Second International Conference on

TROPICAL CLIMATOLOGY, METEOROLOGY AND HYDROLOGY

Climate-related Risk Analysis and Sustainable Development in Tropical Areas

Brussels, 13-14 December, 2001

RMI

Royal Meteorological Institute
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Guest Editors : G. Demarée, M. De Dapper, J. Alexandre

2004

Royal Meteorological Institute
of Belgium
av. Circulaire / Ringlaan 3
B-1180 Brussels (Belgium)
Tel. : 02.373.05.08
Fax : 02.373.05.28
E-mail : rmi_info@oma.be
Web : www.meteo.be/IRM-KMI/

Royal Academy
of Overseas Sciences
rue Defacqzstraat 1/3
B-1000 Brussels (Belgium)
Tel. : 02.538.02.11
Fax : 02.539.23.53
E-mail : kaowarsom@skynet.be
Web : http//www.kaowarsom.be

ISBN 90-75652-36-4
D/2004/0149/5

Second International Conference
"Tropical Climatology, Meteorology and Hydrology"
Proceedings edited by
G. Demarée, M. De Dapper, J. Alexandre
pp. 151-171 (2004)

Modelling the Partitioning of Solar Radiation Capture and Evapotranspiration in Intercropping Systems

by

Christopher B. S. TEH*, Lester P. SIMMONDS** & Tim R. WHEELER***

KEYWORDS. — Radiation ; Evapotranspiration ; Shuttleworth-Wallace ; Maize ; Sunflower ; Intercrop.

SUMMARY. — The primary purpose of this study was to model the partitioning of radiation capture and evapotranspiration in a two-crop (maize and sunflower) intercropping system. Two field experiments were conducted in 1998 and 1999. Detailed canopy architecture was measured, and transpiration and soil evaporation were measured using sap flow gauges and lysimetres, respectively. One- (1D) and two-dimensional (2D) models were developed for modelling radiation attenuation in one dimension (vertical) and two dimensions (vertical and horizontal), respectively. The simpler 1D model was slightly more accurate than the more complex 2D model, where the mean errors (95 % error range in brackets) for estimating the fractional radiation interception were 0.01 (- 0.09 - 0.11) and 0.04 (- 0.13 - 0.06), respectively. Nevertheless, the hourly simulations by the 2D model followed the measured diurnal trend of total radiation capture more closely than those by the 1D model. The Shuttleworth-Wallace evapotranspiration equation was extended and applied to intercropping systems. Its mean prediction error for transpiration was near zero (- 0.01 mm h^{-1}), and its accuracy was not affected by plant growth stages, but simulated transpiration during high measured transpiration rates was underestimated. There were also larger errors in predictions by both models for daily soil evaporation than for plant transpiration.

* Dept. of Land Management, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor (Malaysia).

** Dept. of Soil Science, University of Reading, Whiteknights, P.O. Box 233, Reading, RG6 6DW (UK).

*** Dept. of Agriculture, University of Reading, Earley Gate, P.O. Box 236, Reading, RG6 2AT (UK).

1. Introduction

Factors affecting the plant-radiation regime are the amount and quality of incident radiation, canopy architecture, and the optical properties of leaves and soil (SINOQUET & CALDWELL 1995). The simplest way to model how irradiance varies within canopies is to assume that irradiance varies only vertically ; that is, in one dimension. However, this assumption is only valid in homogenous canopies, achieved when canopies are closed and randomly mixed. Consequently, some workers (SINOQUET & BONHOMME 1992, DE CASTRO & FETCHER 1998) have extended the modelling of radiation attenuation in two or three dimensions in attempts to produce more representative and accurate models.

Compared to radiation modelling, evapotranspiration modelling is usually more difficult because it involves a simultaneous mathematical analysis of above and below ground spaces (TOURNEBIZE *et al.* 1996). Evaporation from the soil or transpiration from the plants is often estimated using the Penman-Monteith (PM) equation (MONTEITH 1965), but the PM equation can only be used to estimate either soil evaporation or plant transpiration, but not both simultaneously. A recent, important extension of the PM equation is the Shuttleworth-Wallace (SW) equation (SHUTTLEWORTH & WALLACE 1985) because it specifies explicitly the energy exchanges at the soil and canopy, thereby making it possible to distinguish the fraction of water transpired and that evaporated from soil (FARAHANI & AHUJA 1996). The SW equation is still relatively new and not extensively used (FARAHANI & AHUJA 1996), but field tests of this equation have been promising (LAFLEUR & ROUSE 1990, WALLACE *et al.* 1990, FARAHANI & BAUSCH 1995).

Thus, the main objectives of this study were : 1) to model the partitioning of captured radiation and evapotranspiration in a maize-sunflower intercropping system in partial- and fully-grown canopies, and 2) to determine the degree of complexity that is required for radiation modelling.

2. Development of Models

Two kinds of models were developed : a one-dimensional (1D), and a two-dimensional (2D) model. The 1D model was so-called because it modelled the radiation regime in one dimension, where irradiance varies only in a vertical direction. This means at a given canopy height, the irradiance at any point within the canopy is equal. The 2D model, however, modelled the radiation regime in two dimensions, where irradiance varies both vertically and horizontally. Both these models, however, modelled evapotranspiration in the same way by applying the extended SW equation to intercropping systems.

2.1. Partitioning of Captured Radiation

Both 1D and 2D models use the same weighting factor as given by Spitters (1989) to partition the captured radiation for a given crop species *i*. The share of intercepted radiation for each species depends on its leaf area index and extinction coefficient ; that is, for species *i*, its share of captured radiation is weighted by

$$A_{c,i} = A \bullet \omega_i$$

where $A_{c,i}$ is the amount of radiation captured by crop species *i* ; *A* is the total amount of radiation captured by all crops in the system ; and ω_i is the weighting factor, a value between 0 and 1, for crop species *i* :

$$\omega_i = \frac{k_i\, L_i \bullet \sqrt{1-\sigma_i}}{\sum_{j=1}^{n}\left[k_j\, L_j \bullet \sqrt{1-\sigma_j}\right]} \quad (1)$$

where k_i and L_i are the extinction coefficient and leaf area index of crop species *i*, respectively ; *n* is the total number of crops in the system ; and s_i is the leaf scattering coefficient of radiation for crops species *i* (Tournebize & Sinoquet 1995) which is 0.14 and 0.10 for sunflower and maize, respectively (Masoni *et al.* 1994).

2.2. Foliage Distribution and Plant-radiation Regime for the 1D Model

The foliage distribution of a crop is characterized mathematically by the 1D model using the G-function defined by Ross & Nilson (1965) as

$$G(\theta, \phi) = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\pi/2} g(r_L)\, |\cos r_L\, r| \sin \theta_L\, d\theta_L\, d\phi_L$$

where $g_L(r_L)$ is the leaf normal distribution function which expresses the probability that a leaf normal is around direction r_L, where direction r_L is described by a very narrow normal inclination range $\theta_L + \partial\theta_L$ and normal azimuth range $\phi_L + \partial\phi_L$ (Lemeur 1973a, b) ; *cos* $r_L r$ is the cosine angle between the leaf normal direction r_L and sun direction r, and is calculated by

$$\cos r_L r = \cos\theta \cos\theta_L + \sin\theta \sin\theta_L \cos(\phi - \phi_L)$$

and $^{g(r_L)}/_{2\pi} \, |\cos r_L r| \, d\Omega_L$ is the projection of the part of the leaf area with normals within the solid angle $d\Omega_L$ around the sun direction r. Consequently, $G(r)$ is regarded as the average projection per unit foliage area in the sun direction r, where the sun direction is described by inclination θ and azimuth ϕ. The function $g(r_L)$ or $g(\theta_L, \phi_L)$ is simplified by assuming that the leaf normal inclination θ_L is independent of the leaf normal azimuth ϕ_L, so then $g(\theta_L, \phi_L) = g(\theta_L) \bullet g(\phi_L)$, where $g(\theta_L)$ is the distribution function for leaf normal inclination, and $g(\phi_L)$ is the function describing leaf normal azimuth distribution (LEMEUR 1973a).

$G(\theta, \phi)$ is corrected to account for two situations : 1) radiation scattering by leaves, and 2) when leaves are not randomly distributed but clumped as found in row crops :

$$\hat{G}(\theta, \phi) = G(\theta, \phi) \bullet \sqrt{1 - \sigma_i} \bullet \Omega(\theta)$$

where $\hat{G}(\theta, \phi)$ is the corrected G-function ; and $\Omega(\theta)$ is the clumping factor (TOURNEBIZE & SINOQUET 1995 ; CAMPBELL & NORMAN 1998, KUSTAS & NORMAN 1999a, b). $\Omega(\theta)$ is determined empirically by

$$\Omega(\theta) = \frac{\Omega_0}{\Omega_0 + [1 - \Omega_0] \exp\left[-2.2\theta^{3.8 - 0.46\varepsilon}\right]}$$

where

$$\Omega_0 = \frac{\ln[f_c \exp(-kL_c) + (1 - f_c)]}{-kL}$$

and ε is the ratio of plant height to width ; and L_c is the localized leaf area index determined by

$$L_c = \frac{L}{f_c}$$

where f_c is the fractional canopy cover which is the fraction per unit ground area occupied by canopy cover and can be approximated by taking the ratio of canopy width to row spacing (CAMPBELL & NORMAN 1998). Extinction coefficient k is related to the G-function by

$$k = \frac{\hat{G}(\theta, \phi)}{\cos\theta}$$

(ROSS & NILSON 1965, LEMEUR 1973a, b).

Direct radiation within mixed canopies is calculated by

$$I_{dr} = (1 - \rho)\, I_{0,dr} \exp\left(- \sum_{j=1}^{n} \frac{\hat{G}(\theta, \phi)_j}{\cos\theta} L_j \right)$$

where $I_{0,dr}$ is the amount of direct radiation above canopy ; n is the total number of crops ; and p is the mean canopy reflection coefficient calculated by

$$\rho = \frac{(1 - \sqrt{1 - \sigma})}{(1 + \sqrt{1 - \sigma})} \times \frac{2}{(1 + 1.6 \cos\theta)}$$

(GOUDRIAAN 1977, 1988). Diffuse radiation within mixed canopies is calculated by

$$I_{df} = (1 - p) \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \exp\left[- \sum_{j=1}^{n} \frac{\hat{G}(\theta, \phi)_j}{\cos\theta} L_j \right] \cos\theta \sin\theta \, d\theta \, d\phi$$

and integrated numerically using the 5-point Gaussian method (GOUDRIAAN 1988). The $B(\theta, \phi)$ is the brightness function or the amount of diffuse radiation component coming from sky direction θ inclination and ϕ azimuth (CHARLES-EDWARDS *et al.* 1986).

The total amount of direct radiation A_{dr} and diffuse radiation A_{df} intercepted by all crops are calculated by

$$A_{dr} = I_{0,dr} - I_{dr}$$
$$A_{df} = I_{0,df} - I_{df}$$

The amount of radiation captured by crop species i is then calculated by

$$A_{dr,c,i} = A_{dr} \bullet \omega_i$$
$$A_{df,c,i} = A_{df} \bullet \omega_i \qquad (2)$$

where $A_{dr,c,i}$ and $A_{df,c,i}$ are the amount of direct and diffuse radiation captured by crop species i, respectively ; and ω_i is determined from Eq. (1).

2.3. FOLIAGE DISTRIBUTION AND PLANT-RADIATION REGIME FOR THE 2D MODEL

Unlike the 1D model, the 2D model divided the canopy space, as described by SINOQUET & BONHOMME (1992), into a set of contiguous rectangular cells, forming a two-dimensional grid network that is perpendicular to the planting row direction (fig. 1). The aerial space from the soil surface to the canopy top is divided into N_z horizontal layers of thickness E_z, and N_x vertical sections of thickness E_x. The horizontal cell thickness E_z needs not be equal to the vertical cell thickness E_x.

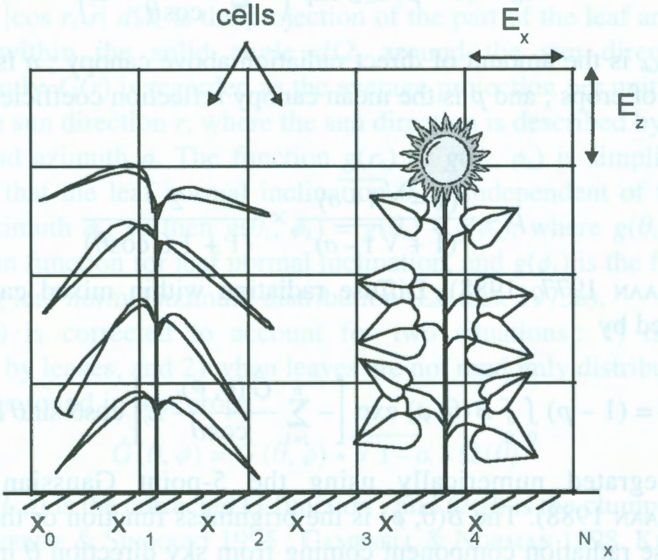

Fig. 1. — The canopy space is divided into a network of cells in the 2D model.

The probability (P_k) of total radiation intercepted within the k-th cell visited by a single beam is calculated by

$$P_k = \left[\prod_{c=1}^{k-1} \exp\left(-\sum_{j=1}^{n} G_{jc}(r) \bullet \rho_{f,jc} \bullet s_c \bullet \sqrt{1-\sigma_j}\right)\right]. \left[1 - \exp\left(-\sum_{j=1}^{n} G_{jk}(r) \bullet \rho_{f,jk} \bullet s_k \bullet \sqrt{1-\sigma_j}\right)\right] \quad (3)$$

where the multiplicative series $c = 1$ to $(k\text{-}1)$ represents every cell visited sequentially by the beam in reaching the target cell k ; $G_{jc}(r)$ is the G-function for the j-th crop in the c-th cell ; $\rho_{f,jc}$ is the leaf area density for the j-th crop in the c-th cell ; s_c is the beam path length in the c-th cell ; and n is the total number of crops (Tournebize & Sinoquet 1995). Consequently, the fraction of total radiation captured by crop species i in k-th cell F_{ki} is determined by

$$F_{ki} = P_k * \omega_{ki}$$

where ω_{ki} is determined from Eq. (1). The height and width of cells were fixed at 0.2 m in this study ($E_x = E_z = 0.2$ m).

As shown in Eq. (3), three properties must be determined for *each* cell in the grid network to determine the irradiance within the canopies : the horizontal and vertical distributions of 1) G-function $G(r)$, 2) leaf area density ρ_f, and 3) distance of beam travel s. Unlike the 1D model, the 2D model used a simpler form of the G-function :

$$G_{ki}(\theta, \phi) = \frac{\sum_{j=1}^{N} L_{ki,j} |\cos(r_L r)_{ki,j}|}{\sum_{j=1}^{N} L_{ki,j}}$$

where $L_{ki,j}$ is the area of the j-th leaf of crop species i in the k-th cell ; and N is the total number of leaves in k-th cell from crop species i (THANISAWANYANGKURA *et al.* 1997). Information about the leaf area density in each cell are obtained from the plant profile method as described by STEWART & DWYER (1993). Calculations for the distance of beam travel are based on simple geometry as described by GIJZEN & GOUDRIAAN (1989) and SINOQUET & BONHOMME (1992).

A beam with the same inclination and azimuth can enter any point on the cell, thus the number of beams "pushed" into the cell was pre-determined by several trial runs to obtain the minimum number of beams that can be used without sacrificing accuracy if more beams were used. This study used two beams to be pushed into a cell for a given sun azimuth and inclination. In several runs of radiation simulation, the error of using two beams instead of ten beams did not exceed 5 %.

Each computed s_c is then substituted into Eq. (3) to determine P_k so that the mean probability of intercepted radiation for a given beam direction can finally be calculated ($\bar{P}_k$). Direct radiation intercepted by all crops within cell k is calculated as

$$A_{dr,k} = (1 - p) \bullet I_{0,dr} \bullet \bar{P}_k$$

where $I_{0,dr}$ is the amount of direct radiation above canopy ; and p is mean crop reflection coefficient. Diffuse radiation intercepted by all crops within cell k is calculated as

$$A_{df,k} = (1 - p) \sum_{\Omega=1}^{n} I_{0,df\,(\Omega)} \bullet \bar{P}_{k(\Omega)}$$

where $I_{0,df(\Omega)}$ is the incident diffuse radiation coming from direction Ω. To determine $I_{0,df(\Omega)}$, the sky is divided into five equal inclination intervals ($\pi/10$) and eight equal azimuth intervals ($\pi/4$). Consequently, the amount of incident diffuse radiation $I_{0,df(\Omega)}$ from each of the 40 directions is determined using the brightness function $B(\theta, \phi)$.

The amount of direct and diffuse radiation captured by crop species i within k-th cell are determined similar to Eq. (2) :

$$A_{dr,ki} = A_{dr,k} \bullet \omega_{ki}$$
$$A_{df,ki} = A_{df,k} \bullet \omega_{ki}$$

Note that the above equation is used to determine the amount of radiation captured by an individual crop species within a given cell. To determine the amount of radiation captured by the whole crop, the 2D model calculated the total amount of radiation that was captured while a beam travelled from the canopy top (represented by the uppermost cell row in the network) to the soil surface (represented by the most bottom cell row in the network) (fig. 1).

2.4. Evapotranspiration

The Shuttleworth-Wallace (SW) (1985) equation was extended to include the transpiration from two or more crops and evaporation from the soil (Wallace 1997). 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 (fig. 2).

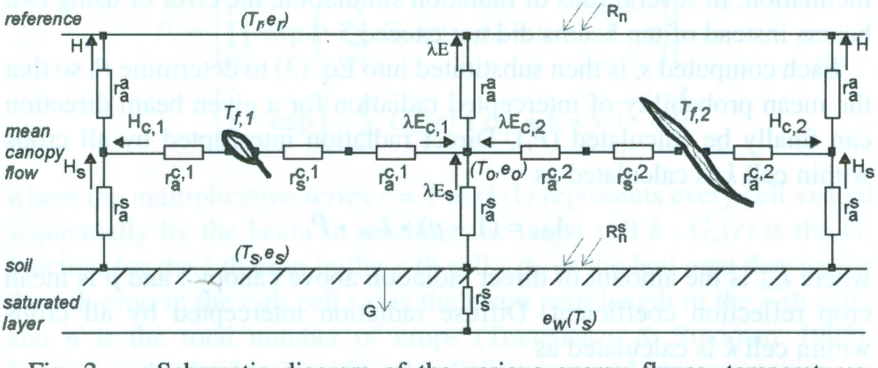

Fig. 2. — Schematic diagram of the various energy fluxes, temperatures, vapour pressures and resistances in a two-crop intercropping system. Key : *λE*, *λEc,1*, *λE c,2* and *λEs* are latent heat fluxes from the system, first crop, second crop and soil, respectively ; *H*, *Hc,1*, *Hc,2* and *Hs* are sensible heat fluxes from

the system, first crop, second crop and soil, respectively ; *Rn* and *Rsn* are net radiation fluxes into the system and to the soil, respectively ; *G* is heat conduction into the soil ; *Tr, Tf,1, Tf,2, To* and *Ts* are temperatures for the reference height, first crop, second crop, mean canopy flow (canopy source height) and soil, respectively ; *er* and *eo* are vapour pressure at the reference height and mean canopy flow, respectively ; *ew(T)* is saturated vapour pressure at temperature *T* ; *raa* is aerodynamic resistance between the mean canopy flow and reference height ; *rc,1s* and *rc,2s* are bulk stomatal resistance for the first crop and second crop, respectively ; *rc,1a* and *rc,2a* are bulk boundary layer resistance of the canopy for the first crop and second crop, respectively ; *rsa* is aerodynamic resistance between the soil and mean canopy flow ; and *rss* is soil surface resistance.

With some algebraic manipulations, it can be shown that the total latent heat flux of the system with *n* crops is given by

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

where

$$PM_{c,i} = \frac{\Delta A + \{\rho c_p D - \Delta r_a^{c,i} (A - A_{c,i})\}/(r_a^a + r_a^{c,i})}{\Delta + \gamma \{1 + r_s^{c,i} / (r_a^a + r_a^{c,i})\}}$$

$$PM_s = \frac{\Delta A + \{\rho c_p D - \Delta r_a^s (A - A_S)\}/(r_a^a + r_a^s)}{\Delta + \gamma \{1 + r_s^s / (r_a^a + r_a^s)\}}$$

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

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

$$R_{c,i} = (\Delta + \gamma) r_a^{c,i} + \gamma r_s^{c,i}$$

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

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

where c_p is the specific heat of water at constant pressure (4,182 J kg^{-1} K^{-1}) ; D is the vapour pressure deficit, or $e_s(T_r) - e_r$; Δ is the mean rate of change of saturated vapour pressure with temperature, or $[e_s(T_r) - e_s(T_0)]/(T_r - T_0)$; 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 :

$$A_{c,i} = F_i R_n$$

where F_i is the fraction of radiation intercepted by crop species i. F_i can thus be regarded as the link between radiation and evapotranspiration models. The energy available to the soil A_s is :

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

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 :

$$\lambda E = \lambda E_s + \lambda E_{c,1} + \lambda E_{c,2}$$

$$= \frac{\Delta A_s + (\rho c_p D_0) / r_a^s}{\Delta + \gamma(1 + r_s^s / r_a^s)} + \frac{\Delta A_{c,1} + (\rho c_p D_0) / r_a^{c,1})}{\Delta + \gamma(1 + r_s^{c,1} / r_a^{c,1})} + \frac{\Delta A_{c,2} + (\rho c_p D_0) / r_a^{c,2}}{\Delta + \gamma(1 + r_s^{c,2} / r_a^{c,2}}$$

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

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

The SW model required several resistance components to be known : r_a^a (resistance between mean canopy flow and reference height) ; $r_s^{c,i}$ (bulk stomatal resistance) ; $r_a^{c,i}$ (bulk canopy boundary layer resistance) ; r_a^s (resistance between soil and mean canopy flow) ; and r_s^s (soil surface resistance). These resistances are calculated from the equations given by Choudhury & Monteith (1988) and Shuttleworth & Gurney (1990).

3. 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, Reading, UK (51°27' N and 0°58' W). 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.

Measurements on canopy architecture followed the method by LEMEUR (1973a,b) and ROSS (1981), where leaf inclination and leaf azimuth were measured using a protractor, measuring tape and compass. Canopy architecture was measured for four to six periods in a day on three plants and all leaves of a plant were measured. Irradiance was measured using a sunfleck ceptometre (Decagon Devices Inc., Pullman, Washington, USA ; Model SF-80). Sap flow was measured using customized sap-flow gauges based on the concept of stem heat balance (KUCERA *et al.* 1977). The sap-flow gauges were fitted to two maize and two sunflower plants. Data was collected every 10 s and averaged at 10-min. intervals using a Campbell CR10 (Campbell Scientific Inc., Shepshed, UK) data logger. PVC lysimeters were used to measure soil evaporation (six replicates). The lysimetres measured 50 mm in diameter and 120 mm in depth. The lysimetres were placed in the middle of two planting rows, and the openings of the lysimetres were placed level with the soil surface. The soil in the lysimetres were changed every seven days or after each raining period, and the lysimetres were weighed every one to two days. Daily and half hourly weather data (air temperature, total incoming radiation, wind speed and vapour pressure) were obtained from the automatic weather station at Sonning Farm.

An exact field experiment as in 1998 was conducted again on 28 May 1999 to obtain the early crop growth periods.

4. Results and Discussion

4.1. Radiation Capture

For the 1D model, there was a close clustering of points along the 1:1 ratio line, and there was no trend of estimation error (fig. 3). The mean error (simulated minus measured) was nearly zero (0.01) and 95 % of these errors were limited to a narrow range (- 0.09 to 0.11). The more complex 2D model, however, tended to underestimate when the fractional radiation interception was around 0.80 - 0.90 (fig. 3). Mean error was - 0.04 which indicated an overall tendency to underestimate, but compared to the 1D model, 95 % of the prediction errors from the 2D model were limited to a narrower range (- 0.13 to 0.06).

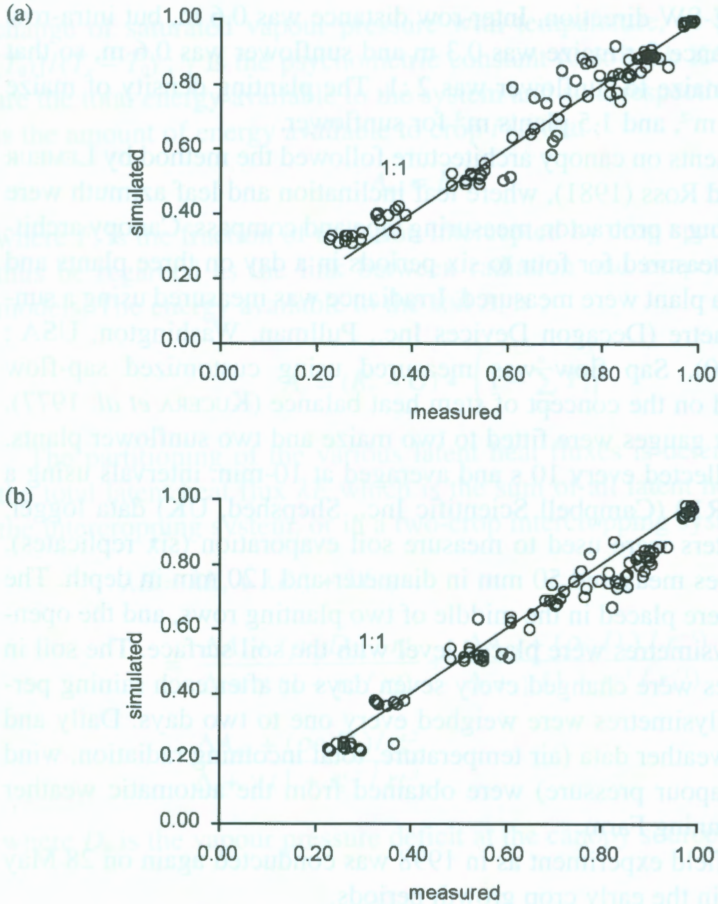

Fig. 3. — Comparisons between simulated and measured fraction of total incident radiation intercepted, where simulation was by the (a) 1D model, and (b) 2D model.

Though the 1D model generally simulated the radiation interception more accurately than the 2D model, the latter model depicted the diurnal trend or pattern of radiation interception more accurately (fig. 4). Radiation interception depended on the solar position, whereby radiation interception decreased gradually as the sun began to align in parallel to the row direction (NE-SW). This gradual decline, however, decreased abruptly and sharply at about 14:30 hours when the sun was parallel to the row direction. The radiation intercepted was at the lowest at 15:30 hours, and after this hour radiation interception began to increase. The existence of a planting row structure has been shown to affect the

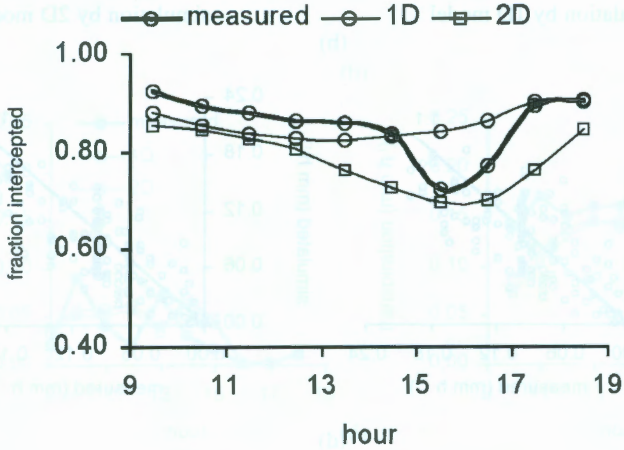

Fig. 4. — Diurnal fraction of total incident radiation intercepted in the 1998 experiment on DAS 78.

diurnal pattern of radiation interception (McCaughey & Davis 1974, Wallace *et al.* 1990).

4.2. Plant Transpiration

Both the 1D and 2D models predicted transpiration of the intercrop components with reasonable accuracy (tab. 1 and fig. 5). For each model, there was a close clustering of points along the 1:1 line of equality, and their mean errors were zero or near zero which indicated little bias in estimation errors. Moreover, 95 % of these estimation errors occurred in a narrow range within - 0.09 to 0.07 mm h^{-1}. The 2D model had a slight-

Table 1

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

Model	Intercrop Component	Mean Error (simulated-measured)	Mean – 2SD	Mean + 2SD
1D model	Maize	0.00	- 0.06	0.05
	Sunflower	0.00	- 0.08	0.07
2D model	Maize	- 0.01	- 0.07	0.05
	Sunflower	- 0.01	- 0.09	0.07

SD = standard deviation.

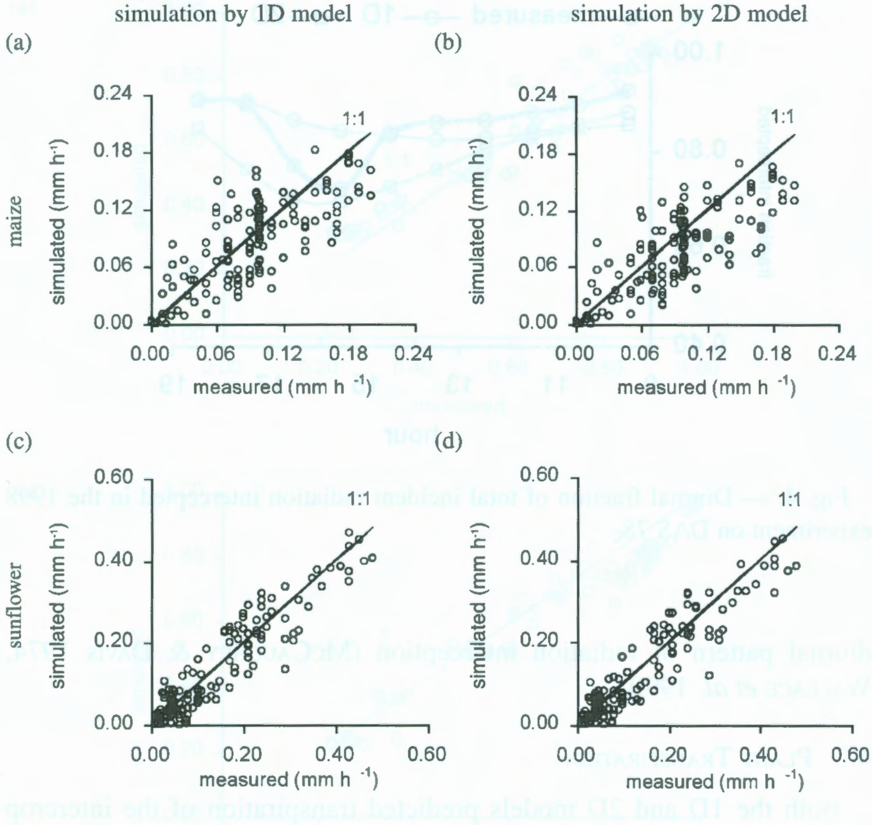

Fig. 5. — Comparisons between simulated and measured transpiration for the intercrop components in the 1998 and 1999 experiments.

ly broader error range than the 1D model, and the mean error by the 2D model was - 0.01 compared to 0.00 by the 1D model. This revealed that the 2D model was slightly less accurate than the 1D model. Nevertheless, both models tended to underestimate transpiration slightly for intercrop maize and intercrop sunflower when measured transpiration exceeded 0.15 and 0.40 mm h^{-1}, respectively (fig. 5). And this underestimation was slightly larger for the 2D model than the 1D model. Prediction by the 2D model was less accurate than the 1D model because, as shown in fig. 3, the 2D model predicted radiation interception in the intercrop slightly less accurately than the 1D model. It followed that because the 2D model tended to underestimate radiation when measured intercepted radiation exceeded 0.80 ; this would also lead to an underestimation of trans-

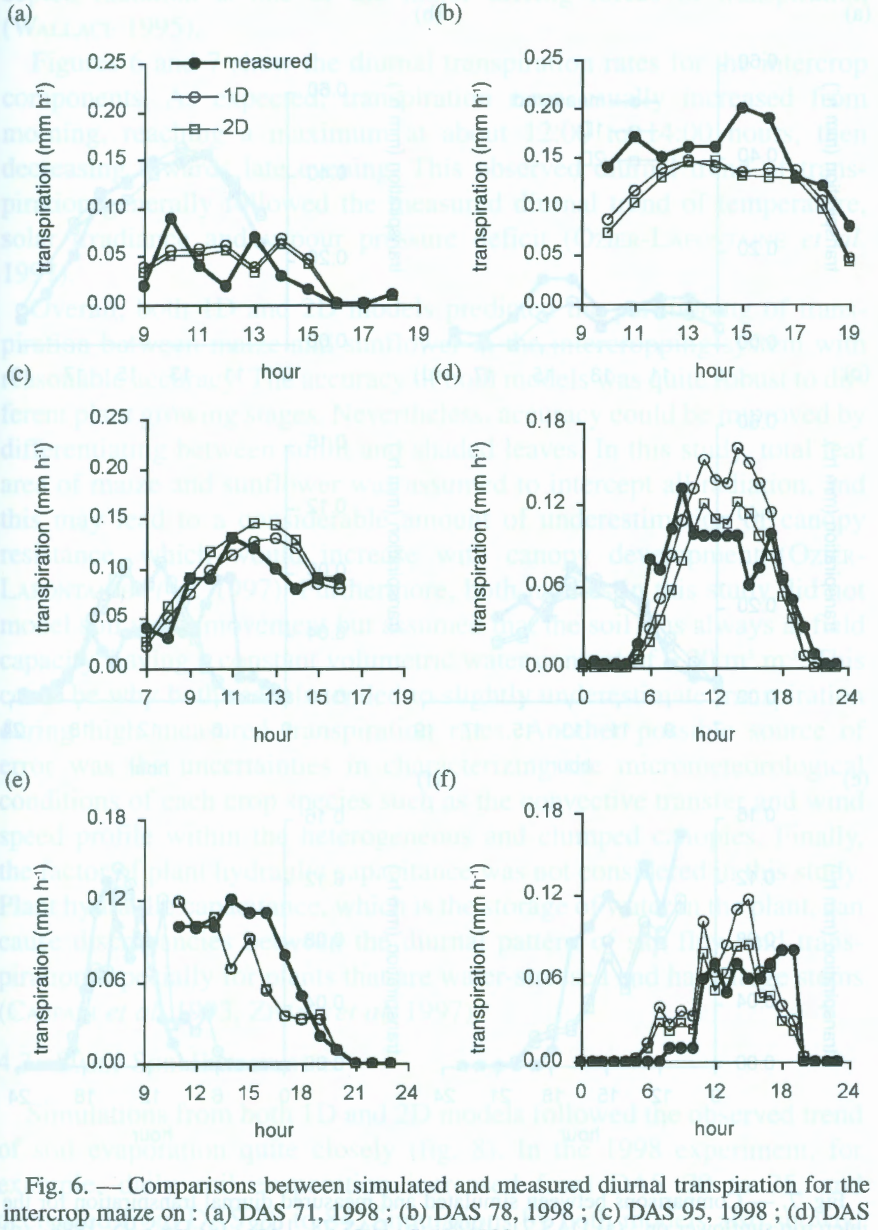

Fig. 6. — Comparisons between simulated and measured diurnal transpiration for the intercrop maize on : (a) DAS 71, 1998 ; (b) DAS 78, 1998 ; (c) DAS 95, 1998 ; (d) DAS 44, 1999 ; (e) DAS 48, 1999 ; and (f) DAS 53, 1999.

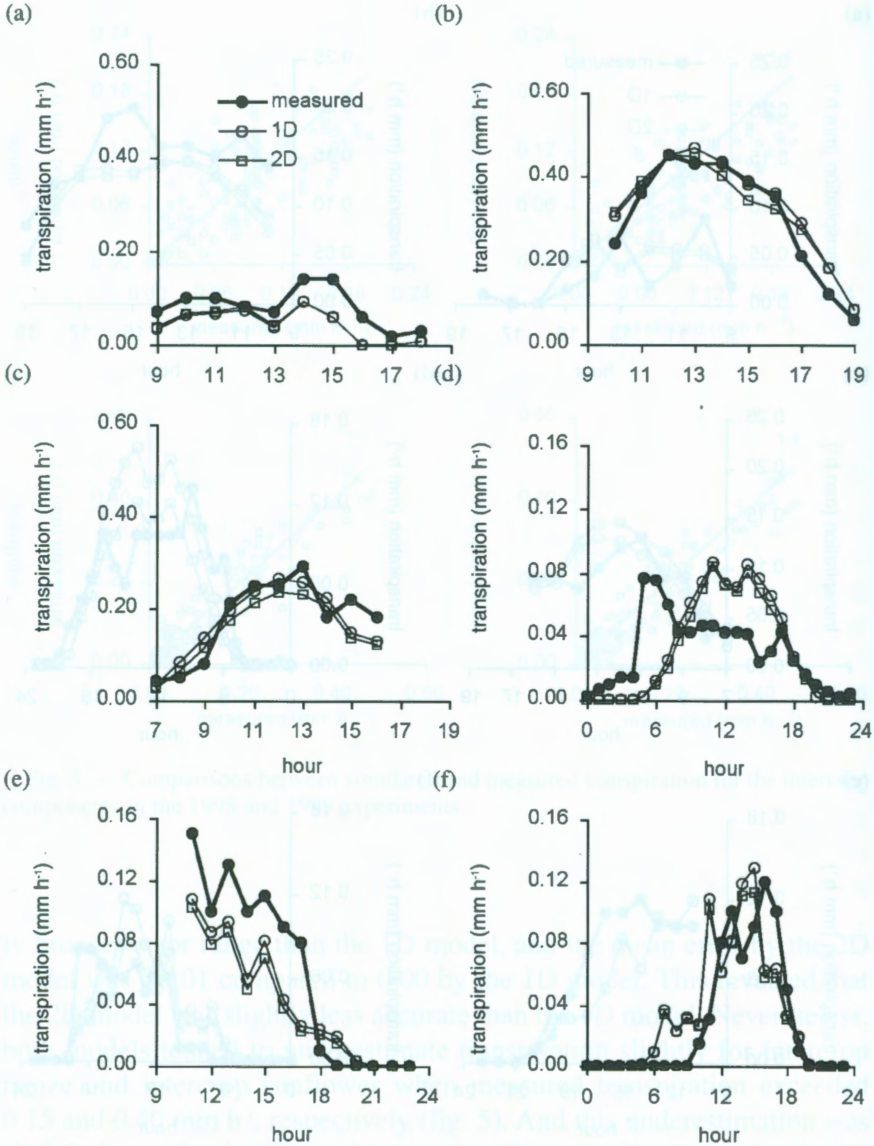

Fig. 7. — Comparisons between simulated and measured diurnal transpiration for the intercrop sunflower on : (a) DAS 71, 1998 ; (b) DAS 78, 1998 ; (c) DAS 95, 1998 ; (d) DAS 44, 1999 ; (e) DAS 48, 1999 ; and (f) DAS 53, 1999.

piration especially during high transpiration rates. This is because intercepted radiation is one of the major driving forces of transpiration (WALLACE 1995).

Figures 6 and 7 show the diurnal transpiration rates for the intercrop components. As expected, 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).

Overall, both 1D and 2D models predicted the partitioning of transpiration between maize and sunflower in the intercropping system with reasonable accuracy. The accuracy of both models was quite robust to different plant growing stages. Nevertheless, accuracy could be improved by differentiating between sunlit and shaded leaves. In this study, total leaf area of maize and sunflower was assumed to intercept all radiation, and this may lead to a considerable amount of underestimation of canopy resistance, which would increase with canopy development (OZIER-LAFONTAINE *et al.* 1997). Furthermore, both models in this study did not model soil water movement but assumed that the soil was always at field capacity, having a constant volumetric water content of 0.20 m^3 m^{-3}. This could be why both models tended to slightly underestimate transpiration during high measured transpiration rates. Another possible source of error was the uncertainties in characterizing the micrometeorological conditions of each crop species such as the convective transfer and wind speed profile within the heterogeneous and clumped canopies. Finally, the factor of plant hydraulic capacitance was not considered in this study. Plant hydraulic capacitance, which is the storage of water in the plant, can cause discrepancies between the diurnal pattern of sap flow and transpiration especially for plants that are water-stressed and have large stems (CASPARI *et al.* 1993, ZHANG *et al.* 1997).

4.3. DAILY SOIL EVAPORATION

Simulations from both 1D and 2D models followed the observed trend of soil evaporation quite closely (fig. 8). In the 1998 experiment, for example, daily soil evaporation increased from DAS 70 to 75, and decreased from DAS 78 to 84. Simulations by both models also showed the same increasing and decreasing patterns for DAS 70 to 75 and DAS 78 to 84, respectively. Of the two models, the 1D model was more accurate in estimating daily soil evaporation. Its mean error was closer to zero

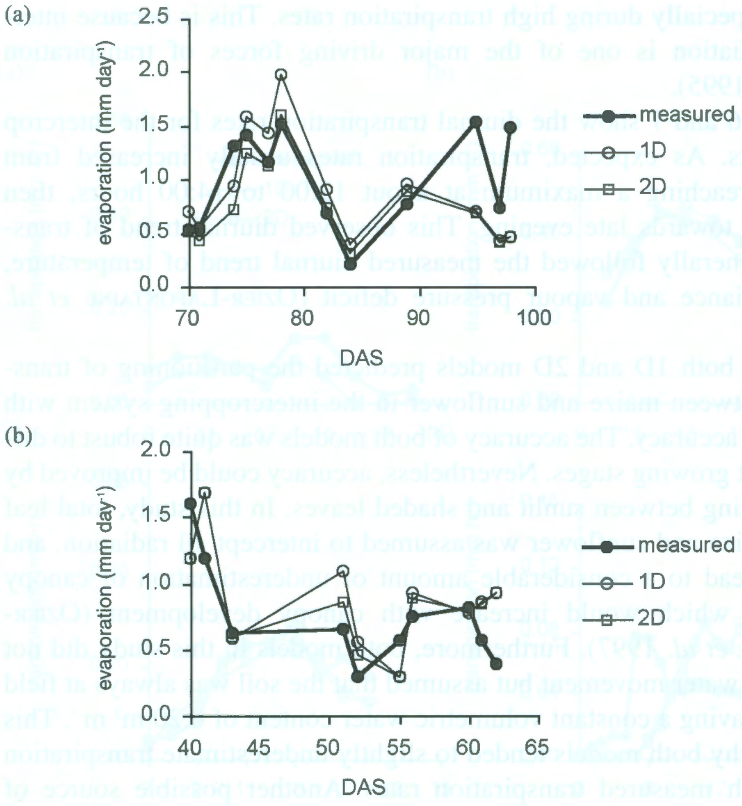

Fig. 8. — Comparisons between simulated and measured daily soil evaporation for the (a) 1998 experiment, and (b) 1999 experiment.

(0.02 mm day^{-1}) as compared to the mean error by the 2D model (- 0.08 mm day^{-1}), showing that the 2D model tended to underestimate the daily soil evaporation. Nevertheless, the 95 % error range for the 1D model was larger (- 0.80 to 0.85 mm day^{-1}) than the 2D model (- 0.84 to 0.69 mm day^{-1}). This showed that though the 1D model was, overall, more accurate than the 2D model, 95 % of the estimation errors by the former model occurred in a slightly wider range than by the latter model.

5. Conclusion

This study successfully developed two models (the 1D and 2D models) that were shown to be reasonably accurate in modelling : 1) the total captured radiation, 2) the partitioning of total captured radiation between two crops of comparable heights : maize and sunflower, and 3) the partitioning of transpiration between these two crops. The accuracy of these two models was also robust to the different crop growth stages and canopy covers. However, compared to the 2D model, the 1D model was overall slightly more accurate. That the simpler 1D model was slightly more accurate than the more complex 2D model already indicated a huge simplification step in the modelling process. Computations by the 1D model were simpler, less data-demanding and much faster than the 2D model.

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