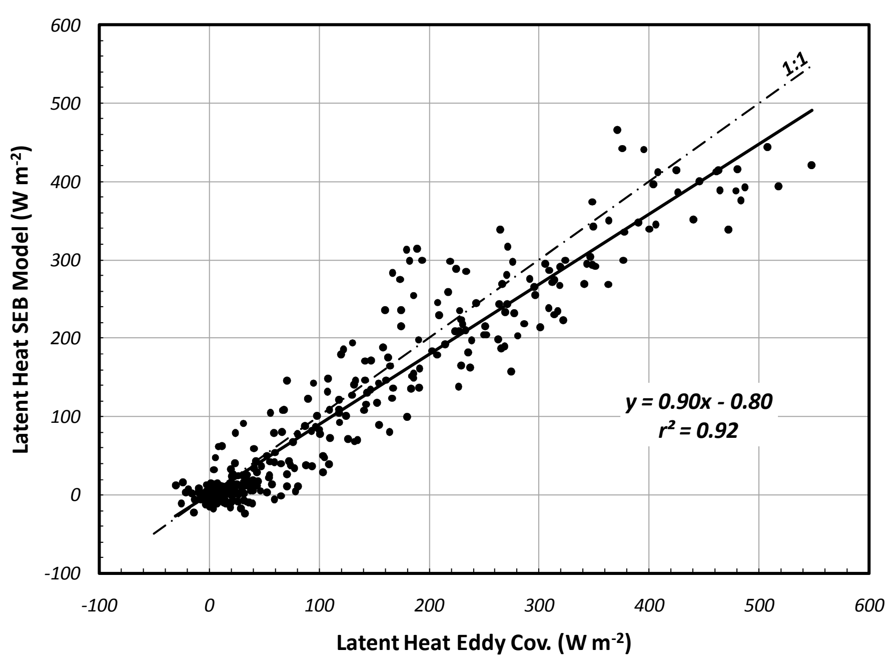


Fig. 9. Measured versus modeled hourly latent heat fluxes.

	LAI	Evapotranspiration (mm day^{-1})	
Date	$m^2 m^{-2}$	SEB	EC
6-Jun	0	3.2	3.7
7-Jun	0	0.7	1.4
8-Jun	0	2.3	3.2
9-Jun	0	3.5	2.7
10-Jun	0	2.4	3.5
24-Jun	1.5	2.9	4.4
25-Jun	1.5	1.7	2.1
26-Jun	1.5	4.1	4.3
27-Jun	1.5	4.0	5.0
28-Jun	1.5	3.8	4.7
16-Jul	5.4	5.1	5.1
17-Jul	5.4	5.8	6.8
18-Jul	5.4	5.2	5.0
19-Jul	5.4	5.0	4.1
20-Jul	5.4	5.1	5.4

Table 1. Daily evapotranspiration estimated with the Surface Energy Balance (SEB) model and measured from the Eddy Covariance (EC) system.

2.2 The modified SEB model for Partially Vegetated surfaces (SEB-PV)

Although good performance of multiple-layer models has been recognized, multiple-layer models estimate more accurate ET values under high LAI conditions. Lagos (2008) evaluated the SEB model for maize and soybean under rainfed and irrigated conditions; results indicate that during the growing season, the model more accurately predicted ET after canopy closure (after LAI=4) than for low LAI conditions. The SEB model, similar to S-W and C-M models, is based on homogeneous land surfaces. Under low LAI conditions, the land surface is partially covered by the canopy and soil evaporation takes place from soil below the canopy and areas of bare soil directly exposed to net radiation. However, in multiple-layer models, evaporation from the soil has been only considered below the canopy and hourly variations in the partitioning of net radiation between the canopy and the soil is often disregarded. Soil evaporation on partially vegetated surfaces & inorchards and natural vegetation include not only soil evaporation beneath the canopy but also evaporation from areas of bare soil that contribute directly to total ET.

Recognizing the need to separate vegetation from soil and considering the effect of residue on evaporation, we extended the SEB model to represent those common conditions. The modified model, hereafter the SEB-PV model, distributes net radiation (Rn), sensible heat (H), latent heat (λE), and soil heat fluxes (G) through the soil/residue/canopy system. Similar to the SEB model, 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.

The SEB-PV model has the same four layers described previously for SEB (Figure 10):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 a lower soil layer where the soil atmosphere is saturated with water vapor.
Total latent heat (λE) is the sum of latent heat from the canopy (λEc), latent heat from the soil (λEs) beneath the canopy, latent heat from the residue-covered soil (λEr) beneath the canopy, latent heat from the soil (λEbs) directly exposed to net radiation and latent heat from the residue-covered soil (λEbr) directly exposed to net radiation.

$$\lambda E = [\lambda E_c + \lambda E_s(1 - f_r) + \lambda E_r f_r] F_V + [\lambda E_{bs}(1 - f_r)](1 - F_V) \tag{37}$$

Where fr is the fraction of the soil affected by residue and Fv is the fraction of the soil covered by vegetation. Similarly, sensible heat is calculated as the sum of sensible heat from the canopy (Hc), sensible heat from the soil (Hs) and sensible heat from the residue covered soil (Hr), sensible heat from the soil (Hbs) directly exposed to net radiation and latent heat from the residue-covered soil (Hbr) directly exposed to net radiation.

$$H = [Hc + Hs\,(1 - fr) + Hr\,fr\,]\,Fv + [\,Hbs\,(1 - fr) + Hbr\,fr]\,(1 - Fv) \tag{38}$$

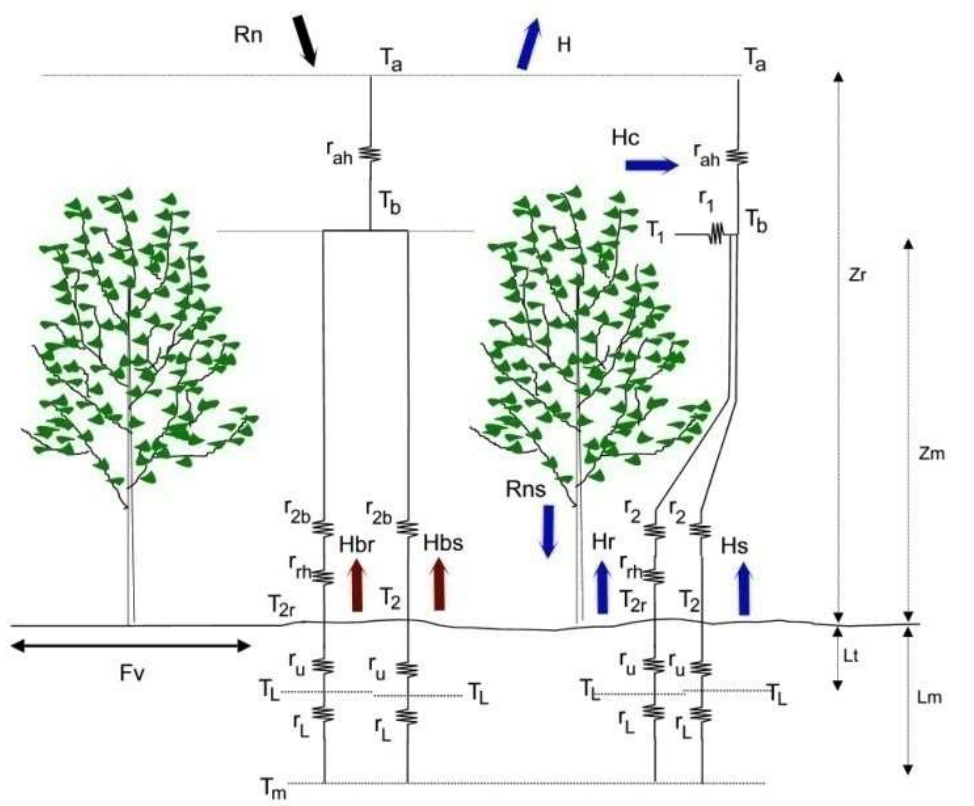
For the fraction of the soil covered by vegetation, the total net radiation is divided into that absorbed by the canopy (Rnc) and the soil beneath the canopy (Rns) and is given by Rn = Rnc + Rns. The net radiation absorbed by the canopy is divided into latent heat and sensible heat fluxes as Rnc = λEc + Hc. Similarly, for the soil Rns = Gos + Hs, where Gos is a conduction term downwards from the soil surface and is expressed as Gos = λEs + Gs, where Gs is the soil heat flux for bare soil. Similarly, for the residue covered soil Rns = Gor + Hr where Gor is the conduction downwards from the soil covered by residue. The conduction is given by Gor = λEr + Gr where Gr is the soil heat flux for residue-covered soil. For the area without vegetation, total net radiation is divided into latent and sensible heat fluxes as Rn = λEbs +λEbr + Hbs + Hbr.
The differences in vapor pressure and temperature between levels can be expressed with an Ohm's law analogy using appropriate resistance and flux terms (Figure 10). Latent and sensible flux terms with in the resistance network were combined and solved to estimate total fluxes. The solution gives the latent and sensible heat fluxes from the canopy, the soil beneath the canopy and the soil covered by residue beneath the canopy similar to equations (9), (10), (11), (12) and (13).
The new expressions for latent heat flux of bare soil and soil covered by residue, both directly exposed to net radiation are:
For bare soil:

$$\lambda E_{bs} = \frac{(R_n \cdot \Delta \cdot (r_{2b}) \cdot r_L + \rho \cdot C_p \cdot \left((e_b^* - e_b) \cdot r_u + r_L + r_{2b}\right) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_{2b}))}{\gamma \cdot (r_{2b} + r_s) \cdot (r_u + r_L + r_{2b}) + \Delta \cdot r_L \cdot (r_u + r_{2b})} \tag{39}$$

For residue covered soil:

$$\lambda E_{br} = \frac{R_n \cdot \Delta \cdot (r_{2b} + r_{rh}) \cdot r_L + \rho \cdot C_p \cdot ((e_b^* - e_b) \cdot (r_u + r_L + r_{2b} + r_{rh}) + (T_m - T_b) \cdot \Delta \cdot (r_u + r_{2b} + r_r))}{\gamma \cdot (r_{2b} + r_s + r_r) \cdot (r_u + r_L + r_{2b} + r_{rh}) + \Delta \cdot r_L \cdot (r_u + r_{2b} + r_{rh})} \tag{40}$$

These relationships define the surface energy balance model, which is applicable to conditions ranging from closed canopies to surfaces partially covered by vegetation. If Fv = 1 the model SEB-PV is similar to the original SEB model and with Fv=1 without residue, the model is similar to that by Choudhury and Monteith (1988).



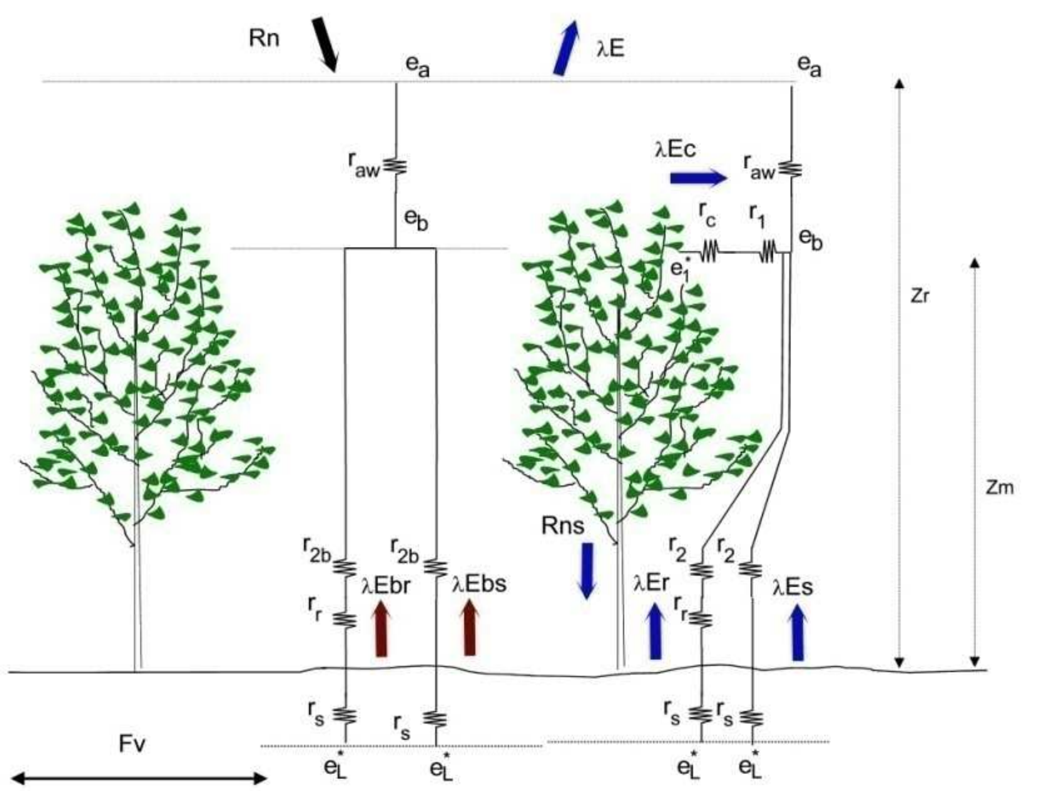


Fig. 10. Schematic resistance network of the modified Surface Energy Balance (SEB - PV) model for partially vegetated surfaces a) Sensible heat flux and b) Latent heat flux.

2.2.1 Model resistances

Model resistances are similar to those described by the SEB model; however, a new aerodynamic resistance (r_{2b}) for the transfer of heat and water flux is required for the surface without vegetation.

The aerodynamic resistance between the soil surface and Zm (r_{2b}) could be calculated by assuming that the soil directly exposed to net radiation is totally unaffected by adjacent vegetation as:

$$r_{as} = \frac{\ln\left(\frac{z_m}{z_o'}\right)^2}{k^2 u} \tag{41}$$

According to Brenner and Incoll (1997), actual aerodynamic resistance (r_{2b}) will vary between r_{as} for Fv=0 and r_2 when the fractional vegetative cover Fv=1. The form of the functional relationship of this change is not known, r_{2b} was varied linearly between r_{as} and r_2 as:

$$r_{2b} = FV(r_2) + (1 - FV)(r_{as}) \tag{42}$$

2.2.2 Model inputs

The proposed SEB-PV model requires the same inputs of the SEB model plus the fraction of the surface covered by vegetation (Fv).

2.3 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 were expressed as changes in total ET (λE) and changes in the crop transpiration ratio. The transpiration ratio is the ratio between crop transpiration (λEc) over total ET (transpiration ratio= λEc / λE).

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, 0.8xT_m=16.8 °C and 1.2xT_m=25.2 °C) (Figure 11), changes in the parameterization of aerodynamic resistances (the attenuation coefficient, α= 1, 2.5 and 3.5), the mean boundary layer resistance, r_b (±40%) the crop height, h (±30%)), selected conditions for the soil surface resistance, r_s (0, 227, and 1500 s m^{-1}) (Figure 12), four values for residue resistance, r_r (0, 400, 1000, and 2500 s m^{-1}), and changes of ±30% in surface canopy resistance, r_c (Figure 13).

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 other parameters evaluated.

Variable	Symbol	Value	Unit
Net Radiation	Rn	500	W m^{-2}
Air temperature	Ta	25	^oC
Relative humidity	RH	68	%
Wind speed	U	2	m s^{-1}
Soil Temperature at 0.5 m	Tm	21	^oC
Solar radiation	Rad	700	W m^{-2}
Canopy resistance coeff.	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	Θs	0.5	m^3 m^{-3}
Soil porosity	ϕ	0.5	m^3 m^{-3}
Soil tortuosity	τs	1.5	
Residue fraction	Fr	0.5	
Thickness of the residue layer	Lr	0.02	m
Residue tortuosity	τr	1	
Residue porosity	ϕ r	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	1000	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} $^oC^{-1}$
Soil thermal conductivity, lower layer	K'	3.8	W m^{-1} $^oC^{-1}$

Table 2. Predefined conditions for the sensitivity analysis.

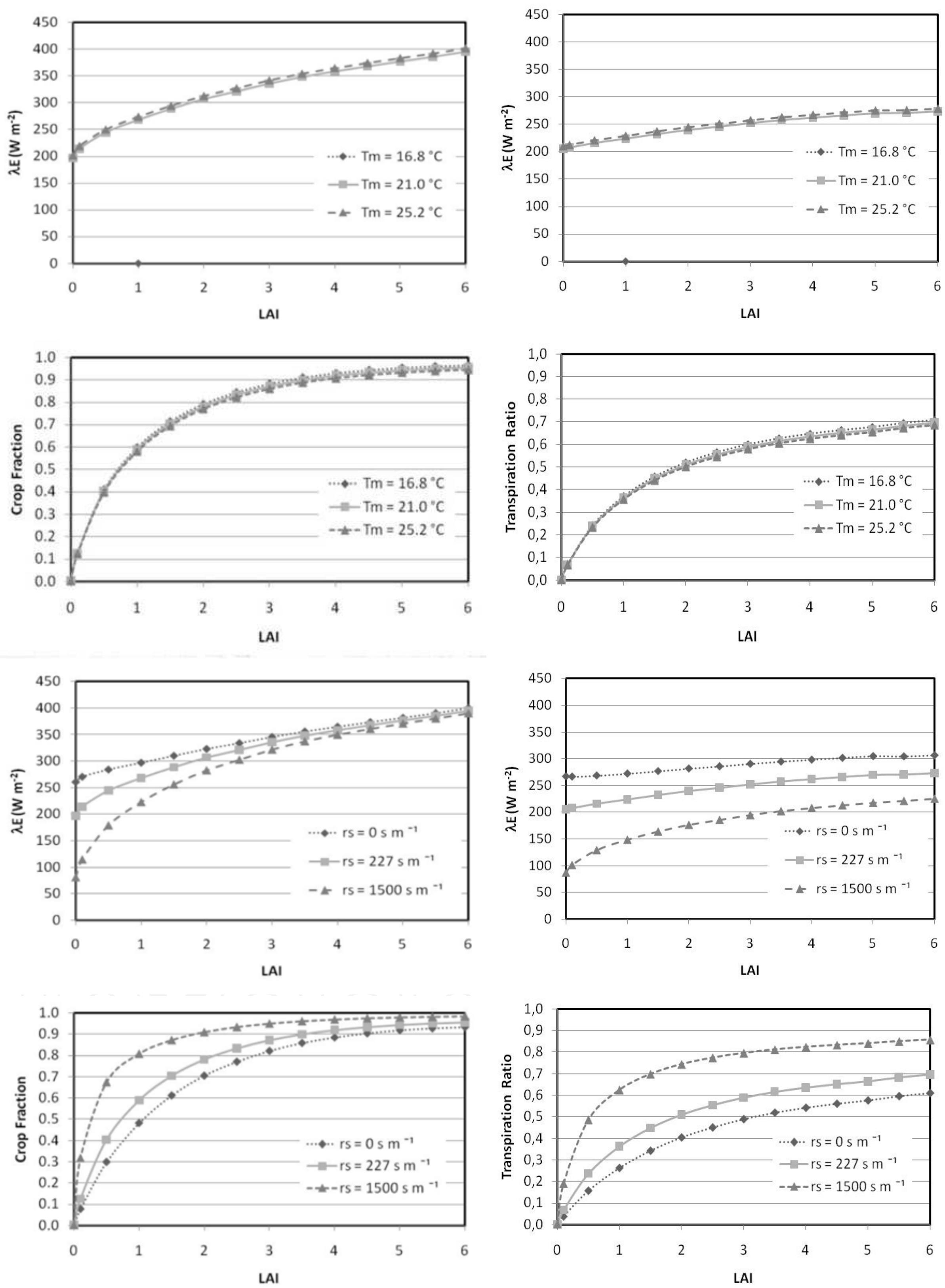


Fig. 11. Sensitivity analysis of the SEB-PV model for Fv=1 (left) and Fv=0,5 (right) under different soil temperatures Tm, and soil resistance conditions.

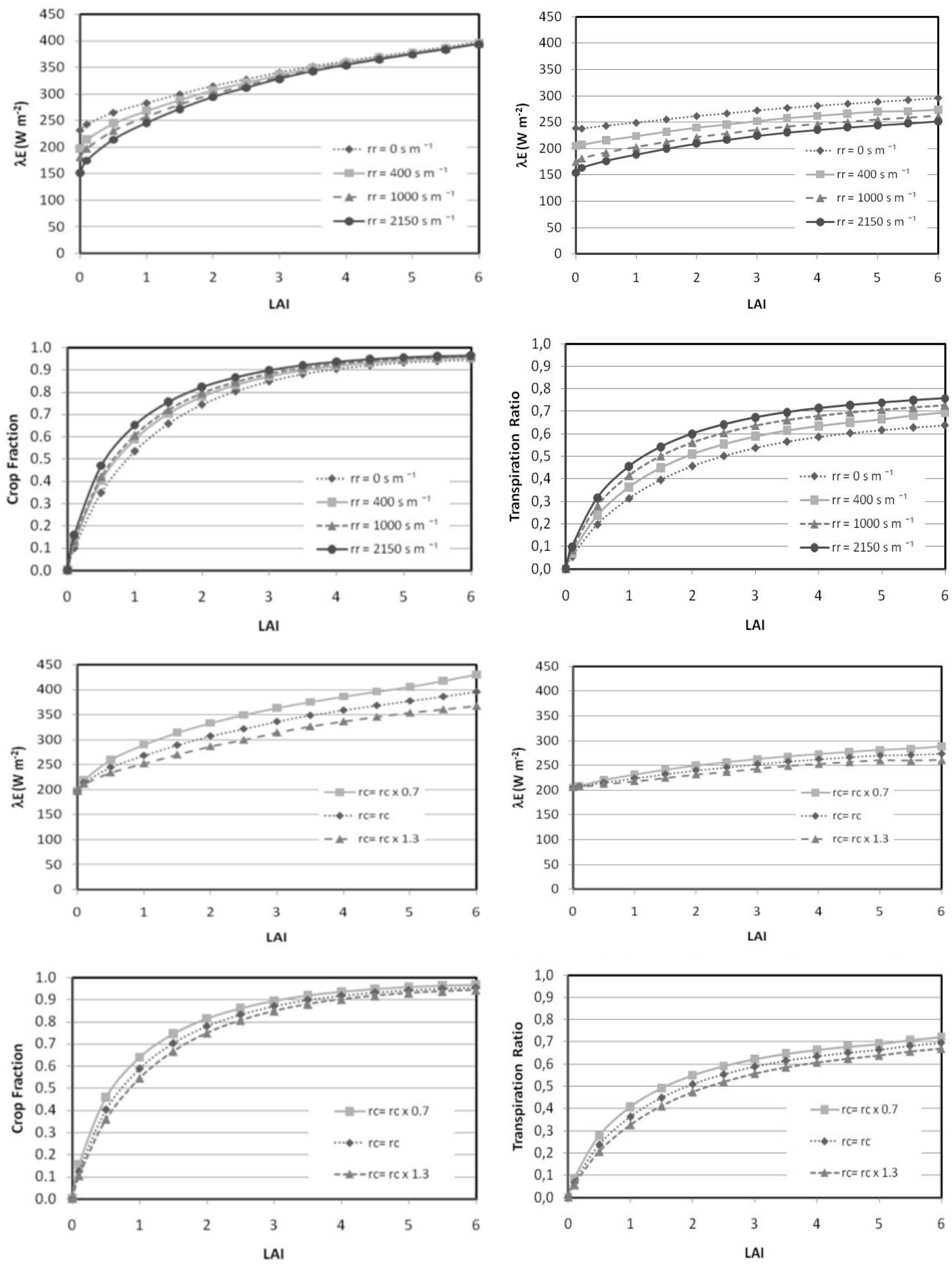


Fig. 12. Sensitivity analysis of the SEB-PV model for Fv=1 (left) and Fv=0,5 (right) under different residue and canopy conditions.

3. Conclusions

A surface energy balance model (SEB) based on the Shuttleworth-Wallace and Choudhury-Monteith models was developed to account for the effect of residue, soil evaporation and canopy transpiration on ET. The model describes the energy balance of vegetated and residue-covered surfaces in terms of driving potential and resistances to flux. Improvements in the SEB model were the incorporation of residue into the energy balance and modification of aerodynamic resistances for heat and water transfer, canopy resistance for water flux, residue resistance for heat and water flux, and soil resistance for water transfer. The model requires hourly data for net radiation, solar radiation, air temperature, relative humidity, and wind speed. Leaf area index and crop height plus soil texture, temperature and water content as well as the type and amount of crop residue are also required. An important feature of the model is the ability to estimate latent, sensible and soil heat fluxes. The model provides a method for partitioning ET into soil/residue evaporation and plant transpiration, and a tool to estimate the effect of residue ET on water balance studies. Comparison between estimated ET and measurements from an irrigated maize field provide support for the validity of the surface energy balance model. Further evaluation of the model is underway for agricultural and natural ecosystems during growing seasons and dormant periods. We are developing calibration procedures to refine parameters and improve model results.

The SEB model was modified for modeling evapotranspiration of partially vegetated surfaces given place to the SEB-PV model. The SEB-PV model can be used for partitioning total ET on canopy transpiration and soil evaporation beneath the canopy and soil directly exposed to net radiation. The model can be used for partitioning net radiation into not only latent heat fluxes but also sensible heat fluxes from each surface. A preliminary sensitivity analysis shows that similar to the SEB model, the proposed modification was sensitive to soil surface resistance, residue resistance, canopy resistance and vapor pressure deficit. Further model evaluation is needed to test this approach. A model to estimate Rn and a model to estimate soil temperature T_m from air temperature and soil conditions are also required to reduce the required inputs of the model.

4. List of variables

Rn	Net Radiation (W m^{-2}).
Rn_c	Net Radiation absorbed by the canopy (W m^{-2}).
Rn_s	Net Radiation absorbed by the soil (W m^{-2}).
λE	Total latent heat flux (W m^{-2}).
λE_c	Latent heat flux from the canopy (W m^{-2}).
λE_s	Latent heat flux from the soil (W m^{-2}).
λE_r	Latent heat flux from the residue-covered soil (W m^{-2}).
λE_{bs}	Latent heat from the soil directly exposed to net radiation (W m^{-2}).
λE_{br}	Latent heat from the residue-covered soil directly exposed to net radiation (W m^{-2}).
H	Total Sensible heat flux (W m^{-2}).
H_c	Sensible heat flux from the canopy (W m^{-2}).
H_s	Sensible heat flux from the soil (W m^{-2}).
H_r	Sensible heat flux from the residue-covered soil (W m^{-2}).
G_{os}	Conduction flux from the soil surface (W m^{-2}).
G_{or}	Conduction flux from the residue-covered soil surface (W m^{-2}).
G_s	Soil heat flux for bare soil (W m^{-2}).

G_r	Soil heat flux for residue-covered soil (W m^{-2}).
f_r	Fraction of the soil covered by residue (0-1).
ρ	Density of moist air (Kg m^{-3}).
C_p	Specific heat of air (J Kg^{-1} $^oC^{-1}$).
γ	Psychrometric constant (Kpa $°C^{-1}$).
T_a	Air temperature (^oC).
T_b	Air temperature at canopy height (^oC).
T_1	Canopy temperature (^oC).
T_2	Soil surface temperature (^oC).
T_{2r}	Soil surface temperature below the residue (^oC).
T_L	Soil temperature at the interface between the upper and lower layers for bare soil (^oC).
T_{Lr}	Soil temperature at the interface between the upper and lower layers for residue-covered soil (^oC).
T_m	Soil temperature at the bottom of the lower layer (^oC).
e_a	Vapor pressure of the air (mb).
e_b	Vapor pressure of the air at the canopy level (mb).
e_1*	Saturated vapor pressure at the canopy (mb).
e_L*	Saturated vapor pressure at the top of the wet layer (mb).
e_b*	Saturated vapor pressure at the canopy level (mb).
e_a*	Saturated vapor pressure of the air (mb).
e_{Lr}*	Saturated vapor pressure at the top of the wet layer for the residue-covered soil (mb).
r_{am}	Aerodynamic resistance for momentum transfer (s m^{-1}).
r_{ah}	Aerodynamic resistance for heat transfer (s m^{-1}).
r_{aw}	Aerodynamic resistance for water vapor (s m^{-1}).
r_{bh}	Excess resistance term for heat transfer (s m^{-1}).
r_{bw}	Excess resistance term for water vapor (s m^{-1}).
r_1	Aerodynamic resistance between the canopy and the air at the canopy level (s m^{-1}).
r_b	Boundary layer resistance (s m^{-1}).
r_2	Aerodynamic resistance between the soil and the air at the canopy level (s m^{-1}).
r_{2b}	Actual aerodynamic resistance between the soil surface and Zm (s m^{-1}).
r_{as}	Aerodynamic resistance between the soil surface and Zm totally unaffected by adjacent vegetation (s m^{-1}).
r_c	Surface canopy resistance (s m^{-1}).
r_r	Residue resistance for water vapor flux (s m^{-1}).
r_s	Soil surface resistance for water vapor flux (s m^{-1}).
r_{rh}	Residue resistance to transfer of heat (s m^{-1}).
r_r	Residue resistance for heat flux (s m^{-1}).
r_u	Soil heat flux resistance for the upper layer (s m^{-1}).
r_L	Soil heat flux resistance for the lower layer (s m^{-1}).
Δ	Slope of the saturation vapor pressure (mb $^oC^{-1}$).
h	Vegetation height (m).
LAI	Leaf area index (m^2 m^{-2}).
LAI_{max}	Maximum value of leaf area index (m^2 m^{-2}).
d	Zero plane displacement (m).
z_r	Reference height above the canopy (m).
Z_m	Reference height (m).
z_o	Surface roughness length (m).
z_o'	Roughness length of the soil surface (m).

k	Von-Karman Constant.
k_h	Diffusion coefficient at the top of the canopy (m^2 s^{-1}).
u^*	Friction velocity (m s^{-1}).
α	Attenuation coefficient for eddy diffusion coefficient within the canopy.
B^{-1}	Dimensionless bulk parameter.
VPD_a	Vapor pressure deficit (mb).
Rad	Solar radiation (W m^{-2}).
Rad_{max}	Maximum value of solar radiation (W m^{-2}).
w	Mean leaf width (m).
u_h	Wind speed at the top of the canopy (m s^{-1}).
L_t	Thickness of the surface soil layer (m).
L_m	Thickness of the surface and bottom soil layers (m)
r_{so}	Soil surface resistance to the vapor flux for a dry layer (m s^{-1}).
τ_s	Soil tortuosity.
D_v	Water vapor diffusion coefficient (m^2 s^{-1}).
k_1	Thermal diffusivity (m^2 s^{-1}).
ϕ	Soil porosity.
β	Fitting parameter.
θ	Volumetric soil water content (m^3 m^{-3}).
θ_s	Saturation water content of the soil (m^3 m^{-3}).
L_r	Residue thickness (m).
τ_r	Residue tortuosity.
ϕ_r	Residue porosity.
u_2	Wind speed at two meters above the surface (m s^{-1}).
K	Thermal conductivity of the soil, upper layer (W m^{-1} $^oC^{-1}$).
K'	Thermal conductivity of the soil, lower layer (W m^{-1} $^oC^{-1}$).
K_r	Thermal conductivity of the residue layer (W m^{-1} $^oC^{-1}$).
C_{ext}	Extinction coefficient.
Fv	Fraction of the soil covered by vegetation.
H_{bs}	Sensible heat from the soil (W m^{-2}).
H_{br}	Latent heat from the residue-covered soil (W m^{-2}).

5. Acknowledgments

We thank the University of Nebraska Program of Excellence, the University of Nebraska-Lincoln Institute of Agriculture and Natural Resources, Fondo Nacional de Desarrollo Cientifico y Tecnologico (FONDECYT 11100083) and Fondo de Fomento al Desarrollo Cientifico y Tecnologico (FONDEF D09I1146) Their support is gratefully recognized.

6. References

Allen, S.J., (1990). Measurement and estimation of evaporation from soil under sparse barley crops in northern Syria. Agric. For. Meteorology, 49: 291-309.

Allen R G, Pereira LS, Raes D and Smith M (1998) Crop Evapotranspiration: Guidelines for computing crop requirement. (Irrigation and Drainage Paper No 56) FAO, Rome, Italy.

Allen, R.G., Tasumi M., and Trezza, R., (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-model. Journal of Irrigation and Drainage Engineering, 133 (4): 380-394.

Alves I., and Pereira, L. S., (2000). Modeling surface resistance from climatic variables? Agricultural Water Management, 42, 371-385.

Anadranistakis M, Liakatas A, Kerkides P, Rizos S, Gavanosis J, and Poulovassilis A (2000) Crop water requirements model tested for crops grown in Greece. Agric Water Manage 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.

Brenner AJ and Incoll LD (1996) The effect of clumping and stomatal response on evaporation from sparsely vegetated shrublands. Agric For Meteorol 84:187-205.

Bristow KL, Campbell GS, Papendick RI and Elliot LF (1986) Simulation of heat and moisture transfer through a surface residue-soil system. Agric For Meteorol 36:193-214.

Bristow KL and Horton R (1996) Modeling the impact of partial surface mulch on soil heat and water flow. Theor Appl Clim 56(1-2):85-98.

Caprio J, Grunwald G and Snyder R (1985) Effect of standing stubble on soil water loss by evaporation. Agric For Meteorol 34:129-144.

Choudhury BJ and Monteith JL (1988) A four layer model for the heat budget of homogeneous land surfaces. Quarterly J Royal Meteorol Soc 114:373-398.

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

Enz J, Brun L and Larsen J (1988) Evaporation and energy balance for bare soil and stubble covered soil. Agric For Meteorol 43:59-70.

Farahani HJ and Ahuja L R (1996) Evapotranspiration modeling of partial canopy/residue covered fields. Trans ASAE 39:2051-2064.

Farahani HJ and 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, Lincoln, Nebraska.

Gregory JM (1982) Soil cover prediction with various amounts and types of crop residue. Trans ASAE 25:1333-1337.

Horton R, Bristow KL, Kluitenberg GJ and Sauer TJ (1996) Crop residue effects on surface radiation and energy balance-review.Theor Appl Clim 54:27-37.

INE, 2007. Instituto Nacional de Estadisticas.Censo agropecuario. www.censoagropecuario.cl.

Irmak, S., Mutiibwa D., Irmak A., Arkebauer T., Weiss A., Martin D., and Eisenhauer D., (2008). On the scaling up leaf stomatal resistance to canopy resistance using photosynthetic photon flux density. Agricultural and Forest Meteorology, 148 1034-1044.

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

Jalota SK and Prihar SS (1998) Reducing soil water evaporation with tillage and straw mulching. Iowa State University, Ames, Iowa.

Jensen ME, Burman RD and Allen RG (1990) Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70 332 pp.

Jensen, J.M., Wright, J.L., and Pratt , B.J., 1971. Estimating soil moisture depletion from climate, crop and soil data. Transactions of the ASAE, 14 (6): 954-959.

Katerji, N. and Rana, G. (2006). Modeling evapotranspiration of six irrigated crops under Mediterranean climate conditions. Agricultural and Forest Meteorology, 138 142-155.

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

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

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

Lagos LO (2008) A modified surface energy balance to model evapotranspiration and surface canopy resistance. PhD Dissertation University of Nebraska-Lincoln Lincoln, Nebraska.

Lagos L.O. Martin D.L., Verma S. Suyker A. and Irmak S. (2009). Surface Energy Balance Model of Transpiration from Variable Canopy Cover and Evaporation from Residue Covered or Bare Soil Systems. Irrigation Science. (28)1:51-64.

Legates DR and McCabe GJ (1999) Evaluating the use of goodness of fit measures in hydrologic and hydroclimatic model validation. Water Res Res 35(1): 233-241.

Lindburg M (2002) A soil surface resistance equation for estimating soil water evaporation with a crop coefficient based model. M.Sc. Thesis University of Nebraska-Lincoln Lincoln, Nebraska.

Lund M.R. and Soegaard H. (2003). Modelling of evaporation in a sparse millet crop using a two-source model including sensible heat advection within the canopy. Journal of Hydrology, 280: 124-144.

Massman, W.J.(1992). A Surface energy balance method for partitioning evapotranspiration data into plant and soil components for a surface with partial canopy cover. Water Resources Research. 28:1723-1732.

Meyers TP and 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 Symposium Soc Expl Biol 19:205-234.

Monteith J.L., and Unsworth M.H. (2008). Principles of environmental physics.Academic Press, Burlington, MA USA.

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

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

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

Parkes M., Jiang W., and Knowles R. (2005). Peak crop coefficient values for shaanxi north-west China. Agricultural Water Management, 73 149-168.

Penman H L (1948) Natural evaporation from open water, bare soil and grass. Proc Royal Soc London , Series A, 193:120-146.

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

Rana, G., Katerji, N., and De Lorenzi F. (2005). Measurement and modeling of evapotranspiration of irrigated citrus orchard under Mediterranean conditions. Agricultural and Forest Meteorology, 128 199-209.

Shaw RH and Pereira AR (1982) Aerodynamic roughness of a plant canopy: A numerical experiment. Agric Meteorol 26(1):51-65.

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

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

Shuttleworth WJ and Wallace JS (1985) Evaporation from sparse crops-an energy combination theory. Quarterly J Royal 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 Res Res 29(5):1379-1392.

Steiner J (1989) Tillage and surface residue effects on evaporation from soils. Soil Sci Soc Am J 53:911-916.

Steiner J (1994) Crop residue effects on water conservation. Managing agricultural residues, Unger P ed, Lewis Publisher, Boca Raton, Florida, 41-76.

Steiner J, Schomberg H, Unger P and Cresap J (2000) Biomass and residue cover relationships of fresh and decomposing small grain residue. Soil Sci Soc Am J 64:2109-2114.

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

Tanner B and Shen Y (1990) Water vapor transport through a flail-chopped corn residue. Soil Sci Soc Am J 54(4):945-951.

Thom AS (1972) Momentum, mass and heat exchange of vegetation. Quarterly J Royal Meteorol Soc 98:124-134.

Todd RW, Klocke NL, Hergert GW and Parkhurst AM (1991) Evaporation from soil influenced by crop shading, crop residue, and wetting regime. Trans ASAE 34:461-466.

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

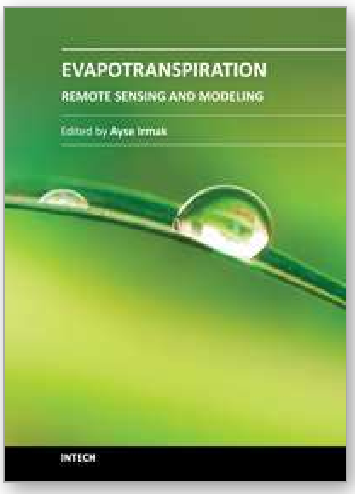
Verma S (1989) Aerodynamic resistances to transfer of heat, mass and momentum. Proc (Estimation of Areal Evapotranspiration) Vancouver BC Canada IAHS Publ #177:13-20.

Verma SB, Dobermann A, Cassman KG, Walters DT, Knops JM, Arkebauer TJ, Suyker AE, Burba GG, Amos B, Yang H, Ginting D, Hubbard KG, Gitelson AA, and Walter-Shea EA (2005) Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric For Meteorol 131:77-96.

Wallace J.S., Jackson N.A. and C.K. Ong. (1999). Modelling soil evaporation in an agroforestry system in Kenya. Agricultural and Forest Meteorology 94: 189-202.

Weseley ML and Hicks BB (1977) Some factors that affect the deposition rates of sulfur dioxide and similar gases on vegetation. J Air Pollution Control Assoc 27(11):1110-1116.

Yu Q, Zhnag Y, Liu Y and Shi P (2004) Simulation of the stomatal conductance of winter wheat in response to light, temperature and CO2 changes. Annals of Bot 93:435-441.



Evapotranspiration - Remote Sensing and Modeling
Edited by Dr. Ayse Irmak

ISBN 978-953-307-808-3
Hard cover, 514 pages
Publisher InTech
Published online 18, January, 2012
Published in print edition January, 2012

This edition of Evapotranspiration - Remote Sensing and Modeling contains 23 chapters related to the modeling and simulation of evapotranspiration (ET) and remote sensing-based energy balance determination of ET. These areas are at the forefront of technologies that quantify the highly spatial ET from the Earth's surface. The topics describe mechanics of ET simulation from partially vegetated surfaces and stomatal conductance behavior of natural and agricultural ecosystems. Estimation methods that use weather based methods, soil water balance, the Complementary Relationship, the Hargreaves and other temperature-radiation based methods, and Fuzzy-Probabilistic calculations are described. A critical review describes methods used in hydrological models. Applications describe ET patterns in alpine catchments, under water shortage, for irrigated systems, under climate change, and for grasslands and pastures. Remote sensing based approaches include Landsat and MODIS satellite-based energy balance, and the common process models SEBAL, METRIC and S-SEBS. Recommended guidelines for applying operational satellite-based energy balance models and for overcoming common challenges are made.