Modelling the partitioning of evapotranspiration in a maize–sunflower intercrop

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ABSTRACT

The primary purpose of this study was to model the partitioning of evapotranspiration in a maize-sunflower intercrop at various canopy covers. The Shuttleworth-Wallace (SW) model was extended for intercropping systems to include both crop transpiration and soil evaporation and allowing interaction between the two. To test the accuracy of the extended SW model, two field experiments of maize-sunflower intercrop were conducted in 1998 and 1999. Plant transpiration and soil evaporation were measured using sap flow gauges and lysimeters, respectively. The mean prediction error (simulated minus measured values) for transpiration was zero (which indicated no overall bias in estimation error), and its accuracy was not affected by the plant growth stages, but simulated transpiration during high measured transpiration rates tended to be slightly underestimated. Overall, the predictions for daily soil evaporation were also accurate. Model estimation errors were probably due to the simplified modelling of soil water content, stomatal resistances and soil heat flux as well as due to the uncertainties in characterising the micrometeorological conditions. The SW's prediction of transpiration was most sensitive to parameters most directly related to the canopy characteristics such as the partitioning of captured solar radiation, canopy resistance, and bulk boundary layer resistance.

Keywords: Shuttleworth-Wallace, Penman-Monteith, evapotranspiration, maize, sunflower, intercrop

INTRODUCTION

The Penman-Monteith (PM) model (Monteith, 1965) is often used to estimate either the soil evaporation or crop transpiration. Nevertheless, its major drawback is that this model can only be used to estimate either soil evaporation or plant transpiration, but not both simultaneously. Recently, an important extension of the PM model is the Shuttleworth-Wallace (SW) model (Shuttleworth and Wallace, 1985). Its improvement over the PM model is that the SW model specifies explicitly the energy exchanges at the soil and canopy, thereby it is possible to distinguish the fraction of water transpired and that evaporated from soil. This means the SW model allows for the interaction between the soil and plant canopy. The SW model, however, was originally developed only for sole crops, and it is still relatively new and not extensively tested (Farahani and Ahuja, 1996). Nevertheless, the few field tests of this model in both agricultural and non-agricultural conditions have been promising (Lafleur and Rouse, 1990; Wallace *et al.*, 1990; Stannard, 1993; Farahani and Bausch, 1995). Stannard (1993), for example, observed that predictions from SW model were significantly more accurate than the PM model when applied in very sparse canopies (leaf area index < 0.2).

The objectives of this study were two-fold. Firstly, it was to model the partitioning of evapotranspiration in a maize-sunflower intercropping system in partial- and fully-grown canopies. This would be achieved by extending the original SW model to intercropping systems. Secondly, this study was to determine the accuracy and to perform a sensitivity analysis of the extended SW model when applied in the maize-sunflower intercrop.

MODEL DEVELOPMENT

The SW model was extended to include the transpiration from two or more crops and evaporation from the soil. This extension of including evapotranspiration from *n* crop species (with soil interaction) was first shown by Wallace (1997). Figure 1 shows how the resistances to the fluxes of radiation, latent and sensible heat are distributed in the soil-plant-atmosphere system involving two crop species. The energy budget of the system is described in a series of equations which are the sum of the various latent heat, sensible heat and radiation fluxes. With some algebraic manipulations, it can be shown that the total latent heat flux of the system with *n* crops is given by

$$\lambda E = \sum_{i=1}^{n} C_{c,i} PM_{c,i} + C_s PM_s \tag{1}$$

where

$$\begin{aligned} PM_{c,i} &= \frac{\Delta A + \left\{\rho c_p D - \Delta r_a^{c,i}\left(A - A_{c,i}\right)\right\} \Big/ \left(r_a^a + r_a^{c,i}\right)}{\Delta + \gamma\left\{1 + r_s^{c,i} \Big/ \left(r_a^a + r_a^{c,i}\right)\right\}} \\ PM_s &= \frac{\Delta A + \left\{\rho c_p D - \Delta r_a^{s}\left(A - A_{s}\right)\right\} \Big/ \left(r_a^a + r_a^{s}\right)}{\Delta + \gamma\left\{1 + r_s^{s} \Big/ \left(r_a^a + r_a^{s}\right)\right\}} \end{aligned} \tag{2}$$

$$C_{c,i} = \left(1 + \frac{1/R_s + \sum_{j=1,\, j\neq i}^{n} 1/R_{c,j}}{\dfrac{1}{R_{c,i}} + \dfrac{1}{R_a}}\right)^{-1} \tag{3}$$

$$C_s = \left\{1 + R_s R_a / R_c \left(R_s + R_a\right)\right\}^{-1} \tag{4}$$

$$\begin{aligned} R_{c,i} &= \left(\Delta + \gamma\right) r_a^{c,i} + \gamma\, r_s^{c,i} \\ R_a &= \left(\Delta + \gamma\right) r_a^{a} \\ R_s &= \left(\Delta + \gamma\right) r_a^{s} + \gamma\, r_s^{s} \end{aligned} \tag{5}$$

where c_p is the specific heat of water at constant pressure (4182 J kg^{-1} K^{-1}); D is the vapour pressure deficit, or $e_s\left(T_r\right) - e_r$; Δ is the mean rate of change of saturated vapour pressure with temperature, or $\left[e_s\left(T_r\right) - e_s\left(T_0\right)\right] / \left(T_r - T_0\right)$; γ is the psychometric constant (0.658 mb K^{-1}); A and A_s are the total energy available to the system and soil, respectively, and $A_{c,i}$ is the amount of energy available to crop i so that:

$$A_{c,i} = F_i R_n \tag{6}$$

where F_i is the fraction of radiation intercepted by crop species i. F_i is determined from the plant-radiation model developed by Spitters (1989), and Kustas and Norman (1999a, 1999b). The available energy available to the soil A_s is:

$$A_s = \left(R_n - G\right) \cdot \left(1 - \sum_{i=1}^{n} F_i\right) \tag{7}$$

Note that Eq. (3) is a correction to the equation given in Wallace (1997). The original equation erroneously excluded the $1/R_s$ term, and showed that the summation of $1/R_{c,j}$ is over $j = 2$ to n, which ought to be over $j = 1$ to n excluding $j = i$.

Figure 1

The partitioning of the various latent heat fluxes is determined from the total latent heat flux λE which is the sum of all latent heat fluxes in the intercropping system, or in a two-crop intercropping system:

$$\begin{aligned}\lambda E &= \lambda E_s + \lambda E_{c,1} + \lambda E_{c,2} \\ &= \frac{\Delta A_s + \left(\rho c_p D_0\right) / r_a^s}{\Delta + \gamma\left(1 + r_s^s / r_a^s\right)} + \frac{\Delta A_{c,1} + \left(\rho c_p D_0\right) / r_a^{c,1}}{\Delta + \gamma\left(1 + r_s^{c,1} / r_a^{c,1}\right)} + \\ &\quad \frac{\Delta A_{c,2} + \left(\rho c_p D_0\right) / r_a^{c,2}}{\Delta + \gamma\left(1 + r_s^{c,2} / r_a^{c,2}\right)}\end{aligned} \qquad (8)$$

where D_0 is the vapour pressure deficit at the canopy source height, or

$$D_0 = D + \frac{r_a^a}{\rho c_p}\left\{\Delta A - \left(\Delta + \gamma\right)\lambda E\right\} \qquad (9)$$

The SW model required several resistance components to be known. These are: r^a_a (resistance between mean canopy flow and reference height); $r^{c,i}_s$ (bulk stomatal resistance); $r^{c,i}_a$ (bulk canopy boundary layer resistance); r^s_a (resistance between soil and mean canopy flow); and r^s_s (soil surface resistance). The calculations for these resistance components were obtained from Choudhury and Monteith (1988), and Shuttleworth and Gurney (1990). A crop's stomatal resistance r_{st}^i was assumed to be related only to PAR (photosynthetically active radiation). This relationship is described by

$$\frac{1}{r_{st}^i} = \frac{a_1 \cdot I_{PAR}}{a_2 + I_{PAR}} \qquad (10)$$

where I_{PAR} is the PAR irradiance; and a_1 and a_2 are the empirical coefficients (Jarvis, 1976). Bulk stomatal resistance is determined simply by

$$r_s^{c,i} = \overline{r_{st}^{i}} \big/ L \tag{11}$$

(Thom, 1972; Shuttleworth, 1978; Stannard, 1993).

Finally, heat flux into the soil G is calculated by

$$G = 0.35 \cos\theta \cdot R_n^s \tag{12}$$

where soil heat flux was simply a fraction (0.35) of the radiation reaching the soil surface (Kustas and Norman, 1999a, b).

MATERIALS AND METHODS

Maize (*Zea mays* L. cv. Hudson) and sunflower (*Helianthus annuus* L. cv. Sanluca) were sown on 22 May 1998 at Sonning Farm (51°27' N and 0°58' W). The soil was a deep, freely draining soil, brown to grey-brown, and having clay and sand contents of 17% and 69%, respectively. Soil pH was 4.5 to 7.0; organic matter content was 1.5 to 2.0%; and bulk density was 1.67 Mg m^{-3}.

Total field size was 0.13 ha, and planting rows were in a NE-SW direction. Inter-row distance was 0.6 m, but intra-row planting distance for maize was 0.3 m and sunflower was 0.6 m, so that the ratio of maize to sunflower was 2:1. The planting density of maize was 3 plants m^{-2}, and 1.5 plants m^{-2} for sunflower. Thirty days after sowing, fertilisers were applied at rates of 120 kg ha^{-1} N, 200 kg ha^{-1} P_2O_5, and 200 kg ha^{-1} K_2O. No herbicides or pesticides were applied; weeding was manual; and the crops were entirely rain-fed.

Data collection started 66 days after sowing (DAS 66), and continued every five to nine days for 30 days. The LAI (leaf area index) was measured using a leaf area machine (LI-COR, Lincoln, Nebraska, USA; Model 3000); the solar irradiance by a sunfleck ceptometer (Decagon Devices Inc., Pullman, Washington, USA; Model SF-80); the stomatal resistance by an infrared gas analyser (CIRAS, PP Systems, Hitchin Hertfordshire, UK); and the soil evaporation by lysimeters, measuring 50 mm in diameter and 120 mm in depth. Plant transpiration or sap flow was measured using customised sap flow gauges based on the concept of stem heat balance (Sakuratani, 1981), whereby its principle is to apply a known rate of heat into a stem segment, then partition the heat input between conductive and convective losses, where the latter is proportional to the volumetric sap flux up the stem. Lastly, daily and half hourly weather data (air temperature, total incoming radiation, wind speed and vapour pressure) were obtained from an automatic weather station at Sonning Farm.

The exact same field experiment as in 1998 was conducted again in 1999. Maize and sunflower were planted on 28 May 1999 at Sonning Farm. The same planting densities, planting row direction, field maintenance and data collection as in the 1998 experiment were repeated for this year. Data collection in the 1999 experiment, however, started on DAS 33, and continued every five to nine days for 35 days.

RESULTS AND DISCUSSION

Plant transpiration

Overall, the SW model predicted the transpiration of the intercrop components with reasonable accuracy (Table 1 and Figure 2). There was a close clustering of points along the 1:1 line of equality, and their mean errors were zero which indicated no overall bias in estimation errors. Moreover, 95% of these errors occurred in a narrow range within -0.08 to 0.07 mm h^{-1}. Nevertheless, the SW model tended to underestimate transpiration slightly for intercrop maize and intercrop sunflower when measured transpiration rates were high, when exceeding 0.15 and 0.40 mm h^{-1}, respectively (Figure 2).

Figure 2
Table 1

Figure 3 and 4 show the diurnal transpiration rates for the intercrop components on some selected days. Transpiration rates usually increased from morning, reaching a maximum at about 12:00 to 14:00 hours, then decreasing towards late evening. This observed diurnal trend of transpiration generally followed the measured diurnal trend of temperature, solar irradiance and vapour pressure deficit (Ozier-Lafontaine *et al.*, 1997). There was overall good agreement between the diurnal simulated and measured transpiration values. Overall, the SW model predicted the partitioning of transpiration between maize and sunflower in the intercropping system with reasonable accuracy. The accuracy of the SW model was quite robust to the different plant growing stages. It gave reasonable estimations throughout the growing season although: 1) stomatal resistance was only related to PAR irradiance (Eq. 10), 2) there was no modelling of soil water movement and content, and 3) simplified modelling of soil heat flux (Eq. 12).

Figure 3
Figure 4

In this study, stomatal resistance was only related to PAR irradiance, omitting the effects of other important factors such as air temperature, vapour pressure deficit, CO_2 concentration, and soil water content (Jarvis, 1976). In addition, the crops in this study were only rain-fed; consequently, it is reasonable to expect that there might be periods on hot, sunny days when plants could be water-stressed and develop water deficit in leaves. Furthermore, this study did not model soil water movement but assumed that the soil was always at field capacity (volumetric water content of 0.22 m^3 m^{-3}). These reasons could be why the SW model tended to slightly underestimate transpiration during high measured transpiration rates.

One possible source of error was the simplified modelling of heat flux into the soil. Soil heat flux was assumed to be only a fraction of solar irradiance reaching the soil surface, and this fraction was diurnally varied. Kustas *et al.* (1989) found that between 9:00 to 16:00 hours the ratio of soil heat flux to solar irradiance reaching the soil surface was 0.35. Jones (1991) stated that the ratio of soil heat flux to solar irradiance could vary from 0.02 for dense canopies to more than 0.30 for sparse canopies. This ratio is also dependent on soil properties such as soil moisture. Accuracy of simulations could be improved by incorporating a soil water transport model to estimate more precisely the canopy and soil resistance, and the soil heat flux and evaporation.

Errors or uncertainties in characterising the micrometeorological conditions of each crop species may be another source of error. Uncertainties, especially for intercropping systems, occur because no satisfactory method exists for simulating the convective transfer inside heterogeneous canopies, and that the intercepted radiation is highly variable within canopies (Gijzen and Goudriaan, 1989; Tournebize *et al.*, 1996). It would be difficult to characterise the large variability of microclimatological parameters within canopies by only using the meteorological data collected above the canopies as was done in this study. Some studies indicated that air-flow and temperature distributions for row crops were likely to differ from profiles in vegetation randomly distributed in aerial space (Arkin and Perrier, 1974; Graser *et al.*, 1987), especially when furrow depth (height) and plant spacing was large relative to vegetation height and amount of cover (Graser *et al.*, 1987; Kustas *et al.*, 1989). Observations from Ham and Heilman (1991) indicated that soil and aerodynamic resistances were not significantly related to meteorological conditions above the canopy. They concluded that approaches using bulk aerodynamic resistances with standard meteorological data were not appropriate for sparse canopies, and that the gradient-driven transport, or the so-called K-theory, was not applicable. The use of K-theory has always been controversial because of its lack of a strong theoretical basis. Contrary to the study by Ham and Heilman (1991), several studies were successful in applying K-theory for sparse canopies (Dolman and Wallace, 1991; Nichols, 1992; Flerchinger *et al.*, 1998). Another possible source of error in this study was the risk of advection due to the heterogeneous canopies and due to the field sizes that may not be sufficiently large enough (Tournebize *et al.*, 1996). More complete micrometeorological profiles would be required to overcome these shortcomings (Ozier-Lafontaine *et al.*, 1997).

Daily soil evaporation

Simulations followed the observed trend of daily soil evaporation quite closely (Figure 5). In the 1998 experiment, for example, daily soil evaporation increased from DAS 70 to 75, and decreased from DAS 78 to 84. Simulations likewise showed the same increasing and decreasing patterns for DAS 70 to 75 and DAS 78 to 84, respectively. Mean estimation error was 0.02 mm day^{-1} with 95% error band within –0.80 to –0.85 mm day^{-1}.

Figure 5

There were larger errors in predictions for the daily soil evaporation than for plant transpiration. For greater accuracy in estimating daily soil evaporation, incorporating a soil water model is warranted for both models. Soil water was always assumed at field capacity, and soil water changes due to rainfall and water movement were neglected in this study. The absolute amount of soil evaporation depends on the available energy at the soil surface (which is strongly related to canopy cover), frequency of soil wetting and soil type (Thornley, 1976; Wallace *et al.*, 1990, 1991).

Sensitivity analyses

Figure 6 illustrates the sensitivity of simulated transpiration by maize and sunflower in the intercropping system to model parameters such as the crop captured radiation $A_{c,i}$, canopy resistance $r^{c,i}_s$, bulk boundary layer resistance $r^{c,i}_a$, aerodynamic resistance between canopy source height and reference level r^a_a, vapour pressure deficit at canopy source height D_0, and volumetric soil water content Θ. These results of sensitivity analyses were simulated for 12:00 hours on DAS 72, 1998, where the average half-hourly values for total incoming radiation was 689 W m^{-2}, air temperature was 17 °C, wind speed was 1.6 m s^{-1}, and vapour pressure was 20 mb. Sensitivity analyses were also done for various plant growth stages, for various daylight hours and for other days, and the results obtained were similar to the results shown in Figure 6. Other model parameters were also tested such as the aerodynamic resistance between the soil surface and canopy source height r^s_a, soil surface resistance r^s_s, and soil heat flux G. Nevertheless, these model parameters produced less than 1% change in transpiration even at 20% change in the model parameters; thus, transpiration was regarded as insensitive to these model parameters.

Figure 6

Simulated transpiration for both crops was most sensitive to $A_{c,i}$, followed by $r^{c,i}_s$ and $r^{c,i}_a$. These three model parameters were more directly related to canopy characteristics than other model parameters. The importance of $A_{c,i}$, $r^{c,i}_s$ and $r^{c,i}_a$ highlighted the importance of determining accurately, for each crop species in the system, the fractional of incident radiation intercepted, the canopy resistance, and the bulk canopy boundary layer resistance. It is not surprising that plant transpiration would be sensitive to canopy resistance $r^{c,i}_s$ considering that water would evaporate from the plant mainly through the stomatal openings. Shuttleworth and Wallace (1985) noted that bulk canopy boundary layer resistance $r^{c,i}_a$ was usually significant when acting in combination with much larger canopy resistance. Sensitivity analyses done by Shuttleworth and Wallace (1985) for a monocrop system revealed that transpiration was insensitive to $r^{c,i}_a$; changing $r^{c,i}_a$ by a factor of two did not change transpiration by more than 2%. In this study, a 20% change in $r^{c,i}_a$ for a two-crop intercropping system produced a maximum of about 8% change in transpiration.

CONCLUSION

This study successfully extended and applied the SW evapotranspiration model to intercropping systems. Mean errors were zero and errors were limited to a narrow 95% range. Model accuracy was robust to the different plant growth stages or canopy cover. However, the SW model tended to slightly underestimate transpiration when the measured transpiration rates were high. For the sunflower and maize components in intercrop, it tended to underestimate slightly when measured transpiration rate exceeded 0.40 mm h^{-1} and 0.15 mm h^{-1}, respectively.

There were larger errors in predictions for the daily soil evaporation than for plant transpiration. This was because this study did not include a soil water transport model, and that soil water content was assumed to be always at field capacity. Simulations nevertheless followed the daily trend of soil evaporation closely.

Finally, sensitivity analyses revealed that modelling plant transpiration was most sensitive to model parameters most directly related to canopy characteristics. It was most sensitive to the partitioning of captured radiation among crops $A_{c,i}$, canopy resistance $r^{c,i}_s$, and bulk boundary layer resistance $r^{c,i}_a$.

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TABLE 1

Simulation error of transpiration (mm h^{-1})

Intercrop Component	Mean Error (simulated – measured)	Mean – 2SD	Mean + 2SD
Maize	0.00	-0.06	0.05
Sunflower	0.00	-0.08	0.07

SD - standard deviation

Figure 1. Schematic diagram of the various energy fluxes, temperatures, vapour pressures and resistances in a two-crop intercropping system. Key: λE, $\lambda E_{c,1}$, $\lambda E_{c,2}$ and λE_s are latent heat fluxes from the system, first crop, second crop and soil, respectively; H, $H_{c,1}$, $H_{c,2}$ and H_s are sensible heat fluxes from the system, first crop, second crop and soil, respectively; R_n and $R^s{}_n$ are net radiation fluxes into the system and to the soil, respectively; G is heat conduction into the soil; T_r, $T_{f,1}$, $T_{f,2}$, T_o and T_s are temperatures for the reference height, first crop, second crop, mean canopy flow (canopy source height) and soil, respectively; e_r and e_o are vapour pressure at the reference height and mean canopy flow, respectively; $e_w(T)$ is saturated vapour pressure at temperature T; $r^a{}_a$ is aerodynamic resistance between the mean canopy flow and reference height; $r^{c,1}{}_s$ and $r^{c,2}{}_s$ are bulk stomatal resistance for the first crop and second crop, respectively; $r^{c,1}{}_a$ and $r^{c,2}{}_a$ are bulk boundary layer resistance of the canopy for the first crop and second crop, respectively; $r^s{}_a$ is aerodynamic resistance between the soil and mean canopy flow; and $r^s{}_s$ is soil surface resistance.

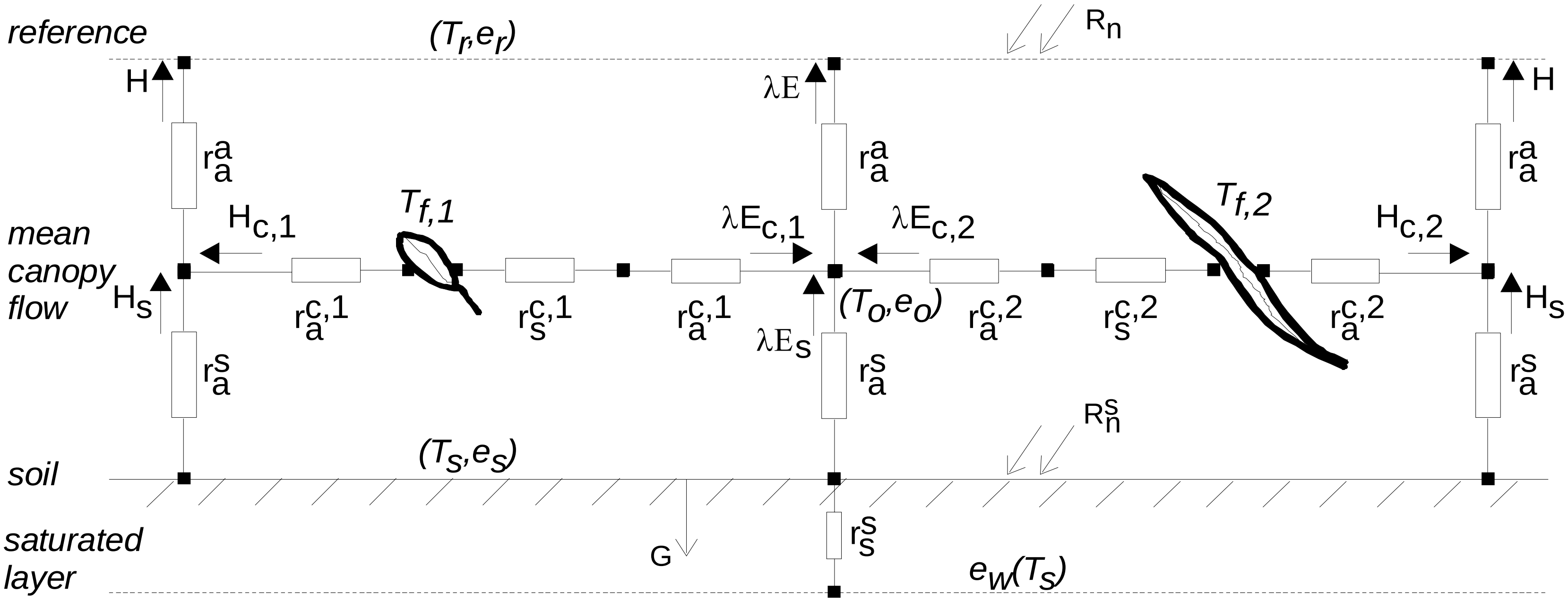
Figure 2. Comparison between simulated and measured transpiration for the intercrop components in the 1998 and 1999 experiments: (a) maize, and (b) sunflower

Figure 3. Comparison between simulated and measured diurnal transpiration for the intercrop maize: (a) DAS 71, 1998; (b) DAS 78, 1998; (c) DAS 95, 1998; (d) DAS 42, 1999; (e) DAS 44, 1999; and (f) DAS 53, 1999.

Figure 4. Comparison between simulated and measured diurnal transpiration for the intercrop sunflower: (a) DAS 71, 1998; (b) DAS 78, 1998; (c) DAS 95, 1998; (d) DAS 42, 1999; (e) DAS 44,1999; and (f) DAS 53, 1999.

Figure 5. Comparison between simulated and measured daily soil evaporation: (a) 1998 experiment, and (b) 1999 experiment

Figure 6. Sensitivity analysis of the SW model. Note: maize is the positive deviations, and sunflower is the negative deviations.


reference
(T_r, e_r)
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$T_{f,2}$
mean canopy flow
$H_{c,1}$
$\lambda E_{c,1}$
$\lambda E_{c,2}$
$H_{c,2}$
H_s
$r_a^{c,1}$
$r_s^{c,1}$
$r_a^{c,1}$
(T_o, e_o)
$r_a^{c,2}$
$r_s^{c,2}$
$r_a^{c,2}$
H_s
λE_s
r_a^s
r_a^s
r_a^s
R_n^s
(T_s, e_s)
soil
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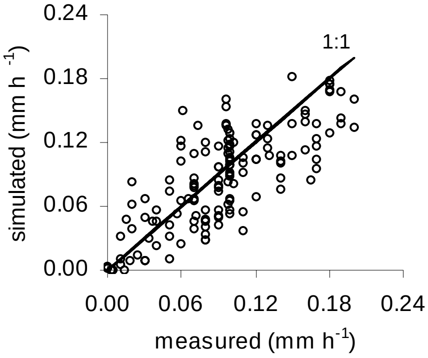
G
r_s^s
$e_w(T_s)$

(a)



1:1
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0.06
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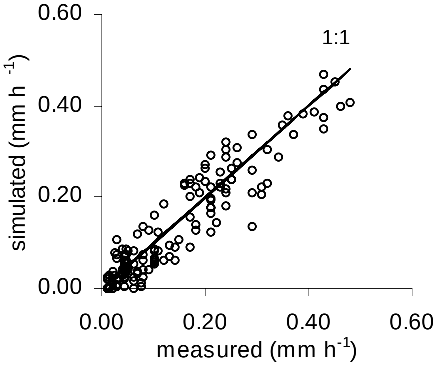
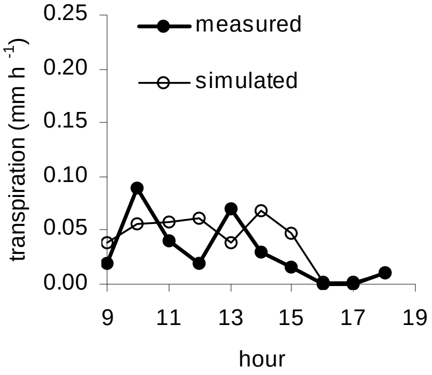
simulated (mm h $^{-1}$)
0.00
0.06
0.12
0.18
0.24
measured (mm h $^{-1}$)

(b)

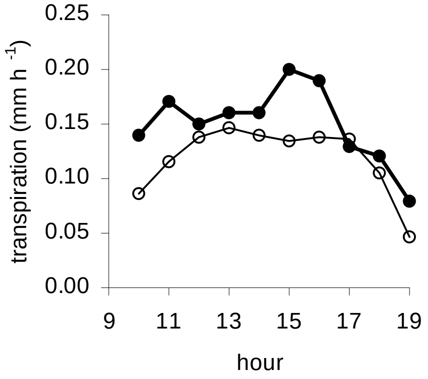


1:1
0.60
0.40
0.20
0.00
simulated (mm h $^{-1}$)
0.00
0.20
0.40
0.60
measured (mm h $^{-1}$)

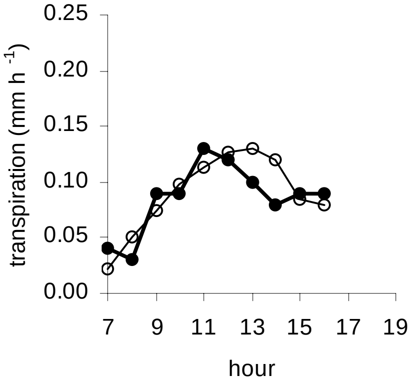
(a)


measured
simulated
transpiration (mm h $^{-1}$)
0.25
0.20
0.15
0.10
0.05
0.00
9
11
13
15
17
19
hour

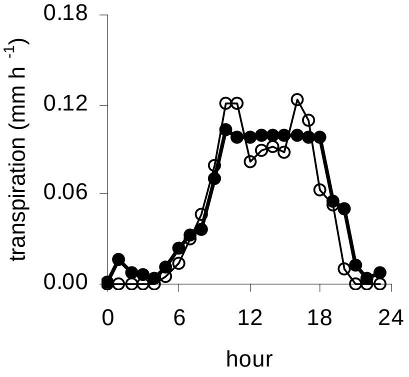
(b)


transpiration (mm h $^{-1}$)
0.25
0.20
0.15
0.10
0.05
0.00
9
11
13
15
17
19
hour

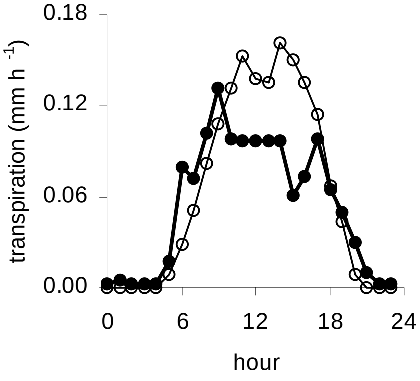
(c)


transpiration (mm h $^{-1}$)
0.25
0.20
0.15
0.10
0.05
0.00
7
9
11
13
15
17
19
hour

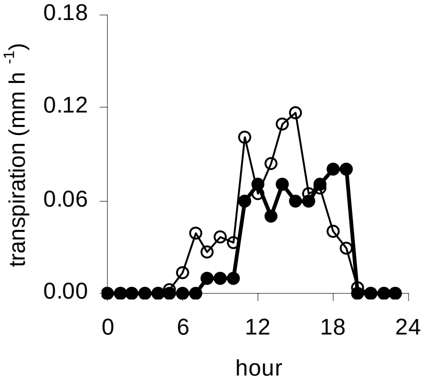
(d)

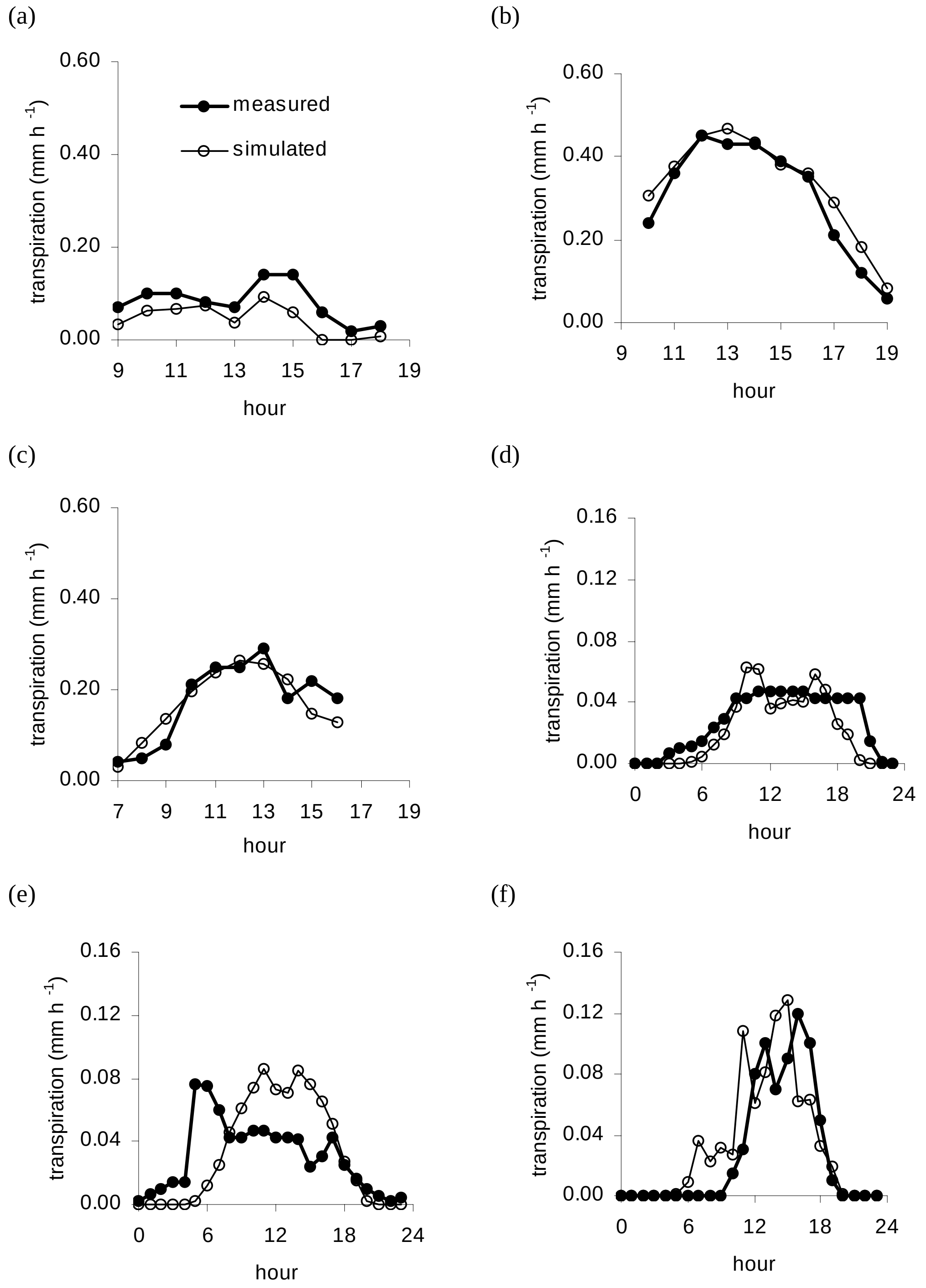

transpiration (mm h $^{-1}$)
0.18
0.12
0.06
0.00
0
6
12
18
24
hour

(e)

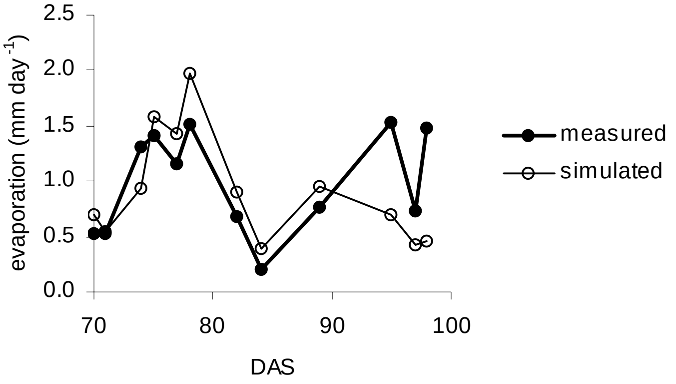

transpiration (mm h $^{-1}$)
0.18
0.12
0.06
0.00
0
6
12
18
24
hour

(f)

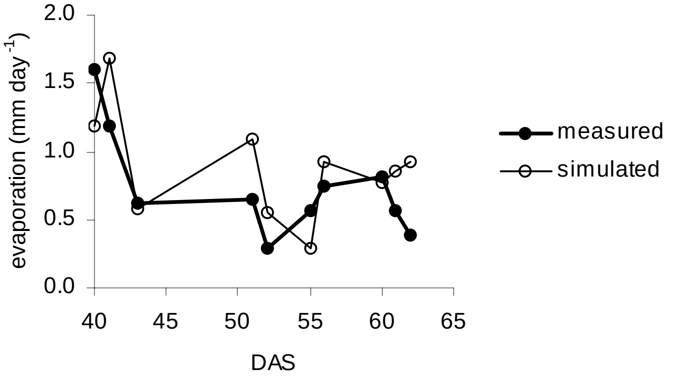

transpiration (mm h $^{-1}$)
0.18
0.12
0.06
0.00
0
6
12
18
24
hour

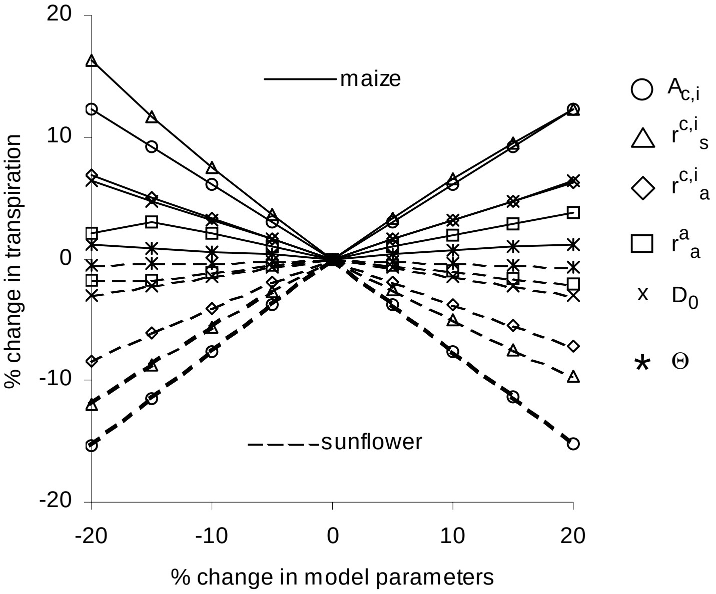

(a)
(b)
(c)
(d)
(e)
(f)
measured
simulated
transpiration (mm h $^{-1}$)
hour
0.00
0.20
0.40
0.60
0.04
0.08
0.12
0.16
7
9
11
13
15
17
19
0
6
12
18
24

(a)


2.5
2.0
1.5
1.0
0.5
0.0
evaporation (mm day^{-1})
70
80
90
100
DAS
measured
simulated

(b)


2.0
1.5
1.0
0.5
0.0
evaporation (mm day^{-1})
40
45
50
55
60
65
DAS
measured
simulated


20
10
0
-10
-20
% change in transpiration
-20
-10
0
10
20
% change in model parameters
maize
sunflower
$A_{c,i}$
$r^{c,i}_s$
$r^{c,i}_a$
r^a_a
x D_0
Θ