SIMULATING MAIZE PRODUCTION, WATER AND SURFACE ENERGY BALANCE, CANOPY TEMPERATURE, AND WATER STRESS UNDER FULL AND DEFICIT IRRIGATION

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ABSTRACT. *Surface energy balance is critical to the understanding of crop evapotranspiration (ET) requirements and crop water stresses. The objective of this study was to evaluate the simulation of crop growth, water and surface energy balance components, canopy temperature, and water stress under fully irrigated and deficit-irrigated corn in eastern Colorado using a hybrid version of the Root Zone Water Quality Model (RZWQM) and the Simultaneous Heat and Water model (SHAW) (RZ-SHAW). The field experiment was conducted in 2010 under both full and deficit irrigation conditions with energy balance measured using the Bowen ratio method. The model simulated grain yield satisfactorily, with an error of less than 5%. Leaf area index, daily ET, soil water content, canopy temperature, and energy balance components, including net radiation (R_n), latent heat (LE), sensible heat (H), and ground heat flux (G), were simulated well, with coefficients of determination (R^2) ≥ 0.64 and model efficiencies (ME) ≥ 0.57 for both full and deficit irrigation fields. The RZ-SHAW model accurately predicted the responses of crop growth and ET to water stress, and the simulated water stress was in good agreement with measured elevated canopy temperature with deficit irrigation after silking. However, the model performance was not acceptable in predicting plant height for water-stressed corn, and the simulated increase in canopy temperature under deficit irrigation was about 30% of the observed temperature increase. This study suggests that while the RZ-SHAW model can be used to evaluate the response of corn yield and water and energy balances to water stress, the simulation of the effects of water deficit on plant height and canopy temperature need further improvement.*

Keywords. *Bowen ratio, Canopy temperature, Corn, Deficit irrigation, Energy balance, Evapotranspiration, Latent heat, RZWQM2, SHAW, Soil water content, Water stress.*

Estimation of crop evapotranspiration (ET) is essential in investigations of the hydrological cycle as well as in irrigation scheduling. ET can be measured through mass balance methods (e.g., soil water balance and weighing lysimeters) or energy balance methods (e.g., Bowen ratio and eddy covariance) (Farahani et al., 2007). With the development of instruments that accurately measure near-surface metrological variables such as heat and vapor flux, the energy balance method is preferable to other approaches for its easy installation and lesser disturbance to the field crop. In a crop canopy, net radiation is partitioned into latent heat, sensible heat, and ground heat flux. Latent heat is converted to evapotranspiration through the specific heat of water evaporation. In the energy balance method, heat and vapor flux are measured along with net radiation and ground heat flux. In the Bowen ratio method, in particular, the net radiation and ground heat flux are measured through a net radiometer and a soil heat flux transducer, respectively, and the ratio of sensible heat to latent heat is computed through the ratio of the measured vertical gradient of temperature to the vertical gradient of vapor pressure (Bausch and Bernard, 1992).

Canopy temperature may be used to calculate the crop water stress index via the temperature difference between the canopy and the air (Idso et al., 1981). Jackson et al. (1981) stated that serious error may occur when soil background is within the view of a canopy temperature measurement instrument (infrared thermometer) because canopy temperature can be drastically different from soil temperature. Bausch et al. (2011) proposed a simple approach to estimate crop water stress through the temperature ratio of a crop canopy under non-optimum conditions (water-

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stressed) versus non-stressed conditions (fully irrigated). A preliminary field investigation by Bausch et al. (2011) suggested that this temperature ratio technique has potential to quantify water stress for a deficit-irrigated crop. However, it would only be feasible when both full and deficit treatments co-existed in close proximity under similar conditions.

In most practical situations where crop evapotranspiration values are needed, field measurement of ET is not feasible due to constraints of time and cost. Therefore, modeling methods are usually preferred because they are easier and less costly (Farahani et al., 2007), and the required meteorological data are increasingly available. Several modeling methods have been developed. The most widely used is the Penman-Monteith reference ET_o equation (Jensen et al., 1990). Crop ET_c is computed by multiplying ET_o with a crop coefficient K_c. Under water-limiting conditions, K_c is adjusted by a crop stress factor K_s (Allen et al., 1998). However, because K_s is difficult to estimate, the reference ET method is mainly used for crop water use and irrigation scheduling under fully irrigated conditions, rather than to estimate water stress impacts on ET_c or crop yield. Therefore, process-based crop models that simulate the response of crop growth, such as leaf expansion and biomass accumulation, to soil water and nutrient stress may need more detailed methods to estimate ET_c under water-limiting conditions (e.g., the Shuttleworth-Wallace approach; Shuttleworth and Wallace, 1985).

Recently, detailed energy balance and crop growth models have been combined to investigate the interactions between crop growth and energy balance at different scales (Li et al., 2013; Song et al., 2013; Papadavid et al., 2013; Cammalleri et al., 2010). One such effort was the development of the RZ-SHAW hybrid model, which coupled the Root Zone Water Quality Model (RZWQM; Ahuja et al., 2000) with the Simultaneous Heat and Water model (SHAW; Flerchinger and Saxton, 1989). RZWQM is a system model designed to simulate management effects on crop production and environmental quality. One of its weaknesses is its assumption that soil surface temperature equals air temperature, which is valid for bare soil but not under a crop or residue cover. The RZ-SHAW hybrid model simulates soil surface temperature and canopy temperature based on canopy energy balance (Ma et al., 2012a; Li et al., 2012). In the RZ-SHAW model, RZWQM supplies SHAW with soil water content, evapotranspiration, and plant growth information (plant height, leaf area index, rooting depth, etc.) on a sub-hourly basis, and SHAW feeds back to RZWQM soil surface and canopy temperature and energy components (latent heat, sensible heat, ground heat flux, and net radiation) (Ma et al., 2012a). Fang et al. (2014a) used the hybrid model to simulate crop growth and energy balance in a wheat-maize cropping system and found that crop growth had a great influence on canopy energy balance, mainly due to its influence on simulated daily transpiration, leaf area index, and soil water content. Latent heat and canopy temperature were better simulated in the mid-crop season than in the early crop season, and latent heat was simulated better for wheat than for maize (Fang et al., 2014a). Yu et al. (2007) reported that sensible heat was simulated with a significantly lower Nash-Sutcliffe model efficiency (0.67) than for net radiation (0.98), latent heat (0.90), or ground heat flux (0.86).

So far, the RZ-SHAW model has not been used to simulate energy balance in a comparative way under both full and deficit irrigation conditions. Usually, the simulated water stress factor has been evaluated using yield loss because water stress can be hard to measure. Bausch et al. (2011) demonstrated that the ratio of canopy temperatures measured in a fully irrigated field and in a water-stressed field can be used as an indicator of water stress. Therefore, there is a need to evaluate the simulated water stress factor using the ratio of canopy temperatures. The objective of this study was to evaluate the performance of the RZ-SHAW model in simulating crop growth, soil moisture and evapotranspiration, surface energy components, canopy temperature, and water stress in fully irrigated and deficit-irrigated corn fields.

MATERIALS AND METHODS

FIELD EXPERIMENT

The field experiment was conducted in 2010 on two adjoining fields at the USDA-ARS Limited Irrigation Research Farm near Greeley, Colorado (40.45° N, 104.64° W). The site contains three soil types: Nunn (fine, smectitic, mesic Aridic Argiustolls), Olney (fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). Weather data were recorded on site with a standard Colorado Agricultural Meteorological Network (http://ccc.atmos.colostate.edu/~coagmet/) weather station (GLY04). In 2010, the average daily growing season (May to October) temperature and precipitation were 17.3°C and 211 mm, respectively, both slightly higher than the equivalent 18-year (1992-2010) average for the site (16.5°C and 191 mm). Two adjoining fields, both 165 m long (N/S) and 155 m wide (E/W), one under full irrigation and one under deficit irrigation, were used to measure crop evapotranspiration (ET_c) by the Bowen ratio energy balance (BREB) method. On May 12, 2010, corn (*Zea mays* L. cv. Dekalb 52-59) was planted in N/S rows at a 0.76 m interrow spacing at an average rate of 81,000 seeds ha^{-1}. The corn crop was harvested on October 19, 2010. Fertilizer as urea-ammonium-nitrate (UAN) was applied at planting and then with irrigation water throughout the growing season on an as-needed basis according to estimated plant growth and expected N uptake. Total N applied was 146 kg N ha^{-1} for both treatments. The irrigation for the two fields (drip irrigation with surface drip tubing adjacent to each row) was designed to meet either 100% (field east) or 55% (field west) of potential crop ET (ET_c) requirements (Ma et al., 2012b) during the growing season. Total irrigation amounts were 29.5 and 17.3 cm for the 100% and 55% ET_c treatments, respectively. For the 100% treatment, irrigation was applied every three to seven days based on the estimated amount of crop water used (actual ET) based on a daily reference ET_o, crop coefficient, rainfall, and soil water deficit (FAO 56; Allen et al., 1998). Total plant-available water (field capacity [FC] minus wilting point soil water) was calculated by assuming the FC to equal the soil water content after a large irrigation or rainfall event that resulted in an increase in soil water content at lower soil depths, while the soil water at wilting point was assumed to be 50% of FC, based on Allen et al. (1998) and Rawls et al. (1982).

A BREB system was installed near the center of each field with a minimum of 60 m fetch within the field. Irrigated agricultural fields surrounded the study fields. Bowen ratio systems were installed on each subplot to calculate crop ET using an energy balance approach. The vertical gradients of air temperature and relative humidity above the corn canopy, which were used to compute the Bowen ratio (β), were measured with REBS aspirated air sensors (Radiation Energy Balance Systems, Inc., Seattle, Wash.) vertically spaced 1 m apart. These sensors were mounted to an exchange mechanism such that the two air sensors periodically exchanged positions at 15 min intervals under data logger control to minimize sensor bias. After each exchange, air temperature and relative humidity were not acquired for 3 min to allow the sensors to equilibrate to their new location. This exchange mechanism was mounted on a vertical mast that allowed continual height adjustment, such that the lower air sensor was maintained 0.15 m above the corn canopy during vegetative growth. Net radiation (R_n) was measured with a REBS Q7 net radiometer mounted to a height-adjustable vertical mast at 2 m above the corn canopy and positioned to the south directly over a corn row. Soil heat flux (G_0) was measured with REBS HFT-3 heat flux plates at two locations: 0.08 m below the soil surface in a corn row and midway between adjacent corn rows within the net radiometer's field-of-view. Soil temperature in the soil layer above the heat flux plates was measured with averaging soil thermocouples installed at 0.02 and 0.06 m depths near the heat flux plates, as well as soil water content sensors (Stevens Hydra Probe II) with their center tines installed at a depth of 0.04 m. Surface soil heat flux was calculated using measured G_0 at 0.08 m, and the change in heat storage above the heat flux plates calculated by the calorimetric method. Averages of the measured parameters were made every 30 min as well as instantaneous measurements of some parameters at the end of each 30 min period. These data were stored in data logger memory and downloaded daily for calculation of latent heat (LE) and sensible heat (H). Detailed information on data processing is available in Bausch and Bernard (1992). Latent heat (LE) was calculated from R_n, G_0, and Bowen ratio (β) as:

$$\mathrm{LE} = \frac{R_n - G_0}{1+\beta} \tag{1}$$

The BREB system had previously been evaluated against lysimeter-measured latent heat (plant transpiration) by Bausch and Bernard (1992) and had shown a less than 10% error during the course of a corn growth season. Bowen ratio measured latent heat was converted to actual ET following procedures outlined by Bausch and Bernard (1992). Sensible heat (H) was then calculated as:

$$H = R_n - \mathrm{LE} - G_0 \tag{2}$$

To measure the canopy temperature, an infrared thermometer (IRT) (Apogee IRR SI-121) was installed on the mast 2 m above the crop surface and positioned at a 63° view angle (27° below horizontal) and at 45° east from north, so as to look across the north/south planted crop rows. The 18° half-angle field of view IRT theoretically viewed an area of 24 m^2. Two additional IRTs were positioned on vertically adjustable masts 30 m north and south of the Bowen ratio mast to provide additional crop surface temperature data. The BREB and canopy temperatures presented in this study were recorded from June 18 to September 26 in 2010.

During the whole growing season, canopy ground cover was measured about twice a week before August 1, 2010, and then once in two weeks using a nadir view digital camera. The measured canopy cover was converted to corn leaf area index (LAI) using the equation in Farahani and DeCoursey (2000). Plant height was measured using a ruler twice a week from June 10 to August 4, 2010. Soil water content was measured twice a week with a portable time domain reflectometry (TDR) for the 0-15 soil layer and with a neutron attenuation moisture probe for the soil layers at depths of 15 to 200 cm in 30 cm intervals. Actual ET was also estimated using the water balance method assuming no surface runoff or deep seepage, as follows:

$$\mathrm{ET} = P + I + \left(\mathrm{SWS}_i - \mathrm{SWS}_e\right) \tag{3}$$

where ET is actual evapotranspiration (cm), P is precipitation (cm), I is irrigation (cm), and SWS_i and SWS_e are initial and end soil water storage (cm) during a given period.

RZ-SHAW Model

The RZ-SHAW model was described in detail by Fang et al. (2014a). Here, only the plant water stress calculations are presented. Two water stress factors in the CERES-Maize model are implemented as a crop growth module in RZ-SHAW. One is primarily responsible for the expansion of leaf growth and is termed turgor factor (TURFAC). The other is responsible for photosynthesis and other dry matter accumulation and is termed SWFAC. TURFAC is computed as:

$$\mathrm{TURFAC} = \frac{\mathrm{SWFAC}}{\mathrm{RWUEP1}} \tag{4}$$

where RWUEP1 is a species-specific parameter used for evaluating water stress impact on expansion growth of cells (currently set at 1.5 for corn), and SWFAC is computed as the ratio of DSSAT potential root water uptake to Shuttleworth-Wallace potential transpiration:

$$\mathrm{SWFAC} = \frac{\sum \mathrm{RWU}(L) \times \mathrm{RLV}(L) \times \Delta L}{\mathrm{PT}} \tag{5}$$

$$\mathrm{RWU}(L) = \frac{k_1 \times e^{k_2 \times [\mathrm{SW}(L) - \mathrm{LL}(L)]}}{k_3 - \ln[\mathrm{RLV}(L)]} \tag{6}$$

where

k_1, k_2, and k_3 = constants (dimensionless). In DSSAT v3.5, $k_1 = 1.32 \times 10^{-3}$, $k_2 = 120 - [250 \times \text{LL}(L)]$, and $k_3 = 7.01$ (Ritchie, 1998)

LL(L) = lower limit of plant-available water in the soil layer ($cm^3\ cm^{-3}$)

PT = potential transpiration (cm)

RLV(L) = root length density in the soil layer (cm root cm^{-3} soil)

RWU(L) = potential root uptake per unit root length for soil layer L (cm^3 water cm^{-3} root)

ΔL = depth of soil layer (cm)

SW(L) = current soil water content in the soil layer ($cm^3\ cm^{-3}$).

Potential transpiration is calculated using the Shuttleworth-Wallace equation (Farahani and DeCoursey, 2000):

$$\text{PT} = \frac{\Delta\left[(R_n - G) - R_{nsub}\right] + \rho c_p \left(\text{VPD}_0\right)/r_a^c}{\left[\Delta + \gamma\left(1 + r_s^c / r_a^c\right)\right]} \tag{7}$$

where

c_p = volumetric heat capacity of air (MJ m^{-3} °C^{-1})

r_a^c = bulk boundary layer resistance of the canopy elements within the canopy (s m^{-1})

r_s^c = bulk stomatal resistance of the canopy (s m^{-1})

G = heat flux below the canopy (MJ m^{-2})

R_n = net radiation above the canopy (MJ m^{-2})

R_{nsub} = net radiation over the bare soil and residue (MJ m^{-2})

VPD_0 = air vapor pressure deficit at the mean canopy height (kPa)

γ = psychrometric constant (kPa °C^{-1})

λ = latent heat flux (MJ kg^{-1})

ρ = density of air (kg m^{-3})

Δ = slope of the saturation vapor pressure versus temperature curve (kPa °C^{-1}).

According to equation 29 in Flerchinger (2000), canopy temperature is computed from sensible heat, which is the difference of all-wave radiation diffused onto leaves and latent heat loss due to water evaporation. Based on equation 27 in Flerchinger (2000), canopy temperature in a given layer can be expressed as:

$$T_{leaf} = \frac{H \times r_h}{\rho_a \times c_a \times \text{LAI}} + T_{air} \tag{8}$$

where

c_a = specific heat capacity of the ambient air (J kg °C^{-1})

r_h = resistance to convective transfer from canopy layer (s m^{-1})

H = sensible heat flux from leaves to air space (W m^{-2})

LAI = leaf area index in the particular layer

T_{air} = ambient temperature of the air (°C)

T_{leaf} = canopy (leaf) temperature (°C)

ρ_a = density of the ambient air (kg m^{-3}).

MODEL SIMULATIONS

The model was calibrated against measured data for the full irrigation (100% ET) field in terms of grain yield, LAI, plant height, ET, and soil water content and was validated using those data from the deficit irrigation field (55% ET). The energy balance data from both the full and deficit irrigation fields, including sensible and latent heat fluxes obtained from the Bowen ratio method and measured net radiation and ground heat flux, as well as canopy temperature, were used to evaluate the performance of RZ-SHAW in predicting energy exchange, canopy temperature, and water stress. To evaluate the performance of RZ-SHAW in simulating water stress, the simulated water stress factor in the deficit irrigation field was plotted in a graph with observed canopy temperatures in both the full and deficit irrigation fields. Because leaf expansion terminated around July 20, water stress was set as TURFAC before July 20 and SWFAC after July 20. Computed water stress using the ratio of measured canopy temperature in the deficit-irrigated corn to the fully irrigated corn canopy from 13:00 to 15:00 MST, as described by Bausch et al. (2011), was compared to the RZ-SHAW-simulated water stress factor as well.

In the calibration procedure, crop, soil, and albedo parameters were adopted from Fang et al. (2014b), who calibrated them for the same cultivar (Dekalb 52-59) in a neighboring field at the same experimental site using PEST. Preliminary results showed that corn yield and ET were generally simulated well, but LAI and plant height were underestimated and soil water content for most layers was not in an acceptable range. Therefore, the parameter PHINT (phylochron interval in thermal time between successive leaf tip appearances) was set back to the value (50) calibrated by Ma et al. (2012b) in order to achieve a better simulation of LAI. Since CERES-Maize does not simulate plant height, RZ-SHAW calculated plant height based on stover biomass (Fang et al., 2014b). To estimate maize canopy height, two additional parameters for the maximum canopy height at maturity (H_{max}, cm) and plant stem biomass at half of maximum canopy height (*Stem_half*, g) were introduced and used to estimate maize canopy height:

$$\text{Height} = H_{max} \times \left(1 - e^{-\alpha stem / 2H_{max}}\right) \tag{9}$$

$$\alpha = \frac{-2H_{max} \times \ln(0.5)}{Stem\_half} \tag{10}$$

where *stem* is aboveground biomass minus maize yield (stem biomass).

We found that H_{max} = 270 cm and *Stem_half* = 30 g provided good simulation of maize canopy height for the fully irrigated treatment. Soil hydraulic parameters were adjusted slightly to get a better simulation of soil water content for each soil layer. Calibrated soil hydraulic parameters are listed in table 1. Values of soil albedo and crop residue on the soil surface, which are related to ET and surface energy exchange, were not changed from those used by Ma et al. (2012b) and Fang et al. (2014b) because the simulated ET in the fully irrigated corn was satisfactory. The calibration of soil parameters for the full irrigation field in this study may be justified because of spatial variability of soil properties in the field and the interactions between soil and plant parameters (Ma et al., 2015). Furthermore, the soil hydraulic parameters were adjusted for the deficit irrigation

Table 1. Soil hydraulic properties for full irrigation.[a]

Depth (m)	BD (Mg m^{-3})	Sand (%)	Silt (%)	P_b (cm)	λ	K_{sat} (mm h^{-1})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	θ_{33} (cm^3 cm^{-3})	θ_{10} (cm^3 cm^{-3})	θ_{1500} (cm^3 cm^{-3})
0-0.15	1.492	85	10	36.0	0.22	20.0	0.035	0.437	0.280	0.355	0.140
0.15-0.30	1.492	85	10	43.8	0.22	50.0	0.035	0.437	0.291	0.369	0.150
0.30-0.60	1.492	85	10	35.0	0.18	50.0	0.035	0.437	0.303	0.368	0.170
0.60-0.90	1.568	81	8	26.7	0.16	50.0	0.035	0.408	0.284	0.337	0.170
0.90-1.20	1.568	81	8	25.8	0.18	50.0	0.035	0.408	0.268	0.325	0.150
1.20-1.50	1.617	85	4	24.4	0.19	40.0	0.035	0.390	0.251	0.306	0.140
1.50-2.00	1.617	88	3	26.2	0.18	40.0	0.035	0.390	0.261	0.314	0.150

[a] BD = bulk density, P_b = air entry pressure, λ = pore size distribution index, K_{sat} = saturated hydraulic conductivity, θ_r = residual water content, θ_s = saturated water content, θ_{33} = soil water content at 33 kPa, θ_{10} = soil water content at 10 kPa, and θ_{1500} = soil water content at 1500 kPa. Bulk density, sand, and silt are measured; other properties are calibrated against soil water content.

field against measured soil water content data because soil surveys and experience with the fields showed that the soil type in the full irrigation field (predominately Nunn Series No. 41) was different from that in the deficit irrigation field (predominately Dacono Series No. 21). Adjusted soil hydraulic parameters are listed in table 2. It should be noted that the adjustment of soil hydraulic parameters for better simulation of soil water content in the deficit irrigation field barely changed the results for energy balance and canopy temperature. It should also be noted that Fang et al. (2014b) did not calibrate plant height, which may have affected their potential ET (PET) calculations.

Evaluation Statistics

Mean difference (MD), coefficient of determination (R^2), Nash-Sutcliffe model efficiency (ME), and root mean squared error (RMSE) were used as statistical factors to evaluate the goodness of fit between simulated and measured values:

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right) \tag{11}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i-\bar{O}\right)\left(P_i-\bar{P}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2\sum_{i=1}^{n}\left(P_i-\bar{P}\right)^2} \tag{12}$$

$$\mathrm{ME} = 1.0 - \frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2} \tag{13}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i-O_i\right)^2} \tag{14}$$

where

n = number of data pairs

$\bar{O}$ and $\bar{P}$ = mean measured and simulated values, respectively

O_i = ith measured value

P_i = ith predicted value.

The ratio of MD to the measured mean is defined as the relative MD. It is difficult to set a simple criterion to determine model performance due to the characteristics of various data sets. However, to reduce the complexity, in this study, the model performance is considered satisfactorily when ME ≥ 0.5, and other statistics are used for comparison with other studies.

Table 2. Calibrated soil hydraulic parameters for deficit irrigation.[a]

Depth (m)	P_b (cm)	λ	θ_{33} (cm^3 cm^{-3})	θ_{10} (cm^3 cm^{-3})	θ_{1500} (cm^3 cm^{-3})
0-0.15	35.0	0.29	0.244	0.331	0.104
0.15-0.30	35.0	0.25	0.264	0.311	0.123
0.30-0.60	30.0	0.21	0.277	0.347	0.144
0.60-0.90	25.0	0.22	0.246	0.310	0.126
0.90-1.20	30.0	0.22	0.255	0.321	0.130
1.20-1.50	34.0	0.15	0.288	0.338	0.178
1.50-2.00	60.0	0.10	0.334	0.372	0.239

[a] P_b = air entry pressure, λ = pore size distribution index, θ_{33} = soil water content at 33 kPa, θ_{10} = soil water content at 10 kPa, and θ_{1500} = soil water content at 1500 kPa.

Results and Discussion

Model Calibration

Simulated yield in the calibration (full irrigation) field was 10.528 Mg ha^{-1}, which was within 3% error of the measured value of 10.908 Mg ha^{-1}. Simulated LAI and plant height are shown in figure 1, and all the pertinent statistics are shown in table 3 (full irrigation). In general, the simulated LAI and plant height were in good agreement with measured data for the calibration field. The RMSE was 0.46 for simulated LAI and 13.93 cm for simulated plant height. The accuracy of the simulation of LAI and

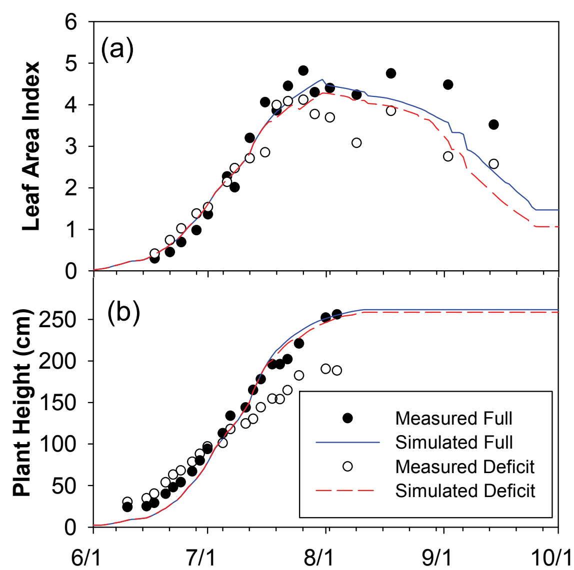

Figure 1. Simulated versus measured (a) LAI with full and deficit irrigation and (b) plant height with full and deficit irrigation.

Table 3. Statistics of comparison for simulated versus measured crop growth, ET and soil water, energy balance, and canopy temperature for the calibration (full irrigation) and validation (deficit irrigation) fields.

Statistics[a]	Calibration (Full Irrigation)[b]						Validation (Deficit Irrigation)[b]					
	Obs.	Sim.	MD	R^2	ME	RMSE	Obs.	Sim.	MD	R^2	ME	RMSE
Grain yield (Mg ha^{-1})	10.908	10.528	-0.380	-	-	-	8.771	8.413	-0.358	-	-	-
Maximum LAI	4.82	4.56	-0.16	0.94	0.92	0.46	4.12	4.27	0.08	0.91	0.88	0.40
Max. plant height (cm)	256	262	-4.79	0.99	0.97	13.93	191	255	9.22	0.98	0.48	36.80
ET (mm d^{-1})	5.4	4.8	-0.59	0.84	0.76	1.06	4.4	3.9	-0.47	0.86	0.78	0.91
SWS (0-200 cm)	40.12	40.20	0.076	0.88	0.88	1.18	38.87	39.05	0.185	0.86	0.84	1.64
SWC (all seven layers)	0.20	0.20	0.000	0.64	0.62	0.02	0.19	0.19	0.004	0.85	0.85	0.02
SWC (0-15 cm)	0.19	0.19	0.005	0.40	0.38	0.04	0.13	0.14	0.007	0.27	0.25	0.04
SWC (15-30 cm)	0.19	0.20	0.011	0.55	0.51	0.02	0.14	0.15	0.015	0.57	0.51	0.03
SWC (30-60 cm)	0.22	0.22	-0.004	0.81	0.77	0.01	0.16	0.17	0.003	0.59	0.52	0.02
SWC (60-90 cm)	0.21	0.21	-0.005	0.86	0.77	0.01	0.15	0.15	-0.002	0.76	0.64	0.01
SWC (90-120 cm)	0.18	0.18	-0.001	0.79	0.63	0.01	0.16	0.16	-0.005	0.86	0.83	0.01
SWC (120-150 cm)	0.19	0.19	0.000	0.74	0.73	0.01	0.21	0.22	0.009	0.95	0.70	0.01
SWC (150-200 cm)	0.20	0.20	0.003	0.66	0.67	0.01	0.29	0.28	-0.006	0.80	0.68	0.01
R_n (W m^{-2})	158.8	128.5	-30.21	0.98	0.96	51.79	154.0	121.9	-32.15	0.99	0.96	47.30
LE (W m^{-2})	157.2	142.8	-14.39	0.90	0.88	71.89	123.9	114.4	-9.50	0.87	0.86	62.05
H (W m^{-2})	-0.70	-18.65	-17.94	0.64	0.57	56.12	26.59	1.27	-25.31	0.74	0.59	52.86
G (W m^{-2})	2.26	4.32	2.06	0.72	0.57	28.23	3.56	6.19	2.63	0.71	0.61	33.61
T_{canopy} (°C)	18.64	20.23	1.59	0.91	0.84	2.77	19.27	20.43	1.16	0.90	0.87	2.78

[a] LAI = leaf area index, ET = evapotranspiration, SWS = soil water storage (cm), SWC = soil water content (cm^3 cm^{-3}), R_n = net radiation, LE = latent heat, H = sensible heat, G = ground heat flux, and T_{canopy} = canopy temperature.

[b] Obs. = measured average, Sim. = simulated average, MD = mean difference, R^2 = coefficient of determination, ME = Nash-Sutcliffe model efficiency, and RMSE = root mean squared error.

plant height was comparable to that of Fang et al. (2014a, 2014b). The underestimation of LAI in the late stage (after August 1) was possibly due to: (1) the crop parameters such as senescence GDD were too short or the abscission rate of leaves was too high, and (2) the leaf area was affected by water stress due to termination of irrigation after September 1, 2010. The senescence GDD is not adjustable through the user interface, but the model can run with water stress ignored, which means full water supply across the entire growing season. The simulated LAI in the late season showed no improvement with no water stress. Therefore, we suspect that the underestimated LAI was attributable to the high constant leaf abscission rate of 5% per day set by the model. This percentage might be too high in the late growing season because the measured decrease in LAI due to water stress in the late growing season was minor. Comparatively, with the model's 5% abscission rate, LAI would be reduced to 60% some ten days after leaf expansion ceased, i.e., $(1 - 5\%)^{10}$.

The simulated daily ET in the calibration field was generally in good agreement with ET measured with the Bowen ratio equipment (fig. 2a). The R^2 and ME for ET simulation were 0.84 and 0.76, respectively (table 3). Our simulation was comparable to that of Ma et al. (2012a) in terms of statistical values. ET was generally underestimated (by 11%), particularly during the major crop growing period of July and August. During the irrigation period, the simulated PET was lower than actual ET (AET) measured by the Bowen ratio instruments. When the albedo of fresh residue was reduced from 0.4 to 0.22 and stomatal resistance decreased from 200 to 100 s m^{-1}, simulated PET was generally higher than measured AET, but simulated AET showed an increase of about 1% and the ME was reduced to 0.49. We suspect that the AET measured by the Bowen ratio instruments was higher than the true AET. The AET computed using the water balance method was the maximum possible ET because other water losses, such as runoff and

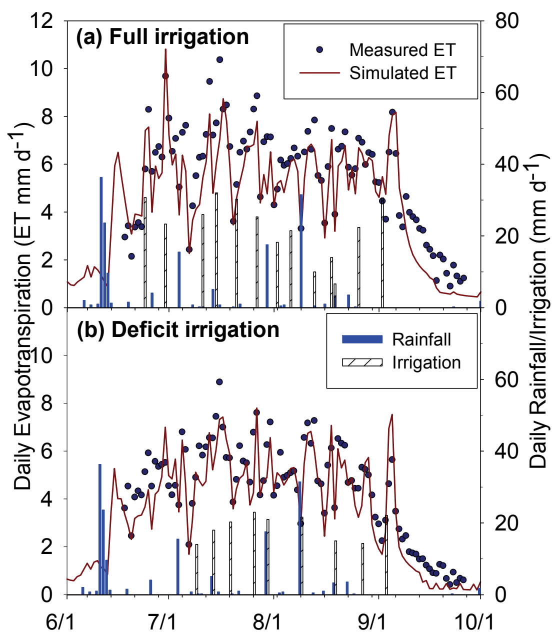

Figure 2. Simulated and Bowen ratio measured daily ET for (a) full irrigation and (b) deficit irrigation corn fields.

deep seepage, were assumed to be zero. Bowen ratio measured ET exceeded the maximum possible ET from the water balance method in both the full and deficit irrigation fields (table 4), suggesting an overestimation of ET from the Bowen ratio method. For example, in the fully irrigated field, during the monitoring period from June 21 to September 20, the measured total ET for the fully irrigated field was 53.27 cm from the Bowen ratio method, about 13% higher than the estimated ET of 46.99 cm from the water balance method, assuming no runoff or seepage (table 4, full irrigation). Therefore, we did not adjust the albedo parameters to increase simulated PET because that would not have improved our simulation of AET.

Table 4. Evapotranspiration as computed using water balance method and measured using Bowen ratio method in 2010 (units are cm).[a]

	Beginning Date	End Date	Rainfall	Irrigation	SWS_b	SWS_e	ET Water Balance	ET Bowen Ratio	ET Simulated
Full irrigation	21 June	2 July	0.41	5.40	43.95	44.98	4.77	7.37	7.15
	3 July	15 July	2.18	5.80	44.98	44.31	8.66	8.34	6.72
	16 July	2 August	1.96	7.37	44.31	40.38	13.26	12.22	10.75
	3 August	13 August	3.33	3.15	40.38	40.98	5.87	6.90	6.23
	14 August	1 Sept.	0.81	4.30	40.98	38.16	7.94	11.28	10.40
	2 Sept.	20 Sept.	0.00	3.06	38.16	34.72	6.50	7.16	6.21
	21 June	20 Sept.	8.69	29.08	43.95	34.72	46.99	53.27	47.46
Deficit irrigation	21 June	2 July	0.41	0.00	46.53	44.41	2.53	5.87	5.09
	3 July	15 July	2.18	3.20	44.41	42.22	7.57	7.07	6.22
	16 July	2 August	1.96	6.43	42.22	40.03	10.57	10.35	9.61
	3 August	13 August	3.33	2.16	40.03	36.95	8.57	6.07	5.75
	14 August	1 Sept.	0.81	2.93	36.95	36.42	4.27	9.12	8.19
	2 Sept.	20 Sept.	0.00	2.21	36.42	34.72	3.92	4.14	3.41
	21 June	20 Sept.	8.69	16.93	46.53	34.72	37.43	42.63	38.27

[a] SWS_b = soil water storage at the beginning of the period (cm), SWS_e = soil water storage at the end of the period (cm), and ET = total evapotranspiration during the period (cm).

The soil water content for each layer and the soil water storage for the whole soil profile were well simulated by the RZ-SHAW model in the calibration field (fig. 3, full irrigation). When comparing simulated soil water content with that measured for all soil layers, the ME and RMSE were 0.62 and 0.018 cm^3 cm^{-3}, respectively. For each soil layer, RMSE ranged from 0.005 to 0.038 cm^3 cm^{-3} and ME exceeded 0.50, except for the top layer (0 to 0.15 m). For the simulation of total soil water storage, R^2 and ME were both equal to 0.88 (table 3). The simulation with manually calibrated soil hydraulic parameters matched measured soil water content better than the simulation with parameters auto-calibrated by PEST in a neighboring field at the same site (Fang et al., 2014b), where ME was -0.44 to 0.25 and R^2 was 0.30 to 0.66 for different soil layers. Another manual calibration (Qi et al., 2013) also showed higher ME (from -0.04 to 0.82) for a seven-year soil water content data set.

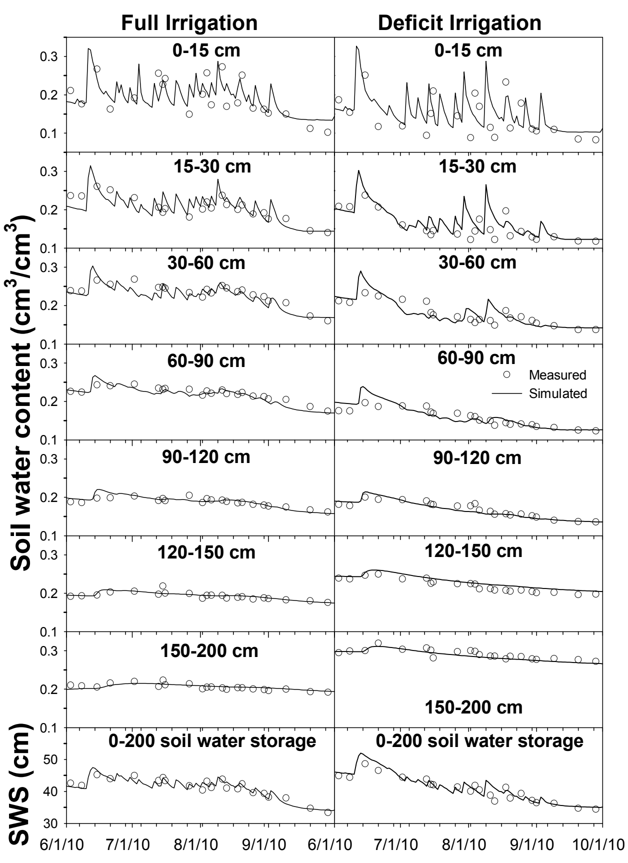

Figure 3. Simulated and measured soil water content and soil water storage (SWS) for the full irrigation field (left) and deficit irrigation field (right).

MODEL VALIDATION

Under water-stressed conditions in deficit irrigation, the model successfully predicted corn grain yield of 8.413 Mg ha^{-1}, within 4% of the measured yield of 8.771 Mg ha^{-1}. The validation procedure showed that the calibrated model performed well in simulating LAI, ET, and soil water storage (0 to 200 cm soil profile) in the deficit irrigation field, with R^2 greater than 0.75, ME greater than 0.50, and relative MD within ±15% (table 3, deficit irrigation). Although the comparison statistics were close to or within acceptable ranges for the simulation of plant height in deficit-irrigated corn (ME = 0.48, R^2 = 0.98, and relative MD = 8.3%), plant height was generally underestimated in the early growth season and overestimated in the late growth season (fig. 1b). In fact, the simulated plant height of deficit-irrigated corn was similar to that of fully irrigated corn across the entire growing season.

The soil water content simulated using adjusted soil hydraulic parameters is shown in figure 3 (deficit irrigation), and the statistical values for the simulations of LAI, ET, and soil water content and storage listed in table 3 indicate good performance of the model (figs. 1 and 2). Measured soil water storage for the 0-200 cm soil depth in the deficit-irrigated field was 40.37 cm, very close to the measured value of 40.90 cm in the fully irrigated field. The soil water storage in the deficit-irrigated field was not less than that in the fully irrigated field because there was high soil water content in the 120-200 cm depth in the deficit-irrigated field. When comparing soil water storage in the 0-120 cm depth, the soil water storage was 24.95 cm in the fully irrigated field, about 30% higher than the soil water storage in the 0-120 cm depth in the deficit-irrigated field, which suggests different soil hydraulic properties and necessary adjustment of those soil parameters for the deficit-irrigated field.

Energy Balance Simulation

Simulated net radiation (R_n) was in good agreement with measured data. The coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (ME) were both greater than 0.95 for the full and deficit irrigation treatments (table 3). Simulated and measured energy balance components for the 20th to the 22nd day of June, July, August, and September are plotted in figure 4. Measured R_n values in the full and deficit irrigation fields were similar before maturity; after maturity, measured R_n in the full irrigation field was slightly higher than that in the deficit irrigation field. However, overall simulated R_n values in the full and deficit irrigation fields were similar during the entire observation period. Although the statistics showed a good agreement, the model performed better in the early stage of corn growth and tended to underestimate R_n after silking (figs. 4(2), 4(3), and 4(4)). Given that the simulated LAI was reasonable before mid-August (fig. 1), and reducing the albedo of fresh corn leaves could not increase simulated R_n, the underestimated R_n during the growing season is likely due to an overestimation of the extinction coefficient for corn (eq. 4 in Flerchinger, 2000), which may result in an underestimated radiation transmissivity in the corn canopy. The simulated LAI of the deficit-irrigated corn was lower than that of fully irrigated corn after mid-July, but the predicted R_n values for both treatments were very simi-

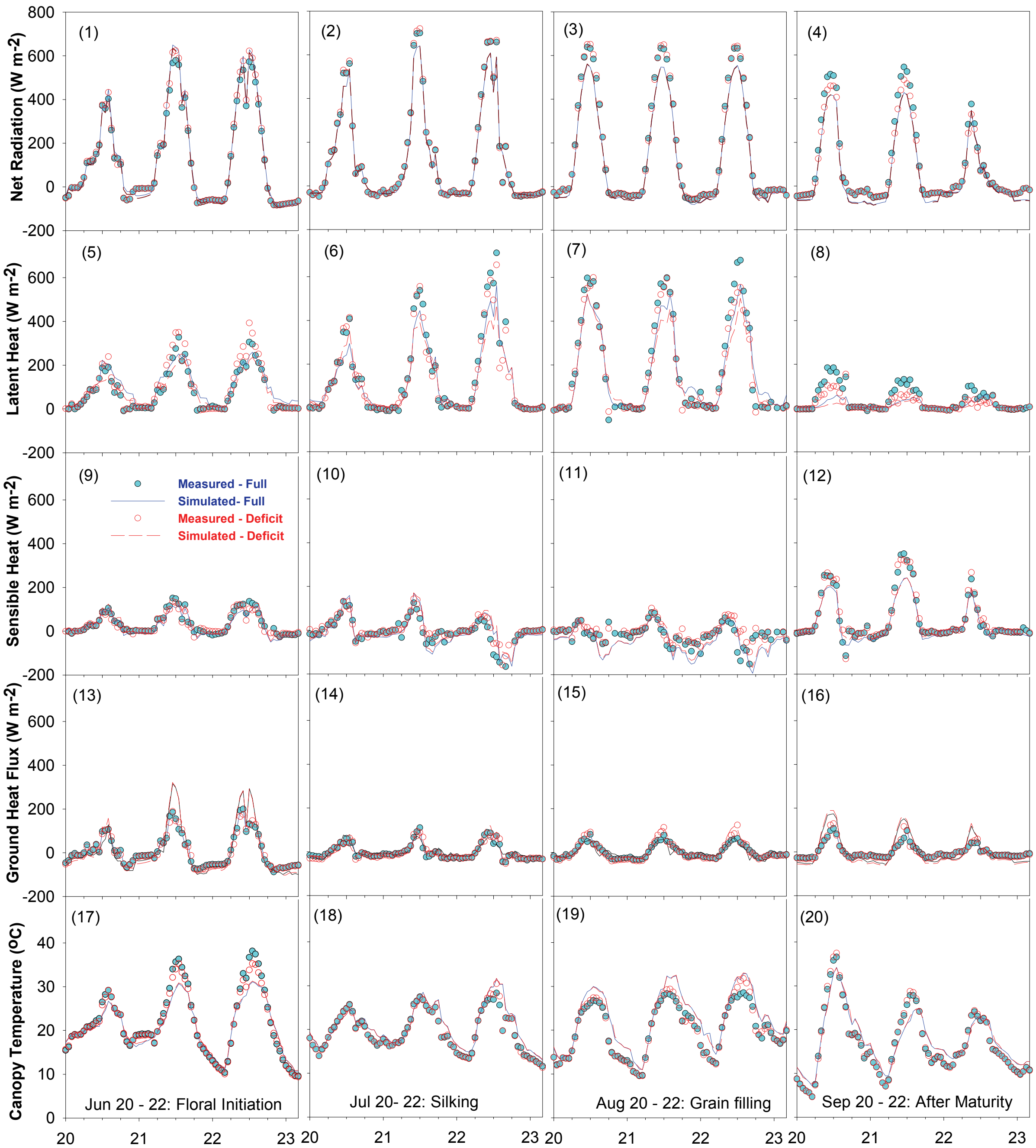

Figure 4. Simulated and measured energy balance and canopy temperature in full and deficit irrigation corn fields.

lar in this period. This result suggests that R_n is not sensitive to LAI in the model.

Simulated latent heat (LE) was in a good agreement with measured data. The coefficient of determination (R^2) and ME were both greater than 0.85, and relative MD was within ±15% for both the full and deficit irrigation treatments (table 3). Similar to R_n, LE was underestimated throughout the growing season (figs. 4(5) to 4(8)), particularly after maturity. Nevertheless, the difference in LE between the full and deficit irrigation fields was well simulated. The measured hourly latent heat in the full irrigation field was 27% higher than the measured average in the deficit irrigation field, which was comparable to the 25% difference simulated by RZ-SHAW.

Simulated sensible heat (H) was generally acceptable with ME ≥ 0.64, although it was slightly underestimated in both the full and deficit irrigation fields, particularly during the grain filling period, when corn had a fully developed canopy, and after maturity (figs. 4(11) and 4(12)). The measured hourly sensible heat average was -0.7 W m^{-2} in the full irrigation field, compared to a simulated average value of -18.5 W m^{-2} (table 3). The mean differences (MD) between simulated and measured hourly sensible heat were -17.9 and -25.3 W m^{-2} for the full and deficit irrigation fields, respectively. In comparison to Ma et al. (2012a), the MD values were higher, but the R^2 and ME values were comparable. However, the model correctly simulated the response of sensible heat to deficit irrigation. The simulation showed a lower sensible heat of 20.0 W m^{-2} in the full irrigation field than in the deficit irrigation field, which was comparable to the measured value of 27.3 W m^{-2}. The ME value for simulation of H was significantly lower than for R_n and LE, similar to the results reported by Yu et al. (2007).

Although ground heat flux (G_0) was generally overestimated in the early and late growing season (figs. 4(13) and (16)), it was simulated reasonably well in terms of statistics (table 3). For the full irrigation field, the G_0 values were comparable to the values under a soybean canopy reported by Ma et al. (2012a). When converted to total energy during the observation period (101 days from June 18 to September 26), the measured G_0 values were 19.7 and 31.1 MJ m^{-2} for the fully irrigated and deficit-irrigated fields, respectively, and the MD values of the G_0 simulations were 18.0 and 23.0 MJ m^{-2}, respectively, which are comparable to the MD values reported by Fang et al. (2014a).

Measured total G_0 during the entire growing season was only about 1% to 2% of total R_n, and is usually neglected when computing daily ET using methods such as the Penman-Monteith equation. However, the diurnal peak G_0 values were about 30% of the peak R_n during the early growing season when LAI was small, 15% during the middle growth stage when LAI was large, and 20% during the late growing season as LAI declined. Therefore, simulation of G_0 is important to the prediction of daily ET.

The performance of RZ-SHAW in this study was comparable to other models in simulating energy balance. In comparison to a model developed by Cammalleri et al. (2010) where MD was between 14.5 and 43.3 W m^{-2}, ME was between 0.29 and 0.98, and RMSE ranged from 19.3 to 55.2 W m^{-2} for all energy balance components, RZ-SHAW showed lower MD, similar ME, but slightly higher RMSE values. Li et al. (2013) reported R^2 values of 0.82 and 0.89 for LE and R^2 values of 0.60 and 0.63 for H simulations using a newly coupled model. The R^2 values for RZ-SHAW in this study were 0.88 and 0.86 for LE, and 0.57 and 0.59 for H, close to the values reported by Li et al. (2013). Papadavid et al. (2013) only reported simulated ET using a modified SEBAL (Surface Energy Balance Algorithm for Land) model, with 9.2% error from measured ET using an evaporation pan. In our simulation, the error was 10.9% for ET simulation in both the full and deficit irrigation fields. Song et al. (2013) only listed Willmott's index (0.90 to 0.83 for R_n, 0.77 to 0.47 for H, and 0.50 to 0.77 for LE) when simulating energy and water balance using a modified Integrated Science Assessment Model (ISAM). Willmott's index was not calculated in our study, but the ME values for RZ-SHAW were slightly higher than those reported for Willmott's index by Song et al. (2013).

CANOPY TEMPERATURE

The simulated hourly canopy temperature was in good agreement with measured values in both the full and deficit irrigation fields (figs. 4(17) to 4(20)). The statistical values were greater than 0.90 for R^2, 0.85 for ME, and less than 10% for relative MD (table 3). Simulated diurnal peak temperature matched the measured values better during the high LAI period (silking to grain filling) than during the early and late seasons of corn growth, when the diurnal peak temperature was usually underestimated (fig. 4). The underestimated canopy temperature in the early and late growing seasons is attributed to underestimated sensible heat. In the early season when total LE was underestimated (i.e., June 20-22, floral initiation in fig. 4(5)), the underestimated H was clearly a result of underestimated heat diffusion onto canopy layers from R_n above the canopy. In the late season (i.e., Sept. 20-22, after maturity), the underestimated H (fig. 4(12)) may be attributed to both the underestimated heat diffusion and the underestimated R_n (fig. 4(4)).

The simulated magnitude of difference in temperature was not as high as the measured values, particularly at noon. For example, the average measured daytime (9:00 a.m. to 5:00 p.m.) canopy temperatures from June 24 through June 28 in the deficit irrigation field were 0.9°C, 5.0°C, 2.6°C, 1.8°C, and 2.8°C higher, respectively, than in the full irrigation field. However, the simulated differences in canopy temperature were 1.9°C, 1.2°C, 1.0°C, 0.5°C, and 0.7°C, respectively. When averaged over the entire observation period, the mean simulated canopy temperature in the deficit-irrigated field was 0.2°C higher than in the fully irrigated field, while the measured difference was 0.63°C. Using July 24 as an example date when simulated H in deficit-irrigated corn was higher than in fully irrigated corn, at 12:00 p.m. the simulated total H was 86 versus 119 W m^{-2} in the full and deficit irrigation fields, respectively, and simulated total LAI was 4.2 versus 3.9. However, the simulated canopy temperature showed no difference (25.1°C for both full and deficit irrigation fields). This suggests that the resistance to heat transfer (r_h) in equation 13 must be underestimated for deficit-irrigated corn relative to fully irrigated non-stressed corn, or that heat storage by the corn canopy cannot be ignored, particularly when one wants to differentiate corn canopy temperature under full and deficit irrigation. This is supported by a field experiment showing that the canopy water mass in corn was significantly lower in water-stressed corn than in fully irrigated corn (Winterhalter et al., 2011).

Water Stress

Water stress simulated by RZ-SHAW using the temperature ratio method of Bausch et al. (2011) was compared with the canopy temperature difference between the two irrigation treatments (fig. 5). Canopy temperature in the deficit irrigation field was higher than in the full irrigation field on many days of the irrigation period, indicating overheating due to less canopy evaporation. RZ-SHAW-simulated water stress represented the overheating in the deficit irrigation field well, starting from mid-July to late August (figs. 5b and 5c). For example, on July 25, the measured maximum temperatures were 32.6°C versus 27.3°C in the deficit and full irrigation fields, respectively. The water stress factor simulated by the model was 0.54 on that day.

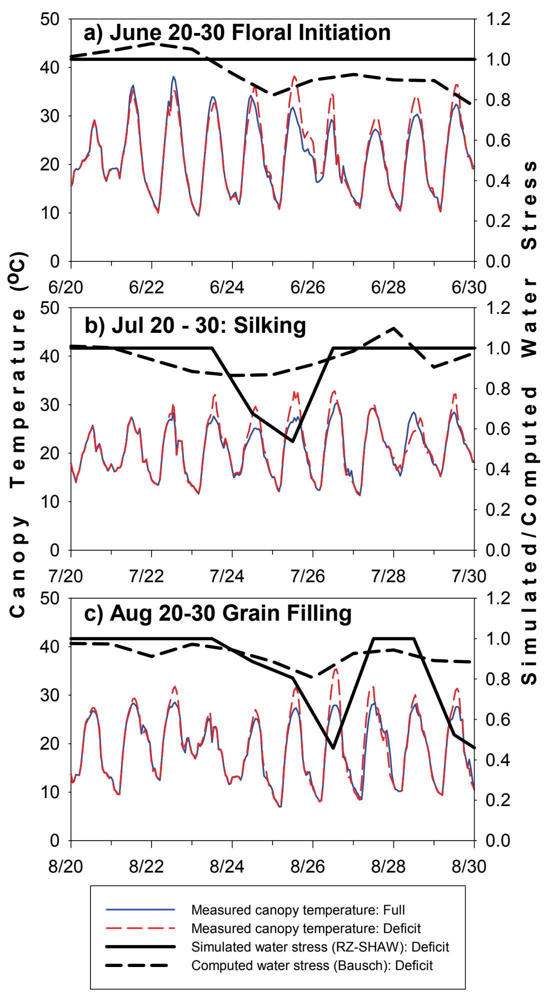

Figure 5. Measured canopy temperature in fully irrigated and deficit-irrigated fields and water stress in the deficit-irrigated field as simulated using RZ-SHAW and computed using Bausch et al. (2011).

However, RZ-SHAW underestimated water stress during the early growing stage when the canopy temperature in the deficit-irrigated field was generally higher than in the fully irrigated field (fig. 5a). From June 24 to 28, the measured canopy temperature (9:00 a.m. to 5:00 p.m.) in the deficit-irrigated field was 0.9°C to 2.5°C higher than in the fully irrigated field. Average measured Bowen ratio ET in the deficit-irrigated field was 5.30 mm d^{-1}, about 20% lower than in the fully irrigated field (6.59 mm d^{-1}). RZ-SHAW simulated the reduced ET in the deficit-irrigated field with an average ET of 3.87 mm d^{-1}, about 36% lower than the simulated ET in the fully irrigated field (6.05 mm d^{-1}). However, RZ-SHAW did not simulate water stress on those days.

Compared to water stress computed using the canopy temperature ratio method of Bausch et al. (2011), RZ-SHAW-simulated water stress showed a similar average but a different temporal pattern. Averaged from June 18, when measurement of energy balance initiated, to September 3, when irrigation terminated, the water stress factor was 0.93 for both RZ-SHAW and the temperature ratio method. However, RZ-SHAW indicated that water stress in the deficit-irrigated field occurred in 13 days, while the temperature ratio method showed water stress in 73 days. The range of RZ-SHAW-simulated water stress was 0.34 to 1, versus 0.75 to 1 for the temperature ratio method. However, the temperature ratio method has a high uncertainty depending on the time of temperature measurement (in our case, 13:00 to 15:00 MST) as well as the integration methods (DeJonge et al., 2015).

Conclusions

The performance of the newly released RZ-SHAW model was evaluated against data collected from full and deficit irrigation corn fields in eastern Colorado. The measured data included crop growth, water, energy balance, and canopy temperature. According to widely used statistics, the model generally performed satisfactorily in simulating corn yield, LAI, daily ET, soil water content, net radiation, latent heat, sensible heat, ground heat flux, and canopy temperature under both full and deficit irrigation. The model also satisfactorily predicted the response of corn yield and ET to water stress. The RZ-SHAW-simulated water stress factor under deficit irrigation showed a similar average value but a different temporal pattern compared to water stress computed using the temperature ratio method. The model performance was not acceptable in terms of simulating plant height for deficit-irrigated corn, and the simulated canopy temperature increase in deficit-irrigated fields compared with fully irrigated fields was about 30% of the observed increase. To predict the canopy temperature difference between fully irrigated and deficit-irrigated corn more accurately, attention should be paid to re-evaluating the parameter for resistance to heat transfer from the canopy layer to the air space, or including the heat capacity of the corn canopy water mass in the energy balance module. Therefore, the RZ-SHAW model can be used to evaluate the response of corn yield to water stress and the exchange of energy in a corn field under climate conditions similar to those of eastern Colorado, while the simulation of the response of plant height and canopy temperature to water-stressed conditions for corn needs improvement.

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