Scaling Up Stomatal Conductance from Leaf to Canopy Using a Dual-Leaf Model for Estimating Crop Evapotranspiration

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Abstract

The dual-source Shuttleworth-Wallace model has been widely used to estimate and partition crop evapotranspiration ($\lambda E_T$). Canopy stomatal conductance ($G_{sc}$), an essential parameter of the model, is often calculated by scaling up leaf stomatal conductance, considering the canopy as one single leaf in a so-called “big-leaf” model. However, $G_{sc}$ can be overestimated or underestimated depending on leaf area index level in the big-leaf model, due to a non-linear stomatal response to light. A dual-leaf model, scaling up $G_{sc}$ from leaf to canopy, was developed in this study. The non-linear stomata-light relationship was incorporated by dividing the canopy into sunlit and shaded fractions and calculating each fraction separately according to absorbed irradiances. The model includes: (1) the absorbed irradiance, determined by separately integrating the sunlit and shaded leaves with consideration of both beam and diffuse radiation; (2) leaf area for the sunlit and shaded fractions; and (3) a leaf conductance model that accounts for the response of stomata to PAR, vapor pressure deficit and available soil water. In contrast to the significant errors of $G_{sc}$ in the big-leaf model, the predicted $G_{sc}$ using the dual-leaf model had a high degree of data-model agreement; the slope of the linear regression between daytime predictions and measurements was 1.01 (R² = 0.98), with RMSE of 0.6120 mm s⁻¹ for four clear-sky days in different growth stages. The estimates of half-hourly $\lambda E_T$ using the dual-source dual-leaf model (DSDL) agreed well with measurements and the error was within 5% during two growing seasons of maize with differing hydrometeorological and management strategies. Moreover, the estimates of soil evaporation using the DSDL model closely matched actual measurements. Our results indicate that the DSDL model can produce more accurate estimation of $G_{sc}$ and $\lambda E_T$, compared to the big-leaf model, and thus is an effective alternative approach for estimating and partitioning $\lambda E_T$.

Introduction

Accurate estimation of evapotranspiration ($\lambda E_T$) is important in understanding terrestrial hydrological cycles because $\lambda E_T$ is the largest component in the terrestrial water balance after precipitation [1]. In agricultural production, improved estimation of crop $\lambda E_T$ is also needed to develop precise irrigation scheduling and enhance water use efficiency, as soil water depletion is mostly determined by the rate of $\lambda E_T$ [2,3,4]. However, direct measurement of $\lambda E_T$ is often difficult, costly and not available in many regions [5,6]. Therefore, mathematical models are needed to estimate $\lambda E_T$ using readily measurable meteorological and environmental variables.

Vegetation transpiration ($T_v$) and soil evaporation ($E_s$), which are controlled by different biotic and physical processes, are the two major components of $\lambda E_T$. Transpiration is strongly linked to crop productivity since it occurs concurrently with photosynthetic gas exchange [7]. Quantifying $T_v$ is also critical to accurately predict the response of crop functioning and physiology to changing climate [8]. Because the two separate processes occur simultaneously, there is no simple way to distinguish between them [9,10].

Several models have been developed to calculate $\lambda E_T$ and separately estimate soil evaporation and transpiration [11,12,13]. Shuttleworth and Wallace [14] described a dual-source model with a resistance-energy combination, which could separately predict $T_v$ and $E_s$, and is also sufficiently simple [8]. This model has been widely used and can also be used to gain an understanding of the interaction of biophysical and hydrological processes in the crop canopy [14,15]. Determination of different resistances or conductances (the reciprocal of resistance) is necessary for its practical application. Specifically, canopy stomatal conductance ($G_{sc}$) is often calculated by scaling up leaf stomatal conductance of the leaves acting in parallel while treating the canopy as one big-leaf, hereafter the big-leaf approach [8,16].

The weakness of using the big-leaf approach is that the use of mean absorbed radiation can significantly overestimate $G_{sc}$, especially in dense canopies, because the light response of stomata

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Scaling Up Stomatal Conductance from Leaf to Canopy

1 Dual-source Evapotranspiration Model

The $\lambda ET$ in the dual-source model was partitioned into two components, canopy transpiration ($\lambda T_c$) and soil evaporation ($\lambda E_s$) with a resistance network [14].

$$\lambda ET = \lambda T_c + \lambda E_s = \omega_1 PM_c + \omega_2 PM_s$$ (1)

$$PM_c = \frac{\Delta A + \left( \rho C_p VPD - \Delta \alpha_c A_s \right) / (r_{sa} + r_{sc})}{\Delta + \gamma (1 + r_{sc} / (r_{sa} + r_{sc}))}$$ (2)

$$PM_s = \frac{\Delta A + \left( \rho C_p VPD - \Delta \alpha_c (A - A_s) \right) / (r_{sa} + r_{sc})}{\Delta + \gamma (1 + r_{sc} / (r_{sa} + r_{sc}))}$$ (3)

$$\omega_1 = \frac{1}{1 + R_c R_s / [R_c + R_s]}$$ (4)

$$\omega_2 = \frac{1}{1 + R_c R_s / [R_c + R_s]}$$ (5)

$$R_c = (\Delta + \gamma) r_{sa} + \gamma r_{st}$$ (6)

$$R_s = (\Delta + \gamma) r_{sc} + \gamma r_{st}$$ (7)

$$R_{r} = (\Delta + \gamma) r_{sa}$$ (8)

where $PM_c$ and $PM_s$ are the terms similar to those in Penman–Monteith model for canopy transpiration and soil evaporation, respectively, and $\omega_1$ and $\omega_2$ are the weighting factors for the crop canopy and soil components, respectively. $\lambda$ is the heat of water vaporization, $C_p$ is air density, $\lambda$ is the specific heat of dry air at constant pressure, $\Delta$ is the slope of the saturation vapor pressure curve, $\gamma$ is the psychrometric constant, $VPD$ is vapor pressure deficit, and $A$ and $A_s$ are the total available energy and available energy for soil, respectively. $r_{sa}$ is canopy stomatal resistance, $r_{st}$ is soil surface resistance, $r_{sc}$ is canopy boundary layer resistance, $r_{st}$ is soil boundary layer resistance between soil and vegetative canopy, and $r_{sa}$ is aerodynamic resistance between canopy source and reference height, respectively. The calculation procedures of the other resistances except $r_{sa}$ and $r_{st}$ are given in Appendix S1.

$$A = R_{sa} - G$$ (9)

$$A_s = R_{sa} - G$$ (10)
where \( R_n \) and \( R_s \) are net radiation above the canopy and at the soil surface, respectively, and \( G \) is the soil heat flux. The canopy extinction coefficient of net radiation, \( \kappa_R \), is dependent on leaf orientation and solar zenith angle \((\zeta)\) [17].

\[
\kappa_R = \frac{G_L}{\cos(\zeta)}
\]

(12)

where \( G_L \) is 0.5 for a spherical leaf angle distribution, \( \zeta \), the angle subtended by the sun at the center of the earth, is perpendicular to the surface of the earth and calculated as in Appendix S1.

The two components, \( \Delta T_c \) and \( \Delta E_c \) were now calculated along the \( VPD \) at the canopy source height \((D_c)\).

\[
D_c = VPD + [\Delta A - (\Delta + \gamma)\Delta T] r_a / \rho C_p
\]

(13)

\[
\Delta T_c = \frac{\Delta A - \rho C_p D_a / r_a}{\Delta + \gamma \frac{1 + r_a / r_a}{1 + r_a / r_a}}
\]

(14)

\[
\Delta E_c = \frac{\Delta A - \rho C_p D_a / r_a}{\Delta + \gamma \frac{1 + r_a / r_a}{1 + r_a / r_a}}
\]

(15)

The measured \( r_a \) was obtained by inverting Eq. (14), with \( \Delta T_c \) calculated by the known or measured \( \Delta T \) and \( \Delta E_c \).

\[
\Delta T_c = \frac{\Delta A - \rho C_p D_a / r_a}{\gamma \frac{1 + r_a / r_a}{1 + r_a / r_a}}
\]

(16)

\[
r_a = \frac{\Delta A - \rho C_p D_a / r_a}{\gamma \frac{1 + r_a / r_a}{1 + r_a / r_a}}
\]

(17)

2 Irradiance within Crop Canopy

Incident PAR light above the canopy \((Q_o)\) was divided into diffuse \((Q_{od})\) and beam irradiance \((Q_{ob})\) through the fraction of diffuse radiation \((f_d)\).

\[
Q_{od} = f_d Q_o
\]

(18)

\[
Q_{ob} = (1 - f_d) Q_o
\]

(19)

The \( f_d \) was calculated from a simple model of atmospheric attenuation of radiation [17,28].

\[
f_d = \frac{1 - \tau_o m_a}{1 + \tau_o m_a (1/f_o - 1)}
\]

(20)

where \( \tau_o \) is the atmospheric transmittance, \( f_o \) is the forward scattering coefficient of PAR in atmosphere, and \( m_o \) is the optical air mass, which can be calculated as follows.

\[
m_o = \frac{P/P_o}{\cos \zeta}
\]

(21)

where \( P \) is local atmospheric pressure and \( P_o \) is atmospheric pressure at sea level.

At a depth \( \zeta \) in the canopy, three types of irradiance can be calculated: the total beam, \( Q_{ob} \) (unintercepted beam plus down scattered beam), direct beam, \( Q_{ob} \) (unintercepted beam) and the diffuse flux, \( Q_{od} \) [17,29].

\[
Q_{ob} (\zeta) = Q_{ob} (1 - \rho_{ib}) \sqrt{2 \kappa_h} \exp(-\sqrt{2 \kappa_h} \zeta)
\]

(22)

\[
Q_{bb} (\zeta) = Q_{bb} (1 - \rho_{ib}) \kappa_h \exp(-\kappa_h \zeta)
\]

(23)

\[
Q_{od} (\zeta) = Q_{od} (1 - \rho_{od}) \sqrt{2 \kappa_d} \exp(-\sqrt{2 \kappa_d} \zeta)
\]

(24)

\[
\rho_{ib} = 1 - \exp(2 \rho_{ib} (1/1 + \kappa_h))
\]

(25)

\[
\rho_h = \frac{1 - \sqrt{2}}{1 + \sqrt{2}}
\]

(26)

\[
\rho_{od} = \frac{2 \kappa_d \rho_h}{\kappa_d + 1}
\]

(27)

where \( \alpha \) is absorptivity of leaves for irradiation, \( \rho_{ib} \) and \( \rho_{od} \) are canopy reflectance for beam and diffuse irradiance respectively with a randomly spherical leaf-angle distribution, \( \kappa_h \) is canopy reflectance for beam irradiance with a horizontal leaf-angle distribution, and \( \kappa_d \) is an extinction coefficient for diffuse radiation.

The absorbed irradiance in a canopy height \((Q_c)\) consists of the total beam radiation \((Q_{ob})\) and the diffuse radiation \((Q_{od})\).

\[
Q_c (\zeta) = Q_{bb} (\zeta) + Q_{bd} (\zeta)
\]

(28)
The total irradiance absorbed by the entire canopy \((Q_c)\) per unit ground area was determined by integrating \(Q_d\) over the total LAI.

\[
Q_c = \int_0^{LAI} Q_d(\xi)\,d\xi = Q_{oh}(1-\rho_{oh})\left[1 - \exp\left(-\sqrt{2}\kappa_b\text{LAI}\right)\right] + Q_{sd}(1-\rho_{sd})\left[1 - \exp\left(-\sqrt{2}\kappa_d\text{LAI}\right)\right]
\]  

(29)

The irradiance absorbed by the sunlit fraction in a specific canopy height \((Q_{c,d})\) can be given as the sum of direct-beam \((Q_{d,b})\), diffuse \((Q_{d,d})\) and scattered-beam components \((Q_{d,s})\).

\[
Q_{c,d}(\xi) = Q_{d,b}(\xi) + Q_{d,d}(\xi) + Q_{d,s}(\xi)
\]  

(30)

\[
Q_{c,d}(\xi) = Q_{oh}(1-\rho_{oh})\sqrt{2}\kappa_b \exp\left(-\sqrt{2}\kappa_b\xi\right) - \kappa_b \exp\left(-\kappa_b\xi\right)
\]  

(31)

The irradiance absorbed by the sunlit fraction in the entire canopy \((Q_c)\) was obtained by integrating \(Q_{c,d}\) over the total LAI.

\[
Q_d = \int_0^{LAI} Q_{c,d}(\xi)f_{c,d}(\xi)\,d\xi = \int_0^{LAI} Q_{d,b}(\xi)f_{d,b}(\xi)\,d\xi + \int_0^{LAI} Q_{d,d}(\xi)f_{d,d}(\xi)\,d\xi + \int_0^{LAI} Q_{d,s}(\xi)f_{d,s}(\xi)\,d\xi
\]  

(32)

\[
Q_{d,b}(\xi)f_{d,b}(\xi)\,d\xi = Q_{oh}(1-\rho_{oh})\left[1 - \exp\left(-\sqrt{2}\kappa_b\text{LAI}\right)\right]
\]  

(32a)

\[
\int_0^{LAI} Q_{d,d}(\xi)f_{d,d}(\xi)\,d\xi = Q_{sd}(1-\rho_{sd})\left[1 - \exp\left(-\sqrt{2}\kappa_d\text{LAI}\right)\right]
\]  

(32b)

\[
\int_0^{LAI} Q_{d,s}(\xi)f_{d,s}(\xi)\,d\xi = Q_{sd}(1-\rho_{sd})\frac{\sqrt{2}\kappa_b}{\sqrt{2}\kappa_b + \kappa_d} \left[1 - \exp\left(-\left(\sqrt{2}\kappa_b + \kappa_d\right)\text{LAI}\right)\right]
\]  

(32c)

The total irradiance absorbed \((Q)\) is the sum of the two parts, irradiance absorbed by the separate sunlit \((Q_d)\) and shade fractions \((Q_s)\) of the canopy. Thus, \(Q_s\) was calculated as the difference between \(Q_c\) and \(Q_d\).

\[
Q_s = Q_c - Q_d
\]  

(33)

3 Leaf and Canopy Stomatal Conductance

The stomatal conductance is represented by \(g_s\) for a single leaf and \(G_s\) for the entire canopy.

3.1. Leaf stomatal conductance. The leaf \(g_s\) can be calculated using the Jarvis-Stewart type multiple formulae.

\[
g_s = \left(\frac{1}{r_s}\right) = \frac{g_{max} F_{X_i}}{r_s}
\]  

(34)

where \(g_{max}\) is the maximum value of the leaf stomatal conductance and \(F_{X_i}\) is the stress function of the specific environmental variables \((x_i)\), \(0 \leq F_{X_i} \leq 1\). The original model used short-wave radiation as the light variable. Here we have used the photosynthetically active radiation absorbed by canopy leaves \((Q_a)\) because stomatal aperture is determined by the received visible wavelength radiation, rather than short-wave radiation [17,18,33]. In addition, we incorporated the environmental stress impact on \(g_s\) by \(VPD\) and available soil water as follows.

\[
F_Q = \frac{500 + k_Q}{500} \frac{Q_a}{Q_a + k_Q}
\]  

(35)

\[
F_D = e^{-k_D VPD}
\]  

(36)

\[
F_w = \frac{1 - \exp(-k_w \theta_F)}{1 - \exp(-k_w)}
\]  

(37)

\[
\theta_F = \frac{\theta - \theta_W}{\theta_F - \theta_W}
\]  

(38)

where the \(k_Q, k_D\) and \(k_w\) are the stress coefficients of \(Q_a, VPD\) and extractable soil water in the root zone \((\theta_Q)\), and \(\theta, \theta_F\) and \(\theta_W\) are the measured soil moisture, field capacity and wilting point in the root zone, respectively.

3.2. Big-leaf model of canopy stomatal conductance. The canopy stomatal conductance in the big-leaf model \((G_{s,1})\) is estimated by scaling up \(g_s\) weighing by the effective \(LAI\) \((LAI_e)\) as if the canopy is a single big-leaf [16,18,32].

\[
G_{s,1} = \frac{1}{r_{s,1}} = g_{s,1} LAI_e
\]  

(39)

where \(g_{s,1}\) is the mean leaf stomatal conductance for the entire big-leaf and can be calculated by Eq. (34) based on the mean absorbed irradiance of the entire canopy using Eq. (29); \(LAI\) is empirically equal to the actual \(LAI\) for \(LAI\leq2\), \(LAI/2\) for \(LAI\leq4\), and 2.0 for others [16].
3.3 Dual-leaf model of canopy stomatal conductance. In the dual-leaf model, $G_{sc}$ is calculated by summing the contributions of sunlit and shaded fractions, $G_{sl}$ and $G_{sh}$, respectively, which are scaled up using the associated $g_s$ weighted by their respective fractions of LAI [18,24].

$$G_{sc2} = \frac{1}{r_{sc2}} = G_{sl} + G_{sh} = g_s LAI_{sl} + g_s LAI_{sh} \quad \text{(40)}$$

where $g_s$ and $g_s$ are the mean leaf stomatal conductance for sunlit and shaded leaves, respectively, and can be calculated by Eq. (34) based on the separate absorbed irradiance using Eqs. (32) and (33). $LAI_{sl}$ and $LAI_{sh}$ are LAI for sunlit and shaded leaves in the entire canopy, respectively.

Assuming that all leaves in a canopy are randomly distributed, the fraction of sunlit leaves ($f_{sl}$) in a specific canopy depth declines exponentially with cumulative leaf area ($\xi$) [29,34].

$$f_{sl}(\xi) = \exp (-\kappa_b \xi) \quad \text{(41)}$$

where $\kappa_b$ is an extinction coefficient for beam radiation, $L_d$ is leaf area density, $\xi$ is height above ground, and $h_c$ is canopy height. $LAI_{sl}$ is therefore calculated by integrating $f_{sl}$ for the entire canopy.

$$LAI_{sl} = \int_0^{LAI} f_{sl}(\xi)d\xi = \frac{1 - \exp (-\kappa_b LAI)}{\kappa_b} \quad \text{(43)}$$

$$LAI_{sh} = LAI - LAI_{sl} \quad \text{(44)}$$

4 Soil Surface Resistance

In this study, $r_s$ was directly calculated with a function dependent on surface soil water content [35], accounting for the effect of plastic mulching on reduction of soil evaporation by introducing a term for fraction of plastic mulch, $f_m$ [i.e. $r_s$ is divided by the area of exposed substrate per unit ground area (1 $-$ $f_m$)].

$$r_s = \frac{1}{1 - f_m} \left[ b_1 \left( \frac{\theta_s}{\theta_i} \right)^{b_2} + b_3 \right] \quad \text{(45)}$$

where $\theta_s$ is the average soil water content between 0 - 0.1 m, $\theta_i$ is the saturated water content of surface soil, and $b_1$, $b_2$, and $b_3$ are the empirical coefficients.
which were defined as one minus the ratio of the summed surface areas of bare soil and holes to ground area. For the 0–1.0 m soil depth, the soil type was silty loam, with a bulk density of 1.30 g cm$^{-3}$; a field capacity of 0.30 m$^3$ m$^{-3}$, and a wilting point of 0.12 m$^3$ m$^{-3}$. Over the entire growing season, maize was border-irrigated four times, with a total irrigation water amount of 420 mm for both years. The amount of each irrigation event was measured by a water meter. Each irrigation amount was 105 mm on June 15, July 6, July 29 and August 20, 2009, and 105, 120, 90, and 105 mm on June 22, July 27, August 5 and August 29, 2010, respectively.

2 Measurements of Evapotranspiration and Soil Evaporation

$\lambda ET$ was measured using an eddy covariance (EC) system installed in the center of the maize field. The EC consists of a fast response 3D sonic anemometer (CSAT3, Campbell Scientific Inc., UT, USA), a Krypton hygrometer (KH20, Campbell Scientific Inc.) and a temperature and humidity sensor (HMP45C, Vaisala Inc., Helsinki, Finland). All sensors were connected to a data logger (CR5000, Campbell Scientific, Inc.). The sonic anemometer and Krypton hygrometer were installed at a height of 1.0 m over the crop canopy. Net radiation ($R_n$) was measured by a net radiometer (NR-LITE, Kipp & Zonen, Delft, Netherlands), installed at a height of 3.5 m. Two soil heat fluxes (HF101, Hukseflux, Delft, Netherlands) were installed at a soil depth of 8.0 cm under the plastic film and bare soil. Soil temperature above each soil heat flux plate was measured using thermocouples at depths of 0.0 cm, 2.0 cm and 6.0 cm. Soil water content from 0–10.0 cm was measured using a soil moisture reflectometer (EnviroSMART, Sentek Sensor Technologies, SA, Australia). Ground heat flux ($G$) was estimated by correcting heat fluxes at 8.0 cm for heat storage above the transducers. The heat storage was determined from changes in soil temperature and moisture above the transducers. Based on the covariance of the 10 Hz air temperature and specific humidity with vertical wind velocity, the latent heat flux in 30 min durations was computed using the eddy covariance methodology with the CarboEurope recommendations [36]. Daytime $\lambda ET$ was adjusted by the Bowen-ratio forced closure method, and nighttime $\lambda ET$ was adjusted using the filtering interpolation method as proposed by Ding et al. [37].

Soil evaporation ($E_s$) was measured by the micro-lysimeter. Eight micro-lysimeter cylinders, made from PVC tubes with a diameter of 10 cm and height of 20 cm, were installed in bare soil between two plastic film rows. The cylinders were weighted at 20:00 every day by an electric scale with a precision of 0.1 g. The micro-lysimeters were reinstalled within one day after each irrigation and heavy rain. $E_s$ at the field scale can be calculated by weighting the fraction of ground-mulching ($f_m$) from the following equation.

$$E_s = (1 - f_m) \frac{\Delta M_t}{\rho_w A_c} \quad (46)$$

where $\Delta M_t$ is the mean weight change of micro-lysimeter every day, $A_c$ is the cross sectional area of the micro-lysimeters (78.3 cm$^2$ here), $\rho_w$ is water density (1.0 g cm$^{-3}$) and 10 is a conversion factor for changing units from cm to mm.

3 Other Measurements

Solar radiation, precipitation, air temperature, relative humidity and wind speed were measured with a standard automatic weather station (Hobo, Onset Computer Corp., USA) at a height of 2.0 m
above the ground. Volumetric soil water content in the root zone \( h_{rz} \) was measured with PVC access tubes using the portable device Diviner 2000 (Sentek Sensor Technologies). Measurements were made at intervals of 0.1 m with a maximal soil depth of 1.0 m at intervals of 3–5 days. Additional samplings were conducted before and after irrigation events, as well as after rainfall events. The measurements were calibrated by oven drying of soil samples. Interpolation was applied between consecutive irrigations to determine \( h_{rz} \) for each day. In addition, two sets of ECH2O probes (Decagon Devices Inc., Pullman, WA, USA) were added to monitor soil moisture at 30 min intervals in 2010.

Ten maize plants were randomly selected to measure leaf length and width, and height at intervals of \( \approx 10 \) days during the growing season. Leaf area was calculated by summing the rectangular area of each leaf (leaf length \( \times \) maximum width) multiplied by a factor of 0.74, a conversion factor obtained by analyzing the ratio of the rectangular area to the real area measured by an AM300 (ADC BioScientific Ltd., UK). LAI is defined as maize green leaf area per unit ground area. The daily LAI was obtained by linear interpolation.

Leaf-scale physiological measurements were performed to derive the stomatal conductance model parameters. A LI-6400 portable photosynthesis system (Li-Cor Inc., Lincoln, NE, USA) was used to measure leaf stomatal conductance on the first fully expanded leaf, which is the fourth leaf counted from the top of the shoot. The diurnal measurements of leaf gas exchange were performed once every 2 h from 8:00 to 18:00 on six sunny days in 10 randomly selected maize plants. Care was taken to keep leaves in their natural positions during measurement. The response of leaf stomatal conductance to varying PAR was measured at 30°C and at a CO₂ concentration of 400 mol mol⁻¹ on 29 August, 2009. Measurements were taken at PAR levels of 2000, 1600, 1300, 1000, 800, 600, 400, 200, 100, 50, 20, and 0 μmol m⁻² s⁻¹. The stomatal light-response curve was fit by a rectangular hyperbola to obtain the parameter values of \( k_{Q} \) using the Jarvis-Stewart model.

4 Model Performance

Half-hourly \( G_{s} \) and \( \lambda ET \) were calculated using the big-leaf and dual-leaf models Eqs. (39) and (40) with the dual-source equation based on the half-hourly measured meteorological data. The LAI and soil water were set as constants at the half-hourly time scale. Daily \( \lambda ET \) was calculated using Eqs. (39) and (40) with the dual-source equation based on the measured average daily meteorological data. We evaluated the two models by comparing with measurements taken over an irrigated maize field.

The parameters in the Jarvis-Stewart model were obtained using measurements of the stomatal light-response curve and the diurnal leaf gas exchange calculated by non-linear least-squares analysis (SPSS 13.0, SPSS Inc., Chicago, IL, USA). There were \( \approx 15 \) days with no crop cover before the emergence of maize, providing the opportunity to parameterize the empirical coefficients in the soil surface resistance model using the flux observations.

The coefficient of determination \( (R^2) \), root mean square error (RMSE) and the Willmott’s index of agreement \( (d) \) were used to evaluate model performance [38].

Results

1 Model Parameter Estimation and Sensitivity

From the stomatal light-response curve, we obtained best-fitting estimates of \( k_{Q} \) by non-linear least-squares analysis using the Jarvis-Stewart model (Table 1). The stress coefficients of \( VPD \) and \( \theta_{E} \), \( k_{D} \) and \( k_{w} \) were optimized using the diurnal measurements of leaf gas exchange (Table 1). Soil surface resistance \( (r_{s}) \) was calculated by inverting the flux-resistance equation for the case of no crops [12]. Based on the relationship between \( r_{s} \) and relative soil water
Table 2. Comparison of measured and estimated evapotranspiration (ET) and soil evaporation (Es) during the growth periods of maize in 2009 and 2010.

| Models          | Average values | Measurements (d) | Linear regression equation with zero intercept R² | RMSE (mm s⁻¹) | Bias (%) |
|-----------------|----------------|------------------|-----------------------------------------------|---------------|----------|
| Time-scales     |                |                  |                                               |               |          |
| 2009            |                |                  |                                               |               |          |
| Half-hourly ET  | Big-leaf       | 102.4            | 79.3                                          | 0.83          | 0.9321   |
|                 | Dual-leaf      | 102.4            | 87.6                                          | 0.9306        | 0.9356   |
| Daily ET        | Big-leaf       | 102.4            | 87.6                                          | 0.90          | 0.9356   |
|                 | Dual-leaf      | 102.4            | 87.6                                          | 0.90          | 0.9356   |
| Half-hourly ET  | Big-leaf       | 107.0            | 82.9                                          | 0.43          | 0.46     |
|                 | Dual-leaf      | 107.0            | 82.9                                          | 0.43          | 0.46     |
| Daily ET        | Big-leaf       | 107.0            | 82.9                                          | 0.44          | 0.46     |
|                 | Dual-leaf      | 107.0            | 82.9                                          | 0.44          | 0.46     |

Note: R² is the coefficient of determination, RMSE is the root mean square error, and d is the Willmott’s index of agreement. The units of half-hourly and daily values are W m⁻² and mm d⁻¹, respectively.
days in different growth stages of maize in 2009 (Fig. 6). The diurnal patterns of estimated $\lambda ET$ were similar to the measurements. $\lambda ET_1$ was overestimated at lower LAI, and underestimated at higher LAI. The linear regression presented that $\lambda ET_1$ was overestimated by 8.7% ($R^2 = 0.97$) and 19.7% ($R^2 = 0.96$) for LAI = 2.62 and 2.99, respectively (Fig. 6b and d). $\lambda ET_1$ was underestimated by 13.9% ($R^2 = 0.97$) for LAI = 5.38 (Fig. 6c). In contrast, $\lambda ET_2$ had a good agreement with measurements for differing LAI, with a linear slope of 1.01 and an $R^2$ of 0.97.

The irrigation scheduling and mulching fractions in 2009 and 2010 were different (See section 3.1), which yielded different LAI and soil water regimes for the two years (See Figure 1 and Table 1 in Ding et al.[39]). The maximum and averaged values of LAI respectively were 5.4 and 3.1 for 2009, and 4.7 and 2.7 for 2010.
The extractable soil water in the root zone \( \theta_e \) was significantly different between the two years. Before the first and second irrigation events in 2010, there were 9 and 12 days of \( \theta_e \) below 50% total available water in the root zone \( \text{TAW} \), which was regarded as a threshold of crop water stress [13]. Conversely, most \( \theta_e \) was higher than 50% of \( \text{TAW} \) in 2009. All of these differences led to differing \( \lambda ET \) and its components, which provided a good dataset to test the big-leaf and dual-leaf models over two different hydrometeorological and management strategies.

The scatterplots of half-hourly \( \lambda ET \) exhibited that \( \lambda ET_1 \) was overestimated for lower values and underestimated for higher values, respectively (Fig. 7a and 7c). Total \( \lambda ET_1 \) was underestimated, with a slope of linear regression of 0.94 (\( R^2 = 0.83 \)) and 0.93 (\( R^2 = 0.82 \)), respectively, for 2009 and 2010. RMSE was 72.22 and 70.97 W m\(^{-2} \), and \( d \) was 0.9521 and 0.9472 for 2009 and 2010, respectively (Table 2). In contrast, there was good data-model agreement between measurements and estimated half-hourly \( \lambda ET_2 \) in 2009 and 2010 (Fig. 7b and 7d). The slopes of linear regressions between the estimates and measurements were 1.02 and 1.03, with \( R^2 \) of 0.90 and 0.88, RMSE of 38.06 and 62.31 W m\(^{-2} \), and \( d \) of 0.9706 and 0.9626 for 2009 and 2010, respectively (Table 2). Daily values of \( \lambda ET_1 \) were underestimated at the early and late stages and overestimated at the middle stage (Fig. 8a and b). In general, total \( \lambda ET_1 \) was underestimated by 5% and 7% for 2009 and 2010, respectively (Fig. 8c and d). In contrast, there was satisfactory data-model agreement between predicted and measured \( \lambda ET_1 \) using the DSDL model for the two years. The slopes of linear regressions between estimates and measurements were 1.02 (\( R^2 = 0.68 \)) and 1.01 (\( R^2 = 0.73 \)), with RMSE of 0.1220 and 0.1565 mm d\(^{-1} \) and \( d \) of 0.9129 and 0.9218 for 2009 and 2010, respectively (Table 2).

**Discussion**

In this paper, we have extended the big-leaf model by developing a dual-leaf model. The dual-leaf model presented here is an improvement over the previous big-leaf model, as more realistic non-uniform vertical profiles of radiation and stomatal conductance are now incorporated into the model. The penetration of beam radiation, its variation and the dynamics of sunlit and shaded \( \text{LAI} \) throughout the day affect the ability of the big-leaf model to simulate diurnal changes in \( G_m \) [18,29]. In the dual-leaf model, these canopy features can be explicitly incorporated by dividing the canopy into sunlit and shaded fractions and modeling seasonal variations of daily estimated and measured \( E_t \) using Eq. (15) combined with Eqs. (39) and (40) are presented in Fig. 8 for 2009 and 2010. Both the dual-source big-leaf and dual-leaf models could capture the variability of \( E_t \) even when irrigation or precipitation occurred and when the canopy partially covered the ground during the initial growth stages. However, daily values of \( E_t \) were underestimated at the early and late stages and overestimated at the middle stage (Fig. 8a and b). In general, total \( E_t \) was underestimated by 5% and 7% for 2009 and 2010, respectively (Fig. 8c and d). In contrast, there was satisfactory data-model agreement between predicted and measured \( E_t \) using the DSDL model for the two years. The slopes of linear regressions between estimates and measurements were 1.02 (\( R^2 = 0.68 \)) and 1.01 (\( R^2 = 0.73 \)), with RMSE of 0.1220 and 0.1565 mm d\(^{-1} \) and \( d \) of 0.9129 and 0.9218 for 2009 and 2010, respectively (Table 2).
each fraction of \( G_{sc} \) by scaling up the respective stomatal conductance separately. It is more complex than the big-leaf model, but the dynamic partitioning of \( LAI \) and irradiance between sunlit and shaded leaves has further reduced the errors associated with simplifying the leaves to only a big-leaf using either the total or empirically effective \( LAI \).

The ability of the dual-leaf model was examined by comparing the estimated values and actual measurements. In contrast to significant errors by the big-leaf model, the dual-leaf model accurately reproduced the variation of \( G_{sc} \) (Fig. 4 and 5). One reason the dual-leaf model works so well is that it accommodates the nonlinear response of stomata to light [25,40]. Stomata-light responses of leaves can vary with depth in the canopy and this variation can be incorporated by partitioning the canopy into several layers and estimating the sunlit and shaded leaf fractions in each layer [20,34]. However, usually this is not necessary and a single, representative light response curve can be used for the entire canopy [17,40]. In the dual-leaf model, the entire \( G_{sc} \) may be calculated by summing contributions of sunlit and shaded leaves. These two contributions are added separately because sunlit leaves will be light-saturated while shaded leaves will be in the linear portion of the light-stomata relationship [18,33]; thus \( G_{sc} \) is not proportional to average light levels [18]. Because of the nonlinear relationship between stomatal conductance and PAR, the predicted \( G_{sc} \) will be overestimated when the average absorbed PAR is used to scale up the leaf stomatal conductance for the entire canopy as in the big-leaf model [17,40]. On the other hand, the \( G_{sc} \) is underestimated when the effective LAI is used to scale up the leaf stomatal conductance at higher LAI (Fig. 4c).

The DSDL model is physically process-based, yet sufficiently simple to be effectively parameterized. The dual-leaf model requires only four additional equations, Eqs (32), (33), (43) and (44), beyond those required in the model of leaf stomatal conductance, to calculate the \( LAI \) and absorbed irradiance of the sunlit and shaded leaves. This simplicity makes it attractive for incorporation into in crop models, land surface schemes, and regional or global water cycle studies [29,40]. This model can also be used to assess effects of climate change on crop ecophysiology.

**Conclusions**

In this paper, a dual-leaf model for scaling-up stomatal conductance from the leaf to the canopy level was developed through the dynamic partitioning of the leaf area index and irradiance between sunlit and shaded leaves. In the model, canopy stomatal conductance was calculated by dividing the canopy into
sunlit and shaded fractions and each fraction was modeled separately based on the absorbed irradiances. The dual-leaf model provided estimates of $G_a$ which were nearly the same as measurements, and were significantly more accurate than those of the big-leaf model. Our results showed excellent agreements between $\lambda ET$ measurements gathered by the eddy covariance technique over an irrigated maize field during 2009 and 2010 under two different hydrometeorological and management conditions, and estimates of $\lambda ET$ using the DSDL. The framework of the model can also satisfactorily estimate soil evaporation. Our proposed model provides an alternative approach to calculate $\lambda ET$, which is simple and attractive for incorporation into other comprehensive crop models.

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