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Evaluating Various Water Stress Calculations in RZWQM and RZ-SHAW for Corn and Soybean Production

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ABSTRACT

Better understanding of water stress calculation is needed to improve crop production simulation. In this study, the Root Zone Water Quality Model (RZWQM) and RZWQM-SHAW (Simultaneous Heat And Water) (RZ-SHAW) Hybrid Model were evaluated for simulating corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] growth and water use under a range of water conditions in the Central Great Plains. In both models, a water stress index (WSI) was calculated as a nonlinear form of the ratio between actual transpiration (AT) and potential transpiration (PT) [$\mathrm{WSI} = (\mathrm{AT/PT})^{\alpha}$, $0 < \alpha < 1$]. Evapotranspiration (ET) was calculated using the Shuttleworth–Wallace approach on a daily basis ($\mathrm{ET_{SW\text{-}DAY}}$) in RZWQM and using either the Shuttleworth–Wallace approach on hourly basis ($\mathrm{ET_{SW\text{-}HR}}$) or the SHAW approach ($\mathrm{ET_{SHAW}}$) in RZ-SHAW. Results showed that RZWQM using $\mathrm{ET_{SW\text{-}DAY}}$ provided similar simulation for both corn and soybean production as RZ-SHAW using the $\mathrm{ET_{SW\text{-}HR}}$ option, given that the same plant parameters were used. However, RZ-SHAW with $\mathrm{ET_{SHAW}}$ provided less accurate simulations for corn and soybean growth. This study demonstrated that, when RZ-SHAW is used for plant simulation, AT and PT should be calculated the same way as in RZWQM to preserve the plant parameters. Otherwise, recalibration of plant growth parameters is needed. This study also showed that the α value varied from crop to crop and among ET calculations. Based on the results, it is suggested to use $\alpha = 0.75$ for corn and $\alpha = 0.5$ for soybean in RZ-SHAW with the $\mathrm{ET_{SW\text{-}HR}}$ option.

Agriculture worldwide is heavily dependent on water availability, making water management one of the most important components of modern agriculture. Good water management in the field and a quick decision in response to soil water availability usually determine profit or failure for many farmers employing irrigation. To assist farmers, extension agents, or crop consultants in making better management decisions, many simulation models have been developed by synthesizing the most current scientific research results. One of the models is the RZWQM, developed by USDA-ARS scientists over a course of 12 yr to simulate management effects on water quality and crop productivity (Ahuja et al., 2000). The model has been tested for its capability of simulating nitrate and pesticide movement in the soil environment (Watts et al., 1999; RZWQM Team, 1998; Ahuja et al., 2000; Ma et al., 2000). Effort has also been made to evaluate the responses of crops to agricultural management using RZWQM (Saseendran et al., 2005; Ma et al., 2003; Nielsen et al., 2002).

Crop water stress has been a subject of study for many decades, as has been the effort to model water stress. The WSI is often defined as the ratio of AT/PT, where AT is the daily actual water uptake and PT is daily potential transpiration (Hanson et al., 1999; Sudar et al., 1981), or a linear function of AT/PT (Hanson, 2000). Evaluation of RZWQM for corn and soybean growth under different irrigation treatments showed that this approach was empirical in nature and good simulation results of crop yield were not directly linked to good simulation of AT. In a soybean study, Nielsen et al. (2002) found that RZWQM oversimulated ET for an irrigation study in 1986 but obtained almost perfect yield simulation and responses to irrigation water. In another study, Ma et al. (2003) found that RZWQM undersimulated ET for an irrigation study with corn in 1985 but accurately simulated yield and yield response to irrigation water. Therefore, correct simulation of ET (or AT) may not transfer to accurate simulation of yield. The relationship between AT and WSI was more complex than the relationships used in the model and may vary from crop to crop.

In addition to the aforementioned deficit in defining and using WSI, variations in estimating AT and PT add further uncertainty and complexity to WSI. In general, once a WSI was defined in a model, reasonable simulation of crop production (especially yield) was then obtained by calibrating a set of plant parameters. Therefore, the empirical nature in WSI was compensated by calibration. Obviously the plant parameters depended on the defined WSI (Ma et al., 2005, 2006). This was especially true when two models were linked together to develop a new model. RZ-SHAW is a new hybrid model that extends the applications of the RZWQM to conditions of frozen soil and canopy structure that affect heat and water transfer at the soil surface. RZ-SHAW has been shown to improve simulation of soil surface temperature under conditions of crop residue cover and overwinter frozen soils (Flerchinger et al., 2000) due to a more realistic application of the temperature boundary condition at the soil surface. Since RZ-SHAW has many ways to calculate AT and PT, it is important to know which AT and PT or WSI should be used in

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Abbreviations: AT, actual transpiration; ET, evapotranspiration; $\mathrm{ET_{SHAW}}$, potential evapotranspiration calculated using the SHAW approach; $\mathrm{ET_{SW\text{-}DAY}}$, potential evapotranspiration calculated using an extended Shuttleworth–Wallace approach in RZWQM on a daily basis; $\mathrm{ET_{SW\text{-}HR}}$, potential evapotranspiration calculated using an extended Shuttleworth–Wallace approach in RZ-SHAW on an hourly basis; LAI, leaf area index; PET, potential evapotranspiration; PT, potential transpiration; RMSE, root mean square error; WSI, water stress index.

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the hybrid model to use the same plant parameters as in RZWQM.

In this study, we evaluated several options for AT and PT calculations from either RZWQM or SHAW models and several estimations for WSI to find out which one is appropriate for the new RZ-SHAW hybrid model. To do so, we used previous published data in the literature where RZWQM was independently evaluated (Ma et al., 2003; Nielsen et al., 2002). Both RZ-SHAW and RZWQM were evaluated for crop growth and water dynamics using various WSI calculations. The objective of this paper was to evaluate different methods of WSI quantification to find the most appropriate WSI for the RZ-SHAW hybrid model.

MODEL BACKGROUND AND DEVELOPMENT

The RZWQM, described by Ahuja et al. (2000), is a system model with components for plant growth, water movement, chemical transport, and soil C/N dynamics with management effects as its centerpiece. RZWQM has been parameterized for corn, soybean, and winter wheat (*Triticum aestivum* L.). Simulations of corn and soybean using RZWQM have been reported for studies across the United States and other countries (Bakhsh et al., 2001; Jaynes and Miller, 1999; Ma et al., 1998; Farahani et al., 1999; Landa et al., 1999; Cameira et al., 1998; Hu et al., 2006; Yu et al., 2006). Evaluations of the model against the MSEA (Management Systems Evaluation Areas) data in the Midwest of the USA showed that RZWQM can simulate corn and soybean growth under a variety of conditions (Ma et al., 2000).

RZWQM simulates plant biomass, crop yield, leaf area index (LAI), and plant height but is not designed to simulate detailed phenology. Currently, the photosynthesis rate is calculated from solar radiation and then reduced by water stress in RZWQM in proportion to the ratio of AT/PT. The root water uptake function of Nimah and Hanks (1973) was used to determine AT. RZWQM uses the extended Shuttleworth–Wallace method for potential ET (PET) (Shuttleworth and Wallace, 1985; Farahini and Ahuja, 1996). However, in RZWQM, the soil heat flux at the soil surface is considered zero for ET calculation. Therefore, the boundary conditions for the heat transfer in the soil are affected, and the model considers an upper boundary condition to equal the ambient air temperature. This described ET method, which uses daily meteorological data in its evaluation, is herein referred to as $\mathrm{ET_{SW\text{-}DAY}}$. This ET option is only applicable to RZWQM.

Because of this limitation at the boundary surface, a hybrid model coupling RZWQM and SHAW (RZ-SHAW) was developed to improve soil and surface temperature and soil water flux simulation in RZWQM. SHAW is designed to calculate canopy energy balance and water and heat transfer for a variety of plant canopies and was originally developed by Flerchinger and Saxton (1989) and modified by Flerchinger and Pierson (1991) to include transpiring plants and a plant canopy consisting of a vertical, one-dimensional profile extending from the vegetation canopy to a specified depth within the soil. A layered system is established through the plant canopy, snow, residue, and soil, and each layer is represented by an individual node. Each type of plant canopy can be divided into a maximum of 10 layers. Water movement from the soil, plant, and atmosphere is driven by water potential at each point. Water transfer and sensible heat are calculated by iteration in each layer for convergence of leaf temperature in an energy balance equation.

The interrelated energy and water fluxes at the surface boundary are computed from weather observations of air temperature, wind speed, relative humidity, and solar radiation in the SHAW model. Heat and vapor fluxes within the canopy are determined by computing transfer between layers of the canopy and considering the source terms for heat and transpiration from the canopy leaves for each layer within the canopy. Detailed descriptions of energy and mass transfer calculations within the canopy, snow, and residue layers are given by Flerchinger and Pierson (1991), Flerchinger et al. (1994, 1996a, 1996b, 1998), and Flerchinger and Saxton (1989). The above ET method, which uses hourly meteorological data in its evaluation, is herein referred to as $\mathrm{ET_{SHAW}}$.

The RZ-SHAW hybrid model also has an option to use Shuttleworth–Wallace ET on an hourly basis ($\mathrm{ET_{SW\text{-}HR}}$). Thus, RZ-SHAW can use either $\mathrm{ET_{SW\text{-}HR}}$ or $\mathrm{ET_{SHAW}}$, whereas RZWQM can only use $\mathrm{ET_{SW\text{-}DAY}}$. The $\mathrm{ET_{SW\text{-}HR}}$ method uses the Shuttleworth–Wallace approach with hourly meteorological data and then calculates WSI by summing the data up for the day. Thus, because of the different heat and ET dynamics (AT, PT, and PET), water stress will vary with respect to each approach as it is currently a function of AT and PT. Furthermore, because meteorological data drive all three ET methods, using average daily or diurnal varying values of ambient air temperature, wind speed, solar radiation, and relative humidity will further affect heat and ET dynamics and therefore water stress.

Water Stress Index

Photosynthesis and yield are a function of WSI, which has been defined in a number of ways in RZWQM or otherwise as,

$$\mathrm{WSI} = \frac{\mathrm{AT}}{\mathrm{PT}} \qquad [1a]$$

or

$$\mathrm{WSI} = 0.85\left(\frac{\mathrm{AT}}{\mathrm{PT}}\right) + 0.15 \qquad [1b]$$

From Eq. [1a] and [1b], it is noted that as AT approaches PT, less water stress occurs in the plant (Hanson, 2000). The method of calculating WSI is rather empirical and has changed slightly due to RZWQM calibrations for different crops, environments, and agricultural systems. It would be beneficial to explore other generic forms of

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WSI calculation and find one that would best describe all crops and conditions.

Based on transpiration use efficiency approach, Kemanian et al. (2005) showed that,

$$Y = \frac{\mathrm{AT}}{D_\mathrm{a}} k_\mathrm{c} \qquad [2]$$

which can be rewritten as a function of AT/PT:

$$Y = \frac{\mathrm{PT}}{D_\mathrm{a}} k_\mathrm{c} \frac{\mathrm{AT}}{\mathrm{PT}} \qquad [3]$$

where Y is crop biomass production, D_a is vapor pressure deficit of the air, and k_c is a canopy level constant. According to Kemanian et al. (2005), k_c increases with water stress. If we assume,

$$k_\mathrm{c} = k_\mathrm{c}' \left(\frac{\mathrm{AT}}{\mathrm{PT}}\right)^{-\beta} \qquad [4]$$

where $0 < \beta < 1$ and k_c' is a constant, then we have,

$$Y = \frac{\mathrm{PT}}{D_\mathrm{a}} k_\mathrm{c}' \left(\frac{\mathrm{AT}}{\mathrm{PT}}\right)^{1-\beta} = \frac{\mathrm{PT}}{D_\mathrm{a}} k_\mathrm{c}' \left(\frac{\mathrm{AT}}{\mathrm{PT}}\right)^{\alpha} \qquad [5]$$

where $0 < \alpha = 1 - \beta < 1$. Thus, the actual effect of water stress on biomass production in RZWQM (or photosynthesis), where the radiation efficiency approach is used, should be nonlinear. Therefore, it is reasonable to define a water stress factor as,

$$\mathrm{WSI} = \left(\frac{\mathrm{AT}}{\mathrm{PT}}\right)^{\alpha} \qquad [6]$$

Based on Eq. [6], a curvilinear relationship is derived. When α is 1, Eq. [6] is the same as Eq. [1a]. When α is less than 1 and greater than 0, a curvilinear relationship downward is observed. Figure 1 shows the general relationships of Eq. [1b] and Eq. [6] with different α values. It is interesting to note that when $\alpha = 0.75$, Eq. [6] overlaps Eq. [1b]. This is how nonlinearity of WSI is taken care of in RZWQM. These relationships for WSI are explored for both RZWQM and RZ-SHAW.

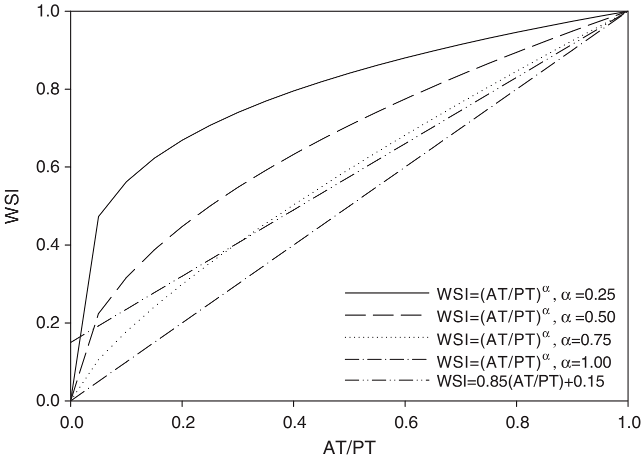

Fig. 1. Theoretical curves of water stress index (WSI) versus the actual to potential transpiration ratio (AT/PT) based on Eq. 1b and Eq. [6] with varying α-values.

In $\mathrm{ET_{SW\text{-}DAY}}$ and $\mathrm{ET_{SW\text{-}HR}}$, the AT and PT from the Shuttleworth–Wallace method is used where,

$$\mathrm{PT} = \frac{\Delta[(R_\mathrm{n} - G) - R_\mathrm{nsub}] + \rho c_p(\mathrm{VPD}_0)/r_a^c}{[(\Delta + \gamma)1 + r_s^c/r_a^c]\lambda} \qquad [7]$$

where Δ is the slope of the saturation vapor pressure versus temperature curve, R_n is the net radiation above the canopy, G is the heat flux below the canopy, R_nsub is the net radiation over the bare soil and residue, ρc_p is the volumetric heat capacity of air, VPD_0 is the air vapor pressure deficit at the mean canopy height, γ is the psychrometric constant, r_a^c is the bulk boundary layer resistance of the canopy elements within the canopy, r_s^c is the bulk stomatal resistance of the canopy, and λ is the latent heat flux (Ahuja et al., 2000). AT is a function of the soil's ability to supply water to the potential demand (Nimah and Hanks, 1973).

For $\mathrm{ET_{SHAW}}$, the total AT rate for a single crop species j (T_j) is calculated as follows,

$$T_j = \sum_{i=1}^{\mathrm{NC}} \frac{\rho_{vs,i,j} - \rho_{v,i}}{r_{s,i,j} + r_{h,i,j}} \mathrm{LAI}_{i,j} \qquad [8]$$

where NC is the number of canopy layers, $\rho_{vs,i,j}$ and $\rho_{v,i}$ are the vapor density within the stomatal cavities (assumed to be saturated vapor density) of plant species i, $r_{s,i,j}$ and $r_{h,i,j}$ are stomatal resistance and resistance to convective transfer from canopy leaves to air within canopy layer i for plant species j, and LAI is the leaf area index of canopy layer i for plant species j. Actual transpiration is the summation of T_j over the entire day.

In $\mathrm{ET_{SHAW}}$, PT can be determined in a number of ways: (i) the $\rho_{v,i}$ in each canopy layer is used to give the vapor pressure deficit, (ii) the ρ_v of the ambient air above the canopy is used, and (iii) the PT from the $\mathrm{ET_{SW\text{-}HR}}$ approach is used. Using one of the three methods to calculate PT, Eq. [1] and [6] can be applied to $\mathrm{ET_{SHAW}}$. Additionally, two new approaches based on the stomatal and aerodynamic resistances were included with respect to the $\mathrm{ET_{SHAW}}$ option where,

$$\mathrm{WSI} = \left(\sum_{i=1}^{\mathrm{NC}} \frac{r_{s,i,j}}{r_s^{\min}}\right)^{\beta'} \qquad [9]$$

$$\mathrm{WSI} = \left(\sum_{i=1}^{\mathrm{NC}} \frac{r_s + r_h}{r_s^{\min} + r_{h,i,j}}\right)^{\beta'} \qquad [10]$$

where $r_s^{\min}$ is the minimum stomatal resistance and β' is an empirical exponent.

In summation, RZ-SHAW allows the use of either the $\mathrm{ET_{SHAW}}$ or $\mathrm{ET_{SW\text{-}HR}}$ to evaluate PET based on user input. If $\mathrm{ET_{SW\text{-}HR}}$ is used, WSI is determined from Eq. [1] and [6] based on AT and PT from Eq. [7]. If $\mathrm{ET_{SHAW}}$ is used, WSI can be determined from Eq. [1] and [6] based on three different methods of calculating AT and PT (Eq. [8]) and Eq. [9] and [10] based on the stomatal resistances.

All three ET methods are inherently related to crop growth parameters, such as LAI, crop height, and rooting density. Essentially, if any of these parameters

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Table 1a. Shuttleworth–Wallace derived potential transpiration (PT) and water stress index (WSI) in RZWQM ($ET_{SW\text{-}DAY}$) and RZ-SHAW ($ET_{SW\text{-}HR}$).

PT	AT	WSI	Simulation option
	$\underline{ET_{SW\text{-}DAY}}$		
$PT = \frac{\Delta[(R_n - G) - R_{nsub}] + \rho c_p(VPD_0)/r_a^c}{[(\Delta + \gamma)1 + r_s^c/r_a^c]\lambda}$	Nimah and Hanks (1973) approach	$WSI = 0.85\left(\frac{AT}{PT}\right) + 0.15$	1
		$WSI = \left(\frac{AT}{PT}\right)^{\alpha}$	2 $\alpha = 0.25$ 3 $\alpha = 0.5$ 4 $\alpha = 0.75$ 5 $\alpha = 1.0$
	$\underline{ET_{SW\text{-}HR}}$		
$PT = \frac{\Delta[(R_n - G) - R_{nsub}] + \rho c_p(VPD_0)/r_a^c}{[(\Delta + \gamma)1 + r_s^c/r_a^c]\lambda}$	Nimah and Hanks (1973) approach	$WSI = 0.85\left(\frac{AT}{PT}\right) + 0.15$	6
		$WSI = \left(\frac{AT}{PT}\right)^{\alpha}$	7 $\alpha = 0.25$ 8 $\alpha = 0.5$ 9 $\alpha = 0.75$ 10 $\alpha = 1.0$

decreases, the resulting AT will decrease for any of these methods. Therefore, there is a possible symbiotic or antagonistic effect between plant growth, transpiration, and water stress (especially for WSI in Eq. [1] and [6]). Therefore, if AT and/or PT is incorrectly evaluated in a particular ET method, crop growth will be affected, and vice versa. This will lead to a "snowball" effect as the AT and/or PT evaluated for the following time step will be incorrect as the derived crop growth parameters are inaccurate. Therefore, there is a very delicate balance between the choice of WSI calculation and ET method.

The three methods ($ET_{SW\text{-}DAY}$, $ET_{SW\text{-}HR}$, and ET_{SHAW}) and the various WSI calculations are evaluated herein and compared with experimental data from corn and soybean field studies in Akron, CO. Tables 1a and 1b summarize the different model options analyzed in this study.

MATERIALS AND METHODS

Studies were conducted during the 1984–1986 summer growing seasons at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°9′ N, 103°9′ W; 1384 m above mean sea level). The soil type is a Rago silt loam (fine smectitic, mesic Pachic Argiustoll) (Nielsen et al., 2002). Ten corn data sets of plant height, LAI, yield, aboveground biomass, water storage, and ET were measured to evaluate water stress effects on corn productivity. The data sets were generated by varying the amount of water applied via line-source gradient irrigation. Growing season precipitation for this region ranges from 100 to 475 mm. The precipitation plus irri-

Table 1b. Actual (AT) and potential (PT) transpiration estimated in RZ-SHAW (ET_{SHAW}) for water stress index (WSI) calculation.

PT	AT	WSI	Simulation option
$PT = \frac{\Delta[(R_n - G) - R_{nsub}] + \rho c_p(VPD_0)/r_a^c}{[(\Delta + \gamma)1 + r_s^c/r_a^c]\lambda}$	$\sum_{day}\sum_{j=1}^{species} T_j = \sum_{i=1}^{NC}\frac{\rho_{vs,i,j} - \rho_{v,i}}{r_{r,j,k} + r_{l,i,j}}LAI_{i,j}$	$WSI = 0.85\left(\frac{AT}{PT}\right) + 0.15$	11
		$WSI = \left(\frac{AT}{PT}\right)^{\alpha}$	12 $\alpha = 0.25$ 13 $\alpha = 0.5$ 14 $\alpha = 0.75$ 15 $\alpha = 1.0$
$\sum_{day}\sum_{j=1}^{species} T_j = \sum_{i=1}^{NC}\frac{\rho_{vs,i,j} - \rho_{v\text{above canopy}}}{r_{r,j,k} + r_{l,i,j}}LAI_{i,j}$	Same as above	$WSI = 0.85\left(\frac{AT}{PT}\right) + 0.15$	16
		$WSI = \left(\frac{AT}{PT}\right)^{\alpha}$	17 $\alpha = 0.25$ 18 $\alpha = 0.5$ 19 $\alpha = 0.75$ 20 $\alpha = 1.0$
$\sum_{day}\sum_{j=1}^{species} T_j = \sum_{i=1}^{NC}\frac{\rho_{vs} - \rho_{lowest}}{r_{r,j,k} + r_{l,i,j}}LAI_{i,j}$	Same as above	$WSI = 0.85\left(\frac{AT}{PT}\right) + 0.15$	21
		$WSI = \left(\frac{AT}{PT}\right)^{\alpha}$	22 $\alpha = 0.25$ 23 $\alpha = 0.5$ 24 $\alpha = 0.75$ 25 $\alpha = 1.0$
N/A	Same as above	$WSI = \left(\sum_{i=1}^{NC}\frac{r_{l,i,j}}{r_l^{min}}\right)^{\beta'}$	26 $\beta' = 0.25$ 27 $\beta' = 0.5$ 28 $\beta' = 0.75$ 29 $\beta' = 1.0$
N/A	Same as above	$WSI = \left(\sum_{i=1}^{NC}\frac{r_{l,j,k} + r_{r,j,k}}{r_l^{min} + r_{r,j,k}}\right)^{\beta'}$	30 $\beta' = 0.25$ 31 $\beta' = 0.5$ 32 $\beta' = 0.75$ 33 $\beta' = 1.0$

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Table 2. Calibrated plant model parameters used in RZWQM and RZ-SAHW for corn and soybean grown at Akron, CO (Ma et al., 2003; Nielsen et al., 2002).

Parameter	Corn	Soybean
Minimum leaf stomatal resistance, s m^{-1}	100	100
Proportion of photosynthate lost to respiration, dimensionless	0.28	0.17
Photosynthesis rate at reproductive stage compared with vegetative stage	0.65	0.70
Photosynthesis rate at seedling stage compared with vegetative stage	0.65	0.70
Coefficient to convert leaf biomass to LAI† (CONVLA), g LAI^{-1}	13.5	1.9
Plant population on which CONVLA is based (CLBASE), plants ha^{-1}	79 800	370 137
Maximum rooting depth, cm	300	300
Maximum plant height, cm	210	70
Aboveground biomass at one half maximum height, g	60	4
Aboveground biomass of a mature plant, g	152	13
Minimum time needed for plant to germinate, d	4	3
Minimum time needed for plant to emerge, d	20	7
Minimum time needed for plant to grow to four-leaf stage, d	37	22
Minimum time needed for plant to complete vegetative growth, d	77	62
Minimum time needed for plant to complete reproductive growth, d	120	92

† LAI, leaf area index.

gation amounts in the experiments generally fell within this range so that the experiments produced water availability conditions that would be experienced under a range of naturally occurring dryland conditions. The corn variety 'Pioneer Hybrid 3732' was used. The three identified irrigation treatments were 23, 68, and 106 mm water in 1984; and the four irrigation treatments were 71, 94, 150, and 188 mm water in 1985 and 146, 203, 258, and 300 mm water in 1986. Further details of corn planting dates, densities, and soil characterization are given in Ma et al. (2003).

Eight soybean data sets of plant height, LAI, yield, aboveground biomass, water storage, and ET were measured to evaluate water stress effects on soybean productivity. The data sets were generated by varying the amount of water applied by line-source gradient irrigation. The soybean variety was 'Pioneer Brand 9291' (Late Maturity Group II). The four identified irrigation treatments were 3, 34, 88, and 129 mm water in 1985 and 16, 72, 171, and 250 mm water in 1986. Details of soybean planting dates, densities, and soil characterization are given in Nielsen et al. (2002).

Soil water measurements were made at planting and harvest and at several intermediate times during the growing seasons. These measurements were made by time-domain reflectometry at 15 cm and with a neutron probe at 45, 75, 105, 135, and 165 cm below the soil surface. Actual ET was calculated as the difference between successive soil water measurements plus precipitation and irrigation during the sampling period. No runoff was observed in the experimental plots. There were no measurements of percolation, but percolation below the root zone was assumed to be minimal due to the low irrigation depths (Ma et al., 2003). Plant height (measured from the soil surface to the top of the plant canopy) was measured periodically throughout the growing season. One meter of row was destructively sampled from each plot during the growing season to obtain LAI and aboveground biomass

Table 3. Root mean square errors (RMSEs) of simulation results with respect to measured results for the 1985 corn experiments.

ET method†	Simulation option‡	Yield (kg ha^{-1})	Aboveground biomass (kg ha^{-1})	LAI (m^3 m^{-3})§	ET (cm)	Soil water storage (cm)
$ET_{SW\text{-}DAY}$	1	297.9	883.1	0.35	3.41	2.57
	2	2205.6	1898.9	0.68	3.43	2.37
	3	967.5	770.4	0.27	3.50	2.45
	4¶	209.9	761.9	0.33	3.41	2.56
	5	317.4	945.3	0.46	3.51	2.67
$ET_{SW\text{-}HR}$	6¶	138.4	771.3	0.29	1.43	2.36
	7	1893.5	1842.7	0.87	1.44	2.27
	8	985.4	881.9	0.42	1.38	2.30
	9	260.7	718.2	0.28	1.46	2.39
	10	455.6	794.5	0.31	1.36	2.48
ET_{SHAW}	11	671.7	1392.1	0.73	3.60	2.97
	12	2512.8	2786.3	1.34	4.73	3.52
	13	946.2	2218.1	1.02	4.20	3.27
	14	737.8	1500.5	0.80	3.79	3.05
	15	722.7	1169.5	0.62	3.25	2.83
	16	739.9	2344.3	1.17	4.55	3.45
	17	2367.2	3387.1	1.53	4.80	3.61
	18	2113.7	2772.8	1.35	4.74	3.55
	19	1097.7	2465.4	1.21	4.59	3.47
	20¶	546.0	2204.6	1.09	4.44	3.39
	21	8152.2	6417.3	2.28	28.59	17.52
	22	1198.7	1463.5	0.79	3.92	4.70
	23	5086.8	4793.6	1.93	20.87	14.15
	24	8223.5	6502.9	2.31	28.44	17.49
	25	8361.8	6722.3	2.39	26.51	16.95
	26	1896.3	3147.8	1.42	4.65	3.45
	27	3926.0	3142.8	1.54	4.41	3.69
	28	3337.3	3046.7	1.49	4.80	3.50
	29	2132.9	3190.2	1.43	4.65	3.44
	30	1951.1	3092.0	1.38	4.57	3.41
	31	1296.4	2608.7	1.27	4.56	3.39
	32	3083.6	3171.0	1.48	4.77	3.49
	33	1834.3	3085.5	1.38	4.57	3.42

† ET, evapotranspiration.
‡ Simulation options defined in Tables 1a and 1b.
§ LAI, leaf area index.
¶ Where best simulation results were obtained with lowest RMSE for yield prediction.

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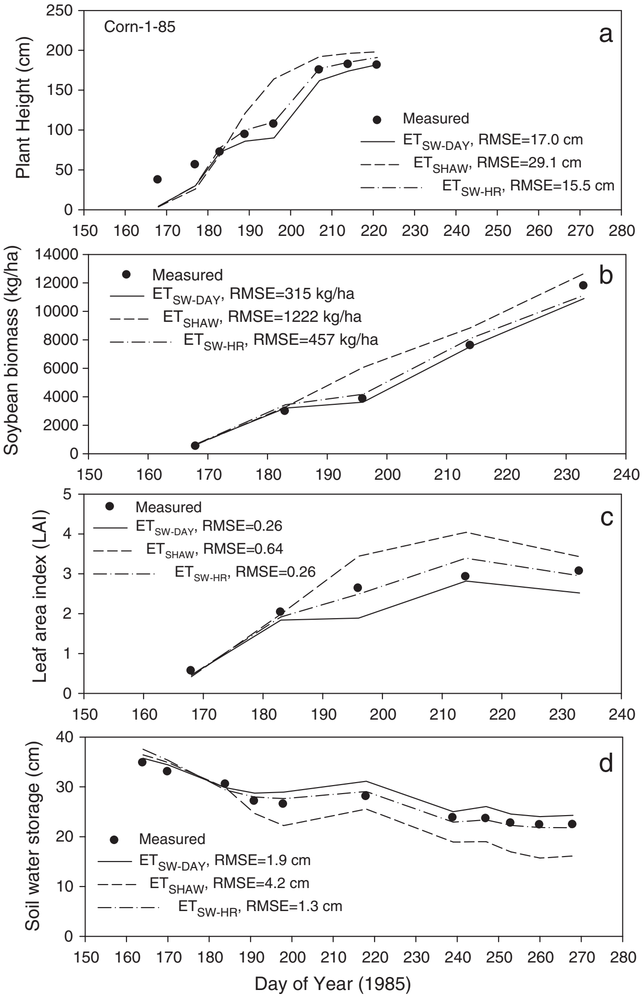

Fig. 2. Measured and ET$_{\text{SW-DAY}}$, ET$_{\text{SW-HR}}$, and ET$_{\text{SHAW}}$ simulation results of (a) plant height, (b) aboveground biomass, (c) leaf area index (LAI), and (d) soil water storage for the Corn-1–85 study.

measurements. Additional LAI was measured with a plant canopy analyzer (LI-3100, LI-COR, Lincoln, NE) periodically during the growing season. An on-site weather station recorded daily air temperature, wind run, solar radiation, rainfall, and relative humidity approximately 300 m from the experimental plots. Daily weather data was used for RZWQM simulations (ET$_{\text{SW-DAY}}$); hourly weather data derived from the daily data were used for RZ-SHAW simulations (ET$_{\text{SW-HR}}$ and ET$_{\text{SHAW}}$). When converting daily weather to hourly, wind speed and dew point were considered constant throughout the day. Hourly air temperature was computed by fitting a sine wave through the maximum and minimum temperatures assuming the minimum air temperature occurs 0.5 h before sunrise and the maximum temperature occurs midway between solar noon and sunset. Daily solar radiation was distributed according to solar altitude and assuming the atmospheric transmissivity to solar radiation was constant throughout the day.

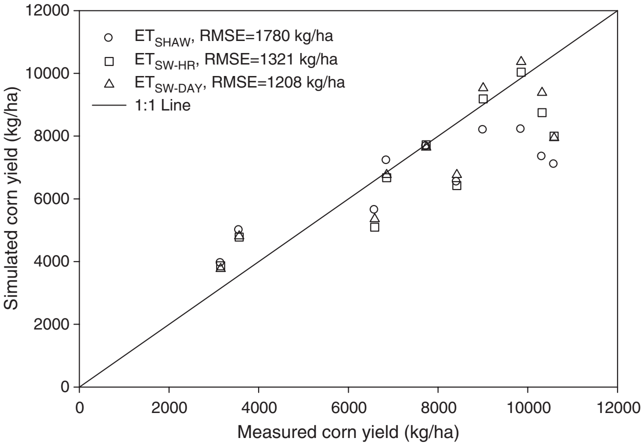

Fig. 3. Measured and ET$_{\text{SW-DAY}}$, ET$_{\text{SW-HR}}$, and ET$_{\text{SHAW}}$ simulation results for yield for all corn studies.

Daily minimum and maximum temperatures, total solar radiation, average wind speed, and average relative humidity are converted to hourly data. Based on sunrise and sunset time, sun angle declination, and solar transmissivity, a sine function segregates the total radiation into hourly values. Likewise, a cosine function is used to define the hourly temperature data with respect to the boundary conditions of the minimum and maximum temperature input. Hourly relative humidity is a function of the hourly air temperature and saturated vapor pressure. Finally, the average daily wind speed is assumed to be the hourly average wind speed. Because hourly meteorological data were derived from daily meteorological data, errors may arise in simulations using ET$_{\text{SW-HR}}$ and ET$_{\text{SHAW}}$. The plant parameters shown in Table 2 were from Ma et al. (2003) and Nielsen et al. (2002).

To accomplish the objectives, RZWQM and RZ-SHAW were used to simulate soil water balance and crop production for the four irrigation treatments in 1985 for both corn and soybean. These simulations differed with respect to the use of ET method and WSI. The measured results of aboveground biomass, yield, ET, and soil water storage were subsequently compared with the simulation results. Using options with root mean square error (RMSE) for yield prediction from the

Table 4. Root mean square errors (RMSEs) of model simulation results with respect to measured results from corn irrigation studies.

	Plant height RMSE (cm)			Aboveground biomass RMSE (kg ha^{-1})			LAI RMSE (m^3 m^{-3})			Soil water storage RMSE (cm)		
Study	ET$_{\text{SW-DAY}}$	ET$_{\text{SHAW}}$	ET$_{\text{SW-HR}}$	ET$_{\text{SW-DAY}}$	ET$_{\text{SHAW}}$	ET$_{\text{SW-HR}}$	ET$_{\text{SW-DAY}}$	ET$_{\text{SHAW}}$	ET$_{\text{SW-HR}}$	ET$_{\text{SW-DAY}}$	ET$_{\text{SHAW}}$	ET$_{\text{SW-HR}}$
Corn-1–84	31.87	38.88	35.35	1802.0	2611.1	2363.6	1.43	1.74	1.62	N/A	N/A	N/A
Corn-1–85	17.03	29.11	15.50	315.4	1222.4	456.7	0.26	0.64	0.26	1.91	4.24	1.33
Corn-1–86	14.38	43.33	28.41	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Corn-2–85	18.04	29.84	16.45	1068.7	500.6	894.4	0.36	0.51	0.27	3.47	3.01	2.69
Corn-2–86	19.33	46.57	34.52	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Corn-3–85	16.22	30.40	15.78	846.8	1451.8	941.5	0.31	0.70	0.36	3.10	2.29	2.82
Corn-3–86	12.92	24.56	36.08	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Corn-4–84	28.64	32.81	30.40	1627.9	2112.2	1875.0	1.43	1.59	1.57	N/A	N/A	N/A
Corn-4–85	16.83	28.26	15.04	613.7	1503.3	792.6	0.24	0.61	0.26	2.37	1.80	2.60
Corn-4–86	19.059	36.32	30.31	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Average	19.43	34.01	25.78	1063.3	1566.9	1220.6	0.67	0.97	0.72	2.71	2.83	2.36

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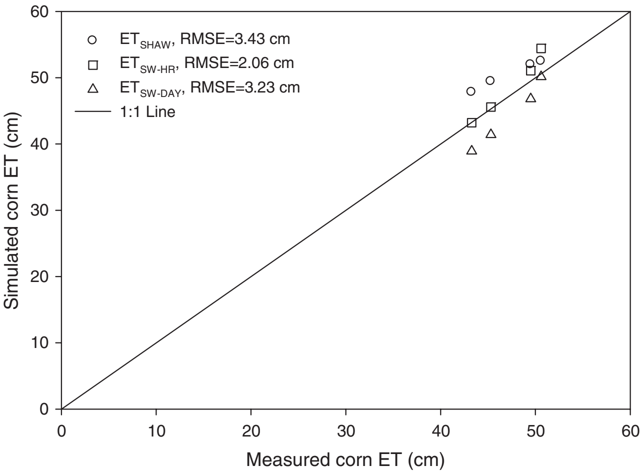

Fig. 4. Measured and $ET_{SW\text{-}DAY}$, $ET_{SW\text{-}HR}$, and ET_{SHAW} simulation results of evapotranspiration (ET) for all corn studies.

$ET_{SW\text{-}DAY}$, $ET_{SW\text{-}HR}$, and ET_{SHAW} for the 1985 corn and soybean experiments, simulations of the corn and soybean in other years and treatments were performed and compared with the measured plant growth, water usage, and soil water storage from each respective study.

RESULTS AND DISCUSSION

Evaluation of WSI for Corn

The 1985 corn data were used to find out which WSI option gave the best simulation results as they were used in model calibration by Ma et al. (2003). Table 3 summarizes the average RMSEs of simulated aboveground biomass, yield, ET, and soil water storage for the 33 different simulation options listed in Tables 1a and 1b. For RZ-SHAW with $ET_{SW\text{-}HR}$, the best results (lowest RMSE for yield prediction) were achieved when using the PT from Eq. [7] and the AT based on the Nimah–Hanks approach, and WSI was calculated according to Eq. [1b] (Option 6). For the ET_{SHAW} option, the best results were achieved when using the PT from Eq. [8] with ρ_v equal to the ambient air vapor density above the canopy and the AT from Eq. [8]; WSI was calculated according to Eq. [6] with $\alpha = 1.0$ (Option 20). For RZWQM with $ET_{SW\text{-}DAY}$, the best results were achieved when using the PT from Eq. [7] and the AT based on the Nimah–Hanks approach; WSI was calculated according

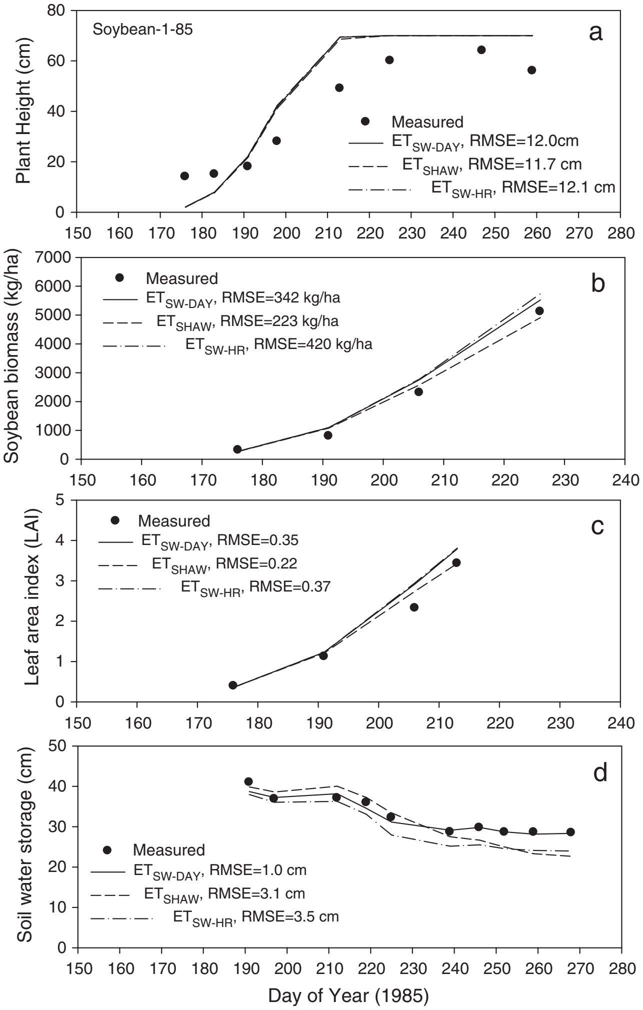

Fig. 5. Measured and $ET_{SW\text{-}DAY}$, $ET_{SW\text{-}HR}$, and ET_{SHAW} simulation results of (a) plant height, (b) aboveground biomass, (c) leaf area index (LAI), and (d) soil water storage for the Soybean-1–85 study.

Table 5. Root mean square errors (RMSEs) of simulation results with respect to measured results for the 1985 soybean experiments.

ET method†	Simulation option‡	Yield (kg ha^{-1})	Aboveground biomass (kg ha^{-1})	LAI ($m^3\ m^{-3}$)§	ET (cm)	Soil water storage (cm)
$ET_{SW\text{-}DAY}$	**1**	**268.3**	**371.8**	**0.43**	**2.86**	**1.62**
	2	**333.0**	**430.7**	**0.43**	**2.81**	**1.61**
	3¶	**77.3**	**400.5**	**0.43**	**2.84**	**1.62**
	4	**262.7**	**376.2**	**0.43**	**2.86**	**1.62**
	5	**412.4**	**358.8**	**0.43**	**2.87**	**1.62**
$ET_{SW\text{-}HR}$	**6**	**261.3**	**456.0**	**0.44**	**1.10**	**2.73**
	7	**457.2**	**463.1**	**0.44**	**1.12**	**2.75**
	8¶	**157.6**	**459.9**	**0.44**	**1.11**	**2.74**
	9	**258.1**	**456.9**	**0.44**	**1.10**	**2.73**
	10	**359.1**	**454.2**	**0.44**	**1.09**	**2.73**
ET_{SHAW}	**21**	**708.8**	**408.2**	**0.28**	**2.98**	**3.75**
	22	**817.9**	**376.3**	**0.36**	**2.91**	**3.63**
	23	**805.2**	**349.1**	**0.31**	**2.94**	**3.68**
	24¶	**633.2**	**383.4**	**0.29**	**2.96**	**3.72**
	25	**659.2**	**455.2**	**0.28**	**3.01**	**3.78**

† ET, evapotranspiration.
‡ Simulation options defined in Tables 1a and 1b.
§ LAI, leaf area index.
¶ Where best simulation results were obtained with lowest RMSE for yield prediction.

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Table 6. Root mean square errors (RMSEs) of model simulation results with respect to measured results from soybean irrigation studies.

	Plant height RMSE (cm)			Aboveground biomass RMSE (kg ha^{-1})			LAI RMSE (m^3 m^{-3})†			Soil water storage RMSE (cm)		
Study	$ET_{SW\text{-}DAY}$	ET_{SHAW}	$ET_{SW\text{-}HR}$	$ET_{SW\text{-}DAY}$	ET_{SHAW}	$ET_{SW\text{-}HR}$	$ET_{SW\text{-}DAY}$	ET_{SHAW}	$ET_{SW\text{-}HR}$	$ET_{SW\text{-}DAY}$	ET_{SHAW}	$ET_{SW\text{-}HR}$
Soybean-1–85	12.00	11.74	12.10	341.6	222.5	420.4	0.35	0.22	0.37	1.01	3.10	3.53
Soybean-1–86	30.06	29.42	30.12	N/A	N/A	N/A	N/A	N/A	N/A	9.33	9.21	8.56
Soybean-2–85	11.77	11.43	11.78	439.4	377.9	512.8	0.58	0.42	0.58	1.79	3.01	2.10
Soybean-2–86	29.14	28.42	29.16	N/A	N/A	N/A	N/A	N/A	N/A	7.44	8.22	7.60
Soybean-3–85	11.66	11.29	11.68	347.7	375.5	396.6	0.43	0.31	0.43	2.59	4.82	2.04
Soybean-3–86	25.53	24.62	25.54	N/A	N/A	N/A	N/A	N/A	N/A	6.85	9.82	8.02
Soybean-4–85	23.98	23.77	23.98	473.5	557.7	498.1	0.37	0.19	0.37	1.07	3.86	3.27
Soybean-4–86	22.71	21.62	22.73	N/A	N/A	N/A	N/A	N/A	N/A	4.56	8.93	6.53
Average	20.85	20.29	20.89	400.5	383.4	456.9	0.43	0.29	0.44	4.33	6.37	5.20

† LAI, leaf area index.

to Eq. [6] with α = 0.75 (Option 4). It should be noted that Options 1 and 4 using the $ET_{SW\text{-}DAY}$ and Options 6 and 9 using the $ET_{SW\text{-}HR}$ provided similar results because WSI calculated using α = 0.75 is close to Eq. [1b]. Figures 2a–2d show the simulation results of plant height, aboveground biomass, LAI, and soil water storage with respect to the measured results for the Corn-1–1985 study. Based on Fig. 2a–2d and the RMSE results in Table 3, RZWQM using $ET_{SW\text{-}DAY}$ and RZ-SHAW using $ET_{SW\text{-}HR}$ produced the best simulation for aboveground biomass; and RZ-SHAW using $ET_{SW\text{-}HR}$ produced better results for soil water storage, LAI, and plant height. RZ-SHAW simulation results using ET_{SHAW} were not as good as the other two ET calculations.

The best options with the lowest RMSE for yield prediction (no. 4, 6, and 20) for each ET method were applied to the other irrigation treatments in 1984 and 1986. The RMSE values with respect to plant heights, aboveground biomass, LAI, and soil water storage for the remaining corn studies are summarized in Table 4. Based on the results, RZWQM using $ET_{SW\text{-}DAY}$ proved to be in better agreement than the other two ET methods for simulating aboveground biomass, plant height, and LAI while RZ-SHAW using $ET_{SW\text{-}HR}$ was in better agreement in simulating soil water storage.

The simulated results of all three ET methods and the experimental results of final yield for all corn studies are plotted in Fig. 3. The RZWQM yield simulations using $ET_{SW\text{-}DAY}$ were comparable to the RZ-SHAW simulations using $ET_{SW\text{-}HR}$. However, ET simulations by $ET_{SW\text{-}HR}$ were more accurate than $ET_{SW\text{-}DAY}$ (Fig. 4). The overall better performance of RZWQM using $ET_{SW\text{-}DAY}$ was expected as the plant parameters were calibrated using this model in previous studies (Ma et al., 2003; Nielsen et al., 2002; Ma et al., 2005, 2006). Better daily ET simulation of RZWQM using $ET_{SW\text{-}HR}$ was due to a more realistic representation of ET demand during a day than using an average ET demand.

Evaluation of WSI for Soybean

Based on the results for the corn study, the same ET methods were examined with respect to the soybean 1985 experiments; however, the use of Eq. [1b] and Eq. [2] with varying α-values was revisited. Table 5 summarizes the average RMSEs between the 1985 soybean measured results of aboveground biomass, yield, ET, and soil water storage and results of 15 different simulation options used in the calibration, i.e., Options 1–10 and 21–25 in Tables 1a and 1b. The 1985 soybean results were used to find the best WSI for soybean as they were used for model calibration by Nielsen et al. (2002). For the RZ-SHAW model with $ET_{SW\text{-}HR}$, the best yield predictions were achieved when using the PT from Eq. [7] and the AT based on the Nimah–Hanks approach; WSI was calculated according to Eq. [6] with α = 0.5 (Option 8). For ET_{SHAW}, the best results were achieved when using the PT from Eq. [8] with ρ_v equal to the ambient air vapor density above the canopy and the AT from Eq. [8]; WSI was calculated according to Eq. [6] with α = 0.75 (Option 24). For $ET_{SW\text{-}DAY}$, the best results were achieved when using the PT from Eq. [7] and the AT based on the Nimah–Hanks approach; WSI was calculated according to Eq. [6] with α = 0.5 (Option 3). Figures 5a–5d show the simulation results of plant height, aboveground biomass, LAI, and soil water storage with respect to the measured results for the Soybean-1–1985 study. All the three ET methods simulated similar plant heights, aboveground biomass, and LAI, but RZWQM using $ET_{SW\text{-}DAY}$ produced the best simulation of soil water storage. Same as the corn results, RZ-SHAW using $ET_{SW\text{-}HR}$ performed better than RZ-SHAW using ET_{SHAW} for yield prediction.

The best WSI options with lowest RMSE for yield prediction (no. 3, 8, and 24) for each ET method were applied to the remaining soybean experiments in 1985 and 1986. The RMSE values with respect to plant

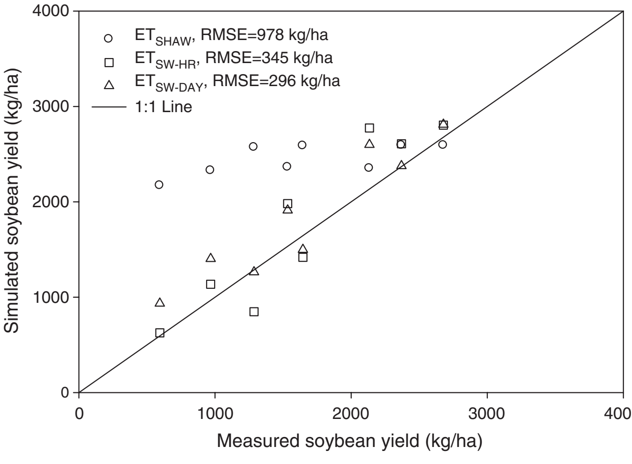

Fig. 6. Measured and $ET_{SW\text{-}DAY}$, $ET_{SW\text{-}HR}$, and ET_{SHAW} simulation results of yield for all soybean studies.

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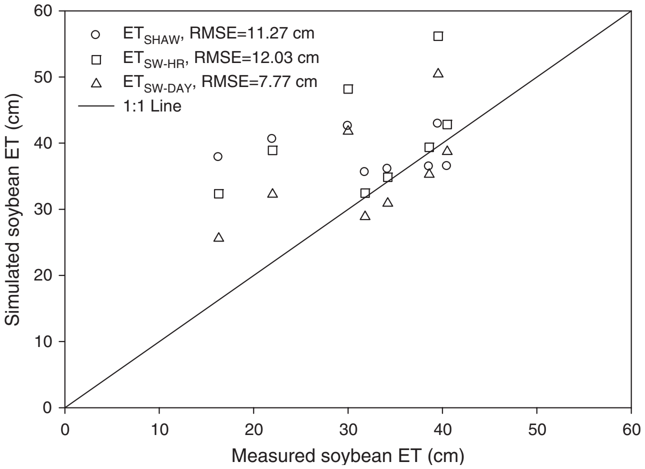

Fig. 7. Measured and ET_{SW-DAY}, ET_{SW-HR}, and ET_{SHAW} simulation results of evapotranspiration (ET) for all soybean studies.

heights, aboveground biomass, LAI, and soil water storage are summarized in Table 6. RZ-SHAW using ET_{SHAW} proved to be slightly better for simulating aboveground biomass and LAI than RZ-SHAW using ET_{SW-HR}, whereas RZWQM using ET_{SW-DAY} was the best for simulating soil water storage. None of the model simulations performed very well with respect to the 1986 soybean studies, especially regarding soil water storage and plant height as noticed by Nielsen et al. (2002). RZWQM yield simulations using ET_{SW-DAY} were slightly better than the RZ-SHAW simulations using ET_{SW-HR} (Fig. 6). RZWQM (ET_{SW-DAY}) simulated better ET than RZ-SHAW (Fig. 7). Same as the corn experiment, better performance of RZWQM using ET_{SW-DAY} was expected as the plant parameters were calibrated using this model in previous studies (Ma et al., 2003; Nielsen et al., 2002; Ma et al., 2005, 2006).

CONCLUSIONS

RZ-SHAW and RZWQM were evaluated for their ability to simulate corn and soybean growth under a range of irrigation treatments in the Central Great Plains (Akron, CO). Simulations were performed using the calibrated plant parameters from previous studies using RZWQM (ET_{SW-DAY}) (Ma et al., 2003; Nielsen et al., 2002). These two models were investigated with respect to various ways of estimating crop ET (ET_{SW-DAY}, ET_{SW-HR}, and ET_{SHAW}) and different methods of calculating water stress (Eq. [1], [6], [7], and [8]). Calculating ET_{SW-DAY} requires only daily average meteorological data, whereas calculating ET_{SHAW} and ET_{SW-HR} needs diurnal varying meteorological data.

The three ET methods were evaluated along with different water stress calculations, and the simulated results were first compared with the measured results from 1985 corn and soybean studies. Based on RMSEs of yield prediction in 1985, one water stress calculation for each ET method was identified and then used to simulate corn and soybean production in other treatments and years. For all three ET methods, WSI generally showed the best results using Eq. [6] with α-values between 0.5 and 1.0. For corn, $\alpha = 0.75$ provided the best simulation results when ET_{SW-DAY} and ET_{SW-HR} were used and $\alpha = 1.0$ when ET_{SHAW} was used. Poor results were obtained when stomatal resistances were used in calculating WSI (Eq. [9] and [10]). Simulated corn results also showed that RZWQM (ET_{SW-DAY}) predictions were in slightly better agreement with the measured results than RZ-SHAW using ET_{SW-HR} and much better than RZ-SHAW using ET_{SHAW}. For soybean, $\alpha = 0.5$ provided best simulation results when ET_{SW-DAY} and ET_{SW-HR} were used and $\alpha = 0.75$ when ET_{SHAW} was used. Simulation results for soybean also showed that RZ-SHAW using ET_{SHAW} predictions provided worst yield predictions than both RZ-SHAW using ET_{SW-HR} and RZWQM (ET_{SW-DAY}). None of the simulations proved to be good in simulating soybean plant height and soil water storage in 1986.

This study demonstrated the validity of RZ-SHAW in simulating crop growth under different irrigation conditions using various WSI calculations and was the first to evaluate RZ-SHAW with respect to crop growth. The results showed that, when two models were linked to develop a hybrid model, it was essential for variables to communicate correctly between components of the two models, not only in unit but also in magnitude. RZ-SHAW using ET_{SW-HR} method performed comparably with RZWQM (ET_{SW-DAY}) in most experiments; discrepancies were observed with respect to some of the soybean experiments. Therefore, RZ-SHAW can be used directly to simulate plant growth using the originally calibrated plant parameters in RZWQM if ET_{SW-HR} was used. RZ-SHAW using ET_{SHAW} did not perform as well for both corn and soybean, and ET_{SHAW} should not be recommended for WSI calculation in RZ-SHAW. This study also demonstrated that WSI was nonlinear with respect to AT/PT and the α value varied from crop to crop. Based on the results, it is recommended to use ET_{SW-HR} in the new developed RZ-SHAW model with $\alpha = 0.75$ for corn and $\alpha = 0.5$ for soybean.

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