Radiation Model for Row Crops: II. Model Evaluation

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ABSTRACT

Relatively few radiation transfer studies have considered the impact of varying vegetation cover that typifies row crops, and methods to account for partial row crop cover have not been well investigated. Our objective was to evaluate a widely used radiation model that was modified for row crops having sparse to full vegetation cover. The radiation model was combined with geometric view factors based on elliptical hedgerows that account for the spatial distribution of row crop vegetation, and this approach was compared with the more commonly used clumping index approach. Irradiance measurements included transmitted and reflected visible and shortwave, outgoing longwave, and total net radiation. The model used optimized parameters for corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.). The elliptical hedgerow and clumping index approaches resulted in similar model agreement; however, the former resulted in up to 7.3 W m^{-2} smaller RMSE and up to 7.5 W m^{-2} smaller mean bias error compared with the latter. Both approaches resulted in similar model sensitivities to inputs, which varied ±25%. Calculated shortwave irradiance fluxes were most sensitive to leaf area index (LAI; −3.25), canopy width (−1.94), ellipsoid leaf angle parameter (−0.77), and visible leaf absorption (−5.54) when LAI = 2.95 m^2 m^{-2}, and visible soil reflectance (0.89) when LAI = 0.21 m^2 m^{-2}. Calculated outgoing longwave irradiance and net radiation were most sensitive to the soil directional brightness temperature (0.55 and −0.61, respectively) when LAI = 0.21 m^2 m^{-2}.

Radiative transfer in the soil–plant–atmosphere continuum is affected by several interrelated factors, including wavelength and beam angle, leaf angle distribution, and the spatial distribution of vegetation. These factors have been accounted for using various approaches in radiative transfer models, where the approach used generally depended on the level of detail required in the model application. Campbell and Norman (1998) described a procedure to estimate the shortwave transmittance and reflectance of vegetated surfaces that accounts for these factors in sufficient but operationally practical detail to be useful for a wide number of applications, such as surface energy balance models used to estimate evapotranspiration (Kustas and Norman, 1999; Anderson et al., 2005; Li et al., 2005; French et al., 2007). Shortwave transmittance and reflectance were calculated in terms of their separate components of photosynthetically active radiation (PAR, 400–700-nm wavelengths), near-infrared radiation (NIR, 700–3000-nm wavelengths), and direct-beam and diffuse components. This accounted for the dependency of extinction and scattering on wavelength and beam angle, where vegetation absorbs much greater PAR than NIR incident on leaves, and diffuse radiation is calculated by integrating the direct-beam components over a half-sphere. Extinction is calculated in terms of the ellipsoid leaf angle distribution function (LADF), where the mean leaf angle is specified in terms of a single, species-specific parameter. Row crops are a common example of vegetation with a nonrandom spatial distribution, which results in different amounts of interception, transmittance, and reflectance compared with uniform or randomly distributed vegetation. The nonrandom spatial distribution of row crop vegetation has been commonly accounted for using either a semiempirical clumping index approach (e.g., Kustas and Norman, 1999; Anderson et al., 2005) or by modeling the canopy using simple geometric shapes such as hedgerows (e.g., Annandale et al., 2004; Pieri, 2010a,b).

Although the Campbell and Norman (1998) procedure has been widely used in studies where the phenomena of interest depended on the radiation balance, relatively few studies have evaluated this procedure to calculate the radiation components themselves. Furthermore, most studies of radiation in vegetated surfaces were limited to a single crop, growth stage, or vegetation type, with little, if any, variation in vegetation cover, and usually only one type of flux was considered, such as transmitted, reflected, or net radiation (Charles-Edwards and Thorpe, 1976; Arkin et al., 1978; Mann et al., 1980; Norman and Wells, 1983; Pieri, 2010a,b). Therefore, the impact on radiation balances of changing vegetation cover, which is important in applications of annual crops, is not well established. Furthermore, few studies have compared alternative approaches to account for partial vegetation cover (i.e., it appears that only the clumping index approach has been used with the Campbell and Norman [1998] procedure), and few

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Abbreviations: DOY, day of the year; LADF, leaf angle distribution function; LAI, leaf area index; MAE, mean absolute error; MBE, mean bias error; NIR, near-infrared radiation; PAR, photosynthetically active radiation; RMSE, root mean square error; RPAR, reflected photosynthetically active radiation; TPAR, transmitted photosynthetically active radiation.

studies have evaluated models for calculating more than one type of irradiance flux for more than one crop species.

A radiation model for row crops, where the Campbell and Norman (1998) procedure was combined with a geometric view factor approach to describe the nonrandom spatial distribution of row crop vegetation, was given by Colaizzi et al. (2012); the view factors were developed by modeling the crop rows as elliptical hedgerows. Using the elliptical hedgerow and clumping index approaches, three model input parameters were optimized for corn, grain sorghum, and cotton by maximizing an objective function based on the model efficiency of the calculated and measured transmitted and reflected global shortwave and PAR. The optimized input parameters were the ellipsoid LADF mean leaf angle parameter (X_E), PAR leaf absorption (ζ_{PAR}), and NIR leaf absorption (ζ_{NIR}).

The objectives of this study were to evaluate the model using the optimized parameters described by Colaizzi et al. (2012). Model evaluation included assessing agreement, using standard statistical parameters, between calculated and measured irradiance fluxes of three row crops (corn, grain sorghum, and cotton) having a wide range of vegetation cover. Measured and calculated irradiance fluxes included transmitted shortwave irradiance, transmitted PAR, reflected shortwave irradiance, reflected PAR, outgoing longwave irradiance, and total net radiation. The measurements used in the model evaluation were from different data and not those used in the parameter optimization. The model evaluation also included calculation of the sensitivity of each irradiance flux to input parameters that were varied ±25%.

MATERIALS AND METHODS

Model Overview

Transmitted and reflected irradiance and total net radiation were calculated for row crops with partial cover by combining the Campbell and Norman (1998) procedure with a geometric view factor approach, where view factors were based on modeling crop rows and elliptical hedgerows. The view factors were developed in terms of radiometer view geometry, where transmitted and reflected irradiance were measured by radiometers having line and inverted hemispherical views, respectively, and net radiation was measured with a bi-hemispherical view. Equations of transmitted and reflected shortwave radiation and the development of view factors were described in Colaizzi et al. (2012); shortwave irradiance flux equations used in the model evaluation are briefly reviewed here. Transmitted shortwave irradiance (TR_S, W m^{-2}) measured beneath a row crop canopy was calculated as

$$TR_S = R_S \tau_C \qquad [1]$$

where R_S is global incoming shortwave irradiance (W m^{-2}) and τ_C is transmittance of shortwave radiation through the canopy (dimensionless). The τ_C contains two view factor terms that were developed in Colaizzi et al. (2012) for the elliptical hedgerow approach, one for direct beam and one for diffuse irradiance that is measured by a line radiometer. The view factor for direct-beam irradiance is the solar canopy view factor (f_{SC}), which is defined as the fraction of canopy visible from the solar beam view angle. The view factor for diffuse irradiance is the upward line-integrated hemispherical canopy view factor (f_{UIC}), which is defined as the fraction of canopy visible when an upward-looking hemispherical view is integrated from the crop row center to the interrow center. Both terms are dimensionless. Considering only the PAR spectra, Eq. [1] becomes

$$TPAR = R_S\left(4.602 F_{PAR}\right)\tau_{C,PAR} \qquad [2]$$

where TPAR is transmitted PAR beneath a row crop canopy (μmol m^{-2} s^{-1}), 4.602 converts radiation flux (W m^{-2}) to quantum flux (μmol m^{-2} s^{-1}) (McCree, 1972), F_{PAR} is the fraction of PAR in R_S (F_{PAR} = 0.457 throughout the year at the study location, which was similar to other locations in the western United States [Meek et al., 1984]), and $\tau_{C,PAR}$ is transmittance of PAR through the canopy (dimensionless). Similar to τ_C, the $\tau_{C,PAR}$ term also contains f_{SC} and f_{UIC}.

Reflected shortwave irradiance (RR_S, W m^{-2}) measured over a row crop canopy was derived in a similar manner, except a hemispherical view factor was used:

$$RR_S = R_S\left[\alpha_C f_{DHC} + \alpha_S \tau_C\left(1 - f_{DHC}\right)\right] \qquad [3]$$

where α_C and α_S are the canopy and soil (or substrate) albedo (dimensionless), respectively, and f_{DHC} is the downward hemispherical canopy view factor (i.e., the fraction of canopy appearing to a radiometer with a downward hemispherical view; dimensionless). Considering only PAR, then

$$RPAR = R_S\left(4.602 F_{PAR}\right) \times\left[\rho_{C,PAR} f_{DHC} + \rho_{S,PAR}\tau_{C,PAR}\left(1 - f_{DHC}\right)\right] \qquad [4]$$

where RPAR is reflected PAR (μmol m^{-2} s^{-1}), $\rho_{C,PAR}$ is the reflectance of PAR from a canopy (dimensionless), and $\rho_{S,PAR}$ is the reflectance of PAR from the soil or substrate (dimensionless). The transmittance and reflectance terms in Eq. [1–4] were calculated by the Campbell and Norman (1998) procedure, where LAI (m^2 m^{-2}) in each term was multiplied by a factor η. For the elliptical hedgerow approach, η is defined as

$$\eta = \frac{r_V}{w_C} P_L M_R \qquad [5]$$

where r_V is the crop row spacing (m), w_C is canopy width (m), P_L is the path length fraction (i.e., the path length of a solar beam through a canopy relative to nadir; dimensionless), and M_R is the multiple row factor that accounts for a solar beam traversing more than one row (dimensionless). The r_V/w_C term converts the field LAI (which accounts for plant and row spacing) to a local LAI (i.e., the LAI within the canopy row), and calculation procedures for P_L and M_R are given in Colaizzi et al. (2012). When TR_S, TPAR, RR_S, and RPAR were calculated using the clumping index instead of the elliptical hedgerow approach, then $f_{SC} = f_{DHC} = f_{UIC}$ = 1.0 in Eq. [1–4] and $\eta = \Omega_{SW}/\cos(\theta_S)$, where Ω_{SW} is the clumping index calculated for shortwave extinction at the solar view angle (Anderson et al., 2005) and θ_S is the solar zenith angle. Therefore, the clumping index approach implicitly accounts for view factors through the Ω_{SW} term. The $\rho_{S,PAR}$ and α_S terms for dry soil were taken as 0.15 and 0.20, respectively, based on reflectance measurements over bare soil at the study location (Howell et al., 1993; Tunick et al., 1994) and are consistent with values suggested by Campbell and Norman (1998). For wet soil, $\rho_{S,PAR}$ and α_S were reduced to 0.09 and 0.12, respectively, which were also based on reflectance measurements at the study location, and are similar to the results of Graser and van Bavel (1982). Following a wetting event, $\rho_{S,PAR}$ and α_S were increased as a linear function of cumulative evaporation using the Penman–Monteith equation-based procedure of Allen et al. (1998). Briefly, this procedure increased $\rho_{S,PAR}$ and α_S until Stage 1 drying was complete and the soil surface was assumed dry (Idso et al., 1974), when $\rho_{S,PAR}$ and α_S returned to 0.15 and 0.20, respectively.

Net radiation (R_N) is the sum of the incoming and outgoing shortwave and longwave components:

$$R_N = R_S - RR_S + LW_{IN} - LW_{OUT} \quad [6]$$

where LW_{IN} is incoming longwave irradiance, and LW_{OUT} is outgoing longwave irradiance (W m^{-2}). The LW terms were calculated from the Stephan–Boltzmann relation (i.e., LW = $\varepsilon\sigma_{SB}T^4$, where ε is emittance, σ_{SB} is the Stephan–Boltzmann constant, equal to 5.67×10^{-8} W m^{-2} K^{-4}, and T is the directional brightness temperature [K] of either the canopy or the soil surface [Norman and Becker, 1995]). For LW_{IN}, the ε of the atmosphere was calculated using the Brutsaert (1982) equation, which is a function of air temperature and vapor pressure, and T was assumed equal to the air temperature. The LW_{OUT} was calculated as

$$\begin{aligned} LW_{OUT} &= \\ &LW_{IN}\left[f_{DHC}(1-\varepsilon_C)+(1-f_{DHC})(1-\varepsilon_S)\right] \\ &+ f_{DHC}\varepsilon_C\sigma_{SB}T_C^4 + (1-f_{DHC})\varepsilon_S\sigma_{SB}T_S^4 \end{aligned} \quad [7]$$

where ε_C and ε_S are emittances of the canopy and soil, respectively, and T_C and T_S are the directional brightness temperatures (K) of the canopy and soil, respectively. The term containing LW_{IN} accounts for the small amount of longwave radiation reflected from the surface. Measurements of bare soil at the study location, made with a Cimel CE 312 multiband thermal radiometer (Cimel Electronique, Paris), indicated that $\varepsilon_S = 0.98$, and it was assumed that $\varepsilon_C = 0.98$ (Idso et al., 1969; Campbell and Norman, 1998). For the clumping index approach, f_{DHC} in Eq. [7] was replaced with w_C/r_V.

Field Measurements

Measurements used to evaluate the model were obtained at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (35°11′ N, 102°6′ W, 1170-m elevation above mean sea level). The climate is semiarid, with high incoming solar irradiance, generally low humidity, low precipitation averaging 470 mm yr^{-1}, strong regional advection of heat energy mainly from the south and southwest, and a high evaporative demand of ~2600 mm yr^{-1} (Class A evaporation). The soil is a Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with slow permeability, having a dense Bt1 layer from about the 0.15- to 0.40-m depth and a calcic horizon that begins at the 1.1-m depth (NRCS, 2011).

Irradiance flux measurements were obtained for irrigated corn (1989 season), grain sorghum (irrigated in 1988 and dryland in the 2007 season), and irrigated upland cotton (2008 season); these measurements were similar to those described in Colaizzi et al. (2012) to derive the X_E, ζ_{PAR}, and ζ_{NIR} parameters for these crops but obtained at different field locations or crop seasons. Cultural practices were similar to those used for high-yield production in the southern High Plains. All crops were planted in rows spaced 0.8 m apart. Corn was planted in east–west oriented raised beds with a planting density of 5.9 seeds m^{-2} and was irrigated with a lateral-move sprinkler system to fully meet the crop water demand (Tolk et al., 1995; Howell et al., 1997). Irrigated grain sorghum (1988 season) was planted in east–west oriented raised beds with a planting density of 16.0 seeds m^{-2} and was irrigated with a lateral-move sprinkler system to fully meet the crop water demand (Steiner et al., 1991; Howell et al., 1997). Dryland grain sorghum (2007 season) was planted on a contoured terrace to the north of a playa lake, with rows oriented in a southwest–northeast direction 10° from east–west with a planting density of 14.0 seeds m^{-2}. The 2008 cotton crop was planted in north–south oriented raised beds at a planting density of 15.8 seeds m^{-2} and irrigated with lateral-move sprinklers to fully meet the crop water demand. Experimental procedures, agronomy, and other details of the 2008 cotton season were similar to previous cotton experiments conducted at this location as described in Howell et al. (2004).

Irradiance flux measurements used for model evaluation included TR_S, TPAR, RR_S, RPAR, LW_{OUT}, and R_N (Table 1). All measurements were sampled every 6 s and averaged to 0.5 h for the 1989 corn and 1988 grain sorghum seasons and 0.25 h for the 2007 grain sorghum and 2008 cotton seasons. Measurements were excluded when θ_S was >80°, which is outside the valid range for calculating the transmittance and reflectance terms contained in Eq. [1–4] (Campbell and Norman, 1998). Measurements were also excluded when instruments were cleaned and checked for levelness or when other equipment maintenance or activity occurred in the vicinity of the instruments, all of which were located at large weighing lysimeters except for the 2007 dryland grain sorghum. Additional measurements of TR_S, TPAR, T_C, and T_S were obtained ~20 m northeast of the lysimeter during the 2008 cotton season.

Measurements of TR_S were made with tube solarimeters (Model TSL, Delta-T Devices, Cambridge, UK). The tube solarimeter glass envelope was 0.88 m along the axis, and the ends of the glass envelope were placed in the centers of adjacent crop rows according to the manufacturer's recommendations. For 0.76-m row spacing, this required the tubes to be deployed at 60° from the row orientation. Instrument sensitivity is known to vary with the solar azimuth angle relative to the tube axis because of the asymmetric geometry of the glass envelope (Mungai et al., 1997). Therefore, instrument calibration was determined by placing the instruments on bare soil with the same orientation that was used for measurements beneath row crops. The instruments were compared with the incident solar irradiance measured with a pyranometer (Model PSP, Eppley Laboratory, Newport, RI). Calibrated tube solarimeter measurements were within 3.6% of the pyranometer measurements using a geometric calibration (i.e., considering only the tube geometry relative to the solar zenith and azimuth) and within 2.3% for instrument-specific calibrations (which also account for individual instrument response).

Measurements of TPAR were made with line quantum sensors (Models LQ and LI-191, LI-COR Biosciences, Lincoln, NE). The sensor surface is a flat acrylic diffuser (1.0 m by 12.7 mm), and the instrument is relatively insensitive to the solar azimuth angle (Φ_S) (Mungai et al., 1997) but is sensitive to θ_S according to the manufacturer. Therefore, calibration of the line quantum sensors were determined in the same manner as the tube solarimeters, except that the line quantum sensors were oriented 50°

Table 1. Instruments used in measurements of irradiance and photosynthetically active radiation (PAR) to test the model.

Variable	Instrument	Crops (no. of instruments)
Incident solar irradiance (RS)†	Eppley PSP‡	corn (2), sorghum (2), cotton (2)
Incident PAR (IPAR)†	LI-COR LI-190 SA§	corn (1), sorghum (1), cotton (1)
Transmitted solar irradiance (TR_S)	Decagon tube solarimeter¶	corn (4), sorghum (2)
	Delta-T TSL#	cotton (3)
Transmitted PAR (TPAR)	LI-COR LQ§	corn (4), sorghum (2)
	LI-COR LI-191§	cotton (3)
Reflected solar irradiance (RR_S)	Eppley B&W 8–4‡	corn (2)
	Kipp & Zonen CM14††	sorghum (1), cotton (2)
Reflected PAR (RPAR)	LI-COR LI-190 SA§	corn (2)
	LI-COR LI-190 SB§	cotton (2)
Outgoing longwave irradiance (LW_{OUT})	Kipp & Zonen CGR3††	cotton (1)
Total net radiation (R_N)	REBS Q*5.5‡‡	corn (1)
	REBS Q*7.1‡‡	sorghum (1), cotton (1)
Directional brightness temperature, soil (T_S) and canopy (T_C)	Everest IRT§§	corn (2)
	Exergen IRT/c¶¶	sorghum (12), cotton (12)

† Incident measurements were taken at a nearby grass reference site.
‡ Eppley Laboratory, Newport, RI.
§ LI-COR Biosciences, Lincoln, NE.
¶ Decagon Devices, Pullman, WA.
# Delta-T Devices, Cambridge, UK.
†† Kipp & Zonen USA, Bohemia, NY.
‡‡ Radiation and Energy Balance Systems, Seattle, WA.
§§ Everest Interscience, Tucson, AZ.
¶¶ Exergen Corp., Watertown, MA.

from east–west, and incident PAR was measured with a quantum sensor (Model LI-190 SA, LI-COR Biosciences). Calibrated line quantum sensors agreed to within 3.5% of the quantum sensor using a calibration equation that accounted for θ_S. Measurements of RR_S, RPAR, and R_N were made with radiometers deployed at 1.2 m above the soil surface for grain sorghum and cotton and 0.5 m over the corn canopy, and all radiometers were deployed directly above the center of the crop row. All instruments were inspected frequently for cleanliness and levelness.

Canopy height (h_C) and width (w_C) were measured at the instrumented sites, and h_C, w_C, and destructive LAI measurements were obtained periodically at key growth stages at three locations in the field away from the instrumented sites. The destructive sample areas were 1.0 to 1.5 m^2. The leaf area of plant samples was measured with a leaf area meter (Model LI-3100, LI-COR Biosciences), and the meter accuracy was verified periodically with a 0.005-m^2 standard disk. The h_C and LAI were related to growing degree days by linear interpolation so that these parameters could be estimated between plant measurement dates (Fig. 1).

Model Evaluation

Agreement between measured and calculated irradiance flux (TR_S, TPAR, RR_S, RPAR, LW_{OUT}, and R_N) was assessed using standard statistical parameters and those recommended by Legates and McCabe (1999). These included measured and calculated sample mean, measured and calculated sample standard deviation, root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE). The extent to which RMSE exceeds MAE indicates the extent of outliers in the data. Model performance was also assessed using the modified coefficient of model efficiency (E_C) described by Legates and McCabe (1999), which is essentially a nonsquared version of the Nash and Sutcliffe (1970) coefficient of model efficiency that is less sensitive to outliers. The E_C parameter ranges from $-\infty$ to 1; $E_C = 0$ indicates that the model does not give a better calculated value than the mean of all measured values and $E_C < 0$ indicates that the model actually gives a worse calculated value than the mean of all measured values. Also, $(1 - E_C)$ indicates the absolute error between measured and calculated values as a percentage of the measured variance (Legates and McCabe, 1999).

The sensitivities of each calculated irradiance flux using both the clumping index and elliptical hedgerow submodels were evaluated with respect to input variables deemed to have the most uncertainty. These included LAI, h_C, w_C, the ellipsoid LADF parameter (X_E), leaf absorption of PAR and NIR (ζ_{PAR} and ζ_{NIR}, respectively; these are required to calculate τ_C and ρ_C), soil reflectance for PAR and NIR, and the directional canopy and soil brightness temperatures (required only for LW_{OUT} and R_N). The canopy size variables (h_C, w_C, and LAI) probably had the largest uncertainties, which were probably up to 20% based on measurements in this and previous studies. For example, Anderson et al. (2004) reported that the uncertainty of LAI estimated from satellite imagery was within 18%. Therefore, all input variables were varied ±25% of their base values. Model sensitivity (S_M) was calculated in a manner similar to Oyarzun et al. (2007) as

$$S_M = \frac{\Delta O}{\Delta I} = \frac{(O_+ - O_-)/O_B}{(I_+ - I_-)/I_B} \qquad [8]$$

where ΔO and ΔI are the relative change in model output and input variables, respectively, the subscripts + and – are the resulting values when the input value is increased or decreased, respectively, from its base value (I_B), and O_B is the resulting output value for I_B. All S_M were calculated for east–west row orientation near solar noon (1245 h); north–south row orientation resulted in very similar but slightly lower S_M values for all fluxes (data not shown). The sensitivity analysis was conducted for three cases of canopy cover, referred to here as

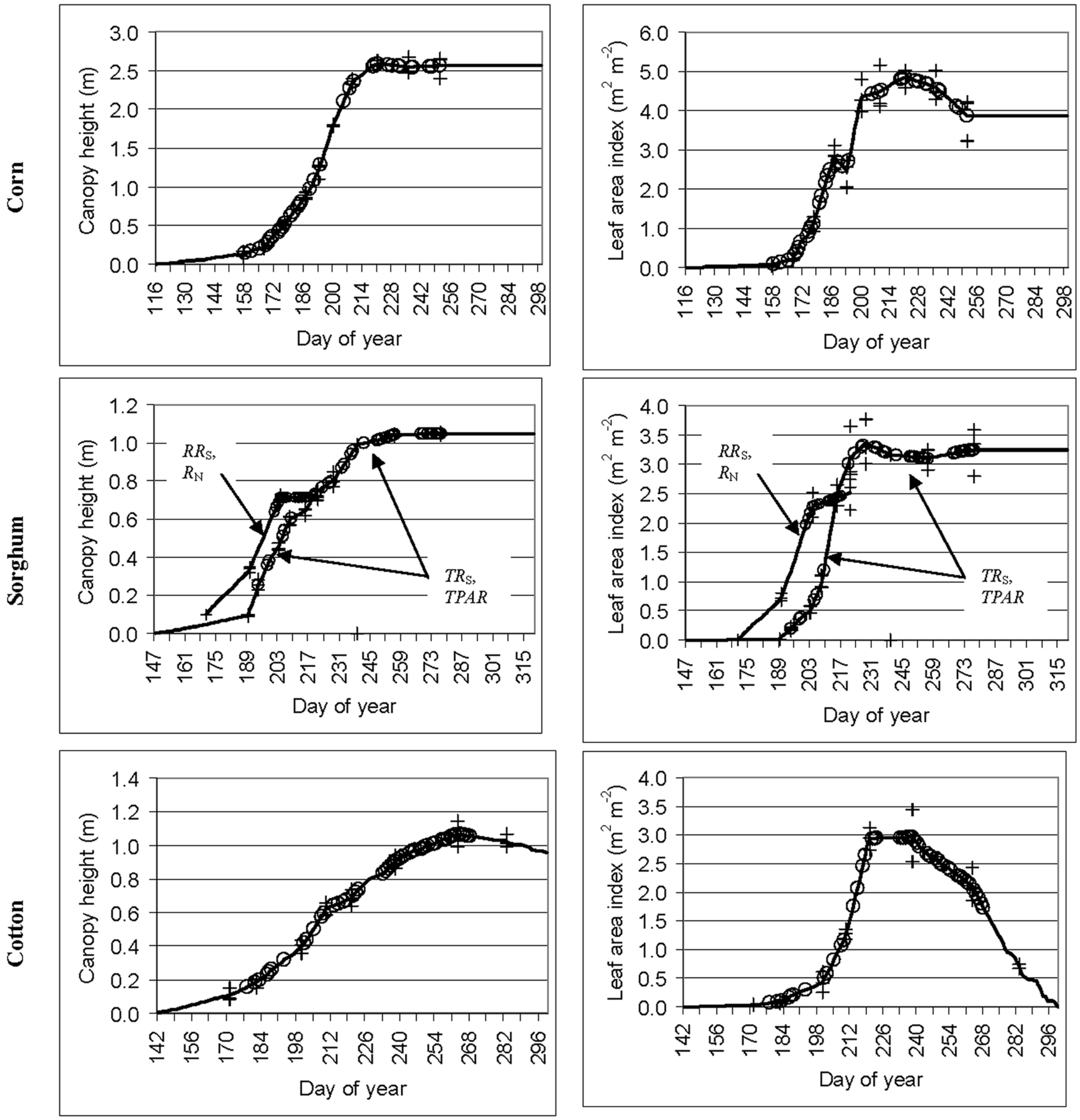

Fig. 1. Canopy height and leaf area index of corn, sorghum, and cotton: field measurements (+), linear interpolation between field measurements as a function of growing degree days (solid line), and days used for model evaluation (O).

small, medium, and large (LAI = 0.21, 1.75, and 2.95 $m^2\ m^{-2}$, respectively; Table 4), which were taken from the cotton season on Day of the Year (DOY) 188, 213, and 235, respectively (Fig. 1). Measurements of incoming solar irradiance (R_S) and calculated θ_S and Φ_S at 1245 h were used for these days to drive the models, and these inputs were not varied.

RESULTS AND DISCUSSION

Canopy height (h_C) was mostly uniform (approximately ±5% of the mean) at different field measurement locations throughout the growing season, but LAI exhibited greater spatial variability, especially around the middle of the season (up to ±18% of the mean; $n = 3$) (Fig. 1). This was in agreement with the uncertainty of LAI retrieval reported in other studies (e.g., Anderson et al., 2004) and supported the choice of varying inputs ±25% of their base values in the sensitivity analysis. Irradiance flux measurements used in evaluating the models (measurement days shown as large circles in Fig. 1) were obtained during most of the season for each crop, which included a wide range of canopy cover; however, RR_S, and R_N measurements for grain sorghum were only available just before peak LAI. Nonetheless, the irradiance flux measurements used in model evaluation represented a much wider range of canopy cover than previous studies, especially for cotton. Canopy width measurements (w_C) were approximately equal to h_C for corn and grain sorghum and $0.75h_C$ for cotton (data not shown). Canopy cover was considered to be less than full when w_C was less than the crop row spacing (0.76 m); therefore, partial canopy cover was inferred when h_C was <0.76 m for corn and grain sorghum and <1.0 m for cotton. From Fig. 1, this included 14 out of 34 d for corn, 21 out of 44 d for grain sorghum, and 35 out of 48 d for cotton.

Table 2. Statistical parameters of agreement between measured and calculated radiation flux components (transmitted solar irradiance [TR_S], transmitted photosynthetically active radiation [TPAR], reflected solar irradiance [RR_S], reflected photosynthetically active radiation [RPAR], outgoing longwave radiation [LW_{OUT}], and total net radiation [R_N]) using the clumping index approach pooled for corn, grain sorghum, and cotton.

Parameter†	TR_S	TPAR	RR_S	RPAR	LW_{OUT}	R_N
	W m^{-2}	μmol m^{-2} s^{-1}	W m^{-2}	μmol m^{-2} s^{-1}	W m^{-2}	W m^{-2}
n	2735	2735	3272	2708	2604	3365
Measured mean	223.2	357.0	116.3	63.7	458.5	389.9
Measured SD	227.4	445.2	47.4	41.5	30.1	184.9
Calculated mean	234.4	377.4	123.2	68.9	452.4	396.8
Calculated SD	234.9	479.5	49.6	49.0	37.4	200.7
E_C	0.82	0.82	0.74	0.79	0.74	0.80
RMSE	57.7	120.3	13.6	13.8	17.6	31.4
MAE	42.3	80.5	10.4	8.87	12.8	25.5
MBE	11.3	20.4	6.94	5.27	–6.10	6.98

† E_C, coefficient of model efficiency; MAE, mean absolute error; MBE, mean bias error.

The distribution of sky conditions was similar to those used in the parameter optimization, where ~80% of irradiance measurements used in this study were obtained under clear skies (data not shown; see Colaizzi et al. [2012] for histograms of a similar data set). Clear skies were inferred when $0.7 < R_S/R_{TOA} < 0.8$, where R_{TOA} is the top-of-atmosphere global irradiance (calculated following Task Committee on Standardization of Reference Evapotranspiration, 2005). The dominance of clear skies was expected due to the semiarid climate of the study location and resulted in direct-beam radiation contributing more than ~70% of the incoming irradiance and the direct-beam portions of the Campbell and Norman (1998) model dominating over the respective diffuse components. Therefore, additional studies of varying canopy cover at cloudy locations would also be appropriate.

Statistical parameters of agreement were calculated for each irradiance flux using the clumping index (Table 2) and elliptical hedgerow (Table 3) approaches. Each irradiance flux was pooled for corn, cotton, and grain sorghum. All E_C were at least 0.74, which indicated that each model provided a better estimate of the irradiance flux than the means of all measurements. The RMSE did not exceed 34% of the measured means, and in most cases the MAE was at least 70% of the RMSE, indicating that the data were relatively free of outliers. Both approaches resulted in similar agreement between calculated and measured irradiance fluxes and overall model error was within the uncertainty of model input parameters and variables, but the elliptical hedgerow approach resulted in slightly but consistently smaller RMSE (up to 7.3 W m^{-2} less for TR_S or 4.9 μmol m^{-2} s^{-1} less for RPAR) and MAE (up to 6.0 W m^{-2} less for TR_S or 3.6 μmol m^{-2} s^{-1} less for RPAR) compared with the clumping index approach. The elliptical hedgerow MBE was also less than that of the clumping index for all shortwave irradiances (up to 7.5 W m^{-2} less for TR_S or 4.8 μmol m^{-2} s^{-1} less for RPAR), but the elliptical hedgerow MBE was greater than that of the clumping index for LW_{OUT} (0.03 W m^{-2} greater) and R_N (3.0 W m^{-2} greater). Although the clumping index approach is simpler, geometric view factor based approaches such as the elliptical hedgerow are more amenable to resolving the light environment of the soil and canopy into their sunlit and shaded components, which is useful for retrieving biophysical information (e.g., Fitzgerald et al., 2005; Williams and Ayars, 2005) or estimating the spatial distribution of the available energy beneath a crop row (e.g., Ham and Kluitenberg, 1993; Sauer et al., 2007).

The range of measured and calculated TR_S and TPAR corresponded to the range of canopy cover under which measurements were obtained for each crop (Fig. 1), where TR_S and TPAR were inversely proportional to canopy cover, as expected (Fig. 2). The variation in transmitted fluxes was also related to the variation in incoming solar irradiance and PAR. Because measurements were obtained on mostly clear days, this was mainly a function of θ_S and Φ_S, but solar angle also determined the shortwave path length through the canopy. The θ_S and Φ_S varied by 12 to 80° from nadir and by 0 to 90° from the crop row, respectively. The maximum measured and calculated TR_S and TPAR approached

Table 3. Statistical parameters of agreement between measured and calculated radiation flux components (transmitted solar irradiance [TR_S], transmitted photosynthetically active radiation [TPAR], reflected solar irradiance [RR_S], reflected photosynthetically active radiation [RPAR], outgoing longwave radiation [LW_{OUT}], and total net radiation [R_N]) using the elliptical hedgerow approach pooled for corn, grain sorghum, and cotton.

Parameter†	TR_S	TPAR	RR_S	RPAR	LW_{OUT}	R_N
	W m^{-2}	μmol m^{-2} s^{-1}	W m^{-2}	μmol m^{-2} s^{-1}	W m^{-2}	W m^{-2}
n	2735	2735	3272	2708	2604	3365
Measured mean	223.2	357.0	116.3	63.7	458.5	389.9
Measured SD	227.4	445.2	47.4	41.5	30.1	184.9
Calculated mean	219.3	369.2	119.3	64.1	452.4	379.9
Calculated SD	239.3	495.5	50.1	42.1	34.0	194.0
E_C	0.84	0.83	0.80	0.85	0.81	0.84
RMSE	50.4	116.2	10.8	8.92	11.9	26.3
MAE	36.3	74.1	7.80	6.31	9.21	20.0
MBE	–3.81	12.2	2.97	0.438	–6.13	–10.0

† E_C, coefficient of model efficiency; MAE, mean absolute error; MBE, mean bias error.

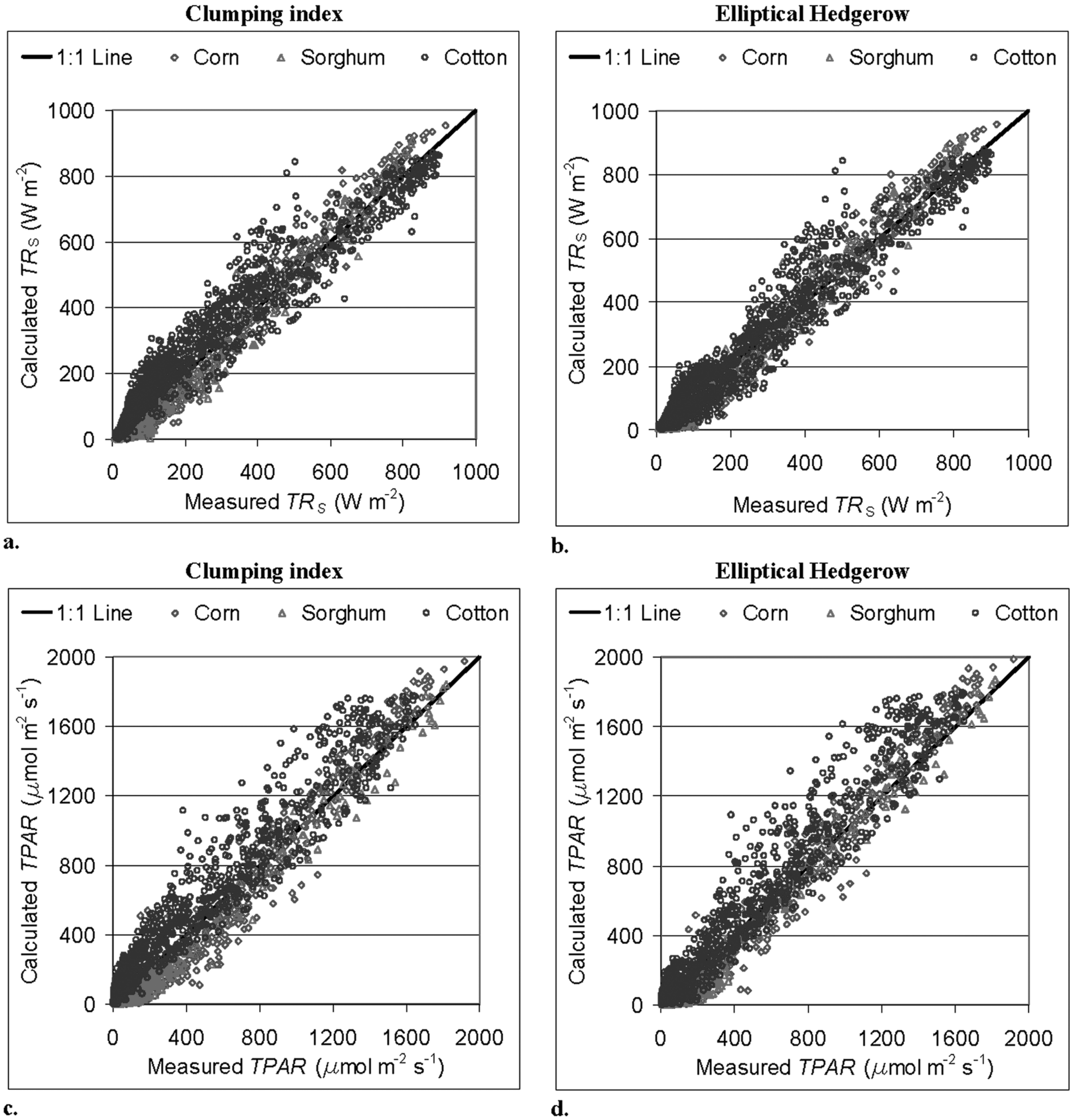

Fig. 2. Calculated vs. measured transmitted solar irradiance (TR_S) for (a) the clumping index approach and (b) the elliptical hedgerow approach, and calculated vs. measured transmitted photosynthetically active radiation (TPAR) for (c) the clumping index approach and (d) the elliptical hedgerow approach. See Tables 2 and 3 for statistical parameters of model agreement.

1000 W m^{-2} and 2000 µmol m^{-2} s^{-1}, respectively, which were the maximum values of incoming solar irradiance and PAR. A relatively sparse canopy (i.e., LAI less then ~0.5 m^2 m^{-2}) was indicated when the transmitted irradiance was greater than ~80% of the maximum values. The smaller values of measured and calculated TR_S and TPAR (less than ~200 W m^{-2} and ~400 µmol m^{-2} s^{-1}, respectively) corresponded to larger canopies with LAI greater than ~2.0 m^2 m^{-2}. The largest scatter was observed for the mid-range values of transmitted fluxes, which occurred for mid-sized canopies where LAI was ~1.0 to ~2.0 m^2 m^{-2}. This would be expected given the uncertainty (related to spatial variability) of LAI as the canopy size increased, which can be seen in the increasing scatter of LAI measurements as the canopy developed (Fig. 1). As discussed below, transmitted fluxes were most sensitive to LAI for a relatively large canopy (i.e., LAI = 2.95 m^2 m^{-2}). The similar model agreement for the clumping index and elliptical hedgerow approaches implied that transmittance calculated using the clumping index could empirically account for the lack of view factors that were explicitly accounted for in the elliptical hedgerow.

The range of measured RR_S was from nearly zero, when R_S was small and θ_S approached 80°, to almost 220 W m^{-2} during midday, when R_S was large (Fig. 3). Similarly, the range of measured RPAR was from almost zero to 240 µmol m^{-2} s^{-1}. Most RPAR values (>75%) were less than ~100 µmol m^{-2} s^{-1}, however, despite being measured across the same range of R_S and θ_S. This was the result of greater PAR leaf absorption ($0.82 \le \zeta_{PAR} \le 0.85$) compared with NIR leaf absorption ($0.14 \le \zeta_{NIR} \le 0.20$), which strongly determine the reflectance and albedo of the canopy (Campbell and Norman, 1998). Larger values of RPAR (greater than ~100 µmol m^{-2} s^{-1}) resulted when LAI was less than~1.0 m^2 m^{-2}, h_C and w_C were less than ~0.5 m, and bare soil was exposed between the canopy rows. As discussed

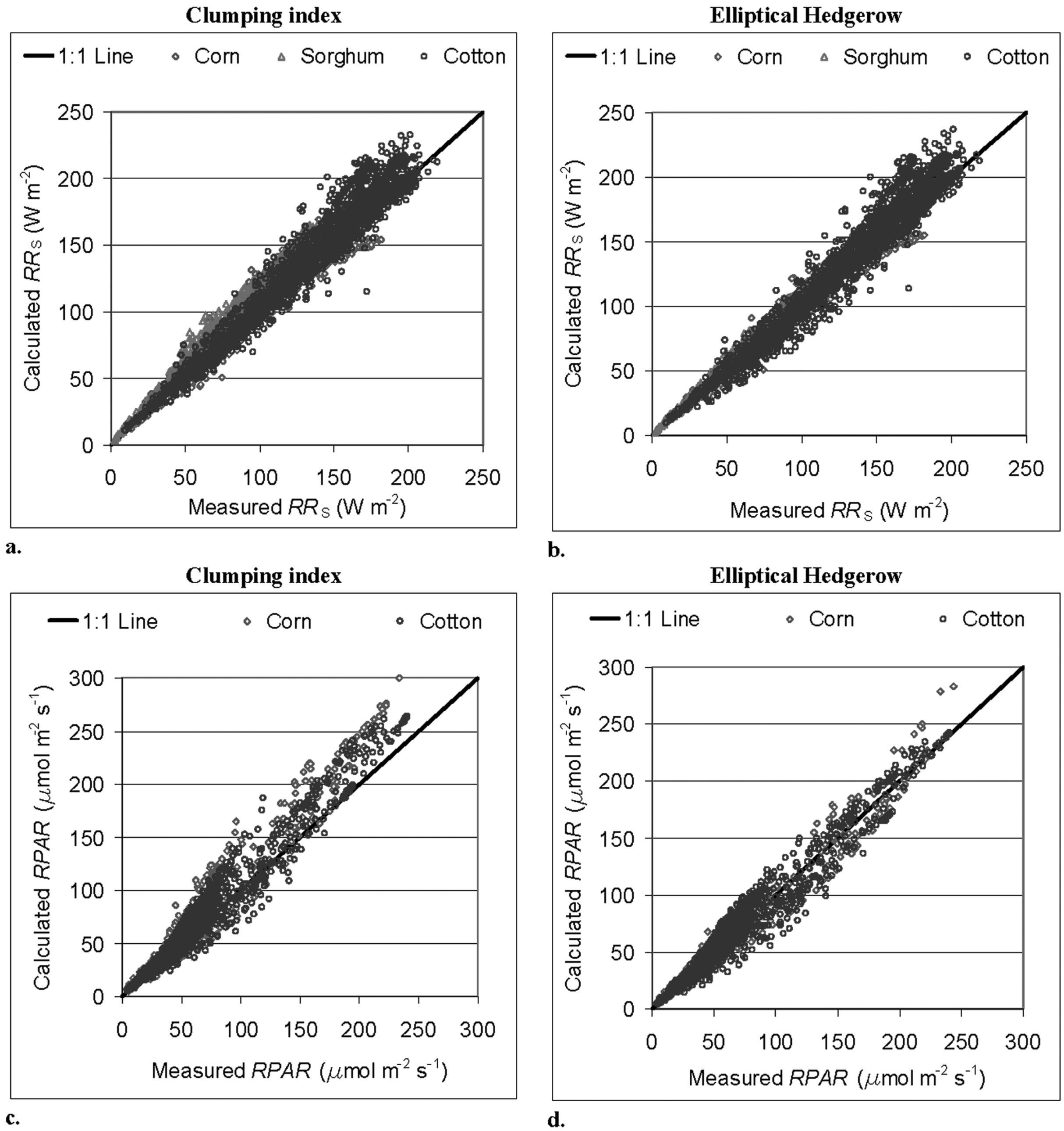

Fig. 3. Calculated vs. measured reflected solar irradiance (RR_S) for (a) the clumping index approach and (b) the elliptical hedgerow approach, and calculated vs. measured reflected photosynthetically active (RPAR) for (c) the clumping index approach and (d) the elliptical hedgerow approach. See Tables 2 and 3 for statistical parameters of model agreement.

below, PAR reflectance for dry bare soil and a deep canopy would probably be ~0.15 and 0.04, respectively, for θ_S values less than ~20° around midday. The surface albedo (containing both PAR and NIR reflectance) for dry bare soil and a deep canopy are likely to be ~0.20 and 0.23, respectively (i.e., a smaller range compared with PAR reflectance). Therefore, the variation in RR_S was more related to variation in incoming solar irradiance, whereas the variation in RPAR was related to both canopy cover and incoming PAR. This can be further deduced by considering RR_S for grain sorghum, which included a relatively small range of canopy cover compared with other measurements (Fig. 1) but still exhibited some variation (Fig. 3a and 3b).

Measurements of LW_{OUT} were available for cotton only, and these varied from ~375 to 550 W m^{-2} (Fig. 4). Similar to transmitted and reflected shortwave irradiance fluxes, LW_{OUT} was inversely proportional to canopy cover. Although the cotton crop was fully irrigated, exposed, sunlit soil usually had greater radiometric temperature than did the vegetation; therefore, the largest LW_{OUT} values corresponded to a sparse canopy. Both the clumping index and elliptical hedgerow approaches underestimated LW_{OUT} by ~25 W m^{-2} for measurements less than ~450 W m^{-2}. The clumping index, however, overestimated LW_{OUT} by up to 80 W m^{-2} for measurements higher than ~500 W m^{-2}, whereas the elliptical hedgerow overestimated LW_{OUT} by ~25 W m^{-2} in this same range of measurements. For R_N, model agreement for the clumping index and elliptical hedgerow approaches was similar. For the clumping index, E_C was 0.80 and RMSE, MAE, and MBE were 31.4, 25.5, and 7.0 W m^{-2}, respectively (Table 2). For the elliptical hedgerow, E_C was 0.84 and RMSE, MAE, and MBE were 26.3, 20.0,

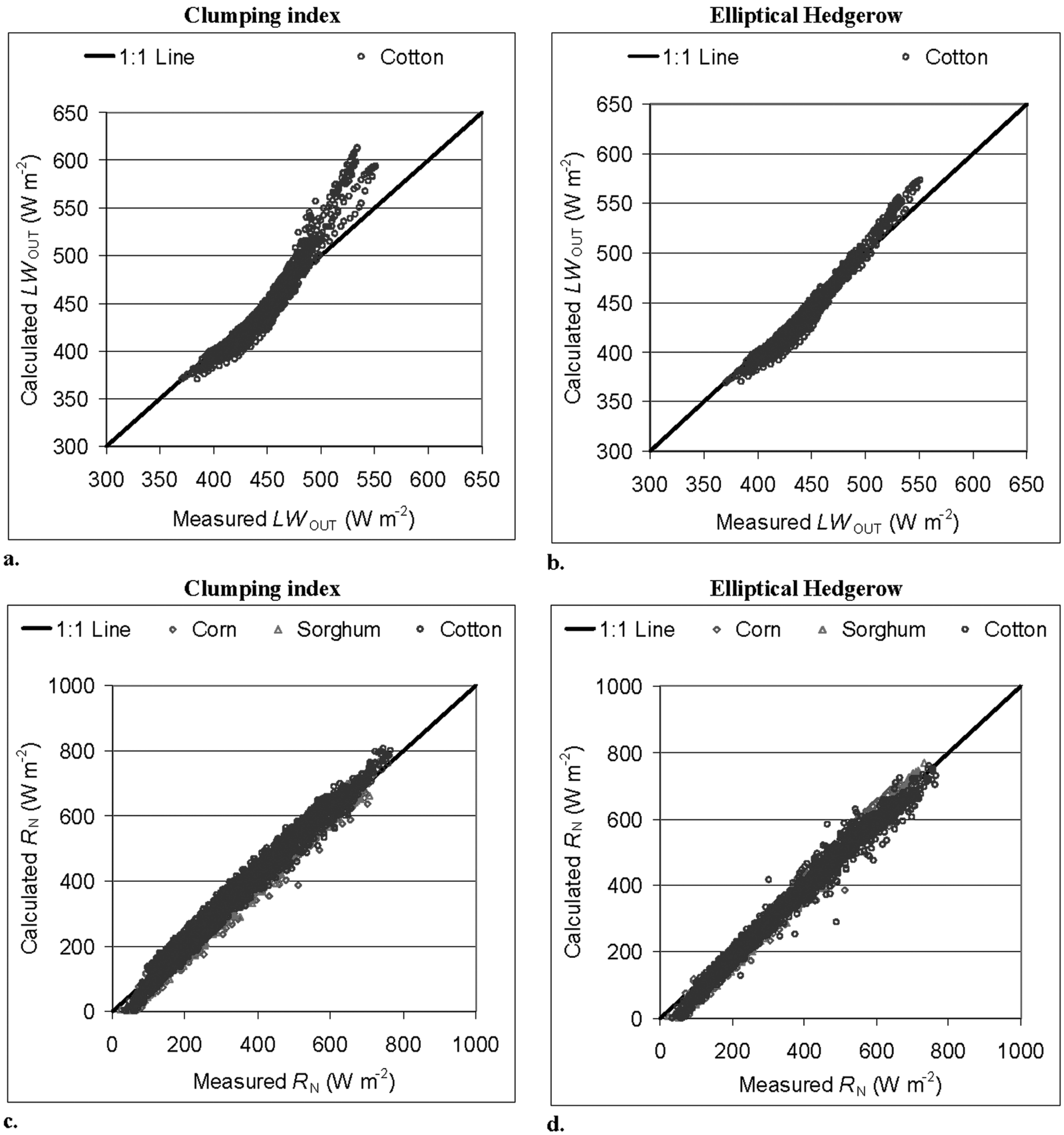

Fig. 4. Calculated vs. measured outgoing longwave irradiance (LW_{OUT}) for (a) the clumping index approach and (b) the elliptical hedgerow approach, and calculated vs. measured total net radiation (R_N) for (c) the clumping index approach and (d) the elliptical hedgerow approach. See Tables 2 and 3 for statistical parameters of model agreement.

and −10.0 W m^{-2}, respectively (Table 3). The similar model performance for each approach was probably influenced by the incoming irradiance (R_S and LW_{IN} in Eq. [6]), which are independent of canopy cover and hence the choice of approach.

The overestimates using the clumping index approach for RPAR (up to 75 μmol m^{-2} s^{-1}, Fig. 3c) and LW_{OUT} (up to 80 W m^{-2}, Fig. 4a), which occurred for sparse to moderate canopy cover (LAI less than ~1.0 m^2 m^{-2}), were related to the partitioning of energy between the soil and canopy components. These overestimates were somewhat mitigated when the elliptical hedgerow approach was used instead. As discussed below, RPAR and LW_{OUT} were rather sensitive to $\rho_{S,PAR}$ and T_S, respectively, when the canopy was sparse. Therefore, the RPAR and LW_{OUT} overestimates resulting with the clumping index could have been more related to sensitivity to input error rather than the merits of one approach over the other. To see how this occurred, it is instructive to compare some variable outputs used in the respective approaches. The variables used in calculating irradiance fluxes were plotted (Fig. 5) for each day of the cotton season (which had the largest number of days with partial canopy cover; Fig. 1) at 1100 h (~1 h 45 min before solar noon at the study location). For partial canopy cover, the values of the transmittance and reflectance terms in Eq. [1–4] depended on whether the clumping index or elliptical hedgerow approach was used. This is because in the Campbell and Norman (1998) model, transmittance and reflectance are nonlinear functions of LAI multiplied by a factor to account for the nonrandom spatial distribution of vegetation (see equations in Colaizzi et al., 2012). Recall that this factor is $\Omega_{SW}/\cos(\theta_S)$ and η (Eq. [5]) for the clumping index submodel and elliptical

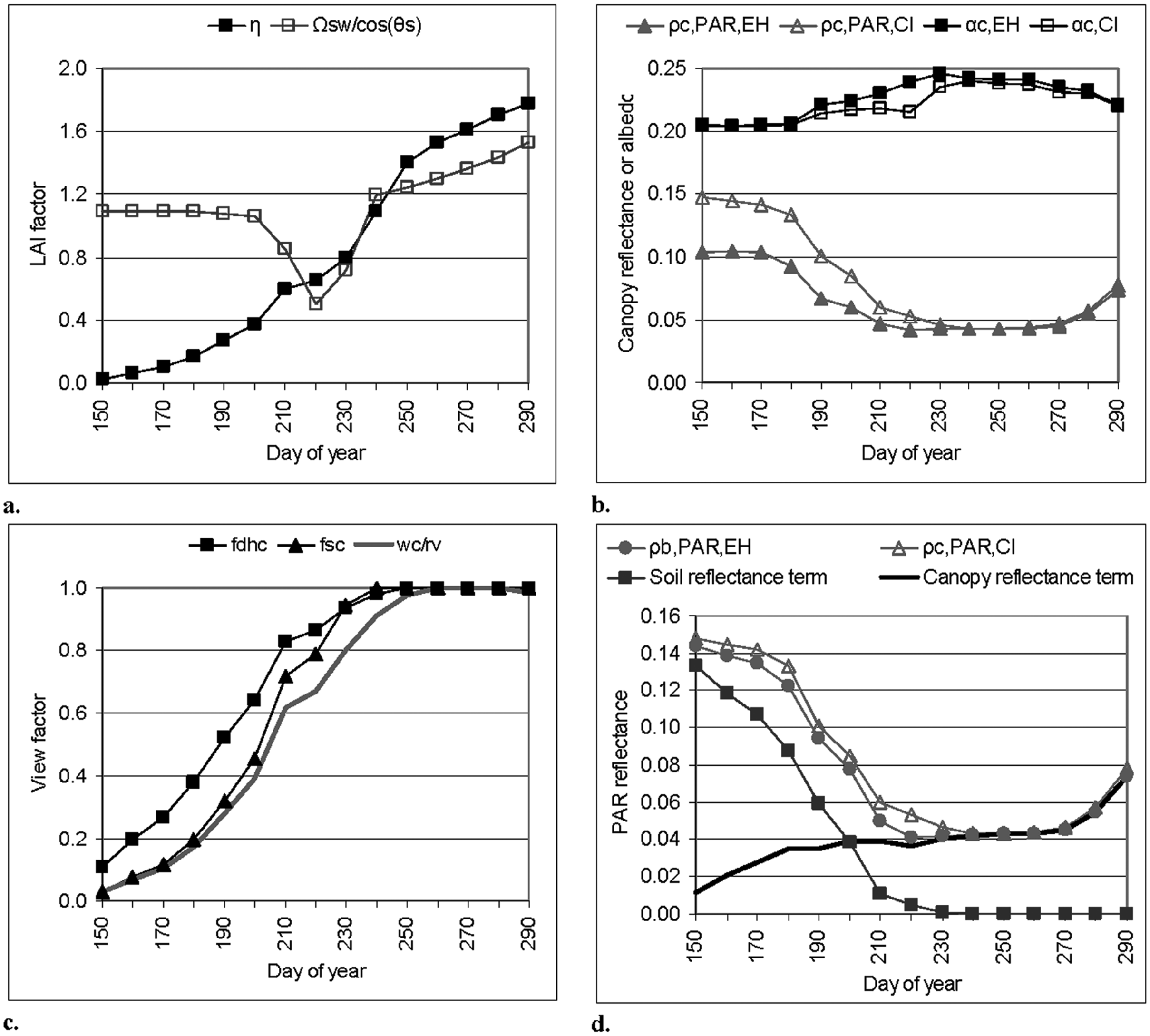

Fig. 5. Variables calculated for the 2008 cotton crop season at 1100 h: (a) leaf area index (LAI) factors used to account for the nonrandom spatial distribution of vegetation used in the elliptical hedgerow (η) and clumping index [$\Omega_{SW}/\cos(\theta_S)$] approaches; (b) canopy reflectance for photosynthetically active radiation (PAR) using the elliptical hedgerow approach ($\rho_{C,PAR,EH}$) and clumping index approach ($\rho_{C,PAR,CI}$) and canopy albedo for shortwave radiation using the elliptical hedgerow approach ($\alpha_{C,EH}$) and clumping index approach ($\alpha_{C,CI}$); (c) downward canopy hemispherical (f_{DHC}) and solar canopy (f_{SC}) view factors used in the elliptical hedgerow approach and the nadir fraction of canopy cover (w_C/r_V); and (d) bulk canopy reflectance for PAR using the elliptical hedgerow approach ($\rho_{b,PAR,EH}$) and clumping index approach ($\rho_{C,PAR,CI}$), and soil and canopy reflectance terms from Eq. [4].

hedgerow submodel, respectively. Both factors are functions of canopy cover, size, and θ_S and Φ_S relative to the crop rows.

Early in the season when the canopy cover was sparse, $\Omega_{SW}/\cos(\theta_S)$ was much greater than η and was insensitive to increases in canopy cover until around DOY 200, when LAI reached 0.5 m^2 m^{-2} (Fig. 5a). This resulted in greater weighting to the underlying soil when calculating the canopy PAR reflectance ($\rho_{C,PAR}$) using the clumping index compared with the elliptical hedgerow (from Eq. [12] and [13] in Colaizzi et al., 2012). Because PAR reflectance for dry bare soil and a deep canopy are ~0.15 and 0.04, respectively, the clumping index resulted in greater PAR reflectance ($\rho_{C,PAR,CI}$) early in the season than did the elliptical hedgerow approach ($\rho_{C,PAR,EH}$), but $\rho_{C,PAR,CI}$ and $\rho_{C,PAR,EH}$ were similar later when full canopy cover was reached (Fig. 5b). Because shortwave albedo (which includes both PAR and NIR reflectance) for dry soil and a deep canopy are ~0.20 and 0.23, respectively, however, there was little difference in the respective canopy albedo terms ($\alpha_{C,CI}$ and $\alpha_{C,EH}$) regardless of canopy cover.

The calculation of irradiance fluxes in Eq. [1–4] includes view factors developed for the elliptical hedgerow approach; for reflected irradiance, these include the solar canopy (f_{SC}) and downward hemispherical canopy (f_{DHC}) view factors. For a row crop with partial cover, f_{DHC} will nearly always be greater than f_{SC} except when θ_S is greater than ~60° because the downward hemispherical view includes elements viewing distant canopy rows at near-perpendicular angles where the soil is obscured, but a planar view has a fixed zenith and azimuth view angle (Fig. 5c). Also for row crops with partial cover, f_{SC} will almost always be greater than the fraction of canopy cover (i.e., a nadir planar view, calculated as w_C/r_V), except when Φ_S is parallel to the crop rows, resulting in $f_{SC} = w_C/r_V$. Early in the season when the canopy was sparse, f_{SC} was barely greater than w_C/r_V because θ_S was only 20 to 30°. Despite the very small canopy, f_{DHC} was still much greater than f_{SC} and w_C/r_V because the view elements viewing perpendicular to the rows included a large proportion of vegetation. As the season

Table 4. Base values of input variables used in the sensitivity analysis for small, medium and large canopies, along with base values of output variables generated using the base input values.

Variable†	Small canopy	Medium canopy	Large canopy
Unvaried inputs			
Row orientation	east–west	east-west	east-west
Local time (h)	1245	1245	1245
Day of the year	188	213	235
Incoming solar irradiance (R_S), W m^{-2}	944	952	918
Solar zenith angle (θ_S), °	13	17	24
Solar azimuth angle relative to rows (Φ_S), °	82	83	87
Base values of input variables (I_B)			
Leaf area index, m^2 m^{-2}	0.21	1.75	2.95
Canopy height (h_C), m	0.26	0.64	0.76
Canopy width (w_C), m	0.26	0.64	0.76
Ellipsoid LADF parameter (X_E)	3.00	3.00	3.00
Leaf absorption of PAR (ζ_{PAR})	0.83	0.83	0.83
Leaf absorption of NIR (ζ_{NIR})	0.14	0.14	0.14
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.15	0.15	0.15
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.25	0.25	0.25
Directional brightness temperature, canopy (T_C), °C	30.2	28.8	26.6
Directional brightness temperature, soil (T_S), °C	50.8	37.7	31.6
Base values of calculated outputs, clumping index			
TR$_S$, W m^{-2}	827	375	195
TPAR, μmol m^{-2} s^{-1}	1651	483	151
RR$_S$, W m^{-2}	193	212	217
RPAR, μmol m^{-2} s^{-1})	234	97	82
LW$_{OUT}$, W m^{-2}	599	485	459
R_N, W m^{-2}	540	647	644
Base values of calculated outputs, elliptical hedgerow			
TR$_S$, W m^{-2}	834	391	153
TPAR, μmol m^{-2} s^{-1}	1675	550	94
RR$_S$, W m^{-2}	183	207	219
RPAR, μmol m^{-2} s^{-1}	203	91	81
LW$_{OUT}$, W m^{-2}	542	473	457
R_N, W m^{-2}	607	664	643

† LADF, leaf angle distribution function; PAR, photosynthetically active radiation; NIR, near-infrared radiation; TR$_S$, transmitted solar irradiance; TPAR, transmitted PAR; RR$_S$, reflected solar irradiance; RPAR, reflected PAR; LW$_{OUT}$, outgoing longwave irradiance; $\boldsymbol{R}_N$, net radiation.

progressed and canopy cover increased, f_{SC} became nearly equal to f_{DHC} because θ_S was increasing at 1100 h, reaching 49° by the end of the season. Both f_{SC} and f_{DHC} reached unity before w_C/r_V, which would be expected for off-nadir views.

Early in the season before full canopy cover occurred, the elliptical hedgerow approach resulted in much greater partitioning of reflected energy from the soil than the clumping index approach, which was due to the f_{SC} and f_{DHC} terms used in the elliptical hedgerow approach. This did not impact the variation in RR$_S$ as much as that of RPAR during the cotton season because the soil and canopy albedo were similar but the soil and canopy PAR reflectance were not. The relative contribution of the canopy and soil PAR reflectance terms (i.e., $\rho_{C,PAR}f_{DHC}$ and $\rho_{S,PAR}\tau_{C,PAR}(1 - f_{DHC})$, respectively, in Eq. [4]), and their sum (termed the bulk surface PAR reflectance for the elliptical hedgerow approach, or $\rho_{b,PAR,EH}$) were compared with $\rho_{C,PAR,CI}$ (Fig. 5d). The $\rho_{C,PAR,CI}$ was used to calculate RPAR in Fig. 3c. The soil reflectance term resulted in greater $\rho_{b,PAR,EH}$ than $\rho_{C,PAR,CI}$ (up to 20%; Fig. 5d) until the soil was mostly obscured by vegetation and the soil reflectance term approached zero around DOY 240. After this time, $\rho_{b,PAR,EH}$, $\rho_{C,PAR,CI}$, and the canopy reflectance term were nearly equal for the remainder of the season. This resulted in similar agreement (e.g., RMSE = 13.8 and 8.9 μmol m^{-2} s^{-1}, Tables 2 and 3, respectively) between the measured and calculated RPAR throughout the season for the elliptical hedgerow and for full cover using the clumping index (Fig. 3c and 3d). Before DOY 240, however, $\rho_{C,PAR,CI}$ was still greater than $\rho_{b,PAR,EH}$, and the clumping index resulted in overestimates of RPAR by up to 75 μmol m^{-2} s^{-1} (Fig. 3c). This would imply that the clumping index approach overcompensated for partial canopy cover and placed too much weight on the underlying soil when calculating the canopy reflectance using the Campbell and Norman (1998) model. This could be mitigated, however, by a small reduction in $\rho_{S,PAR}$, meaning that interpretation of the model performance was confounded by uncertainty in the input parameters in this case. In practice, model bias may be reduced by independent measurements of soil reflectance in different spectral bands. This might be more desirable than estimating soil reflectance for PAR and NIR as a function of evaporation following wetting events, as was done in the current study.

The difference in the calculated LW$_{OUT}$ for larger values for the clumping index and elliptical approaches (greater than ~500 W m^{-2}; Fig. 4a and 4b, respectively) were related to differences in

Table 5. Sensitivity (S_M) of calculated radiation fluxes (transmitted solar irradiance [TR_S], transmitted photosynthetically active radiation [TPAR], reflected solar irradiance [RR_S], reflected photosynthetically active radiation [RPAR], outgoing longwave radiation [LW_{OUT}], and total net radiation [R_N]) to input variables using the clumping index approach. Model sensitivities ($|S_M|$) > 0.50 are in bold type, and $|S_M|$ > 1.00 are in bold, italic type.

Input variable†	TR_S	TPAR	RR_S	RPAR	LW_{OUT}	R_N
Small canopy						
Leaf area index	–0.10	–0.15	0.00	–0.18	–0.03	0.03
Canopy height (h_C)	0.00	–0.01	0.00	–0.01	0.00	0.00
Canopy width (w_C)	–0.03	–0.04	0.00	–0.05	–0.01	0.01
Ellipsoid LADF parameter (X_E)	–0.02	–0.03	0.02	–0.03		–0.01
Leaf absorption of PAR (ζ_{PAR})	–0.04	–0.09	–0.19	**–0.71**		0.07
Leaf absorption of NIR (ζ_{NIR})	–0.01		–0.05			0.02
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.00	0.24	0.89		–0.08
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.01		0.56			–0.20
Directional brightness temperature, canopy (T_C)					0.05	–0.05
Directional brightness temperature, soil (T_S)					0.55	-0.61
Medium canopy						
Leaf area index	**-0.58**	**-1.00**	0.07	–0.29	–0.03	0.00
Canopy height (h_C)	–0.03	–0.05	0.00	–0.01	0.00	0.00
Canopy width (w_C)	**-0.85**	***–1.53***	0.09	**-0.55**	–0.05	0.01
Ellipsoid LADF parameter (X_E)	–0.17	–0.25	0.12	0.03		–0.04
Leaf absorption of PAR (ζ_{PAR})	–0.20	**-0.71**	–0.47	***–4.67***		0.15
Leaf absorption of NIR (ζ_{NIR})	–0.15		–0.25			0.08
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.01	0.02	0.19		–0.01
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.06		0.17			–0.06
Directional brightness temperature, canopy (T_C)					0.26	–0.20
Directional brightness temperature, soil (T_S)					0.14	–0.11
Large canopy						
Leaf area index	***–1.34***	***–2.66***	0.09	–0.10	–0.01	–0.02
Canopy height (h_C)	0.00	0.00	0.00	0.00	0.00	0.00
Canopy width (w_C)	**-0.88**	***–1.94***	0.06	–0.10	–0.02	–0.01
Ellipsoid LADF parameter (X_E)	–0.36	**-0.64**	0.14	0.10		–0.05
Leaf absorption of PAR (ζ_{PAR})	–0.22	***–1.31***	–0.45	***–5.48***		0.15
Leaf absorption of NIR (ζ_{NIR})	–0.34		–0.33			0.11
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.01	0.00	0.02		0.00
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.08		0.06			–0.02
Directional brightness temperature, canopy (T_C)					0.33	–0.23
Directional brightness temperature, soil (T_S)					0.03	–0.02

† LADF, leaf angle distribution function; PAR, photosynthetically active radiation; NIR, near-infrared radiation.

calculating the canopy view factors (w_C/r_V and f_{DHC} in Eq. [7], respectively). Because w_C/r_V is less than f_{DHC} for partial cover (Fig. 5c), greater weight would be placed on longwave irradiance from the soil for the clumping index than the elliptical hedgerow, according to Eq. [7]. The value of T_S is usually greater than T_C for partial cover (e.g., 9 to 20°C; Table 4); therefore, greater weight on soil longwave irradiance resulted in greater LW_{OUT} for the clumping index than the elliptical hedgerow approach. Exponential expressions of the form $1 - \exp(-k\Omega\mathrm{LAI})$, where k and Ω are the extinction coefficient and clumping index, respectively, have been commonly used to approximate canopy view factors (e.g., Campbell and Norman, 1998); however, these resulted in values even lower than w_C/r_V, which exacerbated LW_{OUT} overestimates to up to 120 W m^{-2} (data not shown) compared with the overestimates of up to 80 W m^{-2} in Fig. 4a. Therefore, w_C/r_V appeared to be the simplest alternative to f_{DHC}.

A sensitivity analysis was conducted for each irradiance flux evaluated (TR_S, TPAR, RR_S, RPAR, LW_{OUT}, and R_N) to input parameters and variables deemed to have the most uncertainty in practice (Table 4). For each canopy size, base values of constant and varied input parameters (I_B) resulted in very similar base values of calculated outputs (O_B) for both approaches (Table 4). The clumping index and elliptical hedgerow approaches resulted in similar response patterns in their sensitivities (S_M) to the selected model input parameters, where differences in $|S_M|$ for each approach were <0.60 (Tables 5 and 6). (The selection of ±0.50 and ±1.00 were arbitrary and should not be construed to represent any rigorous S_M category; these values are simply qualitative assessments of moderate and large S_M, respectively, for the purpose of this discussion.) Positive (negative) values of S_M indicate a direct (inverse) relation between I_B and O_B.

For both the clumping index (Table 5) and elliptical hedgerow (Table 6) approaches, transmitted irradiance (TR_S and TPAR) was most sensitive to LAI and w_C and became increasingly sensitive to these variables as the canopy size increased, with $-3.25 \le S_M \le -0.58$ for medium (LAI = 1.75 m^2 m^{-2}) and large (LAI = 2.95 m^2 m^{-2}) canopies. The increases in $|S_M|$ with canopy size were partially the result of reduced transmitted irradiance, which appears in the denominator as O_B in Eq. [8], because greater irradiance would be intercepted by

Table 6. Sensitivity (S_M) of calculated radiation fluxes (transmitted solar irradiance [TR_S], transmitted photosynthetically active radiation [TPAR], reflected solar irradiance [RR_S], reflected photosynthetically active radiation [RPAR], outgoing longwave radiation [LW_{OUT}], and total net radiation [R_N]) to input variables using the elliptical hedgerow approach. Model sensitivities ($|S_M|$) > 0.50 are in bold type, and $|S_M|$ > 1.00 are in bold, italic type.

Input variable†	TR_S	TPAR	RR_S	RPAR	LW_{OUT}	R_N
Small canopy						
Leaf area index	–0.10	–0.14	–0.02	–0.29	0.00	0.01
Canopy height (h_C)	–0.01	–0.02	0.01	–0.05	–0.03	0.03
Canopy width (w_C)	–0.01	–0.01	0.01	0.07	–0.06	0.05
Ellipsoid LADF parameter (X_E)	–0.02	–0.03	0.03	–0.05		–0.01
Leaf absorption of PAR (ζ_{PAR})	–0.03	–0.07	–0.22	**–0.92**		0.07
Leaf absorption of NIR (ζ_{NIR})	–0.01		–0.08			0.02
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.00	0.07	**0.86**		–0.02
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.01		0.25			–0.07
Directional brightness temperature, canopy (T_C)					0.19	–0.17
Directional brightness temperature, soil (T_S)					0.32	–0.28
Medium canopy						
Leaf area index	**-0.70**	***–1.01***	0.09	–0.35	0.00	–0.03
Canopy height (h_C)	–0.13	–0.28	0.01	0.01	0.00	0.00
Canopy width (w_C)	**-0.64**	***–1.30***	0.14	0.03	–0.04	–0.02
Ellipsoid LADF parameter (X_E)	–0.19	–0.26	0.13	0.02		–0.04
Leaf absorption of PAR (ζ_{PAR})	–0.16	**-0.51**	–0.46	***–4.79***		0.14
Leaf absorption of NIR (ζ_{NIR})	–0.14		–0.27			0.09
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.00	0.01	0.17		0.00
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.05		0.14			–0.04
Directional brightness temperature, canopy (T_C)					0.35	–0.25
Directional brightness temperature, soil (T_S)					0.03	–0.02
Large canopy						
Leaf area index	***–1.53***	***–3.25***	0.07	–0.05	0.00	–0.02
Canopy height (h_C)	–0.01	–0.03	0.00	0.00	0.00	0.00
Canopy width (w_C)	**-0.64**	***–1.69***	0.10	0.04	–0.01	–0.03
Ellipsoid LADF parameter (X_E)	–0.41	**-0.77**	0.14	0.11		–0.05
Leaf absorption of PAR (ζ_{PAR})	–0.21	***–1.58***	–0.45	***–5.54***		0.15
Leaf absorption of NIR (ζ_{NIR})	–0.44		–0.35			0.12
Soil reflectance of PAR ($\rho_{S,PAR}$)	0.00	0.01	0.00	0.01		0.00
Soil reflectance of NIR ($\rho_{S,NIR}$)	0.09		0.04			–0.01
Directional brightness temperature, canopy (T_C)					0.35	–0.25
Directional brightness temperature, soil (T_S)					0.00	0.00

† LADF, leaf angle distribution function; PAR, photosynthetically active radiation; NIR, near-infrared radiation.

the canopy. Hence, all S_M were negative for these I_B because they were inversely related to transmitted irradiance. When the canopy was large, transmitted fluxes resulted in $-0.77 \leq S_M \leq -0.36$ for the ellipsoid LADF parameter (X_E). Also for a large canopy, TPAR was relatively sensitive to ζ_{PAR}, with $S_M = -1.31$ and -1.58 for the clumping index and elliptical hedgerow approaches, respectively. Increasing X_E represents more horizontal leaves, which would reduce the transmitted irradiance when θ_S was less than ~45° (but may increase transmitted irradiance when θ_S is greater than ~45°), and increasing X_E would also reduce the transmitted irradiance because a greater amount of PAR would be absorbed by the canopy. For all I_B, TPAR had greater $|S_M|$ compared with TR_S because the response of TR_S is spread across a wider range of spectra (PAR + NIR) and $\zeta_{PAR} > \zeta_{NIR}$. Both TR_S and TPAR, however, were relatively insensitive to soil reflectance ($S_M < 0.10$) because this was a second-order effect in the Campbell and Norman (1998) computation of transmittance, where transmitted irradiance was reflected upward by the soil and re-reflected downward by the canopy.

Reflected irradiance (RR_S and RPAR) was most sensitive to ζ_{PAR} and ζ_{NIR} (which strongly determines canopy reflectance in the Campbell and Norman [1998] procedure) for medium and large canopies, with $-0.47 \leq S_M \leq -0.25$ for RR_S and $-4.67 \leq S_M \leq -5.54$ for RPAR, respectively. Reflected irradiance was not as sensitive (smaller $|S_M|$) to LAI and w_C as transmitted irradiance because differences in the reflected energy from the soil or canopy are smaller than the impact of the canopy intercepting radiation. For all I_B, however, RPAR had greater $|S_M|$ than RR_S because of greater ζ_{PAR} compared with ζ_{NIR} (RR_S is a function of both ζ_{PAR} and ζ_{NIR}), which was congruent with the results for transmitted irradiance. As the canopy size increased, $|S_M|$ increased for ζ_{PAR} and ζ_{NIR} but decreased for $\rho_{S,PAR}$ and $\rho_{S,NIR}$, and reflected irradiance was inversely and directly related to leaf absorption and soil reflectance, respectively. The relatively large $|S_M|$ of RPAR to ζ_{PAR}, especially as the canopy size increased, was mainly the result of reduced RPAR, which appears in the denominator as O_B in Eq. [8], and this was also noted for transmitted fluxes. For a small canopy, $\rho_{S,PAR}$ resulted in RPAR having $|S_M| = 0.89$ and 0.86 for the clumping index and elliptical hedgerow approaches, respectively. These somewhat intermediate values of $|S_M|$ were related to the direct, one-to-one relationship between $\rho_{S,PAR}$ and RPAR for a bare soil; this may have been a confounding factor in the RPAR overestimates observed for the clumping index approach.

The value of LW_{OUT} is mainly influenced by the directional brightness temperatures of the soil (T_S) and canopy (T_C) and their relative partitioning, which is determined by the canopy size (i.e., LAI, h_C, and w_C). Similar to reflected shortwave irradiance, LW_{OUT} was relatively insensitive to LAI, h_C, and w_C ($|S_M| < 0.10$) regardless of canopy size (Tables 5 and 6). This was observed even for a small canopy, when T_S was 20°C warmer than T_C (Table 4). For a small canopy, LW_{OUT} was somewhat sensitive to T_S, where $S_M = 0.32$ and 0.55 for the clumping index and elliptical hedgerow approaches, respectively. As the canopy size increased, $|S_M|$ increased up to 0.35 for T_C and decreased to near zero for T_S, which would be expected as the canopy increasingly covered the soil. For small and medium size canopies, the clumping index resulted in greater S_M of T_S but less S_M of T_C compared with the elliptical hedgerow approach because the former used a smaller canopy view factor than the latter (Fig. 5c). For a large canopy, however, there were essentially no differences in S_M to T_S or T_C for either approach.

Sensitivity of R_N to model parameters was similar to LW_{OUT} in that R_N was most sensitive to T_S for a small canopy and T_C for a large canopy, but these were inversely related compared with those of LW_{OUT} for both approaches (Tables 5 and 6). For a small canopy, T_S resulted in $|S_M| = -0.61$ and -0.28 for the clumping index and elliptical hedgerow approaches, respectively. For a large canopy, T_C resulted in $|S_M| = -0.23$ and -0.25 for the respective approaches. For each canopy size and approach, R_N was relatively insensitive to LAI, h_C, w_C, and X_E, with $|S_M| \le 0.05$, and ζ_{PAR}, ζ_{NIR}, $\rho_{S,PAR}$, and $\rho_{S,NIR}$ resulted in $|S_M| \le 0.20$. Because R_N is the sum of the incoming and outgoing shortwave and longwave radiation components, it would not be expected to be as sensitive to each input that was evaluated in the sensitivity analysis compared with the one-directional irradiance fluxes.

CONCLUSIONS

The clumping index and elliptical hedgerow approaches represent alternative methods to account for the nonrandom spatial distribution of row crop vegetation. Both approaches resulted in similar calculations of irradiance and radiation components (TR_S, TPAR, RR_S, RPAR, LW_{OUT}, and R_N) for a wide range of vegetation cover, although the elliptical hedgerow approach usually resulted in smaller values of the RMSE (up to 7.3 W m^{-2}), MAE (up to 6.0 W m^{-2}), and MBE (up to 7.5 W m^{-2}). For both approaches, RMSE, MAE, and MBE were within 34, 23, and 8%, respectively, of the measured irradiance flux means, where the largest MBE was for RPAR using the clumping index approach. Although the two approaches partition radiation to the soil and canopy differently, the relatively greater MBE for RPAR may have been related to uncertainty of the soil reflectance, which had a substantial impact on reflected fluxes when the canopy cover was sparse. The RMSE, MAE, and MBE for both approaches were not much larger than the operational uncertainty of the input variables; for example, LAI varied up to ±18% of the mean field measurements. Therefore, the model performance was deemed acceptable using either approach, and both approaches were robust in that they could calculate irradiance for a wide range of vegetation cover for different crops; however, geometric approaches based on view factors may be more amenable to detailed studies of energy exchange and crop biophysical properties because they can more easily resolve soil and canopy layers into their sunlit and shaded components. Because very few radiative transfer studies have considered varying vegetation cover, there is a need for additional studies for different locations, crops, and row configurations. In particular, studies in humid climates with a greater proportion of cloudy days are needed to further test calculations of the diffuse components.

Model sensitivities (S_M) to certain input parameters and variables (deemed to have the most operational uncertainty) were also similar for both the clumping index and elliptical hedgerow approaches, where sensitivities were evaluated for small (LAI = 0.21 m^2 m^{-2}), medium (LAI = 1.75 m^2 m^{-2}), and large (LAI = 2.95 m^2 m^{-2}) canopies. For shortwave irradiance, model inputs evaluated included LAI, h_C, w_C, X_E, ζ_{PAR}, ζ_{NIR}, $\rho_{S,PAR}$, and $\rho_{S,NIR}$. Calculated TR_S and TPAR were most sensitive to LAI and w_C ($-3.25 \le S_M \le -0.58$); for a large canopy, TR_S and TPAR were also relatively sensitive to X_E ($-0.77 \le S_M \le -0.36$) and ζ_{PAR} ($-1.58 \le S_M \le -0.21$), although in this case calculated irradiances were relatively small because the large canopy intercepted most of the incident irradiance. Calculated RR_S and RPAR were most sensitive to ζ_{PAR} ($-5.54 \le S_M \le -0.45$) but less sensitive to LAI and w_C than TR_S or TPAR ($|S_M| \le 0.55$). Both TPAR and RPAR were more sensitive to PAR inputs than were TR_S and RR_S because the latter two irradiances also include inputs specific to NIR wavelengths. For LW_{OUT}, the model inputs evaluated included LAI, h_C, w_C, T_C, and T_S. For R_N, the model inputs evaluated included those for shortwave irradiance and T_C and T_S. The LW_{OUT} and R_N were most sensitive to T_S for a small canopy ($-0.61 \le S_M \le 0.55$) and T_C for medium and large canopies ($-0.25 \le S_M \le 0.35$).

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