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A Modified Surface Energy Balance for Modeling Evapotranspiration and Canopy Resistance

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A Modified Surface Energy Balance for Modeling
Evapotranspiration and Canopy Resistance

By
Luis Octavio Lagos

A DISSERTATION

Presented to the Faculty of
The Graduate College at the University of Nebraska
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A MODIFIED SURFACE ENERGY BALANCE FOR MODELING EVAPOTRANSPIRATION AND CANOPY RESISTANCE

L. OCTAVIO LAGOS, Ph.D.

University of Nebraska, 2008

Advisors: Derrel Martin and Suat Irmak

A modified surface energy balance (SEB) model based on the Shuttleworth-Wallace and Choudhury-Monteith methods was developed to estimate evaporation from soil covered by crop residue, and transpiration from crop canopies. The model describes the energy balance and flux resistances for partially-vegetated and residue-covered surfaces. Physical and biochemical energy storage terms and lateral fluxes are neglected in the model. Net radiation is one of the inputs in the SEB model and provides the energy needed for soil evaporation, crop transpiration and heat transfer through the canopy, soil/residue surfaces and the atmosphere.

A sensitivity analysis of the SEB model parameters showed that simulated evapotranspiration was most sensitive to changes in canopy surface resistance, soil surface resistance, and residue surface resistance. Comparisons between estimated ET and measurements from three eddy covariance systems located in soybean and maize fields provided support for the validity of the model. The SEB model accurately simulated hourly and annual amounts of evapotranspiration during periods with a wide range of crop canopy cover.
As in the Penman Monteith (P-M) approach, canopy surface resistance can be back-calculated with the SEB model if latent heat fluxes and other environmental variables are measured. Since the SEB model has the ability to separate ET into canopy transpiration and soil evaporation, canopy surface resistance estimated with the SEB model should be less affected by soil evaporation than with the P-M approach. The SEB model and the P-M model were used to estimate canopy surface resistance for maize under irrigated and rainfed conditions. Canopy resistance estimated with the P-M and the SEB models followed the same pattern during the growing season and during the day but with different magnitudes. As was expected, canopy resistance estimated with the SEB model was higher than calculated with the P-M equation. Differences were more important under low leaf area index conditions. Results suggest that soil evaporation considerably affects the canopy surface resistance obtained with the P-M equation.
This dissertation is dedicated to my Grandmother:

Maria Encarnación Azúa

who always believed in me.
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Chapter I. Introduction.

Introduction.

In evapotranspiration (ET) modeling it is very common to represent the vegetation assuming a single source of energy flux at an effective height within the canopy. Several authors have studied the single source Penman-Monteith model to represent these conditions under common agricultural ecosystems (Rana et al., 1997; Alves and Pereira, 2000; Kjelgaard and Stockle, 2001; Ortega-Farias et al., 2004; Shuttleworth 2006 and Flores, 2007 among others). When crops are sparse, the single source/sink of energy assumption in the Penman-Monteith model is not entirely satisfied. Sparse plant canopy cover accounts for significant portion of the land surface. It occurs seasonally in all agricultural areas and through the year over natural land covers (Massman, 1992).

Multiple-layer models have been developed to estimate ET from sparse canopies. 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 on plant and soil surfaces, and aerodynamic resistances regulate fluxes between the surface and the atmospheric boundary layer. A second approach was presented by Choudhury and Monteith (1988). They proposed a surface energy balance (SEB) to model evapotranspiration. The model is an explicit solution of the equations that define the conservation of heat and water vapor for uniform vegetation and soil. Similar to Shuttleworth-Wallace (1985) the Choudhury-Monteith (1988) model included soil surface resistances to regulate the heat and mass transfer at
the soil surface. However, Choudhury and Monteith (1988) interpret these resistances by describing evaporation through a drying soil from wet soil below the dry soil layer of increasing thickness. Several studies have evaluated the performance of multiple-layers models to estimate ET (Farahani and Baush, 1995; Stannard, 1993; Lafleur and Rouse, 1990; Farahani and Ahuja, 1996; Iritz et al. 2001; Tourula and Heikinheimo, 1998 and 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.

In the Shuttleworth-Wallace (1985) model soil heat flux has been assumed as a fixed percentage of net radiation. Numerous studies have shown that, although the soil heat flux is related to net radiation, it is also affected by others parameters (i.e. surface cover, soil moisture content, and soil thermal conductivity) (Sauer and Horton, 2005). A more complete surface energy balance including the estimation of soil heat flux was presented by Choudhury and Monteith (1988). In their model, soil heat flux is estimated using vertical differences of soil temperature and a soil resistance to heat flux. The model requires soil temperature as input to solve the energy balance.

Crop residue generally increases infiltration and reduces soil evaporation. However, residue effects on the surface energy balance were not included in the Choudhury and Monteith (1988) model. Surface residue affects many of the variables that determine the evaporation rate, including net radiation, soil heat flux, soil temperature, aerodynamic resistance and surface resistances to transport of heat and water vapor fluxes (Steiner, 1994). Caprio et al. (1985), Enz et al. (1988), Steiner (1989) and Bristow et al. (1986) have reported significant decreases in evapotranspiration for residue covered soil compared with evaporation from bare soil.
Surface canopy resistance is also an important parameter required to estimate ET in multiple-layer models as in the Shuttleworth-Wallace (1985) and the Choudhury and Monteith (1988) approaches. Commonly, the surface canopy resistance has been estimated by using measured values of latent heat fluxes and other relevant environmental variables in the Penman-Monteith model. However, authors agreed that the canopy resistance computed with the Penman–Monteith equation could be affected by soil evaporation (Kim and Verma, 1991; Rochette et al, 1991). The effect of soil evaporation on canopy resistance can be minimized by employing multiple layer models, which have the ability to partitioning evapotranspiration into canopy transpiration and soil evaporation.

The importance of all components in the surface energy balance and the effect of residue on evaporation can be represented in a multiple-layer model. As a result, the first objective of this research is to modify and extend the approaches of Choudhury and Monteith (1998) and Shuttleworth and Wallace (1985) to include the effect of residue-covered areas on estimates of evapotranspiration in field conditions varying from partially covered soil to closed canopy surfaces. The second objective of this work is to evaluate the differences between surface canopy resistances estimated with the Penman-Monteith model and the surface canopy resistance obtained when the estimated effect of soil evaporation is minimized by using a SEB model.
**Research Organization.**

To accomplish these objectives, this research has been organized in three main chapters and a final chapter that describe the overall conclusions. In the second chapter the proposed SEB model is presented. The development of the model, the assumptions, the mathematical derivation, and the definition of model inputs and required parameters are presented. The third chapter presents an analysis of sensitivity and the evaluation of the SEB model under agricultural systems typical of eastern Nebraska. First, a sensitivity analysis was performed for selected parameters and resistances to observe their effect on evapotranspiration and transpiration. Second, modeled ET from the SEB model are compared against measured ET from three eddy covariance systems to evaluate the ability of the model to estimate hourly ET. Data from maize and soybean under irrigated and rainfed conditions are used for this analysis. In the fourth chapter the SEB model is used to estimate canopy resistance and values are compared with canopy resistance obtained from the Penman-Monteith equation. In particular, canopy resistances obtained from both approaches are compared for irrigated and rainfed maize during the growing season and under varying canopy conditions. The final chapter describes the overall summary and conclusions of this research and presents recommendations for future research.
References


Chapter II. A Modified Surface Energy Balance to Model Evapotranspiration for Partial Canopy, Residue Cover and Bare Soil: I) Model Development.

Introduction

In most cases, evapotranspiration (ET) is the second largest term (after precipitation) in the hydrological balance. Since 80-90% of precipitation received in semiarid and sub humid watersheds is commonly used in evapotranspiration, small changes in ET can result in significant changes in the hydrological cycle. ET determines the balance between recharge and discharge from aquifers in these ecosystems (Gleen et al., 2007). The determination of ET is not straightforward due to the natural heterogeneity and complexity of hydrological processes in catchments. The growing conditions for agroecosystems are not always ideal, there can be either stress from a water shortage or diseases that can reduce growth and transpiration, causing wide variability of ET over watersheds.

To calculate ET Penman (1948) partitioned net radiation energy into sensible and latent heat fluxes for a layer extending from the reference height to an assumed uniform surface, consisting of open water, bare soil or well-watered grass. This concept has been applied to uniform crops by approximating the canopy as a single uniform surface or as a single “big-leaf” for the Penman-Monteith method (Monteith, 1965) and later by Farahani and Bausch (1995). The Penman-Monteith equation is one of the most accepted models to predict reference ET. ASCE (2002) and FAO(1998) selected this model as a standardized method to estimate reference ET. The Penman-Monteith model can also be used to estimate crop ET directly when aerodynamic and canopy resistances are known for a specific crop. Considerable research has been conducted to develop methods for
predicting crop evapotranspiration with the Penman-Monteith model in a one-step approach (Rana et al., 1997; Alves and Pereira, 2000; Kjelgaard and Stockle, 2001; Ortega-Farias et al., 2004; Shuttleworth 2006 and Flores, 2007). Although different degrees of success have been found, the model has generally performed more satisfactorily when the leaf area index (LAI) is large (LAI>2).

Ortega-Farias et al. (2004) evaluated the Penman Monteith model (P-M) to estimate hourly and daily crop evapotranspiration with a variable surface-canopy resistance over a soybean crop for different soil water content and atmospheric conditions. The largest disagreements between the P-M model and measurements were found for hourly estimates of ET. However, performance of the P-M model on a daily basis was more acceptable when the soil water content was between field capacity and the wilting point, and LAI ranged from 0.3 to 4. Kjelgaard and Stockle (2001) evaluated three surface resistance methods in the P-M model for corn and potatoes. ET estimates were compared with daily crop ET measurements from a Bowen ratio energy balance system. None of the methods used to estimate surface resistance appeared reliable for application to direct estimation of ET for corn. However, all methods performed well for a short potato crop. Rana et al. (1997) estimated actual ET with the P-M model in two sites using data for a stressed soybean crop, grown under a Mediterranean climate. The model gave very good results for both sites on hourly, daily, and seasonal time scales. Shuttleworth (2006) proposed a theoretical analysis that facilitates the use of the P-M model to make a one-step estimation of crop water requirements. To estimate ET, a blending height (BH) was defined in the atmospheric boundary layer where meteorological conditions are independent of the underlying crop. Aerodynamic
resistance related to the BH and vapor pressure deficit at the BH (from climate variables at 2 m) were used in the P-M equation to estimate actual ET using the one-step approach. Flores (2007) analyzed the feasibility of using the P-M method for maize ET estimation and characterized the uncertainties introduced when weather data are measured above grass. Results showed that the model works reasonably well for a full crop cover under well watered conditions. It was critical to estimate the surface resistance as a function of climatic variables. The uncertainty introduced when the maize ET was calculated using weather data measured above grass was relatively small.

Fields with sparse vegetation and agricultural crops with partial canopy cover during the growing season do not satisfy the big-leaf assumption of the P-M model for sources or sinks of energy. To account for this, in their model Shuttleworth and Wallace (1985) combined a one-dimensional model of crop transpiration and a one-dimensional model of soil evaporation (S-W model). Surface resistances regulate the heat and mass transfer on 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 and Baush, 1995; Stannard, 1993; Lafleur and Rouse, 1990; Farahani and Ahuja, 1996; Iritz et al. 2001; Tourula and Heikinheimo, 1998 and 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 the 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 in the soil surface resistance and aerodynamic resistance, over two growing seasons, produced daily and hourly basis 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 the arid atmospheric conditions with a correlation coefficient ($r^2$) of 0.77 and a root mean square error (RMSE) of 29 W m$^{-2}$.

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 ($R_n$). 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 ($ET_{r}$ and $ET_o$), assuming that the soil heat flux beneath a fully vegetated grass or alfalfa reference surface is small in comparison with $R_n$ (i.e. $G=0$). For hourly estimations soil heat flux was estimated as one tenth of the $R_n$ during the daytime and as half of the $R_n$ for the nighttime when grass is used as the reference surface. Similarly $G$ was assumed to be 0.04$xR_n$ for the daytime and 0.2$xR_n$ during the nighttime 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 the 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 $R_n$, $G$, aerodynamic resistance and surface resistances to transport of heat and water vapor fluxes (Steiner, 1994).

Caprio et al. (1985) compared evaporation from three mini-lysimeters having: bare soil, 14 cm, 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 is a very low, nearly constant evaporative rate from very dry soil (Jalota and 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.
The importance of all components in the surface energy balance and the effect of residue on evaporation and consequently ET can be represented in a multiple-layer model. The approaches of Choudhury and Monteith (1998) and Shuttleworth and Wallace (1985) can be extended to include the effect of residue-covered areas on estimates of evapotranspiration for field conditions varying from partially covered soil to closed canopy surfaces.

**Objectives**

The main goal of this work was to develop a surface-energy balance model based on Choudhury and Monteith (1998) and Shuttleworth and Wallace (1985) to estimate ET that accounts for the effects of canopy and residue-covered soil on total ET.

Specifically, the objectives of this chapter are to:

i) Develop a modified surface-energy balance model based on Choudhury and Monteith (1998) and Shuttleworth and Wallace (1985) to estimate evaporation from soil partially covered by residue, and transpiration from crop canopies.

ii) Define model inputs and model parameters required by the proposed surface-energy balance model.
The Surface Energy Balance (SEB) Model

The model presented here combines and extends previous evapotranspiration models proposed by Shuttleworth and Wallace (1985) and Choudhury and Monteith (1988). The model has four layers (Figure 2.1). 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 where surface resistance can be calculated as a function of soil water content and the fourth, a lower soil layer where the soil atmosphere is saturated with water vapor, at the bottom of this layer the soil temperature is held constant at least for a 24 h period. The SEB model distributes net radiation (Rn) in sensible heat (H), latent heat (λE), and soil heat fluxes (G) through the soil-canopy system as illustrated in Figure 2.1. 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). Horizontal gradients of the potentials are assumed to be small enough for lateral fluxes to be ignored. 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 net radiation absorbed by the canopy (Rnc) and the soil (Rns) is given by:

\[ Rn = Rnc + Rns \]  \hspace{1cm} (1)

The net radiation absorbed by the canopy is partitioned into latent heat (λEc) and sensible heat (Hc) fluxes as:
Figure 2.1. Fluxes of the surface energy balance model.

\[ R_{nc} = \lambda E_c + H_c \]  \hspace{1cm} (2)

Similarly for the soil

\[ R_{ns} = G_{os} + H_s \]  \hspace{1cm} (3)

where \( H_s \) is sensible heat flux at the soil surface, \( G_{os} \) is a conduction term downwards from the soil surface, expressed as:

\[ G_{os} = \lambda E_s + G_s \]  \hspace{1cm} (4)

\( \lambda E_s \) is the latent heat flux at the soil surface and \( G_s \) is the soil heat flux for bare soil.

Similarly for the residue covered soil

\[ R_{ns} = G_{or} + H_r \]  \hspace{1cm} (5)

where \( H_r \) is sensible heat flux from the residue-covered soil surface and \( G_{or} \) is the conduction downwards from the soil covered by residue surface, given by:
\[ \text{Gor} = \lambda \text{Er} + \text{Gr} \]  
\[ \lambda \text{Er} \text{ is the latent heat flux and } \text{Gr} \text{ is the soil heat flux for residue-covered soil surface.} \]

Total latent heat flux from the canopy/residue/soil system (\( \lambda E \)) is the sum of the latent heat from the canopy (transpiration) \( \lambda Ec \), latent heat from the soil \( \lambda Es \) and latent heat from the residue covered soil (evaporation) \( \lambda Er \), calculated as:

\[ \lambda E = \lambda Ec + (1 - fr) \cdot \lambda Es + fr \cdot \lambda Er \]  
where \( fr \) is the fraction of the soil affected by residue.

Similarly for total sensible heat (\( H \)), the balance can be expressed as:

\[ H = Hc + (1 - fr) \cdot Hs + fr \cdot Hr \]  
The total amount of sensible heat flux (\( H \)) from the canopy/residue/soil system can be expressed as:

\[ H = \frac{\rho \cdot Cp \cdot (Tb - Ta)}{ra_h} \]  
where, \( \rho \) is the density of moist air, \( Cp \) is the specific heat of air, \( Tb \) is the air temperature within the canopy, \( Ta \) is the air temperature at the height of reference and \( ra_h \) is the aerodynamic resistance for heat transport. Similarly the total latent heat flux (\( \lambda E \)) is given by:

\[ \lambda E = \frac{\rho \cdot Cp \cdot (eb - ea)}{\gamma \cdot ra_w} \]  
where, \( \gamma \) is the psychrometric constant, \( eb \) is the vapor pressure of the atmosphere at the canopy level, \( ea \) is the vapor pressure at the reference height, and \( ra_w \) is the aerodynamic resistance for water vapor transport.

By analogy with Ohm’s law, the differences in vapor pressure and temperature between two levels can be written in terms of resistance and flux as illustrated in Figure
2.2 (Shuttleworth and Wallace, 1985). The sensible and latent heat fluxes from the canopy (H\textsubscript{c} and \(\lambda E\textsubscript{c}\)), the sensible and latent heat fluxes from the bare soil (H\textsubscript{s} and \(\lambda E\textsubscript{s}\)) and the sensible and latent heat fluxes from the soil covered by residue (H\textsubscript{r} and \(\lambda E\textsubscript{r}\)) can be expressed by:

\[
H_c = \frac{\rho \cdot C_p \cdot (T_1 - T_b)}{r_1}
\]

(11)

\[
\lambda E_c = \frac{\rho \cdot C_p \cdot (\varepsilon_1^* - e_b)}{\gamma \cdot (r_1 + r_c)}
\]

(12)

\[
H_s = \frac{\rho \cdot C_p \cdot (T_2 - T_b)}{r_2}
\]

(13)

\[
\lambda E_s = \frac{\rho \cdot C_p \cdot (\varepsilon_{L2}^* - e_b)}{\gamma \cdot (r_2 + r_s)}
\]

(14)

\[
H_r = \frac{\rho \cdot C_p \cdot (T_{2r} - T_b)}{r_2 + r_{r_h}}
\]

(15)

\[
\lambda E_r = \frac{\rho \cdot C_p \cdot (\varepsilon_{Lr}^* - e_b)}{\gamma \cdot (r_2 + r_s + r_r)}
\]

(16)

where \(r_1\) is an aerodynamic resistance between the canopy with mean temperature \(T_1\) and air with mean temperature \(T_b\), \(r_c\) is the surface canopy resistance and \(\varepsilon_1^*\) is the saturation vapor pressure at the canopy. \(r_2\) is the aerodynamic resistance between the soil and the canopy, \(T_2\) is the temperature at the soil surface and \(\varepsilon_{L2}^*\) is the saturation vapor pressure at the top of the wet layer. \(r_s\) is the resistance to the diffusion of water vapor through the soil at the top soil layer and similarly \(r_{r_h}\) is the residue resistance to transfer of heat, and
Figure 2.2. A schematic resistance network of the SEB model a) Latent heat flux and b) Sensible heat flux.
rr is the residue resistance to transfer of vapor flux acting in series with the soil resistance rs. T\textsubscript{2r} is the temperature of the soil covered by residue and e\textsubscript{Lr} is the saturation vapor pressure at the top of the wet layer for the area of the soil covered by residue.

Conduction terms of heat for the bare soil surface and the surface covered by residue are given by:

\[
G_{os} = \frac{\rho \cdot C_p \cdot (T_2 - T_L)}{r_u} \tag{17}
\]

\[
G_s = \frac{\rho \cdot C_p \cdot (T_L - T_m)}{r_L} \tag{18}
\]

\[
G_{or} = \frac{\rho \cdot C_p \cdot (T_{2r} - T_{Lr})}{r_u} \tag{19}
\]

\[
G_r = \frac{\rho \cdot C_p \cdot (T_{Lr} - T_m)}{r_L} \tag{20}
\]

where ru and r\textsubscript{L} are resistance to the transport of heat for the upper and lower soil layer respectively. T\textsubscript{L} and T\textsubscript{Lr} are the temperatures at the interface between the upper and lower layer for the bare soil and the residue-covered soil and T\textsubscript{m} is the temperature at the bottom of the lower layer assumed to be constant.

Choudhury and Monteith (1988) expressed differences of saturation vapor pressure between points in the system as linear functions of the corresponding temperature differences as:

\[
e_1^* - e_b^* = \Delta_1 \cdot (T_1 - T_b) \tag{21a}
\]

\[
e_L^* - e_b^* = \Delta_2 \cdot (T_L - T_b) \tag{21b}
\]

\[
e_r^* - e_a^* = \Delta_3 \cdot (T_b - T_a) \tag{21c}
\]

\[
e_{Lr}^* - e_b^* = \Delta_4 \cdot (T_{Lr} - T_b) \tag{21d}
\]
where $\Delta i$ are the slopes of the saturation vapor pressure-temperature curves between two points.

a) Canopy:

Using equations (2), (11), (12) and (21a) the latent heat flux from the canopy is given by (see appendix for details):

\[
\lambda_{Ec} = \frac{\Delta_1 \cdot r_i \cdot Rnc + \rho \cdot C_p \cdot (e_b^* - eb)}{\Delta_1 \cdot r_i + \gamma \cdot (r_i + rc)}
\] (22)

Sensible heat is calculated using equations (2) and the previous equation for $\lambda_{Ec}$.

\[
H_c = \frac{\gamma \cdot (r_i + rc) \cdot Rnc - \rho \cdot C_p \cdot (e_b^* - eb)}{\Delta_1 \cdot r_i + \gamma \cdot (r_i + rc)}
\] (23)

b) Bare soil

Similarly using equations (3), (4), (10), (17), (18) and (21b), latent heat flux from a bare soil surfaces $\lambda_{Es}$ can be estimated by (see detailed algebra from appendix):

\[
\lambda_{Es} = \frac{\left( Rns \cdot \Delta_2 \cdot r_2 \cdot r_L + \rho \cdot C_p \cdot ((e_b^* - eb) \cdot (ru + r_L + r_2)) + (Tm - Tb) \cdot \Delta_2 \cdot (ru + r_2) \right)}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2)}
\] (24)

Sensible heat for the soil ($H_s$) is calculated using (3), (4), and (18).

\[
H_s = \frac{\left( Rns \cdot r_L \cdot \Delta_2 - \lambda_{Es} \cdot (r_L \cdot \Delta_2 + \gamma \cdot (r_2 + rs)) + \rho \cdot C_p \cdot (e_b^* - eb) \right)}{r_L \cdot \Delta_2 - \rho \cdot C_p \cdot \Delta_2 \cdot (Tb - Tm)}
\] (25)

c) Residue covered soil

Similarly to bare soil, and using equations (5), (6), (15), (16), (20) and (21d) latent heat flux from the residue covered soil $\lambda_{Er}$ can be estimated by: (see appendix for details)
\[
\lambda Er = \left( \frac{\text{Rns} \cdot \Delta_4 \cdot (r_2 + r_{r_h}) \cdot r_L + \rho \cdot \text{Cp} \cdot ((e_b^* - eb) \cdot (ru + r_L + r_2 + r_{r_h}))}{(Tm - Tb) \cdot \Delta_4 \cdot (ru + r_2 + rr)} \right) + \gamma \cdot (r_2 + rs + rr) \cdot (ru + r_L + r_2 + r_{r_h}) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_{r_h}) \]  

(26)

Sensible heat for the residue (Hr) is calculated as:

\[
Hr = \left( \frac{\text{Rns} \cdot r_L \cdot \Delta_4 - \lambda Er \cdot (r_L \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr)) + \rho \cdot \text{Cp} \cdot (e_b^* - eb)}{-\rho \cdot \text{Cp} \cdot \Delta_4 \cdot (Tb - Tm)} \right) \frac{\gamma \cdot r_a}{r_L \cdot \Delta_4} \]  

(27)

Solution of equations for Tb and eb.

Values for Tb and eb are necessary to estimate latent heat and sensible heat fluxes in equation (22) through (27). Using equations (22), (24) and (26) in equation (7) eb can be expressed as (see detailed algebra in appendix):

\[
eb = \left( \frac{Tb \cdot (\Delta_3 \cdot A2 - A3) + \frac{A1}{\rho \cdot \text{Cp}} - \Delta_3 \cdot A2 \cdot Ta}{A2 \cdot e_a^* + Tm \cdot A3 + \frac{ea}{\gamma \cdot r_a}} \right) \cdot \left( \frac{\gamma \cdot r_a}{1 + A2 \cdot \gamma \cdot r_a} \right) \]  

(28)

Similarly for sensible heat and using equations (23), (25) and (27) in equation (8), Tb is given as:

\[
Tb = \left( \frac{B1}{\rho \cdot \text{Cp}} + Ta \cdot \left( \frac{1}{r_a} - \Delta_3 \cdot B2 \right) \right) \cdot \left( \frac{r_a}{1 - \Delta_3 \cdot B2 \cdot r_a + B3 \cdot r_a} \right) \]  

(29)

where A1, A2, A3 and B1, B2 and B3 are given in appendix. Equations (28) and (29) can be used to estimate Tb and eb. Values for \( \Delta_1, \Delta_2, \Delta_3 \) and \( \Delta_4 \) are necessary to solve the model, Choudhury and Monteith (1988) found that a single value \( \Delta \), evaluated at Ta,
usually gave the components of the heat balance with acceptable accuracy. Therefore a single value for $\Delta$ is used in the SEB model.

Equations (22) through (27) define the extended surface energy balance model. The modified SEB model proposed here should be applicable to conditions of surfaces from fully closed canopies to surface with bare soil or those partially covered with residue. In the absence of residue, ($fr=0$) equations (7) and (8) became the original model by Choudhury and Monteith (1988). Equations (26) and (27) have the same form as the equations (24) and (25). When there is almost no residue covering the soil (i.e. $rr$ is close to 0) equation (26) is equal to equation (24). Similarly for sensible heat, when $rr$ is close to zero, equation (27) becomes equal to equation (25) reducing the model to its original form.

**Model Parameters**

**Aerodynamic Resistance**

Thom (1972) stated that the transfer of mass or heat encounters greater aerodynamic resistance than the transfer of momentum. Accordingly, aerodynamic resistances to heat ($ra_h$) and water vapor transfer ($ra_w$) can be estimated as:

\[
ra_h = ra_m + rb_h \quad (30)
\]

\[
ra_w = ra_m + rb_w \quad (31)
\]

where, $ra_m$ is the aerodynamic resistance to momentum transfer and $rb_h$ and $rb_w$ are excess resistance terms for heat and water vapor transfer respectively.
Based on the work of Choudhury and Monteith (1988), Shuttleworth and Gurney (1990) estimated the aerodynamic resistance \( r_{am} \) between the sink of momentum in the canopy, \( d'+z_0 \), and the height, \( z_r \), above the canopy as:

\[
ra_m = \int_{d'+z_0}^{z_r} \frac{1}{K(z)} \, dz
\]  

(32)

where \( K(z) \) is the eddy diffusion coefficient.

\( K(z) \) above the crop is given by:

\[
K(z) = k \cdot u^* \cdot (z - d') \quad z>h
\]  

(33)

where \( k \) is the von Karman constant, \( z \) is height, \( u^* \) is the friction velocity, \( z_0 \) is the surface roughness, and \( d' \) is the zero plane displacement height. For conditions of neutral stability, \( u^* \) is given by:

\[
u^* = \frac{k \cdot U \ln \left( \frac{z_r - d'}{z_0} \right)}{\ln \left( \frac{z_r - d'}{z_0} \right)}
\]

(34)

where \( U \) is the wind speed at the reference \( z_r \).

Within the canopy, the eddy diffusion coefficient decreases exponentially (Shuttleworth and Gurney, 1990) and \( K(z) \) is given by the expression:

\[
K(z) = Kh \cdot \exp \left( \alpha \cdot \left( \frac{z}{h} - 1 \right) \right) \quad z<h
\]  

(35)

where \( Kh \) is the value of \( K(z) \) at the top of the canopy, \( Kh=K(z) \) for \( z=h \), where \( h \) is the height of vegetation, and \( \alpha \) is the attenuation coefficient. A value of \( \alpha=2.5 \) which is typical for agricultural crops was recommended by Shuttleworth and Wallace (1985) and Shuttleworth and Gurney (1990).

Integration of equation (32) gives the following expression for \( ra_m \):
\[
ra_m = \frac{1}{k \cdot u^*} \cdot \ln \left( \frac{z_r - d'}{h - d'} \right) + \frac{h}{\alpha \cdot Kh} \cdot \exp \left( \alpha \cdot \left( 1 - \frac{z_o + d'}{h} \right) \right) - 1 \]

The excess resistance term for heat transfer, \( rb_h \), can be expressed as (Verma, 1989):

\[
rb_h = \frac{k \cdot B^{-1}}{k \cdot u^*} \tag{37}
\]

where \( B^{-1} \) represents a dimensionless bulk parameter. Thom (1972) suggests that \( B^{-1} \) equal 4 for most arable crops, therefore the product \( kB^{-1} \) was assumed to be equal to 2 for this model.

To calculate the aerodynamic resistance to water vapor transfer \( ra_w \), the expression for the excess term, was modified to account for the fact that the basic information was derived from heat transfer observations primarily (Wesely and Hicks, 1977). Therefore for water vapor transfer \( rb_w \) is calculated as:

\[
rb_w = \frac{k \cdot B^{-1}}{k \cdot u^*} \left( \frac{k_1}{Dv} \right)^{2/3} \tag{38}
\]

where, \( k_1 \) is the thermal diffusivity and \( Dv \) is the molecular diffusivity of water vapor in air.

Similarly Shuttleworth and Gurney (1990) expressed the aerodynamic resistance \( (r_2) \) between the soil surface and the sink of momentum in the canopy as:

\[
\begin{align*}
  r_2 = & \int_{z_o'}^{d + z_o} \frac{1}{K(z)}dz \\
  & \tag{39}
\end{align*}
\]

where \( z_o' \) is the roughness length of the soil surface. The integration of equation (39) gives the following expressions for \( r_2 \):
\[ r_2 = \frac{h \cdot \exp(\alpha)}{\alpha \cdot K_h} \left( \exp\left(-\frac{\alpha \cdot z_0}{h}\right) - \exp\left(-\frac{\alpha \cdot (d' + z_0)}{h}\right) \right) \]  

(40)

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 and Gurney, 1990). No attempt has been made to account for stability effects.

Values of surface roughness \( z_0 \) and displacement height \( d' \) are functions of leaf area index (LAI) given by (Shaw and Pereira, 1982):

\[
zo = \begin{cases} 
z_0' + 0.3 \cdot h \cdot X^{1/2} & 0 \leq X \leq 0.2 \\
0.3 \cdot h \cdot \left(1 - \frac{d'}{h}\right) & 0.2 < X \leq 1.5 
\end{cases}
\]

(41)

where

\[ d' = 1.1 \cdot h \cdot \ln\left(1 + X^{0.25}\right) \]

(42)

and,

\[ X = C_d \cdot LAI \]

(43)

where \( z_0' \) is the roughness length of the soil surface, \( h \) is the height of vegetation and \( C_d \) is the mean drag coefficient for individual leaves.

**Canopy Resistance.**

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 and Wallace, 1985).

The mean boundary layer resistance is given by:

\[ r_1 = \frac{r_b}{2 \cdot LAI} \]

(44)
where \( r_b \) is the resistance of the leaf boundary layer, which is proportional to the temperature difference between leaf and surrounding air divided by the associated flux (Choudhury and Monteith, 1988).

According to Shuttleworth and Wallace (1985), the resistance \( r_b \), exhibits some dependence on in-canopy wind speed, with typical values measured in the order of 25 \( \text{s m}^{-1} \). Using \( r_b = 25 \text{ s m}^{-1} \) for a LAI=4, the corresponding canopy boundary layer resistance is \( r_1 = 3 \text{ s m}^{-1} \). Shuttleworth and Gurney (1990) presented the following equation for \( r_b \).

\[
rb = \frac{100}{\alpha} \left( \frac{w}{uh} \right)^{1/2} \left( 1 - \exp \left( -\frac{\alpha}{2} \right) \right)^{-1}
\]  

(45)

where \( w \) is the representative leaf width and \( uh \) is the wind speed at the top of the canopy. In practice this resistance is only significant when acting in combination with a much larger canopy surface resistance. Similarly, Shuttleworth and Gurney (1990) suggest that \( r_1 \) could be neglected for foliage completely covering the ground.

Canopy resistance, \( r_c \), can be calculated by dividing the surface resistance for a single leaf (\( r_l \)) by the effective canopy leaf area index (LAI) (Szeicz and Long, 1969).

\[
rc = \frac{r_l}{\text{LAI}}
\]  

(46)

Under natural conditions, there are five main environmental factors affecting stomata resistance, more frequently named for its reciprocal stomata conductance: solar radiation, air temperature, humidity, \( \text{CO}_2 \) concentration and soil water potential (Yu et al., 2004). Several models have been developed to improve the estimations of stomata conductance and canopy resistance \( r_c \). Stannard (1993) proposed a model to estimate \( r_c \) as a function of vapor pressure deficit, leaf area index, and solar radiation with the following expression:
\[ rc = \left[ C_1 \cdot \frac{\text{LAI}_{\text{max}}}{\text{LAI}} \cdot \frac{C_2}{C_2 + \text{VPD}_a} \cdot \frac{\text{Rad} \cdot (\text{Rad}_{\text{max}} + C_3)}{\text{Rad}_{\text{max}} \cdot (\text{Rad} + C_3)} \right]^{-1} \]  

(47)

where LAI max is the maximum value of leaf area index, VPD_a is vapor pressure deficit, Rad is solar radiation, Radmax is maximum value of solar radiation (estimated at 1000 W m\(^{-2}\)) and C_1, C_2 and C_3 are regression coefficients.

**Soil Resistance.**

According to Farahani and Ahuja (1996), for a given surface soil layer of thickness Lt, the resistance to vapor flux from the diffused evaporating sites to the surface varies between a very low value at saturation to an upper limit when the layer is entirely dry. This upper limit of soil resistance can be expressed by:

\[ r_{so} = \frac{Lt \cdot \tau_s}{D_v \cdot \phi} \]  

(48)

where \( \tau_s \) is a soil tortuosity factor, \( D_v \) is the water vapor diffusion coefficient and \( \phi \) is soil porosity. Farahani and Bausch (1995), Anadranistakis et al. (2000) and Lindburg (2002) found that soil resistance \( r_s \) can be related to measured volumetric soil water content in the top soil layer. Using a number of soil evaporation data sets, Farahani and Ahuja (1996) found that the ratio of soil resistance when the layer Lt is wet, to its upper limit when the layer Lt is dry relates to the degree of soil water saturation (\( \theta/\theta_s \)) and can be described by an exponential decay function as:

\[ r_s = r_{so} \cdot \exp \left( -\beta \cdot \frac{\theta}{\theta_s} \right) \]  

(49)

where \( \theta \) is the average volumetric water content, \( \theta_s \) is the saturation water content in the surface layer Lt, and \( \beta \) is a fitting parameter. In equation (45), \( \theta \) measurements from the
top 0.05 m soil layer were found to be more effective in modeling $r_s$ than $\theta$ from thinner layers.

Choudhury and Monteith (1988) expressed the soil resistance for heat flux ($r_L$) in the lower layer of soil extending from depth $L_t$ to $L_m$ as:

$$r_L = \frac{\rho \cdot C_p \cdot (L_m - L_t)}{K} \quad (50)$$

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

$$r_u = \frac{\rho \cdot C_p \cdot L_t}{K'} \quad (51)$$

Residue Resistance.

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 near the soil surface by developing very strong horizontal gradients across bare soil—mulched soil boundaries. In general, the vapor conductance through residue has been described empirically as a linear function of wind speed. Farahani and Ahuja (1996) based on Tanner and Shen (1990) expressed the evaporative resistance of surface residue ($r_r$) as:

$$r_r = \frac{L_r \cdot \tau_r}{D_v \cdot \phi_r} \left(1 + 0.7 \cdot u_2\right)^1 \quad (52)$$

where $L_r$ is residue thickness, $\tau_r$ is residue tortuosity, $D_v$ is vapor diffusivity in still air, $\phi_r$ is residue porosity and $u_2$ is wind speed measured two meters above the surface. Due to highly porous nature of field crop residue layers, the ratio $\tau_r/\phi_r$ may be assumed unity for modeling purposes (Farahani and 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:

\[
r_{rh} = \frac{\rho \cdot C_p \cdot L_r}{K_r}
\]

where \( L_r \) is the thickness of the residue layer, and \( K_r \) is the residue thermal conductivity.

The fraction of the soil covered by residue (\( fr \)) can be estimated using the amount and type of crop residue (Steiner et al., 2000). Gregory (1982) developed and equation to estimate \( fr \) as:

\[
fr = 1 - \exp(-A_m \cdot M)
\]

where \( M \) is the density of dry surface residue (ton ha\(^{-1}\)) and \( A_m \) is a constant that varies with residue characteristics and randomness of distribution and converts mass to an equivalent area. Gregory (1982) estimated \( A_m \) to be 0.4-0.7, 0.5, 0.4, 0.2, 0.2 and 0.1 for soybean, wheat, maize, sunflower, soybeans stems and cotton stems respectively. An estimate of residue thickness (\( L_r \)) may be obtained from:

\[
L_r = \frac{0.1 \cdot M}{fr \cdot (1 - \phi_r) \cdot \rho_r}
\]

where \( \rho_r \) is residue specific density (170, 298 and 260 kg m\(^{-3}\) for wheat, maize and sorghum respectively from Farahani and Ahuja, 1996).

Equations (30) to (55) describe parameters and resistances required by the model. Model inputs necessary to solve the surface energy balance 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. All others parameters can be calibrated or predefined from literature accordingly with canopy, soil and residue characteristics.
Similar to Shuttleworth and Wallace (1985) and Choudhury and Monteith (1988) models, measurements of incoming net radiation and estimations of net radiation absorbed by the canopy are necessary by the SEB model.

**Net Radiation**

Using the Beer’s law to estimate the radiation passing through the canopy, the proposed modified SEB model assumes that net radiation reaching the surface (Rns) can be calculated with the following relationship (Shuttleworth and Wallace, 1985; Monteith and Unsworth, 2008):

\[
R_{ns} = R_n \cdot \exp(-C_{ext} \cdot \text{LAI})
\]  

(56)

where \(C_{ext}\) is the extinction coefficient of the crop for net radiation. Consequently, net radiation absorbed by the canopy (Rnc) can be estimated as:

\[
R_{nc} = R_n - R_{ns}
\]  

(57)
Conclusions

A surface energy balance model based on the Shuttleworth-Wallace (1985) and Choudhury and Monteith (1988) models was modified to account for the effect of residue, soil evaporation and canopy transpiration on total evapotranspiration. The model describes the energy balance of partially vegetated and residue-covered surfaces in terms of driving potential and resistances to flux. The proposed SEB model assumed that horizontal gradients of the potentials are small enough for lateral fluxes to be ignored. Physical and biochemical energy storage terms in the canopy/residue/soil system are assumed to be negligible. An important feature of the model is the ability to estimate latent, sensible and soil heat fluxes for model evaluation. Others differences with the original model proposed by Choudhury and Monteith (1988) and Shuttleworth Wallace (1985) were the improvements in aerodynamic resistances for heat and water transfer, and canopy resistance for water flux, the incorporation of new residue resistances for heat and water transport and the definition of a new soil resistance for water transfer.

Net radiation is one of the inputs in the proposed surface energy balance model and provides the energy needed for soil evaporation, transpiration and heat transfer through the canopy, soil/residue surfaces and the atmosphere. Weather inputs required by the model are: solar radiation, air temperature, relative humidity, and wind speed; canopy inputs are: LAI and crop height; and soil/residue inputs are: soil texture, soil temperature, soil water content, residue type and amount.

A detailed sensitivity analysis of model parameters and resistances is necessary to evaluate the sensitivity of ET estimation under different canopy conditions. Further evaluation of model with measured data is also necessary to fully test the model for
representative conditions under agricultural and natural ecosystems and to evaluate the model performance during growing and dormant seasons.
References


Weseley M.L., and Hicks B.B., 1977. Some factors that affect the deposition rates of sulfur dioxide and similar gases on vegetation. *Journal of the Air Pollution Control Association*, 27(11), 1110-1116.

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 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 growing conditions are appropriately represented by the idealized Kc values (Parkes et al., 2005; Rana et al., 2005; Katerji and Rana, 2006 and Flores, 2007). In addition, it is difficult to predict the correct crop growth stage 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 has been studied by several authors (Stannard, 1993; Farahani and Bausch, 1995; Rana et al., 1997; Alves and Pereira, 2000; Kjelgaard and Stockle, 2001; Ortega-Farias et al., 2004; Shuttleworth, 2006; Katerji and Rana, 2006; Flores, 2007 and 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 P-M model can be improved for ET estimations under 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 model (Choudhury and Monteith, 1998)). These extended approaches provide the potential for modeling ET for the entire range of plant cover and the ability of partitioning ET between crop transpiration and soil evaporation. The advantage of these models has been recognized by several authors (Shuttleworth and Gurney, 1990; Farahani and Auja, 1996; Stannard, 1993; Massman, 1992; Gardiol et al., 2003; Iritz et al., 2001; Tourula and Heikinheimo, 1998; Ortega-Farias et al., 2007; Anadranistakis et al., 2000; Alves and Cameira, 2002; and Lafleur and Rouse, 1990). Results from using multiple-layer models are encouraging, as the models performed satisfactorily for the entire range of canopy cover.

Recognizing the potential of multiple-layer models to estimate ET a modified surface energy balance model (SEB) was developed (Chapter 2 of this research) to include the effect of crop residue on evapotranspiration. The model relies mainly on the Shuttleworth-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. The background and procedures of the SEB model were described in the previous chapter and only a brief summary is included here. The objective of this work was to perform a sensitivity analysis of model parameters and evaluate the performance of the proposed model to estimate ET during
the growing and non-growing season of maize (*Zea Mays* L.) and soybean (*Glycine max*). Results were compared against measurements made at three sites using eddy covariance systems.

**Objectives**

The general goal of this work was to evaluate the performance of the proposed surface energy balance model to predict ET from irrigated and rainfed maize-soybean cropping systems.

The specifics objectives are to:

i. Evaluate the sensitivity of the proposed SEB model to changes in parameter values and model resistances.

ii. Predict evapotranspiration with the SEB model during the growing and non-growing season of maize and soybean under irrigated and rainfed conditions.

iii. Statistically compare ET predicted from the SEB model and ET measured from three eddy covariance systems.
Materials and Methods

Study Sites

Three sites located at the University of Nebraska Agricultural Research and Development Center (ARDC) near Mead, NE were used for model evaluation. Fields area ranges from 49 to 65 ha, providing sufficient fetch of uniform cover required for adequately measuring mass and energy fluxes using eddy covariance systems (Verma et al., 2005). Site 1 is an irrigated (center pivot) continuous maize system (41°17’N, 96°48’W); Site 2 is an irrigated (center pivot) maize-soybean rotation system (41°16’N, 96°47’W); and Site 3 is a rainfed maize-soybean rotation system (41°18’N, 96°44’W) (Verma et al., 2005). Maize was grown at site 2 and 3 during 2003 and 2005, while soybeans were grown in 2002 and 2004. The soil at the ARDC is a deep silty clay loam, typical of eastern Nebraska (Suyker and Verma, 2008). The fields have been farmed in no-tillage system since 2001. Information about planting densities, residue and grain yield are provided in Table 3.1. Other crop management practices information are given in Verma et al. (2005).

Soil water content in the root zone was measured continuously at four depths (0.10, 0.25, 0.5 and 1.0 m) by employing Theta probes (Delta-T Device, Cambridge, UK). Soil temperature was measured at 0.06, 0.1, 0.2 and 0.5 m depths (Platinum RTD, Omega Engineering, Stamford, CT). Green leaf area index and biomass measurements were made approximately bi-monthly during the growing season. Residue biomass was measured each year after harvest and exponential decay rates of stoves were used to estimate residue during the year (Verma et al., 2005, Suyker and Verma 2008b). At three sites, eddy covariance measurements of latent heat, sensible heat, and momentum fluxes
were made using an omnidirectional three dimensional sonic anemometer (Model R3, Gill Instruments Ltd., Lymington, UK) and an open-path infrared CO2/H2O gas analyzer system (Model LI7500, Li-cor inc, Lincoln, NE). Details of these and supporting meteorological measurements are provided in Verma et al. (2005).

Table 3.1. Crop management details at all Sites.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td>Maize</td>
<td>Soybean</td>
<td>Soybean</td>
</tr>
<tr>
<td>Planting date</td>
<td>May 9</td>
<td>May 20</td>
<td>May 20</td>
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<tr>
<td>Harvest date</td>
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<td>October 7</td>
<td>October 9</td>
</tr>
<tr>
<td>Grain yield (kg ha(^{-1}))</td>
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<td>3320</td>
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<td>370644</td>
<td>370644</td>
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<tr>
<td>Residue after harvest (kg ha(^{-1}))</td>
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<td>12492</td>
<td>9528</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td>Maize</td>
<td>Maize</td>
<td>Maize</td>
</tr>
<tr>
<td>Planting date</td>
<td>May 15</td>
<td>May 14</td>
<td>May 13</td>
</tr>
<tr>
<td>Harvest date</td>
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<td>October 23</td>
<td>October 11</td>
</tr>
<tr>
<td>Grain yield (kg ha(^{-1}))</td>
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<td>64292</td>
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<tr>
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<td>Soybean</td>
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<tr>
<td>Planting date</td>
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<td>June 2</td>
<td>June 3</td>
</tr>
<tr>
<td>Harvest date</td>
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<td>October 19</td>
<td>October 11</td>
</tr>
<tr>
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<tr>
<td>2005</td>
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<tr>
<td>Crop</td>
<td>Maize</td>
<td>Maize</td>
<td>Maize</td>
</tr>
<tr>
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<td>May 2</td>
<td>April 26</td>
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<td>Harvest date</td>
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<td>October 17</td>
<td>October 18</td>
</tr>
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<td>9100</td>
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<tr>
<td>Residue after harvest (kg ha(^{-1}))</td>
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<td>17648</td>
<td>14780</td>
</tr>
</tbody>
</table>
The Modified Surface Energy Balance Model for Evapotranspiration (SEB)

An extension of the Choudhury and Monteith (1988) and Shuttleworth Wallace (1985) models was proposed in the second chapter of this work. The surface energy balance model presented by Choudhury and Monteith (1988) was modified and extended to include the effect of crop residue on the surface energy balance of sparse canopy surfaces and to estimate ET for a wide range of field conditions.

The modified surface energy balance (SEB) model has four layers (Figure 3.1a). 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 at least for 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.

Total latent heat flux from the canopy/residue/soil system (λE) is the sum of the latent heat from the canopy (transpiration) λEc, latent heat from the soil λEs and latent heat from the residue covered soil (evaporation) λEr, calculated as:

\[
\lambda E = \lambda Ec + (1 - fr) \cdot \lambda Es + fr \cdot \lambda Er
\]  

(1)

where \(fr\) is the fraction of the soil affected by residue.
By analogy with Ohm’s law, the differences in vapor pressure between two levels can be written in terms of resistance and latent heat flux as illustrated in Figure 3.1 b (Shuttleworth and Wallace, 1985).

The latent heat flux from the canopy ($\lambda_{Ec}$), the latent heat flux from the bare soil surface ($\lambda_{Es}$) and the latent heat fluxes from the soil affected by residue ($\lambda_{Er}$) can be expressed by:

a) Canopy:

Latent heat flux from the canopy is given by:

$$\lambda_{Ec} = \frac{\Delta \cdot r_i \cdot R_{nc} + \rho \cdot C_p \cdot (e_b^* - e_b)}{\Delta \cdot r_i + \gamma \cdot (r_i + r_c)}$$  \hspace{1cm} (2)

b) Bare soil:

Latent heat flux from bare soil surfaces $\lambda_{Es}$ can be estimated by:

$$\lambda_{Es} = \left\{ \frac{R_{ns} \cdot \Delta \cdot r_2 \cdot r_L + \rho \cdot C_p \cdot ((e_b^* - e_b) \cdot (ru + r_L + r_2))}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta \cdot r_L \cdot (ru + r_2)} \right\}$$  \hspace{1cm} (3)
Figure 3.1 a) Fluxes of the surface energy balance model and b) A schematic resistance network of the SEB model for latent heat flux.
c) Residue covered soil:

Similarly to bare soil latent heat flux from the residue covered soil $\lambda Er$ can be estimated by:

$$
\lambda Er = \frac{\left( Rns \cdot \Delta_4 \cdot (r_L + r_{rh}) \cdot r_1 + \rho \cdot Cp \cdot (e_b^* - eb) \cdot (ru + r_L + r_2 + r_{rh}) \right)}{\gamma \cdot (r_2 + rs + rr) \cdot (ru + r_L + r_2 + r_{rh}) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_{rh})}
$$

where $Rnc$ is the net radiation absorbed by the canopy and $Rns$ is the net radiation absorbed by the soil, $\rho$ is the density of moist air, $Cp$ is the specific heat of air and $\gamma$ is the psychrometric constant. Variable $\Delta_i$ is the mean rate of change of saturated vapor pressure with temperature between two levels. Values for $\Delta_1$, $\Delta_2$, $\Delta_3$ and $\Delta_4$ are necessary to solve the model. Choudhury and Monteith (1988) found that using only $\Delta$, evaluated at $Ta$, usually gave the components of the heat balance with acceptable accuracy. Therefore $\Delta$ evaluated at $Ta$ is used here. Variable $eb$ is the vapor pressure of the atmosphere at the canopy level, $e_b^*$ is the saturation vapor pressure of the atmosphere at the canopy level, $e_1^*$ is the saturation vapor pressure at the canopy and $e_L^*$ is the saturation vapor pressure at the top of the wet layer. Variable $Tb$ represents the air temperature at canopy height and $Tm$ is the temperature at the bottom of the lower layer.

Parameter $r_1$ is an aerodynamic resistance between the canopy and the air within the canopy, $rc$ is the surface canopy resistance, $r_2$ is the aerodynamic resistance between the soil and the canopy, $rs$ is the resistance to the diffusion of water vapor through the soil at the top soil layer, and $rrh$ and $rr$ are the residue resistance to transfer of heat and vapor flux respectively. Variables $ru$ and $r_L$ are resistance to the transport of heat for the upper and lower soil layer respectively.
The modified SEB model is applicable to conditions ranging from fully closed canopies to surface with bare soil partially covered with residue. Values for Tb and eb are necessary to estimate latent heat and sensible heat fluxes in equation (2) through (4). The detailed expression for this parameters were described in the previous chapter.

**SEB Model Parameters**

Aerodynamic resistances to water vapor transfer above (ra\textsubscript{w}) and below the canopy (r\textsubscript{2}) were presented by Shuttleworth and Wallace (1985) and later enhanced by Shuttleworth and Gurney (1990) based on the work of Choudhury and Monteith (1988) and Shaw and Pereira (1982) as:

\[
ra \textsubscript{w} = ra \textsubscript{m} + rb \textsubscript{w} \tag{5}
\]

\[
r_2 = \frac{h \cdot \exp(\alpha)}{\alpha \cdot Kh} \cdot \left( \exp\left(\frac{-\alpha \cdot zo'}{h}\right) - \exp\left(\frac{-\alpha \cdot (d + zo)}{h}\right) \right) \tag{6}
\]

\[
ra \textsubscript{m} = \frac{1}{k \cdot u^*} \cdot \ln\left(\frac{zr - d}{h - d}\right) + \frac{h}{\alpha \cdot Kh} \cdot \left( \exp\left(\alpha \cdot \left(1 - \frac{zo + d}{h}\right)\right) - 1 \right) \tag{7}
\]

\[
rb \textsubscript{w} = k \cdot B^{-1} \left( \frac{k_1}{Dv} \right)^{2/3} \tag{8}
\]

where ra\textsubscript{m} is the aerodynamic resistance to momentum transfer and rb\textsubscript{w} is an excess resistance terms for water vapor transfer, \( \alpha \) is the attenuation coefficient, zo’ is the roughness length of the soil surface, zo is the surface roughness, h is the height of vegetation and d is the displacement height. The eddy diffusion coefficient at the top of the crop is represented by Kh while k is the von Karman constant, zr is the reference height and u* is the friction velocity, B\textsuperscript{-1} represents a dimensionless bulk parameter.
Thom (1972) suggests that $kB^{-1}$ equal approximately 2 for most arable crops. $k_1$ is the thermal diffusivity and $D_v$ is the molecular diffusivity of water vapor in air.

The aerodynamic boundary layer resistance ($r_1$) was defined as $r_1 = rb \cdot (2 \cdot LAI)^{-1}$, where the resistance of the leaf boundary layer ($rb$) is calculated following Shuttleworth and Gurney (1990) as:

$$rb = \frac{100}{\alpha} \cdot \left(\frac{w}{uh}\right)^{1/2} \cdot \left(1 - \exp\left(-\frac{\alpha}{2}\right)\right)^{-1}$$

(9)

where $w$ is the representative leaf width and $uh$ is the wind speed at the top of the canopy.

To estimate the surface canopy resistance ($rc$), Stannard (1993) proposed a model as a function of vapor pressure deficit, leaf area index and solar radiation with the following expression:

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

(10)

where $LAI_{max}$ is maximum value of leaf area index, $VPDa$ is vapor pressure deficit, $Rad$ is solar radiation, $Rad_{max}$ is maximum value of solar radiation (estimated at 1000 W m$^{-2}$) and $C_1$, $C_2$ and $C_3$ are regression coefficients.

Using a number of soil evaporation data sets, Farahani and Ahuja (1996) expressed the soil surface resistance ($rs$) as:

$$rs = \frac{Lt \cdot \tau_s}{D_v \cdot \phi} \cdot \exp\left(-\beta \cdot \frac{\theta}{\theta_s}\right)$$

(11)

where $\tau_s$ is a soil tortuosity factor, $D_v$ is the water vapor diffusion coefficient, $\phi$ is soil porosity, $\theta$ is the average volumetric water content and $\theta_s$ saturation water content in the surface layer $Lt$, and $\beta$ is a fitting parameter.

Similarly the evaporative resistance of surface residue ($rr$) was expressed as:
\[ \text{rr} = \frac{L_r \cdot \tau_r}{D_v \cdot \phi_r} \left( 1 + 0.7 \cdot u_2 \right)^{-1} \] (12)

where \( L_r \) is residue thickness, \( \tau_r \) is residue tortuosity, \( D_v \) is vapor diffusivity in still air, \( \phi_r \) is residue porosity and \( u_2 \) is wind speed measured two meters above the surface.

The resistance to the transport of heat for the upper (ru) and lower (rl) soil layers, and the residue cover (rh) were estimated according to the following equations:

\[ \text{ru} = \frac{\rho \cdot C_p \cdot L_t}{K'} \] (13)

\[ \text{rl} = \frac{\rho \cdot C_p \cdot (L_m - L_t)}{K} \] (14)

\[ \text{rh} = \frac{\rho \cdot C_p \cdot L_r}{K_r} \] (15)

where \( L_t \) is the thickness of the top soil layer, \( K' \) is the thermal conductivity of the soil for the upper layer, \( L_m \) is the distance from the soil surface to the bottom of the lower soil layer and \( K \) is the thermal conductivity of the soil for the lower layer, \( L_r \) is the thickness of the residue layer, and \( K_r \) is the thermal conductivity of the residue.

**Model Performance**

There are several statistical techniques used to evaluate the performance of physical models (Legates and McCabe, 1999). The coefficient of determination \( (r^2) \), the Nash-Sutcliffe coefficient \( (E) \), the index of agreement \( (d) \), the root mean square error \( (\text{RMSE}) \) and the mean absolute error \( (\text{MAE}) \) are common techniques used for model evaluation (Legates and McCabe, 1999; Krause et al., 2005; Moriasi et al., 2007 and Coffey et al., 2004). These statistics criteria were used at all sites to evaluate the performance of the SEB model during complete years and periods of the growing season:
\[ r^2 = \frac{\sum_{j=1}^{n}(ET_{mea_j} - \bar{ET}_{mea})(ETest_j - \bar{ETest})}{\left(\sum_{j=1}^{n}(ET_{mea_j} - \bar{ET}_{mea})^2\right)^{0.5} \left(\sum_{j=1}^{n}(ETest_j - \bar{ETest})^2\right)^{0.5}} \]  

\[ E = 1 - \frac{\sum_{j=1}^{n}(ET_{mea_j} - ETest_j)^2}{\sum_{j=1}^{n}(ET_{mea_j} - \bar{ET}_{mea_j})^2} \]  

\[ d = 1 - \frac{\sum_{j=1}^{n}(ET_{mea_j} - ETest_j)^2}{\sum_{j=1}^{n}(ETest_j - \bar{ET}_{mea_j})^2 + (ET_{mea_j} - \bar{ET}_{mea})^2} \]  

\[ RMSE = \sqrt{\frac{\sum_{j=1}^{n}(ET_{mea_j} - ETest_j)^2}{n}} \]  

\[ MAE = \frac{\sum_{j=1}^{n}|ET_{mea_j} - ETest_j|}{n} \]  

where \( n \) is the total number of observations.
Results

Sensitivity Analysis

A sensitivity analysis was performed to evaluate the response of the modified SEB model to changes in resistances and model parameters. Calculations were made for the meteorological conditions, crop characteristics and soil/residue characteristics given in Table 3.2. Such conditions are typical for midday during the growing season of maize in southeastern Nebraska.

The sensitivity of total latent heat from the system, using the extended SEB model, 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 ($\lambda E$) and changes in the crop transpiration ratio (Transpiration ratio). The transpiration ratio is the ratio between crop transpiration ($\lambda Ec$) over total ET (Transpiration ratio = $\lambda Ec / \lambda E$).

Net radiation absorption. Calculations of total ET and the transpiration ratio were made for the conditions and parameters given in Table 3.2, except that $C_{ext}$ was altered. Three values of the extinction coefficient ($C_{ext}$= 0.4, 0.6 and 0.8) were used. Results showed that under these conditions the response of total ET to changes on $C_{ext}$ was small (Figure 3.2a), generally less than 1% for all values of LAI. However, higher differences were found for the transpiration ratio (Figure 3.2b), 1-6%, with the highest percentage when $1 < \text{LAI} < 2$. 
Table 3.2. Predefined conditions for the sensitivity analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Radiation</td>
<td>Rn</td>
<td>500</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Ta</td>
<td>25</td>
<td>°C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>68</td>
<td>%</td>
</tr>
<tr>
<td>Wind speed</td>
<td>u</td>
<td>2</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>Soil Temperature at 0.5 m</td>
<td>Tm</td>
<td>21</td>
<td>°C</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Rad</td>
<td>700</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Canopy resistance coeff.</td>
<td>C1, C2, C3</td>
<td>5, 0.005, 300</td>
<td></td>
</tr>
<tr>
<td>Maximum leaf area index</td>
<td>LAImax</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Soil water content</td>
<td>Θ</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Saturation soil water content</td>
<td>Θₛ</td>
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<td></td>
</tr>
<tr>
<td>Soil porosity</td>
<td>φ</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Soil tortuosity</td>
<td>τₛ</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Residue fraction</td>
<td>fr</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Thickness of the residue layer</td>
<td>Lᵣ</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>Residue tortuosity</td>
<td>τᵣ</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Residue porosity</td>
<td>φᵣ</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Upper layer thickness</td>
<td>Lₜ</td>
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<td>m</td>
</tr>
<tr>
<td>Lower layer depth</td>
<td>Lₘ</td>
<td>0.5</td>
<td>m</td>
</tr>
<tr>
<td>Soil roughness length</td>
<td>Zo'</td>
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<td>m</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>Cd</td>
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<td></td>
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<td>Reference height</td>
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<td>3</td>
<td>m</td>
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<tr>
<td>Attenuation coefficient</td>
<td>α</td>
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<td></td>
</tr>
<tr>
<td>Maximum solar radiation</td>
<td>Radmax</td>
<td>1000</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Extinction coefficient</td>
<td>Cext</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Mean leaf width</td>
<td>w</td>
<td>0.08</td>
<td>m</td>
</tr>
<tr>
<td>Water vapor diffusion coefficient</td>
<td>Dᵥ</td>
<td>2.56x10⁻⁵</td>
<td>m² s⁻¹</td>
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<tr>
<td>Fitting parameter</td>
<td>β</td>
<td>6.5</td>
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<td>Soil thermal conductivity, upper layer</td>
<td>K</td>
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<td>W m⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>Soil thermal conductivity, lower layer</td>
<td>K’</td>
<td>1.1</td>
<td>W m⁻¹ °C⁻¹</td>
</tr>
</tbody>
</table>
Figure 3.2 a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio ($\lambda_{Ec}/\lambda_{E}$), for three extinction coefficients (0.4, 0.6 and 0.8).
**Vapor pressure deficit.** Three values of vapor pressure deficit were used to evaluate their effect on total ET and the transpiration ratio. Calculations were made for: VPDa = 0.5 kPa, 1.0 kPa and 2.5 kPa under different values of LAI. Result shows that total ET for a VPDa = 1.0 kPa was 7-30% higher than total ET for a VPDa = 0.5 kPa, with the higher difference when LAI=0 (Figure 3.3a). In general, when VPDa was 2.5 kPa total ET was higher than total ET for a VPDa= 0.5 kPa, however, the effect of a high vapor pressure on total ET was reduced at higher LAI because of its effect on canopy resistance in equation (10). Transpiration ratio differences for VPDa= 0.5, 1.0 and 2.5 kPa were between 0-19% with the higher difference for a LAI= 0.5. Minimum differences were observed for LAI> 3 (Figure 3.3b).

**Soil temperature.** Soil temperature, Tm, is required for the SEB model. Measurements of soil temperature are very common for 10 cm below the soil surface and becoming more popular for 20 and 50 cm in weather stations networks. However, partial canopy cover shading, variation in soil thermal properties and/or different moisture content may amplify the variation of Tm. Therefore, it seemed appropriate to evaluate how sensitive the SEB model was to changes in Tm. Estimations were made for three soil temperatures: Tm=21°C, 0.8xTm=16.8 °C and 1.2xTm=25.2 °C. The response of total ET to changes in ± 4.2°C in Tm was generally less than 3% (Figure 3.4a). Similarly, the effects on the transpiration ratio for different LAI conditions were minimal with differences of less than 1% (Figure 3.4b).
Figure 3.3 a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio as function of LAI, for three levels of vapor pressure deficit at the reference height (VPD_a = 0.5, 1.0 and 2.0 KPa).
Figure 3.4 a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio, for three values of soil temperature (Tm x 0.8, Tm and Tm x 1.2), Tm=21°C.
Aerodynamic resistance. Calculations of total ET and the transpiration ratio were made for changes in three quantities used in the parameterization of $r_a$: the attenuation coefficient, $\alpha$, the mean boundary layer resistance, $r_b$, and crop height, $h$.

The attenuation coefficient, $\alpha$, describes the exponential decay in eddy diffusivity through a fully developed canopy. $\alpha$ affects aerodynamic resistance $r_2$ in equation (6), $r_a$ in equation (5), and the mean boundary layer resistance, $r_b$, in equation (9). A typical value for agricultural crops is $\alpha=2.5$ (Shuttleworth and Wallace, 1985, Shuttleworth and Gurney, 1990). The effect of three values for the attenuation coefficient was evaluated. Calculations were made for $\alpha=1$, 2.5 and 3.5. The response of total ET to changes in the attenuation coefficient, in general was small, with differences generally less than 2%. For LAI < 2, differences in total ET were in the range of 2-5% (Figure 3.5a). The effect of the three levels of $\alpha$ on the transpiration ratio was small for the range of LAI values, with differences of less than 2% (Figure 3.5b).

Changes in mean boundary layer resistance, $r_b$, of ±40% in equation (9) were made to test its effect on total ET and the transpiration ratio. As was expected, changes in $r_b$ had minimum effects on total ET. The response of total ET and the transpiration ratio for changes of ±40% on $r_b$ were irrelevant with differences of less than 1% for total ET (Figure 3.6a) and less than 1% for the transpiration ratio (Figure 3.6b).

The effect of changes in crop height during calculations of aerodynamic resistance, $r_2$, in equation (6) and $r_a$ in equation (5) was evaluated for a ±30% change in crop height. Results showed that a change in ±30% of crop height produced differences of less than 2% in total ET (Figure 3.7a) and less than 1% on the transpiration ratio for all LAI range (Figure 3.7b).
Figure 3.5 a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio, for three values of attenuation coefficient ($\alpha = 1, 2.5$ and 5).
Figure 3.6 a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio, for three leaf boundary layer resistances (22, 36 and 50 s m\(^{-1}\)).
Figure 3.7 a) Calculated total evapotranspiration and b) Transpiration ratio as function of LAI, for 30% change in crop height (0.7xh, h and 1.3xh).
Soil surface resistance. The effect of changes in the soil surface resistance, \( r_s \), on total ET and the transpiration ratio was evaluated. Calculations were performed for three values of \( r_s \): 0, 227, and 1500 s m\(^{-1}\). The first value corresponds to a wet soil or free water surface, a value of 227 s m\(^{-1}\) represent an intermediate value calculated with equation (11) for a 0.05 m soil layer with soil characteristics presented in Table 3.2. The third value of 1500 s m\(^{-1}\) corresponds to a relatively dry soil with soil water content \( \Theta = 0.1 \) and soil characteristics presented in Table 3.2. Result shows that total evapotranspiration is significantly altered by the condition of the soil, with the highest impact for low LAI conditions (Figure 3.8a). Differences in total ET range from 1-2% for a LAI of 5-6 to a value of 60% for LAI=0. The effect on the transpiration ratio was also significant with a minimum difference of 2% (LAI=6) and a maximum of 27% for a LAI of 0.5 (Figure 3.8b).

Residue surface resistance. Total ET and the transpiration ratio calculated by changes in the residue resistance, \( r_r \), are illustrated in Figure 3.9a and 3.9b. Estimations were made for four selected values of \( r_r \): 0, 400, 1000, and 2150 s m\(^{-1}\) and soil covered by residue fraction \( f_r = 0.5 \). The \( r_r = 0 \) condition represents no residue cover, a value of 400 s m\(^{-1}\) represents an intermediate value calculated with equation (12) for a 0.02 m residue layer with residue characteristics presented in Table 3.2 and wind speed of 2 m s\(^{-1}\) at 2 m. The third value of \( r_r = 1000 \) s m\(^{-1}\) corresponds to a second intermediate value calculated with equation (12) for a 0.055 m residue layer with residue characteristics presented in Table 3.2 and wind speed of 2 m s\(^{-1}\) measured at 2 m. The last value of \( r_r = 2150 \) s m\(^{-1}\) corresponds to an extreme calculated for a 0.055 m residue layer with residue characteristics presented in Table 3.2 and wind speed of 0 m s\(^{-1}\) measured at 2 m.
Figure 3.8 a) Calculated total evapotranspiration and b) Transpiration ratio as function of LAI, for three soil surface resistances ($rs=0$, $227$ and $1500$ s m$^{-1}$).
Results show that higher residue resistance values produced a reduction in total ET. For residue resistances less than 1000 s m\(^{-1}\), differences on total ET ranged from 0-18% with the highest differences for low LAI conditions (Figure 3.9a). A residue resistance of 2150 s m\(^{-1}\) significantly reduced ET, with differences of 1% to 25% when compared with total ET calculated with \(rr = 400 \text{ m s}^{-1}\). For residue resistances less than 1000 s m\(^{-1}\), the effect on the transpiration ratio range from a minimum difference of 0% to a maximum of 6% for a LAI = 0.5, but was generally less than 2% (Figure 3.9b). A residue resistance of 2150 s m\(^{-1}\) produced a maximum difference in the transpiration ratio of 7% (LAI = 0.5) when was compared with the transpiration ratio calculated with \(rr = 400 \text{ m s}^{-1}\).

**Canopy surface resistance.** According to equation (10) canopy surface resistance vary by changes in LAI. For a LAI=4, solar radiation of 700 W m\(^{-2}\), vapor pressure deficit of 1.0 kPa, and parameters given in Table 3.2 canopy surface resistance calculated with equation (10) gives a resistance of 65.8 s m\(^{-1}\). Changes of ±30% in surface canopy resistance calculated with equation (10) were used to test the effects of rc on total evapotranspiration under different LAI conditions. Results show that total ET was reduced for higher values of rc. As was expected, no effects of rc on total ET was found for LAI=0, however a difference of 9% was found when LAI=6 (Figure 3.10a). The effect on the transpiration ratio due to changes in rc is shown in figure 3.10b. Differences on transpiration ratio for ±30% of change in canopy resistance range within 1-10%. The highest impact was for 0.5 < LAI < 1.5.
Figure 3.9 a) Calculated total evapotranspiration and b) Transpiration ratio as function of LAI, for four residue surface resistances ($rs=0$, 400, 1000 and 2150 s m$^{-1}$).
Figure 3.10 a) Calculated total evapotranspiration and b) Transpiration ratio as a function of LAI, for 30% change in surface canopy resistance (0.7x rc, rc and 1.3 x rc).
Soil heat flux resistance. The effect of the soil heat flux resistance, \( r_u \), in total ET and transpiration ratio was tested for two conditions: (i) Changes of ±30 of \( r_u \), and (ii) changes in the soil layer thickness (\( L_t = 0.025, 0.05 \) and 0.1 m). Using equation (13) for a soil layer thickness of 0.05 m and a soil thermal conductivity of 0.8 W m\(^{-1}\) C\(^{-1}\) the soil heat flux resistance is 63.5 s m\(^{-1}\). Result showed that the changes in ±30% of \( r_u \) (\( r_u \) evaluated at 44.4 and 82.6 s m\(^{-1}\)) had minimum effects on total ET (Figure 3.11a), differences range between 0-8% with the highest value for LAI=0, but less than 3% when LAI>1.5. Differences in transpiration ratio for ±30% change in \( r_u \) were less than 4% for the LAI range (Figure 3.11b).

Total ET and the transpiration ratio calculated by changes in the thickness of the upper soil layer \( L_t \) are illustrated in Figure 3.12 a) and b). Estimations were made for three selected values of \( L_t \): \( L_t = 0.025, 0.05, \) and 0.1 m. Results show that total evapotranspiration was mainly altered by the upper soil layer thickness for low LAI conditions (LAI<1). Total ET was 17% lower when \( L_t = 0.1 \) m than for a \( L_t = 0.05 \) m (LAI=0), and was only 1% lower for LAI=6. Generally differences were less than 3% for LAI>2.5 (Figure 3.12a). The effect on the transpiration ratio was also more important for LAI<1. The maximum difference with respect to \( L_t = 0.05 \) was 8% for a LAI=0.5 (\( L_t = 0.1 \)m) and a minimum difference of 1% when LAI=6 (\( L_t = 0.025 \)m) (Figure 3.12b).

Similarly, changes of ±30% on the estimated soil heat resistance for the lower layer, \( r_l \), on total ET and the transpiration ratio was evaluated. \( r_l \) values of 290, 415 and 540 s m\(^{-1}\) were used. The response of total ET and the transpiration ratio for changes of ±30% on \( r_l \) were minimal with differences of less than 8% for total ET (generally less than 5% for LAI>2) and less than 2% for the transpiration ratio (Figure 3.13a and 3.13b).
Figure 3.11. a) Calculated total evapotranspiration and b) Transpiration ratio as function of LAI, for 30% change in soil resistance for heat flux (0.7x ru, ru and 1.3 x ru), upper layer.
Figure 3.12. a) Calculated total evapotranspiration and b) Transpiration ratio as function of LAI, for three upper layer thickness (lt = 0.025, 0.05 and 0.1 m).
Figure 3.13. a) Calculated total evapotranspiration as function of LAI and b) Transpiration ratio, for 30% change in soil resistance for heat flux (0.7 x rl, rl and 1.3 x rl), lower layer.
In general, the sensitivity analysis of model resistances showed that simulated ET was most sensitive to changes in canopy surface resistance for high LAI conditions, and soil surface resistance and residue surface resistance for low LAI conditions. The model was less sensitive to changes in the extinction coefficient, soil temperature, the attenuation coefficient, the surface boundary layer, errors in the crop height, and soil heat flux resistances.
**Model Evaluation**

Model evaluation is a two-step process that includes model calibration and model validation. However, to assure that the calibrated SEB model properly estimate evapotranspiration an evaluation of the energy balance closure of the measurements from the eddy covariance systems was performed.

**Energy Balance Closure**

Measured net radiation, Rn, was compared against the sum of measured latent heat flux (\(\lambda E\)), sensible heat flux (H), soil heat flux (G), and energy storage (S). It is difficult to accurately calculate all relevant energy storage terms. Here soil storage, canopy storage and energy used in photosynthesis were roughly approximated (Verma et al 2005). Linear regressions between hourly values of Rn and \(H + \lambda E + G + S\) for the three study sites were calculated during the 4 years of measurements (2002 to 2005). The regression slopes ranged from 0.82 to 0.93 (generally bigger than 0.87), giving a fairly good closure of the energy balance at all study sites. The coefficient of determination, \(r^2\), for all sites under study ranged from 0.96 to 0.97 (Table 3.3). The intercepts ranged from -2.5 to 4.65 (W m\(^{-2}\)), which can be considered insignificant for hourly values.
Table 3.3 Energy balance closure of eddy covariance measurements.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Regression</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2002</td>
<td>( Y=0.82X+2.06 )</td>
<td>0.96</td>
</tr>
<tr>
<td>1</td>
<td>2003</td>
<td>( Y=0.90X+1.04 )</td>
<td>0.97</td>
</tr>
<tr>
<td>1</td>
<td>2004</td>
<td>( Y=0.88X+1.22 )</td>
<td>0.97</td>
</tr>
<tr>
<td>1</td>
<td>2005</td>
<td>( Y=0.89X-1.11 )</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>2002</td>
<td>( Y=0.87X-2.50 )</td>
<td>0.96</td>
</tr>
<tr>
<td>2</td>
<td>2003</td>
<td>( Y=0.89X-1.65 )</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>2004</td>
<td>( Y=0.87X-1.40 )</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>2005</td>
<td>( Y=0.92X-3.31 )</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>2002</td>
<td>( Y=0.87X+4.65 )</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>2003</td>
<td>( Y=0.92X+1.63 )</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>2004</td>
<td>( Y=0.89X+3.02 )</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>2005</td>
<td>( Y=0.93X-0.25 )</td>
<td>0.97</td>
</tr>
</tbody>
</table>

\( X= Rn \ (W \ m^{-2}) \); \( Y=\lambda E+H+G+S \ (W \ m^{-2}) \)

Acceptable energy closure was found at all study sites, however for calibration purposes, measurements where the energy closure was within \( \pm 10\% \) were selected.

Figure 3.14 shows the energy closure during 2002 and 2003 at Site 2 for the whole year and the data selected for calibration. The regression slopes for the data selected for calibration was 0.97 and 0.96 during 2002 and 2003 respectively, with intercepts of -0.12 and -0.04 (W m\(^{-2}\)).
Figure 3.14 Energy closure for the eddy covariance measurements at Site 2 (all circles) and data selected for calibration (closed circles), a) Soybeans 2002 and b) Maize 2003.
**Model Calibration**

Soybeans and maize under irrigated conditions were used to calibrate the SEB model during the growing and non-growing seasons of 2002 and 2003 at Site 2. As a result of the sensitivity analysis, parameters affecting canopy resistance were used to adjust model ET estimations to eddy covariance measurements under high LAI conditions (LAI>2). Accordingly, parameters affecting soil and residue resistance were calibrated for low LAI conditions. The slopes of the regression between measured and estimated ET, the coefficient of determination, \( r^2 \), and the Nash-Sutcliffe coefficient, \( E \), were used to calibrate the model. Model parameters after calibration are presented in Table 3.4a, initial range of calibrated values are presented in parenthesis. All other non-calibrated parameters are presented in Table 3.4b.

Under high vapor pressure deficit conditions the canopy resistance calculated with equation (10) produce that the SEB model underestimate ET. To improve the performance of the SEB model under these conditions a change in the effect of VPDa in canopy resistance was introduced in this work. The modified equation is based on Stannard (1993) but with a different function for the effect of VPDa:

\[
rc = \left[ C_1 \cdot \frac{\text{LAI}}{\text{LAI}_\text{max}} \cdot \left( \frac{C_4}{1 - \exp(-\text{VPDa} / 10)} \right) \cdot \frac{\text{Rad} \cdot (\text{Rad max} + C_3)}{\text{Rad max} \cdot (\text{Rad} + C_3)} \right]^{-1} \quad \text{VPDa > 0}
\]

\[
rc = \left[ C_1 \cdot \frac{\text{LAI}}{\text{LAI}_\text{max}} \cdot \left( \frac{C_4}{0.1} \right) \cdot \frac{\text{Rad} \cdot (\text{Rad max} + C_3)}{\text{Rad max} \cdot (\text{Rad} + C_3)} \right]^{-1} \quad \text{VPDa = 0} \quad (21)
\]

Equation (21) has the same variables affecting canopy resistance as does equation (10), except values of parameters \( C_2 \) and \( C_4 \) can be different. Canopy resistance estimated with equation (10) and (21) is presented in Appendix 2 (Figure A2.1) under different
vapor pressure deficits conditions. The linear effect of VPDa in \( r_c \) is reduced by using the exponential function proposed in equation (21). The effect of three levels of VPDa in ET estimations using equation (21) is presented in Figure A2.2 (Appendix 2). From this figure total ET constantly increase under higher VPDa conditions.

Table 3.4a. Model parameters after calibration. In parenthesis initial range of calibrated parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value after Calibration</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canopy</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Canopy resistance coefficients, ( C_1 )</td>
<td>5</td>
<td>(4-6)</td>
<td></td>
</tr>
<tr>
<td>Canopy resistance coefficients, ( C_4 )</td>
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<td>(0.002-0.007)</td>
<td></td>
</tr>
<tr>
<td>Canopy resistance coefficients, ( C_3 )</td>
<td>300</td>
<td>(200-500)</td>
<td></td>
</tr>
<tr>
<td>Maximum leaf area index, maize ( \text{LAI}_{\text{max}} )</td>
<td>6</td>
<td>(5-6.5)</td>
<td>m² m⁻²</td>
</tr>
<tr>
<td>Maximum leaf area index, soybeans ( \text{LAI}_{\text{max}} )</td>
<td>5</td>
<td>(4-6.5)</td>
<td>m² m⁻²</td>
</tr>
<tr>
<td>Attenuation coefficient ( \alpha )</td>
<td>2.5</td>
<td>(1-3.5)</td>
<td></td>
</tr>
<tr>
<td>Extinction coefficient ( C_{\text{ext}} )</td>
<td>0.6</td>
<td>(0.4-0.7)</td>
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</tr>
<tr>
<td><strong>Soil</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper layer thickness ( L_t )</td>
<td>0.05</td>
<td>(0.025-0.1)</td>
<td>m</td>
</tr>
<tr>
<td>Saturation soil water content ( \Theta_s )</td>
<td>0.5</td>
<td>(0.4-0.55)</td>
<td></td>
</tr>
<tr>
<td>Soil porosity ( \phi )</td>
<td>0.5</td>
<td>(0.4-0.6)</td>
<td></td>
</tr>
<tr>
<td>Soil tortuosity ( \tau_s )</td>
<td>1.5</td>
<td>(1.1-2.0)</td>
<td></td>
</tr>
<tr>
<td>Fitting parameter ( \beta )</td>
<td>6.5</td>
<td>(5-7)</td>
<td></td>
</tr>
<tr>
<td>Soil thermal cond., upper layer ( K )</td>
<td>0.5</td>
<td>(0.3-2.5)</td>
<td>W m⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>Soil thermal cond., lower layer ( K' )</td>
<td>2.5</td>
<td>(1-2.5)</td>
<td>W m⁻¹ °C⁻¹</td>
</tr>
<tr>
<td><strong>Residue</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residue tortuosity ( \tau_r )</td>
<td>1.0</td>
<td>(1.0-1.2)</td>
<td></td>
</tr>
<tr>
<td>Residue porosity ( \phi_r )</td>
<td>0.99</td>
<td>(0.5-0.99)</td>
<td></td>
</tr>
<tr>
<td>Residue thermal conductivity ( K_r )</td>
<td>0.2</td>
<td>(0.05-0.4)</td>
<td>W m⁻¹ °C⁻¹</td>
</tr>
</tbody>
</table>
Table 3.4b. SEB Model parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canopy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean leaf width, maize</td>
<td>W</td>
<td>0.08</td>
<td>m</td>
</tr>
<tr>
<td>Mean leaf width, Soybean</td>
<td>W</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>Maximum solar radiation</td>
<td>Radmax</td>
<td>1000</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>Cd</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td><strong>Soil</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower layer depth</td>
<td>Lm</td>
<td>0.5</td>
<td>m</td>
</tr>
<tr>
<td><strong>Residue</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residue constant, soybean</td>
<td>Am</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Residue constant, maize</td>
<td>Am</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

After calibration agreement between measured and estimated evapotranspiration was very good (Figure 3.15a. and 3.16a). During 2002, for soybeans, and for selected data where the energy balance closure was within ±10%, the coefficient of determination \(r^2\) was 0.87 for the whole year with a slope of 1.01 (measured on a 60 min basis). Root means square error (RMSE) of the model was 39.5 W m\(^{-2}\), the mean absolute error (MAE) was 25.9 W m\(^{-2}\), the Nash-Sutcliffe coefficient (E) was 0.78 and the index of agreement (d) was 0.95. During 2003, for maize, and for selected data where the energy balance closure was within ±10%, the coefficient of determination \(r^2\) was 0.93 with a slope of 0.99. The root means square error (RMSE) of the model was 43.9 W m\(^{-2}\), the mean absolute error (MAE) was 28.2 W m\(^{-2}\), the Nash-Sutcliffe coefficient (E) was 0.89 and the index of agreement (d) was 0.97. A summary of these statistics is presented in Table 3.5.
Figure 3.15 a) Measured and estimated ET after calibration for selected measurements where energy balance closure was within ±10% and all data, b) Comparison between cumulative measured ET and estimated ET for the complete year and for selected measurements where energy balance closure was within ±10%. 
a) Measured and estimated ET after calibration for selected measurements where energy balance was within ±10% and all data, b) Comparison between cumulative measured ET and estimated ET for the complete year and for selected measurements where energy balance was within ±10%.
Table 3.5. Statistics coefficients calculated after calibration Site 2, 2002 and 2003.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>Period</th>
<th>E</th>
<th>d</th>
<th>RMSE (W m⁻²)</th>
<th>MAE (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Soybean</td>
<td>Selected data where energy balance was within ±10%.</td>
<td>0.78</td>
<td>0.95</td>
<td>39.4</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annual</td>
<td>0.90</td>
<td>0.98</td>
<td>29.0</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Growing season</td>
<td>0.91</td>
<td>0.98</td>
<td>38.2</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.68</td>
<td>0.93</td>
<td>45.6</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.96</td>
<td>0.99</td>
<td>35.5</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.95</td>
<td>0.99</td>
<td>32.6</td>
<td>23.0</td>
</tr>
<tr>
<td>2003</td>
<td>Maize</td>
<td>Selected data where energy balance was within ±10%.</td>
<td>0.89</td>
<td>0.97</td>
<td>43.7</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annual</td>
<td>0.89</td>
<td>0.97</td>
<td>33.7</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Growing season</td>
<td>0.90</td>
<td>0.98</td>
<td>42.2</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.71</td>
<td>0.92</td>
<td>45.5</td>
<td>30.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.82</td>
<td>0.97</td>
<td>58.7</td>
<td>40.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.93</td>
<td>0.98</td>
<td>39.4</td>
<td>25.7</td>
</tr>
</tbody>
</table>

X=Measured ET (W m⁻²) and Y=Estimated ET (W m⁻²)

For soybean (2002) from the beginning of the year until planting the model tended to underestimate total ET. After planting, the SEB model underestimated ET until the canopy reached a LAI value of 1.1. After that time the performance of the model was very good for the rest of the growing season and after harvest. During the growing season the RMSE of the model calculated with all data was 38.2 W m⁻², the MAE was 25.7 W m⁻², the E was 0.91 and the index of agreement (d) was 0.985. During the period from planting until the LAI reached a value of two, the RMSE of the model was 45.6 W m⁻², the MAE was 30.0 W m⁻², the E was 0.68 and the index of agreement (d) was 0.99. For the period of the growing season where 2 < LAI < 4, the RMSE of the model was 35.5 W m⁻², the MAE was 24.4 W m⁻², the E was 0.96 and the index (d) was 0.99. At the
end of the growing season where $4 \text{ < LAI < harvest}$, the RMSE of the model was $32.6 \text{ W m}^{-2}$, the MAE was $23.0 \text{ W m}^{-2}$, the $E$ was 0.95 and the index $d$ was 0.99.

Similarly, for maize (2003) the model tended to underestimate total ET during the period from the beginning of the year until planting. After planting and during the growing season, the SEB model underestimated ET until the canopy reached a LAI value of 1.5, after that moment the performance of the model was very good during the rest of the growing season and after harvest. During the growing season the RMSE of the model calculated with all data was $33.7 \text{ W m}^{-2}$, the MAE was $20.3 \text{ W m}^{-2}$, the $E$ was 0.89 and the index of agreement ($d$) was 0.97. During the period from planting until the LAI reached a value of two, the RMSE of the model was $45.5 \text{ W m}^{-2}$, the MAE was $30.3 \text{ W m}^{-2}$, the $E$ was 0.71 and the index of agreement ($d$) was 0.92. For the period of the growing season where $2 \text{ < LAI < 4}$, the RMSE of the model was $58.7 \text{ W m}^{-2}$, the MAE was $40.6 \text{ W m}^{-2}$, the $E$ was 0.82 and the index ($d$) was 0.97. At the end of the growing season where $4 \text{ < LAI < harvest}$, the RMSE of the model was $39.4 \text{ W m}^{-2}$, the MAE was $25.7 \text{ W m}^{-2}$, the $E$ was 0.93 and the index $d$ was 0.98. Measured and estimated cumulated ET for soybeans and maize during 2002 and 2003 are presented in figure 3.15b and 3.16b. The ratio of annual ET calculated with the modified model and the annual ET measured with the eddy covariance was 1.00 during 2002 and 0.95 during 2003. The ratio, for measurements where the energy balance closure was in the range of ±10%, was 1.11 and 1.00 for 2002 and 2003 respectively.

With the SEB model calibrated the model was evaluated for the other available years at Site 2 and the others two sites.
**Model Validation**

*Site 1.* To evaluate the performance of the model, evapotranspiration predicted by the SEB model was compared with eddy covariance measurements made for an irrigated maize field during the growing and non-growing seasons of 2002 through 2005. SEB model inputs included net radiation, air temperature, relative humidity, soil temperature at 50 cm, wind speed, solar radiation, soil water content, residue amount covering the soil by hectare, and calibrated parameters given in Table 3.3a and Table 3.3b.

Linear regressions between hourly values of $\lambda E$ estimated with the model and measured by the eddy covariance system were calculated during the four years of measurements. The regression slopes ranged from 1.02 (2004) to 1.09 (2002). The coefficients of determination, $r^2$, were 0.92 (2002), 0.92 (2003), 0.91 (2004), and 0.90 (2005), giving a fairly good agreement between measure and estimated ET for all years of study at Site 1. During the growing seasons, regression slopes range from 1.04 (2005) to 1.11 (2002) with $r^2$ ranges between 0.93-0.95 (Figure 3.17 and 3.18).

Cumulated measured ET and cumulated estimated ET were calculated for all years. The ratios of annual ET calculated with the modified model to the annual ET measured with the eddy covariance system were 1.06 during 2002, 1.01 during 2003, 0.94 (2004) and 0.98 (2005), resulting in annual $\lambda E$ differences of less than 6%. The SEB model has the capability to separate total evapotranspiration into canopy transpiration and soil evaporation. The ratio of annual canopy transpiration over total ET was 0.70 for 2002, 0.74 for 2003, 0.67 for 2004, and 0.64 for 2005.

The statistics indices of agreements, $E$, $d$, RMSE and MAE were used to evaluate the performance of the model. Calculations were made for complete years, growing
seasons (planting to harvest), early growing seasons where LAI < 2, growing seasons where 2 < LAI < 4, and growing seasons where LAI > 4. Results are given in Table 3.6. The Nash-Sutcliffe coefficient, E, ranges from 0.88 to 0.90 for the complete year analysis, 0.89 to 0.91 for the growing season, 0.54 to 0.68 growing season where LAI < 2, 0.73-0.91 for 2 < LAI < 4, and 0.92 to 0.95 for growing season where LAI > 4. In the same way, the index of agreement, d, ranges from 0.97 to 0.98 during the whole year, 0.98 for the growing season, 0.89 to 0.92 growing season where LAI < 2, 0.92-0.98 for 2 < LAI < 4, and 0.98 to 0.99 for growing season where LAI > 4.

The RMSE ranges from 27.9 W m\(^{-2}\) to 33.3 W m\(^{-2}\) during the whole year, 35.0 W m\(^{-2}\) to 43.5 W m\(^{-2}\) for the growing season, 39.4 W m\(^{-2}\) to 46.6 W m\(^{-2}\) growing season where LAI < 2, 46.8 W m\(^{-2}\) to 70.3 W m\(^{-2}\) for 2 < LAI < 4, and 30.6 W m\(^{-2}\) to 39.8 W m\(^{-2}\) for growing season where LAI > 4. Similarly, the mean absolute error, MAE, ranges from 17.6 W m\(^{-2}\) to 21.3 W m\(^{-2}\) during the whole year, and 24.5 W m\(^{-2}\) to 28.6 W m\(^{-2}\) for the growing season. See Table 3.4 for the rest of the periods analyzed.

In general for all years of analysis at Site 1, the model performed best during the growing season where LAI > 4. On the contrary, poor model performance was found when the LAI < 2 during the early growing season. The model has more difficulties estimating ET for sparse canopy than closed canopy surfaces.
Table 3.6 Statistic indices for ET estimations using the SEB model at Site 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>E</th>
<th>d</th>
<th>RMSE (W m⁻²)</th>
<th>MAE (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Annual</td>
<td>0.88</td>
<td>0.97</td>
<td>33.3</td>
<td>19.7</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.89</td>
<td>0.98</td>
<td>43.5</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.54</td>
<td>0.90</td>
<td>46.6</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.76</td>
<td>0.96</td>
<td>70.3</td>
<td>49.7</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.92</td>
<td>0.98</td>
<td>39.8</td>
<td>26.0</td>
</tr>
<tr>
<td>2003</td>
<td>Annual</td>
<td>0.89</td>
<td>0.98</td>
<td>32.5</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.89</td>
<td>0.98</td>
<td>43.3</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.64</td>
<td>0.92</td>
<td>43.4</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.73</td>
<td>0.95</td>
<td>68.8</td>
<td>45.7</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.92</td>
<td>0.98</td>
<td>40.5</td>
<td>26.5</td>
</tr>
<tr>
<td>2004</td>
<td>Annual</td>
<td>0.90</td>
<td>0.98</td>
<td>27.9</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.91</td>
<td>0.98</td>
<td>35.0</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.68</td>
<td>0.92</td>
<td>39.4</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.85</td>
<td>0.97</td>
<td>48.1</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.95</td>
<td>0.99</td>
<td>30.6</td>
<td>21.6</td>
</tr>
<tr>
<td>2005</td>
<td>Annual</td>
<td>0.89</td>
<td>0.97</td>
<td>32.9</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.90</td>
<td>0.98</td>
<td>41.5</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.54</td>
<td>0.89</td>
<td>46.8</td>
<td>30.9</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.91</td>
<td>0.98</td>
<td>46.8</td>
<td>33.0</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.93</td>
<td>0.98</td>
<td>38.2</td>
<td>26.0</td>
</tr>
</tbody>
</table>
Figure 3.17. Measured vs estimated hourly ET (above), (open circles for complete year and closed circles for the growing season), and cumulative ET (below) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration ($\lambda Ec$) estimated with the SEB model. Site 1 during 2002 and 2003.
Figure 3.18. Measured vs estimated hourly ET (above), (open circles for complete year and closed circles for the growing season), and cumulative ET (below) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration (λEc) estimated with the SEB model. Site 1 during 2004 and 2005.
Site 2. At site 2 the modified SEB model was evaluated during 2004 for irrigated soybean and irrigated maize during 2005.

Similar to site 1, linear regressions between hourly values of $\lambda E$ estimated with the model and measured by the eddy covariance system were calculated during the two years of measurements (2004 to 2005). The regression slopes were 0.94 (2004) and 1.01 (2005). The coefficient of determination, $r^2$, was 0.9 for 2004 and 2005. During the growing seasons, regression slopes were 0.98 (2004), and 1.04 (2005) with $r^2$ of 0.93 and 0.92 for 2004 and 2005 respectively (Figure 3.19). Cumulated measured ET and cumulated estimated ET were calculated for 2004 and 2005. The ratios of annual ET estimated with the modified SEB model and the annual ET measured with the eddy covariance were 0.85 (2004) and 0.97 (2005). The ratio of annual canopy transpiration over total ET was 0.59 for 2004, and 0.68 for 2005.

Statistics indices E, d, RMSE and MAE are given in Table 3.7. The Nash-Sutcliffe coefficient, E, ranged from 0.88 to 0.89 for the annual analysis, 0.9 to 0.92 for the growing season, 0.62 to 0.79 growing season where LAI < 2, 0.88 to 0.96 for 2<LAI<4, and 0.94 to 0.95 for growing season where LAI >4. In the same way, the index of agreement, d, was 0.97 during the annual analysis and 0.98 for the growing season. Others periods are given in Table 3.7.

The RMSE ranges from 29.6 W m$^{-2}$ to 32.9 W m$^{-2}$ during the whole year, and 34.5 W m$^{-2}$ to 41.2 W m$^{-2}$ for the growing season. Similarly, the mean absolute error, MAE, ranged from 18.6 W m$^{-2}$ to 19.9 W m$^{-2}$ during the whole year, and 24.0 W m$^{-2}$ to 27.2 W m$^{-2}$ for the growing season.
Figure 3.19. Measured vs estimated hourly ET (above), (open circles for complete year and closed circles for the growing season), and cumulative ET (below) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration ($\lambda Ec$) estimated with the SEB model. Site 2 during 2004 and 2005.
In general at site 2, similar to site 1, the best performance of the model was found during the growing season where LAI > 4. Poorer model performance was found when the LAI < 2 during the early growing season.

Table 3.7 Statistic indices for ET estimations using the SEB model at Site 2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>E</th>
<th>d</th>
<th>RMSE (W m(^{-2}))</th>
<th>MAE (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Annual</td>
<td>0.88</td>
<td>0.97</td>
<td>29.6</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.92</td>
<td>0.98</td>
<td>34.5</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.79</td>
<td>0.94</td>
<td>41.2</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.96</td>
<td>0.99</td>
<td>28.8</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.95</td>
<td>0.99</td>
<td>30.2</td>
<td>21.4</td>
</tr>
<tr>
<td>2005</td>
<td>Annual</td>
<td>0.89</td>
<td>0.97</td>
<td>32.9</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Growing season</td>
<td>0.90</td>
<td>0.98</td>
<td>41.2</td>
<td>27.2</td>
</tr>
<tr>
<td></td>
<td>Planting &lt; LAI &lt; 2</td>
<td>0.62</td>
<td>0.90</td>
<td>48.7</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>2 &lt; LAI &lt; 4</td>
<td>0.88</td>
<td>0.97</td>
<td>52.4</td>
<td>36.0</td>
</tr>
<tr>
<td></td>
<td>4 &lt; LAI &lt; Harvest</td>
<td>0.94</td>
<td>0.99</td>
<td>35.8</td>
<td>23.9</td>
</tr>
</tbody>
</table>

Site 3. Data from rainfed maize and soybean rotation system at site 3 were used to evaluate model performance during 2002 through 2005. Linear regressions between hourly values of $\lambda E$ estimated with the model and measured by the eddy covariance system were calculated during the 4 years of measurements (2002 to 2005). The regression slopes ranged from 0.94 (2004) to 1.15 (2005), giving a fairly good agreement between measure and estimated ET for all years of study. The coefficients of determination, $r^2$, were 0.90 (2002), 0.89 (2003), 0.90 (2004), and 0.89 (2005). During the growing seasons, regression slopes range from 0.96 (2004) to 1.17 (2005) with $r^2$ ranges between 0.91-0.93 (Figure 3.20 and 3.21).
Cumulated measured ET and cumulated estimated ET were calculated for all years. The ratios of annual ET estimated with the SEB model and the annual ET measured with the eddy covariance were 0.98 during 2002, 0.97 during 2003, 0.88 (2004) and 1.14 (2005). At site 2, the ratio of annual canopy transpiration over total ET was 0.53 for 2002, 0.61 for 2003, 0.55 for 2004 and 0.64 for 2005.

The statistics indices of agreements, E, d, RMSE and MAE are given in Table 3.8. The Nash-Sutcliffe coefficient, E, ranges from 0.82 to 0.9 for the complete year analysis, and 0.81 to 0.92 for growing seasons. In the same way, the index of agreement, d, ranged from 0.96 to 0.97 during the whole year, and 0.96 to 0.98 during the growing season. The RMSE ranges from 26.4 W m\(^{-2}\) to 37.1 W m\(^{-2}\) during the whole year, and 33.0 W m\(^{-2}\) to 48.3 W m\(^{-2}\) for the growing season. Similarly, the mean absolute error, MAE, ranges from 16.8 W m\(^{-2}\) to 21.2 W m\(^{-2}\) during the whole year, and 22.3 W m\(^{-2}\) to 30.9 W m\(^{-2}\) for growing season analysis.
Figure 3.20. Measured vs estimated hourly ET (above), (open circles for complete year and closed circles for the growing season), and cumulative ET (below) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration ($\lambda Ec$) estimated with the SEB model. Site 3 during 2002 and 2003.
Figure 3.21. Measured vs estimated hourly ET (above), (open circles for complete year and closed circles for the growing season), and cumulative ET (below) measured with the eddy covariance system, estimated with the SEB model and canopy transpiration (\(\lambda Ec\)) estimated with the SEB model. Site 3 during 2004 and 2005.
Table 3.8 Statistic indices for ET estimations using the SEB model at Site 3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>E</th>
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<th>MAE (W m(^{-2}))</th>
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**Summary**

In general the SEB model compared favorably to the total latent heat flux measured by the eddy covariance system. Results showed that the model performed better during the growing season than for complete year. During the growing season the model predicted more accurately after canopy closure than for the period from planting until the LAI reached a value of two. The model predicted more accurately for irrigated sites than for the rainfed site. Under irrigated maize the ratio of annual ET calculated with the modified model and the annual ET measured with the eddy covariance ranged between 0.94 – 1.06, resulting in annual λE differences of less than 6%. Under rainfed maize the ratio ranged from 0.97-1.14, and rainfed soybean ranged from 0.88-0.98. Under irrigated maize conditions crop transpiration estimated with the modified SEB model was 64 -74% of the annual evapotranspiration. Under rainfed maize conditions annual transpiration was within 61-64% of total ET. Under irrigated soybean the percentage was 59%, and under rainfed soybean conditions annual transpiration was 53-55% of annual evapotranspiration.

During this study, the evaluation of the capability of the SEB model to estimate evapotranspiration compared favorably with measurements by eddy covariance systems.
Conclusions

A sensitivity analysis of model parameters and an evaluation of the SEB model to estimate ET was completed during the growing and non-growing season of maize and soybeans on eastern Nebraska. Results were compared with measured data from three eddy covariance systems.

In general, the sensitivity analysis of model parameters showed that simulated ET was most sensitive to changes in surface canopy resistance, soil surface resistance, and residue surface resistance. The model was less sensitive to changes in the extinction coefficient, soil temperature, the attenuation coefficient, the surface boundary layer, errors in the crop height, and soil heat flux resistances.

Comparison between estimated ET and measurements made in soybean and maize fields provided support for the validity of the modified surface energy balance model. The statistics indices of agreements, Nash-Sutcliffe coefficient, index of agreement, the root mean square error, and the mean absolute error, were used to evaluate the performance of the model. Agreement between measured and estimated evapotranspiration was very good. For annual estimations, the coefficient of determination $r^2$ ranged from 0.88 to 0.92 with linear regression slopes in the range of 0.93 to 1.14. The Nash-Sutcliffe coefficients were in the range 0.82-0.90, and the RMSE of the model was 26.4 – 37.1 W m$^{-2}$. Estimates of ET during the growing seasons resulted in an $r^2$ range of 0.91-0.95, and linear regression slopes in the range of 0.96 to 1.17. The Nash-Sutcliffe coefficients ranged from 0.81 to 0.92 for growing seasons estimates. The RMSE varied from 33.0 to 48.3 W m$^{-2}$. During the growing season the model predicted more accurately after canopy closure (i.e. after LAI=4 until harvest). Performance prior
to canopy closure was less accurate. The model predicted ET values more accurately for the irrigated sites than for the rainfed site.

The ratio of annual ET calculated with the modified model to the annual ET measured with the eddy covariance system ranged between 0.94 and 1.06 for irrigated maize, resulting in annual λE differences of less than 6%. For cornfields, crop transpiration estimated with the modified SEB model was 64-74% of the annual evapotranspiration under irrigated conditions and 61-64% under rainfed conditions. For soybeans fields, crop transpiration was 59% of the annual ET under irrigated conditions and 53-55% under rainfed agriculture. Overall the evaluation of the SEB model estimating evapotranspiration with measurements by eddy covariance systems during this study was satisfactory.
References


and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology*, 131 77-96.
Chapter IV. Using Modified Surface Energy Balance and Penman-Monteith Models to Determine the Canopy Resistance for Irrigated and Rainfed Maize.

Introduction.

When crops are well-established with close canopies most of the incident radiation is intercepted and partitioned by the vegetation (Shuttleworth and Gurney, 1990). Evapotranspiration (ET) for such conditions is frequently simulated assuming a single source of energy flux positioned at an effective height within the canopy. Several authors have utilized the single-source Penman-Monteith (P-M) model to represent close canopy conditions for agricultural ecosystems (Stannard, 1993; Farahani and Bausch, 1995; Rana et al., 1997; Alves and Pereira, 2000; Kjelgaard and Stockle, 2001; Ortega-Farias et al., 2004; Shuttleworth, 2006; Katerji and Rana, 2006; Flores, 2007 and Irmak et al. 2008). However, when crops are sparse the assumption of a single source/sink of energy is not entirely satisfied.

Regions characterized by partial or sparse plant canopy cover account for a significant fraction of the land surface (Massman, 1992). They occur seasonally in all agricultural areas and through the year over natural land covers. Multiple-layer models allow the heat and mass transfer between the canopy, the soil surface and the environment and they have been proposed to account for sparse canopies (Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988; and the surface energy balance (SEB) model proposed in the second chapter of this research). These models have been evaluated in a variety of ecosystems (Shuttleworth and Gurney, 1990; Lafleur and Rouse, 1990; Massman, 1992; Stannard, 1993; Farahani and Ahuja, 1996; Tourula and Heikinheimo, 1998; Anadranistakis et al., 2000; Daamen and Mcnaughton, 2000; Iritz et
al., 2001; Alves and Cameira, 2002; Gardiol et al., 2003; Kato et al., 2004 and Ortega-Farias et al., 2007). A common conclusion is that multiple-layer models are more appropriate for the range of canopy-cover conditions encountered in agricultural ecosystems.

Canopy resistance ($r_c$) is one of the most important parameters to estimate ET for single and multiple-layer models. Canopy resistance represents a bulk resistance to water vapor or mass transfer from the canopy. Frequently $r_c$ is replaced by its reciprocal the canopy conductance ($C_C$). This resistance was proposed by Monteith (1965) as an expansion of the energy balance equation to more closely link biological factors with meteorological conditions (Amer and Hatfield, 2004). A sensitivity analysis of canopy resistance in the SEB model, (Chapter 3), showed that $r_c$ is one of the most important parameters to estimate ET under high leaf area index (LAI) conditions (LAI > 3). Total ET decreased approximately 10% when the canopy resistance increased 30% for the environmental conditions evaluated in chapter 3.

Canopy resistance is often back calculated by rearranging the P-M model using measured values of latent heat flux and other relevant environmental variables (i.e.: net radiation, soil heat flux, air temperature, relative humidity, wind speed, and crop height). Several authors have used this approach, know as the “top down” approach (Kim and Verma, 1991; Steduto and Hsiao, 1998a, 1998b; and Irmak et al., 2008). Authors agreed that canopy resistance computed with this method is not a purely physiological parameter, but also contains information about net radiation and aerodynamic resistance. They recognize that $r_c$ values could also be affected by soil evaporation (Kim and Verma, 1991; Rochette et al, 1991).
Multiple-layer models have the ability to separate total ET into canopy transpiration and evaporation from the soil. As in the P-M approach, canopy resistance can be back-calculated with multiple-layers models if latent heat fluxes and other environmental variables are measured. Consequently, canopy resistance estimated with a multiple-layer model should be less affected by soil evaporation than with the P-M approach. Therefore, my first objective is to compare the canopy resistance estimated with a multiple-layer model to that back calculated with the single-source P-M model. It is hypothesized that a) the canopy resistance calculated with a multiple-layer model will exceed values calculated with the P-M model and b) differences in rc should be smaller for high LAI conditions.

Canopy resistance can also be calculated with a method known as the “scaling up” approach. In this approach, the stomata resistance of individual leaves is serially integrated for the entire vegetation weighted by leaf area index. In the “scaling up” approach stomata resistance can be directly measured (porometers) or simulated (stomata resistance models) at different levels of the canopy and then scale up to the canopy. The stomata resistance scaled up to the whole canopy may not be identical to the surface canopy resistance derived from the rearranged P-M equation (Baldocchi et al., 1991; Stewart and Verma, 1992). The resistance derived by the “scaling up” method is primarily a physiological parameter (Kim and Verma, 1991; Rochette et al, 1991). The strengths and weakness of the two approaches for estimating canopy stomata conductance were described by Baldocchi et al. (1991). From their work, the “top down” approach is attractive since it is integrative, requires few measurements, and is based on physical laws. However, to study the biological control of gas transfer by stomata, it is
particularly important to extract the stomata conductance instead of the surface-canopy conductance from the “top down” model. “Scaling up” models can provide valuable detail on the canopy microclimate, which is needed to parameterize models.

Numerous studies have been conducted to estimate stomata resistance from environmental variables (i.e. Jarvis, 1976; Baldocchi et al, 1987; Stewart, 1988; Niyogi and Raman, 1997; Yu et al., 2004), and canopy resistance using the “scaling up” approach (Stockle et al.,1992a, and 1992b; Baldocchi et al, 1987; Stewart, 1988; Stewart and Gay, 1989; Kim and Verma, 1991; Stewart and Verma, 1992; Irmak et al 2008). Several authors have compared “scaling up” model predictions with canopy resistance back calculated with the P-M model (i.e. Baldocchi et al, 1987; Stewart, 1988; Stewart and Gay, 1989; Kim and Verma, 1991; Stewart and Verma, 1992; Irmak et al 2008). Varying degrees of success have resulted when comparing the resistance methods.

Baldocchi et al. (1987) compared a canopy stomata resistance model, based on Jarvis (1976), against values measured with a porometer and computed with the P-M equation. Computed canopy stomata resistance from soybean in both well-watered and water-stressed conditions closely matched canopy resistance estimated from measured data with a diffusion porometer. However, the difference between the “scaling up” method and the P-M model was on the order of 30-50%. Stewart (1988) evaluated four models to estimate surface resistance of pine forest. In the simplest model the conductance was independent of all environmental variables, whereas in the most complex model the surface resistance was a non-linear function of solar radiation, specific humidity deficit, temperature and soil moisture deficit. As the complexity of the model increased, the difference between measured and estimated ET decreased from 22%
to 1%. Results from modeling surface conductance for other years were much poorer. Stewart and Gay (1989) evaluated a surface resistance model that depended on solar radiation and specific humidity deficit to estimate ET with the P-M equation. Results from nine days of measurements, produced differences in ET of ±5%. Field measurements of stomata conductance were used by Kim and Verma (1991) to develop a leaf stomata conductance model for C4 grass species in a temperate grassland ecosystem. Their model relied on incoming photosynthetic active radiation, vapor pressure deficit, green leaf area index and extractable soil water content. The stomata conductance estimated with the model were compared with canopy conductance back calculated from flux measurements using the P-M equation. Diurnal patterns and magnitudes of the estimates were in good agreements under well-watered conditions. The agreement was poor when moisture stress occurred. Rochete et al. (1991) compared the performance of six methods of scaling up from leaf stomata conductance to canopy conductance obtained from back calculation with the P-M equation. Canopy conductance from scaling up leaf stomata conductance generally did not agree with the back-calculated values. These results confirm that canopy conductance computed with the P-M equation is not a purely physiological parameter, but also contains information about net radiation, aerodynamic resistance and soil evaporation. Recently, Irmak et al. (2008) presented an integrated approach to scale up stomata resistance to canopy resistance for subsurface drip-irrigated maize (Zea mays L.). Stomata resistance was scaled up as a function of photosynthetic photon flux density (PPFD). PPFD alone explained 85% of the variability in rc. The average root mean square difference between the scaled up rc and estimated rc by back calculating with the P-M model on an hourly time-step was 11.1 s m\(^{-1}\). The integrated
approach for non-stressed plants does not account for the effect of other factors such as vapor pressure deficit, carbon dioxide concentration, wind speed, and soil evaporation.

Several authors have shown different degrees of success comparing rc estimated with the “scaling up” approach to back calculated with the P-M model. Since canopy resistance estimated with a multiple-layer model should not be affected by soil evaporation one would expect canopy resistance models based on environmental conditions (i.e. Jarvis type models) to predict canopy resistance back calculated with a multiple-layer model better than with the P-M model. Therefore, my second objective is to compare predictions from selected “scaling up” models to rc obtained from back calculation with the P-M equation and a multiple layer model.

To accomplish the first objective, canopy resistance was calculated with a modified surface energy balance model (SEB) and with the P-M model for maize under irrigated and rainfed conditions. Estimates were compared under varying LAI conditions. For the second objective two models were selected to predict canopy resistance for maize. Simulations were compared with rc back calculated with the P-M model and the multiple-layer SEB model.
Objectives.

The main objective of this work was to evaluate the differences between canopy resistances calculated with a modified surface energy balance model and the Penman-Monteith model for irrigated and rainfed maize.

Specific objectives are to:

i. Calculate and compare canopy resistance with a modified surface energy balance model and the Penman-Monteith equation for maize under irrigated and rainfed conditions.

ii. Compare two selected “scaling up” canopy resistance models with values derived from the P-M equation and a multiple-layer SEB model for irrigated and rainfed maize.
Materials and Methods

Study Sites

Three eddy covariance systems are located at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Fields areas range from 49 to 65 ha, providing sufficient fetch of uniform cover required for adequately measuring mass and energy fluxes using eddy covariance systems (Verma et al., 2005). Site 1 is an irrigated (center pivot) continuous maize system (41°17’N, 96°48’W); Site 2 is an irrigated (center pivot) maize-soybean rotation system (41°16’N, 96°47’W); and Site 3 is a rainfed maize-soybean rotation system (41°18’N, 96°44’W). Data collected during the growing seasons of maize at the irrigated site 2 and the rainfed site 3 were used for this work. Maize was grown at site 2 and 3 during 2001, 2003 and 2005. For all sites the soil is a deep silty clay loam, typical of eastern Nebraska (Suyker and Verma, 2008). The fields have not been tilled since 2001. Detailed information about planting densities and crop management practices are provided by Verma et al. (2005), and Suyker and Verma (2008).

Soil water content was measured continuously at four depths (0.10, 0.25, 0.5 and 1.0 m) by employing Theta probes (Delta-T Device, Cambridge, UK). Destructive green leaf area index and biomass measurements were made approximately bi-monthly during the growing season. 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 CO2/H2O gas analyzer system (Model LI7500, Li-cor inc, Lincoln, NE). The eddy covariance sensors were mounted at 3 m above the ground when the canopy was
shorter than 1 m, and later moved to 6 m until harvest. Air temperature and humidity were measured at 3m and 6m (Humitter 50Y, Vaisala, Helsinki, Finland), net radiation at 5.5 m (CNR1, Kipp nad Zonen, Delft, NLD) and soil heat flux at 0.06 m depth (Radiation and energy Balance systems Inc, Seattle, WA). Soil temperature was measured at 0.06, 0.1, 0.2 and 0.5 m depths (Platinum RTD, Omega Engineering, Stamford, CT). More details of flux measurements, data filling and flux corrections are given in Verma et al. (2005), and Suyker and Verma (2008).

**Penman-Monteith and the Surface Energy Balance Models**

The surface canopy resistance ($r_c$) can be obtained by rearranging the Penman-Monteith equation (Figure 4.1a) as:

$$rc = \frac{ra \cdot \left( \Delta \cdot (Rn - G) + \rho \cdot Cp \cdot \frac{VPDa}{ra} - \lambda E \cdot (\Delta + \gamma) \right)}{\gamma \cdot \lambda E}$$

(1)

where $\Delta$ is the slope of the saturated specific humidity curve versus air temperature; $\lambda$ is the latent heat of vaporization; $Cp$ is the specific heat of air at constant pressure; $\rho$ is the density of dry air; $VPDa$ is the vapor pressure deficit; $E$ is evapotranspiration; and $ra$ is the aerodynamic resistance.

Thom (1972) stated that the transfer of mass or heat encounters greater aerodynamic resistance than the transfer of momentum. Accordingly, aerodynamic resistances to water vapor transfer ($ra$) can be estimated as:

$$ra = ra_m + rb_w$$

(2)
where, \( r_a = \frac{U}{u^*} \) is the aerodynamic resistance to momentum transfer and \( r_w \) is an excess resistance term for water vapor transfer calculated as (Wesely and Hicks, 1977):

\[
r_b = \frac{k \cdot B^{-1} \left( \frac{k_1}{k} \right)^{2/3}}{u^* (D_v)}
\]  

where, \( U \) is the wind speed, \( u^* \) is the friction velocity, \( k \) is the von Karman constant (0.41), \( B^{-1} \) represents a dimensionless bulk parameter, \( k_1 \) is the thermal diffusivity and \( D_v \) is the molecular diffusivity of water vapor in air. The product \( kB^{-1} \) was assumed to be equal to 2 for this model and thermal stability effects were neglected.

The SEB model was developed to include the effect of crop residue on evapotranspiration, and estimate ET for a wide range of field conditions. Total latent heat flux from the canopy/residue/soil system (\( \lambda E \)) is the sum of the latent heat from the canopy (transpiration) \( \lambda Ec \), latent heat from the soil \( \lambda Es \) and latent heat from the residue covered soil (evaporation) \( \lambda Er \). By analogy with Ohm’s law, the differences in vapor pressure between two levels can be written in terms of resistance and latent heat flux as illustrated in Figure 4.1 b (Shuttleworth and Wallace, 1985).

The latent heat flux from the canopy is given by:

\[
\lambda Ec = \frac{\Delta_i \cdot r_h \cdot Rnc + \rho \cdot Cp \cdot (e_h^* - eb)}{\Delta_i \cdot r_h + \gamma \cdot (r_i + rc)}
\]  

(4)
Figure 4.1 A schematic resistance network for latent heat flux of a) Single-source Penman-Monteith model and b) Multiple-layer SEB model.
The latent heat flux from bare soil surfaces can be estimated by:

$$\lambda_{Es} = \frac{\left( Rns \cdot \Delta_2 \cdot r_2 \cdot r_L + \rho \cdot Cp \cdot ((e_b^* - eb) \cdot (ru + r_L + r_2)) \right)}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2)}$$  \hspace{1cm} (5)

Similarly the latent heat flux from the residue covered soil can be estimated by:

$$\lambda_{Er} = \frac{\left( Rns \cdot \Delta_4 \cdot (r_2 + rr_b) \cdot r_L + \rho \cdot Cp \cdot ((e_b^* - eb) \cdot (ru + r_L + r_2 + r_{rh})) \right)}{\gamma \cdot (r_2 + rs + rr) \cdot (ru + r_L + r_2 + r_{rh}) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_{rh})}$$  \hspace{1cm} (6)

where $Rnc$ is the net radiation absorbed by the canopy and $Rns$ is the net radiation absorbed by the soil, $\rho$ is the density of moist air, $Cp$ is the specific heat of air and $\gamma$ is the psychrometric constant. The mean rate of change of saturated vapor pressure with temperature between two levels is represented by $\Delta_i$. Values for $\Delta_1$, $\Delta_2$, $\Delta_3$ and $\Delta_4$ are necessary to solve the model. Choudhury and Monteith (1988) found that a single value $\Delta$, evaluated at $T_a$, provided acceptable accuracy. Therefore a single value for $\Delta$ was used. The vapor pressure of the atmosphere at the canopy level is denoted by $eb$, while $e_b^*$ is the saturation vapor pressure of the atmosphere at the canopy level, $e_1^*$ is the saturation vapor pressure at the canopy and $e_L^*$ is the saturation vapor pressure at the top of the wet layer. The parameter $Tb$ represents the air temperature at canopy height and $Tm$ is the temperature at the bottom of the lower layer. The aerodynamic resistance between the canopy and the air within the canopy is given by $r_1$, and $rc$ is the canopy resistance, $r_2$ is the aerodynamic resistance between the soil and the canopy, $rs$ is the resistance to the diffusion of water vapor through the soil at the top soil layer, and $rrh$ and $rr$ are the residue resistance to the transfer of heat and vapor flux respectively. Resistance
to the transport of heat for the upper and lower soil layer are denoted as $r_u$ and $r_L$ respectively.

The SEB model is applicable to surfaces ranging from fully closed-canopies to bare soil partially covered with residue. Values for $T_b$ and $e_b$ are necessary to estimate latent heat and sensible heat fluxes in equation (2) through (4). Detailed derivation of these equations was presented in the Chapter 2 of this dissertation. As in the P-M model, canopy resistance in the multiple layer SEB model can be estimated if latent heat fluxes and other environmental variables are measured.

### Canopy Conductance Models

Several “scaling up” models currently exist to predict canopy resistance, or its reciprocal canopy conductance, from environmental and surface conditions. Two models were selected to compare predictions with canopy conductance back calculated with the P-M and the SEB model approaches.

A commonly recommended equation to estimate canopy resistance (Szeicz and Long, 1969; Allen, 1998; Kjelgaard ans Stockle, 2001) is:

$$ r_c = \frac{r_{st}}{LAI_{eff}} $$

(7)

where, $r_c$ is the canopy resistance, $r_{st}$ is the stomata resistance for a single leaf (or frequently named by its reciprocal the stomata conductance $C_s$, $(C_s = 1/r_{st})$, and $LAI_{eff}$ is the effective LAI, which is the portion of the canopy from which the bulk of transpiration originates. Usually $LAI_{eff}$ is assumed to be half the crop LAI ($LAI_{eff} = 0.5$ LAI).
The stomata conductance of a leaf has been shown to be primarily a function of light (L), air temperature (T), vapor pressure deficit (VPDa), soil water content (Θ) and carbon dioxide concentration (CO₂) (Kim and Verma, 1991). The multiplicative Jarvis (1976) model was used to estimate stomata conductance:

\[
Cs = C_{\text{max}} \cdot f_1(L) \cdot f_2(T) \cdot f_3(\text{VPDa}) \cdot f_4(\Theta) \cdot f_5(\text{CO}_2)
\]  
(8)

where \( C_{\text{max}} \) is the maximum stomata conductance under optimal conditions, and \( f_i(X) \) are functions for light, temperature, vapor pressure deficit, soil water content, and CO₂ concentration. Values of the relationships \( f_1(L), f_2(T), f_3(\text{VPDa}), f_4(\Theta), \) and \( f_5(\text{CO}_2) \) range from 0 to 1.

Jarvis (1976) observed the relationship between stomata conductance and photon flux density (PPFD) as:

\[
f_1(L) = \frac{a_1 \cdot (\text{PPFD} - \frac{a_2}{C_{\text{max}}})}{C_{\text{max}} + a_1 \cdot (\text{PPFD} - \frac{a_2}{C_{\text{max}}})}
\]  
(9)

where, \( a_1 \) is the \( \frac{d(gs)}{d(\text{PPFD})} \) at \( \text{PPFD}=0 \) and \( a_2 \) is the value of \( cs \) in the dark and is given by the intercept on the ordinate. The value \( a_2 \) was introduced to allow for stomata to be open at night, and was not intended to be cuticular conductance.

The dependence of \( cs \) on temperature can be represented by the following function (Jarvis, 1976; Baldocchi et al., 1987; Steward, 1988):

\[
f_2(T) = \frac{(T - T_{10})}{(T_{0} - T_{10})} \cdot \left( \frac{T_{h} - T}{T_{h} - T_{0}} \right)^b
\]  
(10)

\[
b = \frac{(T_{h} - T_{0})}{(T_{h} - T_{10})}
\]
where $T_{lo}$ and $T_{h}$ are the minimum and maximum temperatures at which stomata closure occurs, and $T_{o}$ is the optimum temperature. For maize Baldocchi (1987) used $T_{o} = 22 - 25^\circ C$ and $T_{lo}$ and $T_{h}$ as 5 and 45 $^\circ C$ respectively.

A linear reduction in $cs$ with increasing vapor pressure difference was assumed by (Jarvis, 1976; Baldocchi et al., 1987) as:

$$f_3(VPDa) = 1 - a_3 \cdot VPDa$$

(11)

where $a_3$ is a regression coefficient.

To examine the role of soil water in controlling $Cs$, Kim and Verma (1991) used the daily value of extractable soil water $\Theta_e$ (computed as the ratio of actual to total soil moisture held with a water potential between $-1/30$ and $-1.5$ MPa), obtained over the primary root zone. The response of $Cs$ to $\Theta_e$ was estimated as:

$$f_4(\Theta) = 1 - \exp(-a_4 \cdot \Theta_e)$$

(12)

The effect of changes in carbon dioxide concentration was omitted ($f_5(CO_2) \approx 1$).

Combining equations (7) to (12) gives the canopy conductance ($Cc$) as:

$$Cc_1 = LAI_{eff} \cdot Cs_{max} \left[ \frac{a_1 \cdot \left( PPFD - \frac{a_2}{Cs_{max}} \right)}{Cs_{max} + a_1 \cdot \left( PPFD - \frac{a_2}{Cs_{max}} \right)} \right] \left[ \frac{\left( T - T_{io} \right)}{\left( T_o - T_{io} \right)} \cdot \left( \frac{T_h - T}{T_h - T_o} \right)^b \right] \cdot \left[ 1 - a_3 \cdot VPDa \right] \cdot \left[ 1 - \exp(-a_4 \cdot \Theta_s) \right]$$

(13)

A second model to estimate canopy conductance was proposed by Stannard (1993). The model estimate $Cc$ as a function of vapor pressure deficit, leaf area index and solar radiation. The model is based on previous canopy resistance models of Lohammar et al. (1980) and Stewart (1988).
where LAI max is maximum value of leaf area index (estimated as 6 m$^2$ m$^{-2}$), VPDa is vapor pressure deficit, Rad is solar radiation, Radmax is maximum value of solar radiation (estimated at 1000 W m$^{-2}$) and $c_1$, $c_2$ and $c_3$ are regression coefficients.

To calibrate the models, parameters ($a_1$, $a_2$, $a_3$, $a_4$, $c_1$, $c_2$ and $c_3$) in equations (13) and (14) were adjusted by fitting hourly Cc estimated with models 1 and 2 to hourly Cc obtained from the SEB and the P-M models. The Nash-Sutcliffe model efficiency coefficient (E) was used during this process. Canopy conductance calculated with models 1 and 2 were adjusted for the irrigated and rainfed sites during the growing seasons of maize at sites 2 and 3.
Results
Maize was grown at site 2 and 3 during 2001, 2003 and 2005. Information about crop, residue and grain yields are given in Table 4.1. Residue biomass was measured each year after harvest and exponential decay rates of stoves were used to estimate residue during the year (Verma et al., 2005, Suyker and Verma 2008b). Green leaf area index was measured during the growing season (Figure 4.2). Peak LAI at site 2 and 3 were observed in the middle of July during all years. Higher LAI values were found at site 2 than at site 3. Smaller differences were measured during 2005 probably due to increased precipitation. Precipitation from May to September measured with an automated weather station (Meadturffarm, NE) located near both sites (41.17° N 96.47° W) was 397, 303 and 307 mm during 2001, 2003 and 2005 respectively. Although similar amounts of rain were measured during these months, the distribution of precipitation was different. Monthly rainfall in July was 5.6 and 17.0 mm during 2001 and 2003 respectively; however, during 2005, precipitation during July was 98.3 mm.

Table 4.1 Crop details for maize at sites 2 and 3.

<table>
<thead>
<tr>
<th></th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2001</td>
<td>2003</td>
</tr>
<tr>
<td>Planting</td>
<td>May 11</td>
<td>May 14</td>
</tr>
<tr>
<td>Peak LAI ( (m^2 \cdot m^{-2}) )</td>
<td>6.1</td>
<td>5.5</td>
</tr>
<tr>
<td>Grain Yield ( (kg \cdot ha^{-1}) )</td>
<td>13410</td>
<td>14000</td>
</tr>
<tr>
<td>Residue after Harvest ( (kg \cdot ha^{-1}) )</td>
<td>10218</td>
<td>17220</td>
</tr>
</tbody>
</table>
Figure 4.2. Leaf area index during 2001, 2003 and 2005 at sites 2 and 3.
Comparison of SEB and P-M Models

Hourly canopy resistance was calculated by inverting the P-M model and the SEB model during the growing seasons of 2001, 2003 and 2005. For each year four days were selected to compare the diurnal trends of canopy resistances calculated with both methods.

During 2001, June 23, June 26, July 08 and July 16 were selected at sites 2 and 3. For these days, at site 2, LAI ranged from 1.3 to 6 m² m⁻² and from 0.95 to 3.84 m² m⁻² at site 3. Canopy resistance calculated with the P-M and the SEB model follow the same tendency during the day; however, as was expected, canopy resistance calculated with the SEB which is a multiple-layer model was higher than that calculated with P-M approach (Figure 4.3). For higher LAI conditions canopy resistance calculated with both methods tended to decrease at both sites. In general, lower canopy resistances were found under irrigated conditions (site 2). During 2003, June 23, July 2, July 16 and August 05 were selected at sites 2 and 3. At site 2, LAI ranged from 1.45 to 5.3 and from 1.45 to 3.7 m² m⁻² at site 3. Canopy resistance calculated with the P-M and the SEB model follows the same tendency during the day, especially July 2 and during July 16 (Figure 4.4). Again, canopy resistance calculated with the SEB model was higher than that calculated with P-M approach. During 2005, LAI conditions were similar at both sites (Figure 4.2). Selected days in 2005 were June 19, June 26, July 13 and August 16. Under similar LAI conditions canopy resistances calculated at site 3 were higher than calculated at site 2 using the P-M and the SEB approaches (Figure 4.5). Maximum resistances were observed either early in the morning or late afternoon. Overall, resistances from each model follow the same diurnal pattern but the magnitudes were different.
Figure 4.3. Canopy resistance estimated with the P-M model and the SEB model for June 26, June 23, July 08 and July 16 2001, at sites 2 and 3.
Figure 4.4. Canopy resistance estimated with the P-M model and the SEB model for June 23, July 2, July 16 and August 3, 2003, at sites 2 and 3.
Figure 4.5. Canopy resistance estimated with the P-M model and the SEB model for June 19, June 24, July 13 and August 16 2005, at sites 2 and 3.
Box plots of hourly canopy resistance calculated with both methods at two sites were constructed to provide a graphical representation of hourly $r_c$ during the day. The lower edge of the box represents the first quartile and the top of the box represents the third quartile. The line in between the first and the third quartile represents the median, and the diamond symbol represents the mean. Whiskers extent vertically up and down from the box representing maximum and minimum values.

Box plots of canopy resistance under low LAI ($LAI < 2$), medium LAI ($2 < LAI < 4$), and fully canopy cover ($LAI > 4$) conditions were constructed for hourly data during the day from 9:30am to 4:30pm with the P-M and the SEB model at sites 2 and 3. For this analysis the energy closure of the eddy covariance measurements were within 10%.

Under low LAI conditions at site 2, mean canopy resistance values calculated with the P-M approach ($r_c$-PM) ranged between 140 and 200 s m$^{-1}$, and calculated with the SEB model ($r_c$-SEB) ranged from 270 to 380 s m$^{-1}$. At site 3, $r_c$-PM ranged from 140 to 280 s m$^{-1}$ and $r_c$ using the SEB model ranged from 360 to 460 s m$^{-1}$ (Figure 4.6). For low LAI conditions canopy resistance calculated with the SEB model was typically twice the value calculated with the P-M model. Under medium LAI conditions ($2 < LAI < 4$) at site 2, $r_c$-P-M ranged 95 to 150 s m$^{-1}$ and $r_c$-SEB ranged from 150 to 190 s m$^{-1}$. At site 3, $r_c$-PM ranged from 90 to 140 s m$^{-1}$ and $r_c$-SEB ranged from 150 to 180 s m$^{-1}$ (Figure 4.7). On average, under these conditions $r_c$-SEB was 1.5 times the $r_c$ obtained from the P-M model. Under full canopy cover ($LAI > 4$), for the irrigated site $r_c$-PM ranged from 45 to 75 s m$^{-1}$ and $r_c$-SEB from 65 to 85 s m$^{-1}$. At site 3, $r_c$-PM ranged from 80 to 125 s m$^{-1}$ and $r_c$-SEB ranged from 100 to 150 s m$^{-1}$. For closed canopies $r_c$-SEB was about 1.3 times the $r_c$ from the P-M model.
Figure 4.6. Box plot of canopy resistance estimated with the P-M model and the SEB model at sites 2 and 3. For this analysis leaf area index was less than 2 (0 < LAI < 2) and the energy closure of eddy covariance measurements was within ±10%.
Figure 4.7. Box plot of canopy resistance estimated with the P-M model and the SEB model at sites 2 and 3. For this analysis leaf area index was higher than 2 but less than 4 ($2 < \text{LAI} < 4$) and the energy closure of eddy covariance measurements was within $\pm 10\%$. 
Figure 4.8. Box plot of canopy resistance estimated with the P-M model and the SEB model at sites 2 and 3. For this analysis leaf area index was higher than 4 (LAI > 4) and the energy closure of eddy covariance measurements was within ±10%.
Results showed that during the day (9:30am – 4:30pm) the canopy resistance calculated with the SEB model is consistently higher than calculated with the P-M model. Under low LAI condition differences between rc-SEB and rc-PM were bigger than at higher LAI conditions. Both methods yielded higher resistance values for the rainfed than for the irrigated site.

The relationship between rc estimates with the P-M and the SEB models were evaluated using linear regression analysis. Hourly canopy resistance was calculated with the P-M and the SEB models during the growing season for varying canopy cover conditions (LAI < 2, 2 < LAI < 4, and LAI > 4). Under full-canopy cover conditions (LAI > 4), the regression slope (ratio of SEB to P-M) was 1.26 and 1.35 with coefficients of determination ($r^2$) of 0.50 and 0.66 for sites 2 and 3 respectively (Figure 4.9). Under LAI < 2, the regression slope was 1.92 and 2.04 with correlation coefficients of 0.73 and 0.59 for sites 2 and 3 respectively. Other LAI conditions are presented in Table 4.2.

Results show that under full-canopy cover conditions, differences between rc obtained from the P-M model and the SEB model are smaller than differences evaluated for sparse canopies. Additionally, a linear regression was calculated between average midday (11:30am – 2:30pm) canopy resistance estimated with the P-M and from the SEB models, for LAI values higher than 2. Regression slopes of 1.41 and 1.48 were estimated at site 2 and 3 respectively (Figure 4.10).
Table 4.2. Regression analysis of hourly canopy resistance estimated with the P-M and the SEB models.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Site</th>
<th>Slope b and standard error</th>
<th>r^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAI &gt; 0</td>
<td>2</td>
<td>1.68 ±0.019</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.83 ±0.018</td>
<td>0.72</td>
</tr>
<tr>
<td>0 &lt; LAI &lt; 2</td>
<td>2</td>
<td>1.92 ±0.044</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.04 ±0.037</td>
<td>0.59</td>
</tr>
<tr>
<td>2 &lt; LAI &lt; 4</td>
<td>2</td>
<td>1.43 ±0.044</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.54 ±0.016</td>
<td>0.61</td>
</tr>
<tr>
<td>LAI &gt; 4</td>
<td>2</td>
<td>1.26 ±0.014</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.35 ±0.017</td>
<td>0.66</td>
</tr>
<tr>
<td>LAI &gt; 2 at midday</td>
<td>2</td>
<td>1.40 ±0.021</td>
<td>0.82</td>
</tr>
<tr>
<td>(11:30 – 14:30)</td>
<td>3</td>
<td>1.48 ±0.020</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Y = b X
Y = rc-SEB (s m^{-1}) ; X = rc-PM (s m^{-1})
Figure 4.9. Relationship between canopy resistance (from 9:30am to 4:30pm) estimated with the P-M model and the SEB model at sites 2 and 3 (2001, 2003 and 2005). When LAI > 4.
Figure 4.10. Relationship between average canopy resistance (from 11:30am to 2:30pm) estimated with the P-M model and the SEB model at midday at sites 2 and 3 (2001, 2003, and 2005). When LAI > 2.
Average midday canopy conductance (Cc) (the inverse of canopy resistance) from 11:30am to 2:30pm was calculated during the growing seasons at sites 2 and 3. Midday Cc calculated with the P-M and the SEB models follow the same tendency during the growing seasons for the three years evaluated. As the plants began to mature Cc values began to increase and near maturity Cc decreased due to leaf senescence.

During 2001, canopy conductance at sites 2 and 3 shows a large variation during the growing season (Figure 4.11). Minimum values were found at low LAI conditions, either at the beginning or at the end of the growing season. Using the P-M model maximum values ranged from 20 to 30 mm s\(^{-1}\) at site 2 and 15 to 20 mm s\(^{-1}\) at site 3.

Maximum conductance using the SEB model ranged from 15 to 20 mm s\(^{-1}\) and 10 to 15 mm s\(^{-1}\) at site 2 and 3 respectively. During the growing seasons of 2003 and 2005 similar ranges of maximum conductance were found at both sites (Figure 4.12 and 4.13). At site 2, peak conductances were found at the end of July during 2001 (LAI of 5.9), at the beginning of August during 2003 (LAI of 5.3) and at the end of July during 2005 (LAI of 4.7). At site 3, peak conductances were found at the end of July during 2001 (LAI of 3.7), 2003 (LAI of 4.0) and 2005 (LAI of 4.2).

Comparables values for maximum Cc are found in the literature, Rochette et al. (1991) reported maximum canopy conductance in the range of 20 to 30 mm s\(^{-1}\) for maize estimated with the P-M equation. Kelliher et al. (1995) reported a maximum Cc of 32.5 ±10.9 mm s\(^{-1}\) for cereals. Baldocchi (1994) showed a maximum canopy conductance of 10 – 15 mm s\(^{-1}\) for maize (LAI = 2). Steduto and Hsiao (1998), using the Penman-Monteith equation, reported corn canopy conductance values up to 40 mm s\(^{-1}\) under the
Figure 4.11. Average canopy conductance (from 11:30am to 2:30pm) estimated with the P-M model and the SEB model at midday at sites 2 and 3 during 2001.
Figure 4.12. Average canopy conductance (from 11:30am to 2:30pm) estimated with the P-M model and the SEB model at midday at sites 2 and 3 during 2003.
Figure 4.13. Average canopy conductance (from 11:30am to 2:30pm) estimated with the P-M model and the SEB model at midday at sites 2 and 3 during 2005.
most favorable water conditions. Irmak et al. (2008) reported midday values of Cc of 30 - 35 mm s$^{-1}$ for maize irrigated with a subsurface drip system. The Cc values estimated using the P-M model in this study are in concordance with the reported values found in the literature. However, Cc obtained from the SEB model are lower than those estimated by rearranging the P-M equation.

In summary, canopy resistance estimated with the P-M approach and the SEB model follows the same pattern during the day. As was expected, canopy resistance estimated with the SEB model was higher than that calculated with the P-M model. During the day (9:30am – 4:30pm) the canopy resistance calculated with the SEB model is constantly higher than calculated with the P-M model. Under low LAI conditions differences between rc-SEB and rc-PM were larger than found at higher LAI conditions. Using both methods, higher resistances occurred for rainfed conditions at site 3 than for irrigated maize at site 2. A linear regression analysis between hourly canopy resistance from the P-M and SEB models was conducted for varying canopy conditions during the growing season (LAI < 2, 2 < LAI < 4, and LAI > 4). Results showed that under full canopy cover conditions, differences between rc obtained from the P-M model and the SEB model are smaller than differences evaluated under sparse canopies. For full-canopy cover condition (LAI > 4) the regression slope was 1.26 and 1.35 for sites 2 and 3 respectively. For sparse canopies (LAI < 2), the regression slope was 1.92 at site 2 and 2.04 at site 3.
**Comparison of Canopy Conductance Models**

Sites 2 and 3 were used to evaluate two models to predict canopy conductance (Cc). Model parameters were estimated by fitting hourly Cc estimated with equation 13 (Model 1) and equation 14 (Model 2) to hourly Cc obtained from the SEB and the P-M models. The parameters (a1, a2, a3, a4 and c1, c2, and c3) were determined for each site using nonlinear optimization (the Generalized Reduced Gradient nonlinear optimization code of the Solver tool in Microsoft Office Excel). Three canopy conditions (all season LAI>0, small canopies LAI > 2 and full canopy LAI > 4) were used for this analysis. Values of the parameters determined with each Cc model at site 2 and 3 are listed in Table 4.3 and 4.4 respectively. Data during precipitation events, when the energy closure was not within ±10%, and during the night (7:30P-M – 7:30am) were excluded.

Figure 4.14 shows the form of the functions for light $f_1(L)$, temperature $f_2(T)$, vapor pressure deficit $f_3$ (VPD) and soil water content $f_4$ ($\Theta$) for model 1. Functions were similar for all canopy conditions using values from the SEB and the P-M model. Different parameters were found when the model was calibrated with Cc from the SEB than when calibrated with data from the P-M model. Light in function $f_1$ (L), has more effect in Cc estimated with the P-M than with the SEB model. The effect of vapor pressure deficit was similar for the SEB and the P-M model. On contrary, after the optimization, the effect of soil water content was only significant for canopy resistance estimated with the SEB model. There was no effect of soil water content on canopy resistance estimated with the P-M model.
Table 4.3. Model parameters for the canopy conductance (Cc) models at site 2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Condition</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a1</td>
</tr>
<tr>
<td>Model #1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 0</td>
<td>0.119</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 2</td>
<td>0.094</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 4</td>
<td>0.167</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 0</td>
<td>0.018</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 2</td>
<td>0.015</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>0.017</td>
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<tr>
<td>Model #2</td>
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<td></td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 0</td>
<td>912.4</td>
</tr>
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<td>SEB</td>
<td>LAI &gt; 2</td>
<td>986.3</td>
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<tr>
<td>SEB</td>
<td>LAI &gt; 4</td>
<td>1198.6</td>
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<tr>
<td>PM</td>
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<td>PM</td>
<td>LAI &gt; 2</td>
<td>1440.1</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>1498.4</td>
</tr>
</tbody>
</table>

Table 4.4. Model parameters for the canopy conductance (Cc) models at site 3.

<table>
<thead>
<tr>
<th>Source</th>
<th>Condition</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a1</td>
</tr>
<tr>
<td>Model #1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 0</td>
<td>0.036</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 2</td>
<td>0.029</td>
</tr>
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<td>SEB</td>
<td>LAI &gt; 4</td>
<td>0.076</td>
</tr>
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<td>PM</td>
<td>LAI &gt; 0</td>
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<td>PM</td>
<td>LAI &gt; 2</td>
<td>0.025</td>
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<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>0.024</td>
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<tr>
<td>Model #2</td>
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<td></td>
</tr>
<tr>
<td>SEB</td>
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<td>SEB</td>
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<td>437.5</td>
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</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>618.6</td>
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</table>
Figure 4.14. Functions for light $f_1(L)$, temperature $f_2(T)$, vapor pressure deficit $f_3(VPD)$ and soil water content $f_4(\Theta)$ for model 1 at site 2.
The form of the functions found at site 3 using model 1 is shown in Figure 4.15. The form of the light function \( f_1 (L) \) was similar for the SEB and the P-M models. Vapor pressure deficit has more effect on \( C_c \) estimated with the P-M than estimated with the SEB model. Similar to site 2, there was no effect of soil water content on canopy resistance estimated with the P-M model. The function of temperature \( f_2 (T) \) was the same and constant at both sites, using minimum, maximum and optimum temperatures given by Baldocchi (1987).

For model 2, the effect of radiation and vapor pressure deficit on canopy conductance is presented in Figure 4.16. Similar effects of solar radiation were found at sites 2 and 3 using \( C_c \) from the SEB model. On contrary, lower effects of vapor pressure deficit on \( C_c \) estimated with the SEB model was found at these sites. Using \( C_c \) from the P-M model, the effect of solar radiation was similar at site 2 and 3, and there was more effect of vapor pressure deficit on \( C_c \) estimated from the P-M than for the SEB model.

The Nash-Sutcliffe coefficient (E), the coefficient of determination \( r^2 \) and the linear regression slope were used to evaluate the performance of the models to estimate hourly \( C_c \). Table 4.5 shows the statistics for models 1 and 2 at sites 2 and 3. For this analysis the energy closure of the measurements was within 10%, and data during rain events were removed. Calculations were made for the whole growing season \( LAI > 0 \), partial canopy when \( LAI > 2 \), and full canopies when \( LAI > 4 \).

For model 1, the regression slopes ranged from 1.0 to 1.07 at site 2 and from 0.99 to 1.04 at site 3. In general the \( r^2 \) was low at both sites. During the growing season when \( LAI > 0 \) the average \( r^2 \) was 0.15 at site 2 and 0.02 at site 3. The maximum
Figure 4.15. Functions for light $f_1(L)$, temperature $f_2(T)$, vapor pressure deficit $f_3(VPD)$ and Soil water content $f_4(\Theta)$ for model 1 at site 3.
Figure 4.16. Effect of solar radiation (Rad) and vapor pressure deficit (VPD) on canopy conductance estimated with model 2, a) Site 2, b) Site 3.
Table 4.5. Statistic indices for hourly Cc estimations using model 1 and 2 for three canopy conditions at site 2 and 3.

<table>
<thead>
<tr>
<th>Source</th>
<th>Condition</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope</td>
<td>$r^2$</td>
</tr>
<tr>
<td>Model #1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 0</td>
<td>1.00</td>
<td>0.17</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 2</td>
<td>1.00</td>
<td>0.41</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 4</td>
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<td>0.28</td>
</tr>
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<td>PM</td>
<td>LAI &gt; 0</td>
<td>1.07</td>
<td>0.13</td>
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<td>PM</td>
<td>LAI &gt; 2</td>
<td>1.07</td>
<td>0.12</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>1.05</td>
<td>0.07</td>
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<td>Model #2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 0</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>SEB</td>
<td>LAI &gt; 2</td>
<td>1.00</td>
<td>0.45</td>
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<td>SEB</td>
<td>LAI &gt; 4</td>
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<td>0.30</td>
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<tr>
<td>PM</td>
<td>LAI &gt; 0</td>
<td>0.99</td>
<td>0.14</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 2</td>
<td>1.00</td>
<td>0.12</td>
</tr>
<tr>
<td>PM</td>
<td>LAI &gt; 4</td>
<td>1.00</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The variance explained by model 1 was 41% for partial canopies when LAI > 2. The coefficient E ranged from 0.07 to 0.41 at site 2, and from 0.0 to 0.22 at site 3. The best performance was found for LAI > 2 using Cc estimated with the SEB model. When considering both sites, model 1 performed better when was used to estimate Cc obtained from the SEB model than when the P-M equation was used to calibrate the model.

For model 2, the regression slopes were constantly equal to 1.0 at site 2 and 3. The coefficient of determination was low for all cases. Maximum variance explained by model 2 was 0.45 for partial canopies when LAI > 2. The efficiency coefficient E ranged from 0.07 to 0.45 at site 2 and ranged from 0.0 to 0.22 at site 3. Similar to model 1, the best performance occurred when the LAI > 2. Model 2 was more accurate when Cc was
calibrated from the SEB model than from the P-M model. The performance of models 1 and 2 was better for the irrigated site than for rainfed conditions.

Hourly (8:30am – 6:30pm) canopy conductance estimated with models 1 and 2 and with the SEB and P-M models are shown in Figure 4.17. For this analysis, data during the growing season where LAI > 2 at site 2 was used. From this figure, it is possible to observe that there are no clear differences between the performance of model 1 and model 2. The linear regression slopes were constantly 1.0 for both models. More variability and higher conductance values were found when models were calibrated to canopy conductance obtained from the P-M equation than when calibrated to the SEB model. Maximum canopy conductance predicted by model 1 and 2 for Cc obtained from the P-M equation ranged from 40 to 45 mm s\(^{-1}\). The maximum canopy conductance predicted by model 1 and 2 ranged from 20 to 25 mm s\(^{-1}\) when models were calibrated to the SEB model. A slightly better performance can be observed when models estimate Cc obtained from the SEB model than when calculated from the P-M equation. The Nash Sutcliffe coefficient E was 0.41 and 0.45 for models 1 and 2 when calibrated to the SEB model.

Similar results were observed for site 3 (Figure 4.18). The linear regression slope for both canopy conductance models was equal to 1.0. More variability and higher conductance values were found when models where calibrated to the P-M equation than the SEB model. Maximum canopy conductance predicted by model 1 and 2 were lower than maximum conductance.
Figure 4.17. Hourly (8:30am – 6:30pm) canopy conductance (Cc) estimated with models 1 and 2 when calibrated to the SEB and the P-M models at site 2. For this analysis LAI exceeded 2, and the energy closure was within 10%. Data during rain events were removed.
Figure 4.18. Hourly (8:30am – 6:30pm) canopy conductance (Cc) estimated with models 1 and 2 when calibrated to the SEB and the P-M models at site 3. For this analysis LAI exceed 2, and the energy closure was within 10% . Data during rain events were removed.
estimated at site 2. Predicting canopy conductance from the P-M gave maximum values from 20 to 30 mm s\(^{-1}\). For Cc estimated with the SEB model, the maximum values with model 1 and 2 ranged from 10 to 11 mm s\(^{-1}\). Slightly better performance can be observed when models were calibrated to the SEB model than the P-M equation.

Overall, slightly better performance of model 1 and 2 was found estimating Cc obtained from the SEB model than the P-M model. Similar results were also found by Baldocchi (1987). He compared canopy resistance calculated using a scaling up model with canopy resistance from the P-M model. The difference between these two models was on the order of 30-50%. According to Baldocchi (1987), these differences were expected since canopy resistance in the P-M model does not equal the parallel, area weighted sum of the stomata resistance of individual leaves in the canopy. Instead the P-M canopy resistance is a function of the stomata and aerodynamic resistance of the leaves in the canopy and net radiation incident on those leaves (Baldocchi 1987). The best performance for model 1 and 2 was found during the growing season for partial canopies when LAI > 2. Canopy conductance predictions using models 1 and 2 were better for irrigated conditions than for the rainfed site. Model 1 and 2 performed equally for these sites and conditions. This suggests that the effect of temperature and soil water content do not improve estimates of canopy conductance.

The SEB model has the ability to separate evapotranspiration into transpiration and evaporation. This allows an analysis of evaporation and transpiration separation as function of canopy conductance. Midday canopy conductance (11:30am – 2:30P-M) was plotted against hourly transpiration at sites 2 and 3 (Figure 4.19). Transpiration was normalized with total evapotranspiration (ET). The relationship found using these data
suggest that transpiration is significantly influenced when $C_c$ drops below 10 mm s$^{-1}$.

This conductance threshold is lower than observed by Suyker and Verma (2007) (10-15 mm s$^{-1}$) and Steduto and Hsiao (1998) (15 mm s$^{-1}$) in maize using $C_c$ obtained from the P-M model.
Figure 4.19. Ratio of transpiration (T) to evapotranspiration (ET) estimated from the SEB model as a function of midday hourly (11:30am – 2:30pm) canopy conductance (Cc) for maize at site 2 (above) and site 3 (below).
Conclusions.

A modified SEB model and the P-M model were used to estimate canopy resistance for maize under irrigated and rainfed conditions. Canopy resistance was calculated during 2001, 2003 and 2005 growing seasons.

Canopy resistance estimated with the P-M approach and the SEB model follow the same pattern during the growing season and during the day but with different magnitudes. As was expected, canopy resistance estimated with the SEB model was higher than calculated with the P-M model. During the day (9:30am – 4:30pm) the canopy resistance calculated with the SEB model is consistently higher than calculated with the P-M model. Higher resistances were calculated for the rainfed condition at site 3 than for irrigated conditions at site 2. Midday (11:30 am– 2:30 pm) canopy conductance was calculated with the P-M equation and the SEB model for each year at both sites. Results showed that Cc values estimated using the P-M model are in concordance with the reported values found in the literature. However, Cc obtained from the SEB model was lower than estimated by rearranging the P-M equation.

In general these results suggest that soil evaporation considerably affects the canopy conductance obtained with the P-M equation. As expected, the effect of soil evaporation was more important under low LAI conditions.

Sites 2 and 3 were used to evaluate two selected “scaling up” models to predict canopy conductance with Cc data obtained from the P-M equation and the SEB model. Three canopy conditions were evaluated (LAI>0, LAI > 2 and LAI > 4). Overall, a slightly better performance of model 1 and 2 was found in estimating Cc values when calibrated to the SEB model than when calibrate to the P-M model. The best model
performance for model 1 and 2 was found during the growing season when LAI > 2.

Canopy conductance using model 1 and 2 was better predicted under irrigated conditions than for the rainfed site. Models 1 and 2 performed about the same in estimating canopy conductance. The greater array of model parameters used in model 1 does not significantly improve estimates of conductance. The relationship between canopy conductance and transpiration at both sites suggest that transpiration is significantly influenced by canopy conductance when Cc drops below 10 mm s\(^{-1}\).

In general, results suggest that canopy conductance obtained with the SEB model, where the estimated soil evaporation effect has been removed, are lower and slightly better predicted by “scaling up” methods than canopy conductance obtained from the P-M equation.
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Chapter V. Summary, Conclusions and Recommendations

Summary and Conclusions

The first objective of this research was to modify and extend a surface energy balance (SEB) model to include the effect of residue-covered areas on estimates of evapotranspiration.

In chapter 2, a SEB model based on the Shuttleworth-Wallace (1985) and Choudhury and Monteith (1988) was modified to account for the effect of residue, soil evaporation and canopy transpiration on total evapotranspiration, for field conditions varying from partially covered soil to closed canopy surfaces. The model describes the energy balance of partially vegetated and residue-covered surfaces in terms of driving potential and resistances to flux. The proposed SEB model assumed that horizontal gradients of the potentials are small enough for lateral fluxes to be ignored. Physical and biochemical energy storage terms in the canopy/residue/soil system are assumed to be negligible. An important feature of the model is the ability to estimate latent, sensible and soil heat fluxes for model evaluation. Others differences with the model proposed by Choudhury and Monteith (1988) and Shuttleworth Wallace (1985) were the improvements in aerodynamic resistances for heat and water transfer, and canopy resistance for water flux, the incorporation of new residue resistances for heat and water transport and the definition of a new soil resistance for water transfer.

The following inputs are required for the model: net radiation, solar radiation, air temperature, relative humidity, and wind speed, LAI and crop height, soil texture, soil temperature and soil water content, and for residue, the type and amount.
In Chapter 3, a sensitivity analysis and the evaluation of the proposed SEB model to estimate ET was completed during the growing and non-growing seasons for maize and soybean. Results were compared with measured data from three eddy covariance systems.

In general, the sensitivity analysis of model parameters showed that simulated ET was most sensitive to changes in surface canopy resistance, soil surface resistance, and residue surface resistance. The model was less sensitive to changes in the extinction coefficient, soil temperature, the attenuation coefficient, the surface boundary layer, errors in crop height, and soil heat flux resistances.

Comparisons between estimated ET and measurements made in soybean and maize fields provided support for the validity of the surface energy balance model. The statistics indices of agreements, Nash-Sutcliffe coefficient, index of agreement, the root mean square error, and the mean absolute error, were used to evaluate the performance of the model. Agreement between measured and estimated evapotranspiration was very good. For annual estimations, the Nash-Sutcliffe coefficients were in the range 0.82-0.90, and the RMSE of the model was 26.4 – 37.1 W m\(^{-2}\). Estimates of ET during the growing seasons resulted in an Nash-Sutcliffe coefficients ranged from 0.81 to 0.92 and the RMSE varied from 33.0 to 48.3 W m\(^{-2}\). During the growing season the model predict more accurately after canopy closure (i.e. after LAI=4 until harvest). Performance prior to canopy closure was less accurate. The model predicted ET values more accurately under irrigated conditions than for rainfed agriculture.

The ratio of annual ET calculated with the modified model to the annual ET measured with the eddy covariance system ranged between 0.94 and 1.06 for irrigated
maize, resulting in annual $\lambda E$ differences of less than 6%. For maize fields, crop transpiration estimated with the modified SEB model was 64 - 74% of the annual evapotranspiration under irrigated conditions and 61 - 64% under rainfed conditions. For soybeans fields, crop transpiration was 59% of the annual ET under irrigated conditions and 53 - 55% under rainfed agriculture. Overall the evaluation of the SEB model estimating evapotranspiration with measurements by eddy covariance systems during this study was satisfactory.

The second objective of this research was to evaluate the differences between surface canopy resistances estimated with the Penman - Monteith model and the surface canopy resistance obtained when the estimated effect of soil evaporation is removed by using the SEB model.

The modified SEB model and the Penman – Monteith model were used in Chapter 4 to estimate canopy resistance for maize under irrigated and rainfed conditions. Canopy resistance estimated with the P-M approach and the SEB model follow the same pattern during the growing season and during the day but with different magnitudes. As was expected, canopy resistance estimated with the SEB model was higher than calculated with the P-M model. Under low LAI conditions differences between canopy resistance estimated with the SEB and the P-M models were larger than at higher LAI conditions. A linear regression analysis between hourly canopy resistance from the P-M and the SEB model was calculated during the growing season and under varying canopy cover conditions. Results show that, under full canopy cover conditions, differences between $rc$ obtained from the P-M model and the SEB model are smaller than differences for sparse canopies. Under full canopy cover condition (LAI > 4), the regression slopes
between rc obtained from the P-M equation and the SEB model were 1.27 and 1.24 for sites 2 and 3 respectively. Under LAI < 2, the regression slopes were 1.92 at site 2 and 2.02 at site 3. Higher resistances values were calculated at site 3 than at site 2.

In general these results suggest that the soil evaporation considerably affects the canopy conductance obtained with the P-M equation. As was expected the effects of soil evaporation was more important under low LAI conditions.

Additionally, the irrigated and rainfed maize sites were used to evaluate “scaling up” models to predict canopy conductance with data from the P-M equation and the SEB model. Three canopy conditions were evaluated (LAI>0, LAI > 2 and LAI > 4). Both models performed better when they were calibrated to the SEB model than when calibrated to the P-M model. The models performed best for the growing season when LAI > 2. Canopy conductance was better predicted under irrigated conditions than for the rainfed site. Inclusion of more model parameters in model 1 did not significant improve model estimates of canopy conductance. Our results suggest that canopy conductance from a multiple-layer model, where the estimated soil evaporation effect has been removed, is better source for calibrating scaling up methods than canopy conductance from the P-M equation.

**Recommendations for Future Research.**

Results of this study show that a surface energy balance model can be adapted to include the effect of residue covered areas on estimates of evapotranspiration. Comparisons between estimated ET with the SEB model and measured ET provided support for the validity of the model. Since the model requires meteorological inputs (net radiation, solar radiation, air temperature, relative humidity, and wind speed), canopy
inputs (LAI and crop height) and soil/residue inputs (soil texture, soil temperature, soil water content, and residue type and amount), future research should include the evaluation of others methods to estimates these parameters. In particular, net radiation, leaf area index, soil temperatures and residue amount are variables rarely measured in fields other than at research sites. Another approach can study the viability to incorporate the proposed SEB model into an existing crop model where some inputs of the SEB model are already estimated.

Since the model has the ability to estimate latent, sensible and soil heat fluxes, further research could include the evaluation of these fluxes under different canopy cover conditions. The performance of the model prior to canopy closure was less accurate than for close canopy surfaces. To improve model estimations under low LAI conditions, the SEB model could be applied to two independent surfaces, one for bare soil and another for areas with vegetation. An analysis of this approach can be performed if the fraction of the soil covered by vegetation is measured or estimated.

Others evaluations can include the effect of stability on the surface energy balance and the incorporation of storage terms on model simulations. Applications of the model can include the study of crop coefficients for different agricultural and natural vegetations. Since the model has the ability to separate canopy transpiration and soil evaporation, the study of crop coefficients can be performed. In particular, the dual crop coefficient approach where the effect of crop transpiration and soil evaporation is determined separately could be evaluated. Another application can test several “scaling up” methods to predict canopy resistance obtained from the SEB model and select the most appropriate model to be used with the proposed SEB. According to our results, soil
evaporation accounts for approximately 40% of the annual ET. More detailed evaluation of the performance of the model during the non-growing season can provide additional information to future improvements of the SEB model during this period.
**Appendix 1**

**List of Variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>Coefficient of the light function $f_1(L)$.</td>
</tr>
<tr>
<td>$a_2$</td>
<td>Coefficient of the light function $f_1(L)$.</td>
</tr>
<tr>
<td>$a_3$</td>
<td>Coefficient of the vapor pressure deficit function $f_3(VPD)$.</td>
</tr>
<tr>
<td>$a_4$</td>
<td>Coefficient of the soil water content function $f_4(\Theta)$.</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Constant.</td>
</tr>
<tr>
<td>$B^{-1}$</td>
<td>Bulk parameter.</td>
</tr>
<tr>
<td>$C_1$</td>
<td>Canopy resistance coefficient.</td>
</tr>
<tr>
<td>$c_1, c_2, c_3$</td>
<td>Regression coefficients.</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Canopy resistance coefficient.</td>
</tr>
<tr>
<td>$C_3$</td>
<td>Canopy resistance coefficient.</td>
</tr>
<tr>
<td>$C_4$</td>
<td>Canopy resistance coefficient.</td>
</tr>
<tr>
<td>$C_{c1}$</td>
<td>Canopy conductance model 1 ($m s^{-1}$).</td>
</tr>
<tr>
<td>$C_{c2}$</td>
<td>Canopy conductance model 2 ($m s^{-1}$).</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Drag coefficient.</td>
</tr>
<tr>
<td>$C_{ext}$</td>
<td>Extinction coefficient.</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat of air ($J Kg^{-1} \circ C^{-1}$).</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Stomata conductance ($m s^{-1}$).</td>
</tr>
<tr>
<td>$C_{s\text{max}}$</td>
<td>Maximum stomata conductance ($m s^{-1}$).</td>
</tr>
<tr>
<td>$d$</td>
<td>Index of agreement.</td>
</tr>
<tr>
<td>$d'$</td>
<td>Zero plane displacement (m).</td>
</tr>
<tr>
<td>$D_v$</td>
<td>Water vapor diffusion coefficient ($m^2 s^{-1}$).</td>
</tr>
<tr>
<td>$E$</td>
<td>Nash-Sutcliffe coefficient.</td>
</tr>
</tbody>
</table>
\( e_{1}^{*} \)  Saturated vapor pressure at the canopy (mb).
\( e_{a} \)  Vapor pressure of the air (mb).
\( e_{a}^{*} \)  Saturated vapor pressure of the air (mb).
\( e_{b} \)  Vapor pressure of the air at the canopy level (mb).
\( e_{b}^{*} \)  Saturated vapor pressure at the canopy level (mb).
\( e_{L}^{*} \)  Saturated vapor pressure at the top of the wet layer (mb).
\( e_{Lr}^{*} \)  Saturated vapor pressure at the top of the wet layer for the residue-covered soil (mb).
\( E_{\text{Test}} \)  Average estimated evapotranspiration (W m\(^{-2}\)).
\( E_{\text{Test}} \)  Estimated evapotranspiration (W m\(^{-2}\)).
\( E_{\text{mea}} \)  Average measured evapotranspiration (W m\(^{-2}\)).
\( E_{\text{mea}} \)  Measured evapotranspiration (W m\(^{-2}\)).
\( f_{r} \)  Fraction of the soil covered by residue (0-1).
\( G_{or} \)  Conduction flux from the residue-covered soil surface (W m\(^{-2}\)).
\( G_{os} \)  Conduction flux from the soil surface (W m\(^{-2}\)).
\( G_{r} \)  Soil heat flux for residue-covered soil (W m\(^{-2}\)).
\( G_{s} \)  Soil heat flux for bare soil (W m\(^{-2}\)).
\( H \)  Total Sensible heat flux (W m\(^{-2}\)).
\( h \)  Vegetation height (m).
\( H_{c} \)  Sensible heat flux from the canopy (W m\(^{-2}\)).
\( H_{r} \)  Sensible heat flux from the residue-covered soil (W m\(^{-2}\)).
\( H_{s} \)  Sensible heat flux from the soil (W m\(^{-2}\)).
\( K \)  Thermal conductivity of the soil, upper layer (W m\(^{-1}\) °C\(^{-1}\)).
k  Von-Karman Constant.
K(z)  Eddy diffusion coefficient (m^2 s^{-1}).
K'  Thermal conductivity of the soil, lower layer (W m^{-1} oC^{-1}).
k_1  Thermal diffusivity (m^2 s^{-1}).
K_r  Thermal conductivity of the residue layer (W m^{-1} oC^{-1}).
LAI  Leaf area index (m^2 m^{-2}).
LAI_{eff}  Effective leaf area index (m^2 m^{-2}).
LAI_{max}  Maximum leaf area index (m^2 m^{-2}).
L_m  Lower layer depth (m).
L_r  Thickness of the residue layer (m).
L_t  Thickness of soil layer (m).
M  Density of dry surface residue (ton ha^{-1}).
MAE  Mean absolute error.
n  Number of observations.
PPFD  Photon flux density (µmol m^2 s^{-1}).
r_1  Aerodynamic resistance between the canopy and the air at the canopy level (s m^{-1}).
r^2  Coefficient of determination.
r_2  Aerodynamic resistance between the soil and the air at the canopy level (s m^{-1}).
ra  Aerodynamic resistance for water vapor (s m^{-1}).
Rad  Solar radiation (W m^2).
Rad_{max}  Maximum value of solar radiation (W m^2).
ra_h \quad \text{Aerodynamic resistance for heat transfer (s m}^{-1}).
ra_m \quad \text{Aerodynamic resistance for momentum transfer (s m}^{-1}).
ra_w \quad \text{Aerodynamic resistance for water vapor (s m}^{-1}).
br \quad \text{Boundary layer resistance (s m}^{-1}).
rb_h \quad \text{Excess resistance term for heat transfer (s m}^{-1}).
rb_w \quad \text{Excess resistance term for water vapor (s m}^{-1}).
rc \quad \text{Surface canopy resistance (s m}^{-1}).
r_L \quad \text{Soil heat flux resistance for the lower layer (s m}^{-1}).
\text{RMSE} \quad \text{Root mean square error.}
R_n \quad \text{Net Radiation (W m}^2).\nR_{nc} \quad \text{Net Radiation absorbed by the canopy (W m}^2).\nR_{ns} \quad \text{Net Radiation absorbed by the soil (W m}^2).\nr_r \quad \text{Residue resistance for water vapor flux (s m}^{-1}).\nr_r h \quad \text{Residue resistance for heat flux (s m}^{-1}).\nr_s \quad \text{Soil surface resistance for water vapor flux (s m}^{-1}).\nr_{so} \quad \text{Soil surface resistance to the vapor flux for a dry layer (m s}^{-1}).\nr_{st} \quad \text{Stomata resistance (s m}^{-1}).\nr_u \quad \text{Soil heat flux resistance for the upper layer (s m}^{-1}).\nS \quad \text{Energy storage term (W m}^2).\nT \quad \text{Temperature (°C}).\nT_0 \quad \text{Optimum temperature (°C}).\nT_1 \quad \text{Canopy temperature (°C}).\nT_2 \quad \text{Soil surface temperature (°C}).
$T_{2r}$  Soil surface temperature below the residue ($^\circ$C).

$T_a$  Air temperature ($^\circ$C).

$T_b$  Air temperature at canopy height ($^\circ$C).

$T_h$  Maximum temperature at which stomata closure occurs ($^\circ$C).

$T_L$  Soil temperature at the interface between the upper and lower layers for the bare soil ($^\circ$C).

$T_{lo}$  Minimum temperature at which stomata closure occurs ($^\circ$C).

$T_{Lr}$  Soil temperature at the interface between the upper and lower layers for the residue-covered soil ($^\circ$C).

$T_m$  Soil temperature at the bottom of the lower layer ($^\circ$C).

$U$  Wind speed (m s$^{-1}$).

$u^*$  Friction velocity (m s$^{-1}$).

$u_2$  Wind speed at two meters above the surface (m s$^{-1}$).

$u_h$  Wind speed at the top of the canopy (m s$^{-1}$).

$VPD_a$  Vapor pressure deficit (mb)

$w$  Mean leaf width (m).

$z$  Reference height (m).

$z_o$  Surface roughness length (m).

$z_o'$  Roughness length of the soil surface (m).

$\alpha$  Attenuation coefficient for eddy diffusion coefficient within the canopy.

$\beta$  Fitting parameter.

$\gamma$  Psychrometric constant (mb C$^{-1}$).
$\Delta_1$  Mean rate of change of saturated vapor pressure with temperature between the canopy and the air at the canopy level (mb °C$^{-1}$).

$\Delta_2$  Mean rate of change of saturated vapor pressure with temperature between the soil and the air at the canopy level (mb °C$^{-1}$).

$\Delta_3$  Mean rate of change of saturated vapor pressure and temperature between the canopy level and the air (mb °C$^{-1}$).

$\Delta_4$  Mean rate of change of saturated vapor pressure and temperature between the soil and the air at the canopy level for the residue covered soil (mb °C$^{-1}$).

$\theta$  Volumetric soil water content (m$^3$ m$^{-3}$).

$\theta_e$  Extractable soil water.

$\theta_s$  Saturation water content of the soil (m$^3$ m$^{-3}$).

$\lambda$  Latent heat of vaporization (KJ kg$^{-1}$).

$\lambda_E$  Total latent heat flux (W m$^2$).

$\lambda_{Ec}$  Latent heat flux from the canopy (W m$^2$).

$\lambda_{Er}$  Latent heat flux from the residue-covered soil (W m$^2$).

$\lambda_{Es}$  Latent heat flux from the soil (W m$^2$).

$\rho$  Density of moist air (Kg m$^3$).

$\rho_r$  Residue density (Kg m$^3$).

$\tau_r$  Residue tortuosity.

$\tau_s$  Soil tortuosity.

$\phi_r$  Residue porosity.

$\phi$  Soil porosity.
Procedure to solve heat and vapor transfer equations.

a) Canopy

Using (2) (11) and (12)

\[ R_{nc} = \frac{\rho \cdot C_p \cdot (e_i^* - e_b^*)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (T_i - T_b)}{r_i} \]

from (21a)

\[ \Delta_t \cdot (T_i - T_b) = (e_i^* - e_b^*) + (e_b^* - e_b^*) \]

therefore

\[ R_{nc} = \frac{\rho \cdot C_p \cdot (e_i^* - e_b^*)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_i^* - e_b^*)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_b^* - e_b^*)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_b^* - e_b^*)}{\gamma \cdot (r_i + r_c)} \]

The ratio \( \lambda_{Ec}/R_{nc} \) can be expressed:

\[ \frac{\lambda_{Ec}}{R_{nc}} = \frac{\rho \cdot C_p \cdot (e_i^* - e_b)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_i^* - e_b)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_b^* - e_b)}{\gamma \cdot (r_i + r_c)} + \frac{\rho \cdot C_p \cdot (e_b^* - e_b)}{\gamma \cdot (r_i + r_c)} \]

\[ \frac{\lambda_{Ec}}{R_{nc}} = \frac{\Delta_t}{\gamma \cdot (r_i + r_c)} + \frac{1}{r_i} + \frac{(e_b^* - e_b^*)}{r_i \cdot (e_i^* - e_b)} \]

\[ \frac{\lambda_{Ec}}{R_{nc}} = \frac{\Delta_t \cdot r_i}{\Delta_t \cdot r_i + \gamma \cdot (r_i + r_c) + \gamma \cdot (r_i + r_c) \cdot \frac{(e_b^* - e_b^*)}{(e_i^* - e_b)}} \]

\[ \frac{\lambda_{Ec}}{R_{nc}} = \frac{\Delta_t \cdot r_i}{\Delta_t \cdot r_i + \gamma \cdot (r_i + r_c) + \frac{\rho \cdot C_p \cdot (e_b^* - e_b)}{\lambda_{Ec}}} \]

then,
Sensible heat is calculated using (2) and the previous equation for $\lambda_{Ec}$.

$$\lambda_{Ec} = \frac{\Delta_1 \cdot r_i \cdot Rnc + \rho \cdot Cp \cdot (e_b^* - eb)}{\Delta_1 \cdot r_i + \gamma \cdot (r_i + rc)}$$  \hspace{1cm} (A1)

$$Hc = \frac{\gamma \cdot (r_i + rc) \cdot Rnc - \rho \cdot Cp \cdot (e_b^* - eb)}{\Delta_1 \cdot r_i + \gamma \cdot (r_i + rc)}$$  \hspace{1cm} (A2)

b) Bare soil

Using (10) and (21b)

$$\lambda_{Es} = \frac{\rho \cdot Cp \cdot (e_l^* - eb)}{\gamma \cdot (r_2 + rs)} = \frac{\rho \cdot Cp \cdot \Delta_2 \cdot (T_L - T_b) + \rho \cdot Cp \cdot (e_b^* - eb)}{\gamma \cdot (r_2 + rs)}$$

$$(T_L - T_b) = \frac{\lambda_{Es} \cdot \gamma \cdot (r_2 + rs) - \rho \cdot Cp \cdot (e_b^* - eb)}{\rho \cdot Cp \cdot \Delta_2}$$

Using (4), (17) and (18)

$$\lambda_{Es} = \frac{\rho \cdot Cp \cdot (T_2 - T_l)}{ru} - \frac{\rho \cdot Cp \cdot (T_l - T_m)}{ru}$$

$$\lambda_{Es} = \frac{\rho \cdot Cp \cdot (T_2 - T_l)}{ru} - \frac{\rho \cdot Cp \cdot (T_l - T_b)}{ru} - \frac{\rho \cdot Cp \cdot (T_b - T_m)}{ru}$$

Using (T_L-Tb), (T_2-T_L) can be expressed as:

$$(T_2 - T_L) = \frac{\lambda_{Es}}{\rho \cdot Cp} \cdot \left( ru + \frac{\gamma \cdot (r_2 + rs) \cdot ru}{\Delta_2 \cdot r_l} \right) - \frac{(e_b^* - eb) \cdot ru}{\Delta_2 \cdot r_l} + \frac{(T_b - T_m) \cdot ru}{r_l}$$

Using (3) and (4)

$$Rns = Hs + \lambda_{Es} + Gs$$

$$Rns = \frac{\rho \cdot Cp \cdot (T_2 - T_b)}{r_2} + \lambda_{Es} + \frac{\rho \cdot Cp \cdot (T_l - T_m)}{r_l}$$

$$Rns = \frac{\rho \cdot Cp \cdot (T_2 - T_L)}{r_2} + \frac{\rho \cdot Cp \cdot (T_l - T_b)}{r_2} + \lambda_{Es} + \frac{\rho \cdot Cp \cdot (T_l - T_b)}{r_l} + \frac{\rho \cdot Cp \cdot (T_b - T_m)}{r_l}$$
Then using the previous equations for \((T_2-T_L)\) and \((T_L-T_b)\), \(\lambda E_s\) can be estimated by:

\[
\lambda E_s = \frac{\left( Rns \cdot \Delta_2 \cdot r_2 \cdot r_L + \rho \cdot Cp \cdot ((e^*_b - eb) \cdot (ru + r_L + r_2)) + (Tm - Tb) \cdot \Delta_2 \cdot (ru + r_2) \right)}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2)}
\]

(A3)

Sensible heat for the soil (Hs) is calculated using (3), (4), and 12.

\[
Hs = \frac{\left( Rns \cdot r_L \cdot \Delta_2 - \lambda E_s \cdot (r_L \cdot \Delta_2 + \gamma \cdot (r_2 + rs)) + \rho \cdot Cp \cdot (e^*_b - eb) \right)}{\rho \cdot Cp \cdot \Delta_2 \cdot (Tb - Tm)}
\]

(A4)

c) Residue covered soil

Similarly to bare soil, using equation (16) and (21d):

\[
\lambda Er = \frac{\rho \cdot Cp \cdot (e^*_r - eb)}{\gamma \cdot (r_2 + rs + rr)} = \frac{\rho \cdot Cp \cdot \Delta_4 \cdot (T_{lr} - Tb) + \rho \cdot Cp \cdot (e^*_b - eb)}{\gamma \cdot (r_2 + rs + rr)}
\]

\[
(T_{lr} - Tb) = \frac{\lambda Er \cdot \gamma \cdot (r_2 + rs + rr) - \rho \cdot Cp \cdot (e^*_b - eb)}{\rho \cdot Cp \cdot \Delta_4}
\]

Using (6)

\[
\lambda Er = \frac{\rho \cdot Cp \cdot (T_2r - T_{lr})}{ru} - \frac{\rho \cdot Cp \cdot (T_{lr} - Tm)}{r_L}
\]

\[
\lambda Er = \frac{\rho \cdot Cp \cdot (T_2r - T_{lr})}{ru} - \frac{\rho \cdot Cp \cdot (T_{lr} - Tb)}{r_L} - \frac{\rho \cdot Cp \cdot (Tb - Tm)}{r_L}
\]

Using \((T_{lr} - Tb)\), \((T_2r - T_{lr})\) can be expressed as:

\[
(T_2r - T_{lr}) = \frac{\lambda Er}{\rho \cdot Cp} \left( ru + \frac{\gamma \cdot (r_2 + rs + rr) \cdot ru}{\Delta_4 \cdot r_L} \right) - \frac{(e^*_b - eb) \cdot ru}{\Delta_4 \cdot r_L} + \frac{(Tb - Tm) \cdot ru}{r_L}
\]

Now, using (5) and (6)

\[
Rns = Hr + \lambda Er + Gr
\]

\[
Rns = \frac{\rho \cdot Cp \cdot (T_2r - Tb)}{r_2 + rr_b} + \lambda Er + \frac{\rho \cdot Cp \cdot (T_{lr} - Tm)}{r_L}
\]
Rns = \frac{\rho \cdot Cp \cdot (T_2r - T_{Lr})}{r_2 + r_{rh}} + \frac{\rho \cdot Cp \cdot (T_{Lr} - Tb)}{r_2 + r_{rh}} + \lambda Er + \frac{\rho \cdot Cp \cdot (T_{Lr} - Tb)}{r_L} + \frac{\rho \cdot Cp \cdot (Tb - Tm)}{r_L}

Rns = \frac{\rho \cdot Cp \cdot (T_2r - T_{Lr})}{r_2 + r_{rh}} + \rho \cdot Cp \cdot (T_{Lr} - Tb) \cdot \left( \frac{1}{(r_2 + r_{rh})} + \frac{1}{r_L} \right) + \lambda Er + \frac{\rho \cdot Cp \cdot (Tb - Tm)}{r_L}

Then using the previous equations for \((T_2r - T_{Lr})\) and \((T_{Lr} - Tb)\), \(\lambda Er\) can be estimated by:

\[
\lambda Er = \frac{\left( Rns \cdot \Delta_4 \cdot (r_2 + r_{rh}) \cdot r_L + \rho \cdot Cp \cdot ((e_r^* - eb) \cdot (ru + r_L + r_2 + r_{rh})) \right)}{\gamma \cdot (r_2 + rs + rr) \cdot (ru + r_L + r_2 + r_{rh}) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_{rh})} \quad (A5)
\]

Sensible heat for the residue \((Hr)\) is calculated as:

\[
Hr = \frac{\left( Rns \cdot r_L \cdot \Delta_4 - \lambda Er \cdot (r_L \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr)) + \rho \cdot Cp \cdot (e_r^* - eb) \right)}{r_L \cdot \Delta_4} \quad (A6)
\]

d) Solution of equations for \(Tb\) and \(eb\)

Values for \(Tb\) and \(eb\) are necessary to estimate latent heat and sensible heat fluxes in equation \((A1)\) through \((A6)\)

\(\lambda E\) from equation \((7)\) is:

\[\lambda E = \lambda Ec + (1 - fr) \cdot \lambda Es + fr \cdot \lambda Er\]

Then, using equation \((10)\), \((22)\), \((24)\) and \((26)\) in \((7)\)
\[
\begin{align*}
\rho \cdot \text{C} \cdot \text{P} \cdot (\text{eb} - \text{ea}) &= \\
&= \\
\gamma \cdot \text{ra}_w + \Delta_i \cdot r_i \cdot \text{Rnc} + \rho \cdot \text{C} \cdot \text{P} \cdot (\text{e}_b^* - \text{eb}) + \\
&+ \frac{\Delta_i \cdot r_i \cdot \text{Rnc}}{\Delta_i \cdot r_i + \gamma \cdot (r_i + \text{rc})} + \\
(1 -fr) \cdot \frac{\text{Rns} \cdot \Delta_2 \cdot r_2 \cdot r_L}{\Delta_i \cdot r_i + \gamma \cdot (r_i + \text{rc})} + &+ \frac{\text{Rns} \cdot \Delta_2 \cdot r_2 \cdot r_L}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2 + r_r)} + \\
&+ \frac{\text{Rns} \cdot \Delta_4 \cdot (r_2 + r_r) \cdot r_L}{\gamma \cdot (r_2 + rs + \text{rr}) \cdot (ru + r_L + r_2 + r_r) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_r)} + \\
&+ \rho \cdot \text{C} \cdot \text{P} \cdot (\text{e}_b^* - \text{eb}) \cdot \frac{1}{\Delta_i \cdot r_i + \gamma \cdot (r_i + \text{rc})} + \\
&+ \frac{\text{Rns} \cdot \Delta_2 \cdot (ru + r_2) + \Delta_2 \cdot (ru + r_2 + r_r)}{\gamma \cdot (r_2 + rs + \text{rr}) \cdot (ru + r_L + r_2 + r_r) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_r)} + \\
&+ \frac{\text{Rns} \cdot \Delta_2 \cdot (ru + r_2)}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2)} + \\
&+ \frac{\text{Rns} \cdot \Delta_4 \cdot (ru + r_2 + r_r)}{\gamma \cdot (r_2 + rs + \text{rr}) \cdot (ru + r_L + r_2 + r_r) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_r)}
\end{align*}
\]

Using
Vapor pressure deficit can be expressed as:

\[
V = A_1 + A_2 + A_3
\]

\[
A_1 = \left[ \frac{\Delta_1 \cdot r_1 \cdot Rnc + (1 - fr) \cdot Rns \cdot \Delta_2 \cdot r_2 \cdot r_1}{\Delta_1 \cdot r_1 + \gamma \cdot (r_1 + rc) + \gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2) + \Delta_3 \cdot r_2 \cdot r_L \cdot (ru + r_2 + r_h)} \right]
\]

\[
A_2 = \left[ \frac{1}{\Delta_1 \cdot r_1 + \gamma \cdot (r_1 + rc) + \gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_2 \cdot r_L \cdot (ru + r_2) + \Delta_3 \cdot r_2 \cdot r_L \cdot (ru + r_2 + r_h) + 1} \right]
\]

\[
A_3 = \left[ \frac{(1 - fr) \cdot \Delta_2 \cdot (ru + r_2) + \Delta_4 \cdot (ru + r_L + r_h) + \Delta_3 \cdot r_2 \cdot r_1 \cdot (ru + r_2 + r_h)}{\gamma \cdot (r_2 + rs) \cdot (ru + r_L + r_2) + \Delta_4 \cdot r_L \cdot (ru + r_2 + r_h) + 1} \right]
\]

\[
\frac{\rho \cdot Cp \cdot (eb - ea)}{\gamma \cdot ra_w} = A_1 + \frac{\rho \cdot Cp \cdot (e_b^* - eb)}{\gamma \cdot ra_w} \cdot A_2 + \rho \cdot Cp \cdot (Tm - Tb) \cdot A_3
\]

Vapor pressure deficit can be expressed as:

\[
(e_b^* - eb) = e_b^* - e_a^* + e_a^* - eb = \Delta_3 \cdot (Tb - Ta) + e_a^* - eb
\]

Then,

\[
\frac{\rho \cdot Cp \cdot (eb - ea)}{\gamma \cdot ra_w} = A_1 + \rho \cdot Cp \cdot (\Delta_1 \cdot (Tb - Ta) + e_b^* - eb) \cdot A_2 + \rho \cdot Cp \cdot (Tm - Tb) \cdot A_3
\]

\[
\frac{(eb - ea)}{\gamma \cdot ra_w} = \frac{A_1}{\rho \cdot Cp} + \Delta_3 \cdot A_2 \cdot (Tb - Ta) + A_2 \cdot (e_a^* - eb) + (Tm - Tb) \cdot A_3
\]

\[
eb = \left[ \frac{A_1}{\rho \cdot Cp} + \Delta_3 \cdot A_2 \cdot (Tb - Ta) + A_2 \cdot e_a^* + (Tm - Tb) \cdot A_3 + \frac{ea}{\gamma \cdot ra_w} \right] \cdot \left[ \frac{\gamma \cdot ra_w}{1 + A_2 \cdot \gamma \cdot ra_w} \right]
\]
\[
eb = \left[ \frac{Tb \cdot (A_3 \cdot A_2 - A_3) + \frac{A_1}{\rho \cdot C_p} - \Delta_3 \cdot A_2 \cdot Ta}{\Delta_3 \cdot A_2} \right] \cdot \left[ \frac{\gamma \cdot \rho_a}{1 + A_2 \cdot \gamma \cdot \rho_a} \right] (A7)
\]

Similarly for sensible heat

Using (A4)

\[
H_s = \frac{\text{Rns} \cdot r_l \cdot \Delta_2 - \lambda \cdot \text{Es} \cdot (r_l \cdot \Delta_2 + \gamma \cdot (r_r + rs)) + \rho \cdot C_p \cdot (e_b - \eb) - \rho \cdot C_p \cdot \Delta_2 \cdot (Tb - Tm)}{r_l \cdot \Delta_2}
\]

Then using \( \lambda \cdot \text{Es} \) from (A3)

\[
H_s = \text{Rns} - \frac{\lambda \cdot \text{Es} \cdot (r_l \cdot \Delta_2 + \gamma \cdot (r_r + rs)) + \rho \cdot C_p \cdot (e_b - \eb) - \rho \cdot C_p \cdot (Tb - Tm)}{r_l \cdot \Delta_2}
\]

Using

\[
X_s = \left( \frac{1}{\gamma \cdot (r_r + rs) \cdot (ru + r_l + r_s)} \right) \left( \frac{\Delta_2 \cdot (ru + r_l + r_s)}{r_l \cdot \Delta_2} \right) \left( \frac{r_l \cdot \Delta_2 + \gamma \cdot (r_r + rs)}{r_l \cdot \Delta_2} \right)
\]
Using

\[ H_s = Rns \cdot \left( l - \Delta_2 \cdot r_2 \cdot r_l \cdot X_s \right) \]

\[ + \rho \cdot C_p \cdot (c_b^* - e_b) \cdot \left( \frac{1}{r_l \cdot \Delta_2} - \frac{1}{(ru + r_l + r_2) \cdot X_s} \right) + \rho \cdot C_p \cdot (Tm - Tb) \cdot \left( \frac{1}{r_l \cdot \Delta_2} - \frac{1}{(ru + r_2) \cdot X_s} \right) \]

Similarly for \( H_r \) from equation (A6)

\[ H_r = \frac{Rns \cdot r_l \cdot \Delta_4 - \lambda Er \cdot \left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right) + \rho \cdot C_p \cdot (c_b^* - e_b) - \rho \cdot C_p \cdot (Tb - Tm)}{r_l \cdot \Delta_4} \]

Then using \( \lambda Er \) from (A5)

\[ H_r = Rns \]

\[ \frac{\left( \frac{Rns \cdot \Delta_4 \cdot (ru + r_l + r_2 + r_3 + r_4) \cdot (ru + r_1 + r_2 + r_3 + r_4)}{r_l \cdot \Delta_4} \right) - \left( \frac{1}{\Delta_2} \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_2} \right)}{\gamma \cdot \left( r_2 + rs + rr \right) \cdot \left( ru + r_l + r_2 + r_3 + r_4 \right) + \Delta_2 \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_4} + \Delta_4 \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_4} + \Delta_4 \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_4}} + \rho \cdot C_p \cdot (e_b^* - e_b) \cdot \left( \frac{1}{r_l \cdot \Delta_4} \right) + \rho \cdot C_p \cdot (Tm - Tb) \cdot \left( \frac{1}{r_l \cdot \Delta_4} \right) \]

Using

\[ X_r = \left( \frac{1}{\gamma \cdot (r_2 + rs + rr) \cdot (ru + r_l + r_2 + r_3 + r_4) + \Delta_4 \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_4} + \Delta_4 \cdot \frac{\left( r_l \cdot \Delta_4 + \gamma \cdot (r_2 + rs + rr) \right)}{r_l \cdot \Delta_4}} \right) \]
\[ H_r = \]
\[ \text{Rns} \cdot (1 - \Delta_z \cdot (r_2 + \rho \cdot \cdot Xr) + \rho \cdot \cdot (e^* - eb) \cdot \left( \frac{1}{r_L \cdot \Delta_z} - (ru + r_L + r_2 + \rho \cdot \cdot Xr) \right) + \]
\[ \rho \cdot \cdot (Tm - Tb) \cdot \left( \frac{1}{r_L} - \Delta_z \cdot (ru + r_2 + \rho \cdot \cdot Xr) \right) \]

Similarly for sensible heat, total sensible heat flux from (8) is:

\[ H = Hc + (1 - fr) \cdot Hs + fr \cdot Hr \]

Then, using (9), (23), (25) and (27) in (8)

\[ \frac{\rho \cdot \cdot (Tb - Ta)}{ra_h} = \frac{\gamma \cdot (r_i + rc) \cdot \cdot Rnc - \rho \cdot \cdot (e^* - eb)}{\Delta_i \cdot \gamma \cdot (r_i + rc)} \]

\[ + (1 - fr) \cdot \left[ \text{Rns} \cdot (1 - \Delta_z \cdot r_2 \cdot \cdot Xs) + \rho \cdot \cdot (e^* - eb) \cdot \left( \frac{1}{r_L \cdot \Delta_z} - (ru + r_L + r_2) \cdot \cdot Xs \right) \right] \]

\[ + fr \cdot \left[ \text{Rns} \cdot (1 - \Delta_z \cdot (r_2 + rr) \cdot \cdot Xr) + \rho \cdot \cdot (e^* - eb) \cdot \left( \frac{1}{r_L \cdot \Delta_z} - (ru + r_L + r_2 + rr) \cdot \cdot Xr \right) \right] \]

\[ + \rho \cdot \cdot (Tm - Tb) \cdot \left( \frac{1}{r_L} - \Delta_z \cdot (ru + r_2 + rr) \cdot \cdot Xr \right) \]
\[
\frac{\rho \cdot C_p \cdot (T_b - T_a)}{r_a} = \frac{B_1}{r_a} + \rho \cdot C_p \cdot (e^*_b - e_b) \cdot B_2 + \rho \cdot C_p \cdot (T_m - T_b) \cdot B_3
\]

\[
\frac{(T_b - T_a)}{r_a} = \frac{B_1}{\rho \cdot C_p} + (e^*_b - e_b) \cdot B_2 + (T_m - T_b) \cdot B_3
\]

Vapor pressure deficit can be expressed as:

\[
(e^*_b - e_b) = e^*_b - e^*_a + e^*_a - e_b = \Delta_a \cdot (T_b - T_a) + e^*_a - e_b
\]
Then,

\[
\frac{(T_b - T_a)}{r_{ah}} = \frac{B_1}{\rho \cdot C_p} + (\Delta_3 \cdot (T_b - T_a) + e_a^* - e_b) \cdot B_2 + (T_m - T_b) \cdot B_3
\]

\[
(T_b - T_a) \left( \frac{1}{r_{ah}} - \Delta_3 \cdot B_2 \right) = \frac{B_1}{\rho \cdot C_p} + (e_a^* - e_b) \cdot B_2 + (T_m - T_b) \cdot B_3
\]

\[
T_b \left( \frac{1}{r_{ah}} - \Delta_3 \cdot B_2 + B_3 \right) = \frac{B_1}{\rho \cdot C_p} + T_a \left( \frac{1}{r_{ah}} - \Delta_3 \cdot B_2 \right) + (e_a^* - e_b) \cdot B_2 + T_m \cdot B_3
\]

\[
T_b = \left[ \frac{B_1}{\rho \cdot C_p} + T_a \left( \frac{1}{r_{ah}} - \Delta_3 \cdot B_2 \right) \right] \cdot \left[ \frac{r_{ah}}{1 - \Delta_3 \cdot B_2 \cdot r_{ah} + B_3 \cdot r_{ah}} \right]
\]

Equations (A7) and (A8) can be used to find \( T_b \) and \( e_b \):

From the previous equation (A7) \( e_b \) was expressed as:

\[
e_b = \left[ T_b \cdot (\Delta_3 \cdot A_2 - A_3) + \frac{A_1}{\rho \cdot C_p} - \Delta_3 \cdot A_2 \cdot T_a + A_2 \cdot e_a^* + T_m \cdot A_3 + \frac{e_a}{\gamma \cdot r_{aw}} \right] \cdot \left[ \frac{\gamma \cdot r_{aw}}{1 + A_2 \cdot \gamma \cdot r_{aw}} \right]
\]

Using \( T_b \) from (A8)

\[
e_b = \left[ \frac{B_1}{\rho \cdot C_p} + T_a \left( \frac{1}{r_{ah}} - \Delta_3 \cdot B_2 \right) + (e_a^* - e_b) \cdot B_2 + T_m \cdot B_3 \right] \cdot \left[ \frac{r_{ah}}{1 - \Delta_3 \cdot B_2 \cdot r_{ah} + B_3 \cdot r_{ah}} \right] \cdot \left[ \frac{\gamma \cdot r_{aw}}{1 + A_2 \cdot \gamma \cdot r_{aw}} \right]
\]
\[ e_b \left( 1 + \left[ \frac{r_{h}}{1 - \Lambda_3 \cdot B_2 \cdot r_{h} + B_3 \cdot r_{h}} \cdot \left[ \frac{\gamma \cdot r_{w}}{1 + A_2 \cdot \gamma \cdot r_{w}} \right] \right] \right) = \]

\[
\begin{bmatrix}
\frac{B_1}{\rho \cdot C_p} + T_a \left( \frac{1}{r_{h}} - \Delta_3 \cdot B_2 \right) + e_a^* \cdot B_2 + T_m \cdot B_3 \\
\frac{r_{h}}{1 - \Lambda_3 \cdot B_2 \cdot r_{h} + B_3 \cdot r_{h}} \cdot \left[ \Delta_3 \cdot A_2 - A_3 \right]
\end{bmatrix}
\begin{bmatrix}
\frac{\gamma \cdot r_{w}}{1 + A_2 \cdot \gamma \cdot r_{w}}
\end{bmatrix}
\]

\[
+ \frac{A_1}{\rho \cdot C_p} - \Delta_3 \cdot A_2 \cdot T_a + A_2 \cdot e_a^* + T_m \cdot A_3 + \frac{e_a}{\gamma \cdot r_{w}}
\]

\[
e_b = \frac{\begin{bmatrix}
\frac{B_1}{\rho \cdot C_p} + T_a \left( \frac{1}{r_{h}} - \Delta_3 \cdot B_2 \right) + e_a^* \cdot B_2 + T_m \cdot B_3 \\
\frac{r_{h}}{1 - \Lambda_3 \cdot B_2 \cdot r_{h} + B_3 \cdot r_{h}} \cdot \left[ \Delta_3 \cdot A_2 - A_3 \right]
\end{bmatrix}
\begin{bmatrix}
\frac{\gamma \cdot r_{w}}{1 + A_2 \cdot \gamma \cdot r_{w}}
\end{bmatrix}
\]

\[
\left( 1 + \left[ \frac{r_{h}}{1 - \Lambda_3 \cdot B_2 \cdot r_{h} + B_3 \cdot r_{h}} \cdot \left[ \frac{\gamma \cdot r_{w}}{1 + A_2 \cdot \gamma \cdot r_{w}} \right] \right] \right)
\]
Figure A2.1. Canopy surface resistance calculated with equation (10) and (21) under different vapor pressure conditions, $C_1=5$, $C_2=0.005$, $C_3=300$, $C_4=0.005$, LAI=4, LAImax=6, Radmax=1000 W m$^2$ and Rad=600 W m$^2$. 
Figure A2.1. Total evapotranspiration as function of LAI for three levels of vapor pressure deficit. For this figure canopy resistance was calculated using equation (21) and conditions are similar to the sensitivity analysis presented in Table 3.1.
Appendix 3

Visual Basic Code for The Surface Energy Balance Model

*******************************************************************************
'Surface Energy Balance model by L.O. Lagos 2008
'Based on Choudhury and Monteith (1998) and Shuttleworth Wallace (1985): A four
layer Evapotranspiration Model
*******************************************************************************
'Density of moist air Kg/m3
rho = 1.013
'Specific heat for moist air J/Kg/K
Cp = 1003.5
c = 0
ld = 0.05 'm upper layer depth
'Atmospheric pressure P Kpa
zelev = 300
p = 101.3 * ((293 - 0.0065 * zelev) / 293) ^ 5.26
'Psychrometric constant Psy (mb/K)
psy = 0.000665 * p * 10
kh = 0.01
Z = 3 'reference height z (m)

For c= 1 to 25000 ' Hourly Data
*******************************************************************************
Model inputs
*******************************************************************************
Rn = Cells(c, 7) 'Net radiation
RH = Cells(c, 24) 'Relative humidity RH %
RH6 = Cells(c, 23) 'Relative humidity at 6m
ta = Cells(c, 22) 'Air temperature
Ta6 = Cells(c, 21) 'Air temperature at 6m
u = Cells(c, 19) 'wind speed u at 3 m m/s
u6 = Cells(c, 18) 'wind speed at 6m
H = Cells(c, 34) 'crop height h
L = Cells(c, 35) 'Leaf area index
Tm = Cells(c, 36) 'temperature at the bottom of the wet soil layer
rads = Cells(c, 28) 'Solar Radiation Rads W/m2
fr = Cells(c, 39) 'residue fraction
M = Cells(c, 38) / 1000 * 10 'residue amount T/ha
crop = Cells(c, 41) 'Crop type 1=corn, 0=Soybean
*******************************************************************************

'Changing reference height values
If \( H > 0.99 \) Then
\[
RH = RH6 \\
u = u6 \\
ta = ta6 \\
Z = 6 \\
End If
\]

'Slope of the Saturation Vapor Pressure-Temperature Curve, Delta (mb/K)
\[
\Delta = 10 \times 2504 \times \exp(17.27 \times \frac{ta}{(ta + 237.3)}) / (ta + 237.3)^2
\]
\[
delta1 = \Delta \\
delta2 = \Delta \\
delta3 = \Delta \\
delta4 = \Delta
\]

'ra Aerodynamic resistance for latent heat flux
If \( H < 0.01 \) Then
\[
H = 0.001 \\
L = 0.001 \\
End If
\]
\[
\text{cd} = 0.07 \\
k = 0.41 \\
\text{zos} = 0.01 \\
alpha = 2.5
\]
If \( H < 0.05 \) Then
\[
d = 0.0001 \\
ra = (\log((Z - d) / \text{zos}))^2 / (k^2 \times u) \\
u^2 = u * \log((2 - d) / \text{zos}) / \log((Z - d) / \text{zos}) \\
zoo = \text{zos}
\]
Else
\[
x = \text{cd} \times L \\
d = 1.1 \times H \times \log(1 + x \times 0.25)
\]
If \( x < 0.2 \) Then
\[
zoo = \text{zos} + 0.3 \times H \times x^0.5
\]
Else
\[
zoo = 0.3 \times H \times (1 - d / H)
\]
End If
\[
kh = k^2 \times u / (\log((Z - d) / \text{zoo})) \times (H - d)
\]
\[
ra = 1 / (k^2 \times u / (\log((Z - d) / \text{zoo})) \times \log((Z - d) / (H - d)) + H / \alpha / kh \times (\exp(\alpha \times (1 - (\text{zoo} + d) / H)) - 1))
\]
If \( H < 2 \) Then
\[
u^2 = u \times \log((2 - d) / \text{zos}) / \log((Z - d) / \text{zos})
\]
Else
\[
u = u \times \log((H - d) / \text{zoo}) / \log((Z - d) / \text{zoo})
\]
\[
u^2 = uh \times \exp(\alpha \times (2 / H - 1))
\]
End If
End If
k1 = 2 * 10^-5 'thermal diffusivity
Dv = 2.56 * 10^-5 'water vapor diffusivity m2/s
rbw = 2 / (k * 2 * u / (Log((Z - d) / zoo)) * (k1 / Dv) ^ (2 / 3))
ra = ra + rbw
Cells(c, 51) = ra

'rah Aerodynamic resistance for sensible heat flux
rbh = 2 / (k * 2 * u / (Log((Z - d) / zoo)))
rah = ra + rbh

'r2 Aerodynamic resistance between the soil surface and the sink of momentum
r2 = H * Exp(alpha) / (alpha * kh) * (Exp(-alpha * zos / H) - Exp(-alpha * (zoo + d) / H))
Cells(c, 52) = r2

'r1 Boundary layer resistance s/m
a = 0.01 'm/s-1/2
If crop = 0 Then
w = 0.05 'leaf width
ElseIf crop = 1 Then
w = 0.08 'leaf width
End If
ustar = u * k / Log((Z - d) / zoo)
uh = ustar / k * Log((H - d) / zoo)
  If uh < 0 Then
   uh = 0.001
  End If
gb = (a / alpha) * (uh / w) ^ 0.5 * (1 - Exp(-alpha / 2))
r1 = 1 / gb / (2 * L)
Cells(c, 53) = r1

'Vapor pressure deficit VPDa of the air at z(mb)
ew = 10 * 0.6108 * Exp(17.27 * ta / (ta + 237.3))
ea = RH / 100 * ew
VPDa = ew - ea
Cells(c, 62) = VPDa

'rc Canopy Resistance s/m based on Stannard (1993) and non-linear VPD effect
If crop = 0 Then
LAImax = 5
Rsmax = 1000
c1 = 4.5
c2 = 0.005
c3 = 300
ElseIf crop = 1 Then
LAImax = 6
Rsmax = 1000
\(c_1 = 5\)
\(c_2 = 0.005\)
\(c_3 = 300\)
End If
If \(rads \leq 0\) Then
\(rads = 0.001\)
End If
\(rc = \frac{LAImax}{(c_1 \cdot L)} \cdot (1 - \text{Exp}(-\text{VPDa} / 10)) \cdot 300 \cdot \frac{Rsmax \cdot (rads + c_3)}{(rads \cdot (Rsmax + c_3))}\)
Cells(c, 54) = rc

'ru Soil heat flux resistance for the top soil layer
\(key2 = 0.5\) W/m/K
\(ld = 0.05\)
\(ru = \rho \cdot Cp \cdot ld / key2\)
Cells(c, 55) = ru

'rl Soil resistance bottom layer
\(lm = 0.5\) m
\(Key = 2.5\) W/m/K
\(rl = \rho \cdot Cp \cdot (lm - ld) / Key\)
Cells(c, 56) = rl

'rs Soil heat flux resistance to water vapor diffusion
\(Hsoil = 0.05\) ' surface layer thickness m
'Cells(c, 70) = Hsoil
\(ts = 1.5\) 'tortuosity
\(Dv = 2.56 \times 10^{-5}\) 'water vapor diffusivity m2/s
\(por = 0.5\) 'porosity
\(B = 6\)#
\(theta = \text{Cells(c, 37)}\) 'soil water content
\(thetas = 0.45\) 'saturation water content
\(rs = Hsoil \cdot ts / Dv / por \cdot \text{Exp}(\ -B \cdot theta / thetas)\)
Cells(c, 57) = rs

'Surface Residue resistance \(rr \) s/m
\(tsres = 1\) # 'residue tortuosity
\(Dv = 2.56 \times 10^{-5}\) 'water vapor diffusivity m2/s
\(porres = 0.8\) 'Residue porosity
\(resden = 298\) 'residue density kg/m3
If \(fr > 0\) Then
\(hsres = 0.1 \times M / fr / (1 - porres) / resden\) ' surface residue thickness m
Else
\(hsres = 0\)
End If
Cells(c, 58) = hsres
rr = hsres / Dv * (1 + 0.7 * u2) ^ -1
Cells(c, 59) = rr

'Surface Residue resistance for heat transfer rrh s/m
Keyr = 0.2 'W/m/K residue termal conductivity
rrh = rho * Cp * hsres / Keyr
Cells(c, 66) = rrh

'Radiation reaching the soil surface Rs and absorbed by the canopy Rv
cext = 0.6
Rns = Rn * Exp(-cext * L)
rv = Rn - Rns
Cells(c, 60) = Rns
'Cells(c, 61) = rv
it = 0
100 it = it + 1
Cells(c, 88) = it

'Vapor pressure (eb) and temperature (tb) within the canopy by L.O.Lagos 2008
A1 = (delta1 * r1 * rv) / (delta1 * r1 + psy * (r1 + rc)) + (1 - fr) * (Rns * delta2 * r2 * rl) / (psy * (r2 + rs) * (ru + rl + r2) + delta2 * rl * (ru + r2)) + fr * (Rns * delta2 * (r2 + rrh) * rl) / (psy * (r2 + rs + rr) * (ru + rl + r2 + rrh) + delta2 * rl * (ru + r2 + rrh))
A2 = 1 / (delta1 * r1 + psy * (r1 + rc)) + (1 - fr) * (ru + rl + r2) / (psy * (r2 + rs) * (ru + rl + r2) + delta2 * rl * (ru + r2)) + fr * (ru + rl + r2 + rrh) / (psy * (r2 + rs + rr) * (ru + rl + r2 + rrh) + delta2 * rl * (ru + r2 + rrh))
A3 = (1 - fr) * (delta2 * (ru + r2)) / (psy * (r2 + rs) * (ru + rl + r2) + delta2 * rl * (ru + r2)) + fr * (delta2 * (ru + r2 + rrh)) / (psy * (r2 + rs + rr) * (ru + rl + r2 + rrh) + delta2 * rl * (ru + r2 + rrh))
XS = 1 / (psy * (r2 + rs) * (ru + rl + r2) + delta2 * rl * (ru + r2)) / (rl * delta2)
XR = 1 / (psy * (r2 + rs + rr) * (ru + rl + r2 + rrh) + delta2 * rl * (ru + r2 + rrh)) / (rl * delta2)
B1 = (rv * psy * (r1 + rc)) / (delta1 * r1 + psy * (r1 + rc)) + Rns * ((1 - fr) * (1 - delta2 * r2 * rl * XS) + fr * (1 - delta2 * (r2 + rrh) * rl * XR)
B2 = -1 / (delta1 * r1 + psy * (r1 + rc)) + (1 - fr) * (1 / (rl * delta2) - (ru + rl + r2) * XS) + fr * (1 / (rl * delta2) - (ru + rl + r2 + rrh) * XR)
B3 = (1 - fr) * (1 / rl - delta2 * (ru + r2) * XS) + fr * (1 / rl - delta2 * (ru + r2 + rrh) * XR)

Cells(c, 69) = ebolagos

tbolagos = (B1 / (rho * Cp)) + ta * (1 / rah - delta3 * B2) + (ew - ebolagos) * B2 + Tm * B3) * (rah / (1 - delta3 * B2 * rah + B3 * rah))

Cells(c, 71) = tbolagos

'Vapor pressure deficit VPDb of the air within the canopy(mb)

\[ VPDb = \text{ew} + \text{delta3} \times (\text{tb} - \text{ta}) - \text{cb} \]

Cells(c, 63) = VPDb

Cells(c, 64) = delta2

Cells(c, 65) = psy

'The Transpiration from the canopy

\[ \text{LambdaEv} = \left(\frac{\delta1 \times \text{rv} + \rho \times \text{Cp} \times \text{VPDb} / \text{r1}}{\delta1 + \text{psy} \times (1 + \text{rc} / \text{r1})}\right) \]

Transpiration

Cells(c, 72) = LambdaEv

'Evaporation from the soil

\[ \text{ESolagos} = \left(\frac{\text{Rns} \times \delta2 \times r2 \times \text{rl} + \rho \times \text{Cp} \times ((\text{VPDb}) \times (\text{ru} + \text{rl} + r2) + (\text{Tm} - \text{tb}) \times \delta2 \times (\text{ru} + r2)) / (\text{psy} \times (\text{r2} + \text{rs}) \times (\text{ru} + \text{rl} + r2) + \delta2 \times \text{rl} \times (\text{ru} + r2))}{\text{psy} \times (\text{r2} + \text{rs}) \times (\text{ru} + \text{rl} + r2) + \delta2 \times \text{rl} \times (\text{ru} + r2)}\right) \]

Soil evaporation by Octavio

Cells(c, 73) = ESolagos

If H < 0.05 Then

\[ \text{ESolagos} = \left(\frac{\text{Rn} \times \delta2 \times \text{rah} \times \text{rl} + \rho \times \text{Cp} \times ((\text{VPDa}) \times (\text{ru} + \text{rl} + \text{rah}) + (\text{Tm} - \text{ta}) \times \delta2 \times (\text{ru} + \text{rah})) / (\text{psy} \times (\text{ra} + \text{rs}) \times (\text{ru} + \text{rl} + \text{rah}) + \delta2 \times \text{rl} \times (\text{ru} + \text{rah}))}{\text{psy} \times (\text{ra} + \text{rs}) \times (\text{ru} + \text{rl} + \text{rah}) + \delta2 \times \text{rl} \times (\text{ru} + \text{rah})}\right) \]

Soil evaporation by Octavio

End If

Cells(c, 74) = ESolagos

'Evaporation from the residue-covered soil

\[ \text{ERolagos} = \left(\frac{\text{Rns} \times \delta4 \times (\text{r2} + \text{rrh}) \times \text{rl} + \rho \times \text{Cp} \times ((\text{VPDb}) \times (\text{ru} + \text{rl} + r2 + \text{rrh}) + (\text{Tm} - \text{tb}) \times \delta4 \times (\text{ru} + r2 + \text{rrh})) / (\text{psy} \times (\text{r2} + \text{rs} + \text{rr}) \times (\text{ru} + \text{rl} + r2 + \text{rrh}) + \delta4 \times \text{rl} \times (\text{ru} + r2 + \text{rrh}))}{\text{psy} \times (\text{r2} + \text{rs} + \text{rr}) \times (\text{ru} + \text{rl} + r2 + \text{rrh}) + \delta4 \times \text{rl} \times (\text{ru} + r2 + \text{rrh})}\right) \]

Cells(c, 75) = ERolagos

If H < 0.05 Then

\[ \text{ERolagos} = \left(\frac{\text{Rn} \times \delta4 \times (\text{rah} + \text{rrh}) \times \text{rl} + \rho \times \text{Cp} \times ((\text{VPDa}) \times (\text{ru} + \text{rl} + \text{rah} + \text{rrh}) + (\text{Tm} - \text{ta}) \times \delta4 \times (\text{ru} + \text{rah} + \text{rrh})) / (\text{psy} \times (\text{ra} + \text{rs} + \text{rr}) \times (\text{ru} + \text{rl} + \text{rah} + \text{rrh}) + \delta4 \times \text{rl} \times (\text{ru} + \text{rah} + \text{rrh}))}{\text{psy} \times (\text{ra} + \text{rs} + \text{rr}) \times (\text{ru} + \text{rl} + \text{rah} + \text{rrh}) + \delta4 \times \text{rl} \times (\text{ru} + \text{rah} + \text{rrh})}\right) \]

End If
Cells(c, 76) = ERolagos

'Canopy Sensible Heat Flux
Psy1 = psy * (1 + rc / r1)
Hc = (psy * (r1 + rc) * rv - rho * Cp * VPDb) / (delta1 * r1 + psy * (r1 + rc)) 'Sensible Heat Ologos
Cells(c, 78) = Hc

'Soil Sensible Heat Flux
Hs = (Rns * delta2 * rl - ESolagos * (delta2 * rl + psy * (r2 + rs)) + rho * Cp * VPDb - rho * Cp * delta2 * (tb - Tm)) / (delta2 * rl)
If H < 0.05 Then
    Hs = (Rn * delta2 * rl - ESolagos * (delta2 * rl + psy * (ra + rs)) + rho * Cp * VPDa - rho * Cp * delta2 * (ta - Tm)) / (delta2 * rl)
End If
Cells(c, 79) = Hs

'Residue covered soil Heat flux
Hr = (Rns * delta4 * rl - ERolagos * (delta4 * rl + psy * (r2 + rs + rr)) + rho * Cp * VPDb - rho * Cp * delta4 * (tb - Tm)) / (delta4 * rl)
If H < 0.05 Then
    Hr = (Rn * delta4 * rl - ERolagos * (delta4 * rl + psy * (ra + rs + rr)) + rho * Cp * VPDa - rho * Cp * delta4 * (ta - Tm)) / (delta4 * rl)
End If
Cells(c, 80) = Hr

'Total evapotranspiration from the crop/residue/soil system
ET = LambdaEv + (1 - fr) * ESolagos + fr * ERolagos
Cells(c, 81) = ET

'Total Sensible Heat from the crop/residue/soil system
HT = Hc + (1 - fr) * Hs + fr * Hr
Cells(c, 82) = HT

Next c