Enhancing the Water Stress Factors for Simulation of Corn in RZWQM2

S. A. Saseendran,* L. R. Ahuja, L. Ma, D. C. Nielsen, T. J. Trout, A. A. Andales, J. L. Chávez, and J. Ham

ABSTRACT

Enhancement of agricultural system models for more accurate simulations of the water stress response of crops can improve their application under limited water management. Currently, the crop system model RZWQM2 uses a ratio of potential root water uptake (supply) to potential transpiration (demand) as a water stress factor (WSDef) that modulates plant growth processes. We tested two progressive modifications of the WSDef (WSI1 and WSI2) in the DSSAT-CSM-CERES-Maize (Version 4.0) module embedded within the RZWQM2 model for simulating the response of corn (*Zea mays* L.) to different levels of water and compared them with the use of WSDef. The WSI1 was a modification of the SWFAC (Soil Water FACtor) for photosynthesis-related processes in RZWQM2 using the daily potential root water uptake (TRWUP) calculated by the Nimah and Hanks approach. The WSI2 was WSI1 with terms accounting for stress due to additional heating of the canopy from unused energy of potential soil evaporation in both the supply and demand terms of the WSI1. These factors were evaluated using the data for corn grain yield, biomass, soil water, and leaf area index (LAI) derived from canopy cover data from multiple water-level experiments conducted at Greeley, CO, from 2008 to 2011, irrigated and rainfed corn at Akron, CO, and irrigated corn at Gainesville, FL, on different soil types. Overall, the stress factors WSI1 and WSI2 were found to be superior to WSDef in simulations of grain yield, biomass, and LAI in all three experiments. Further, in general, WSI2 simulations of the crop were either comparable to or more accurate than WSI1 simulations in most of the crop seasons simulated in this study. The stress factor WSI2 has been incorporated in the RZWQM2 for simulating corn.

Soil water deficit is one of the major abiotic stresses that adversely affect crop growth and yield (Hsiao et al., 2007). This adverse effect is brought about in two major ways. Lack of adequate soil water supply and reduced plant water uptake reduce cell division for leaf elongation and root enlargement, which lead to a decline in leaf area for photosynthesis and nutrient ion transport to the root surface in the soil. The water stress also directly affects many biochemical reactions and physiological growth processes, such as photosynthesis, C allocation and partitioning, phasic developmental rates, and phenology (Chen and Reynolds, 1997; Tardieu et al., 2000; Chaves et al., 2002; Cakir, 2004; Shao et al., 2008). Corn has long been reported to be very sensitive to water deficits, especially during its reproductive stages (Denmead and Shaw, 1960; Hall et al., 1981; Grant et al., 1989; Bai et al., 2006).

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Corn production on the Great Plains of Colorado has increased noticeably in the past decades with the availability of irrigation systems and cultivars with improved radiation and water use efficiency (Norwood, 2001; Castleberry et al., 1984; Hergert et al., 1993). Like other regions in the world, crop water stress due to low precipitation, limited irrigation water available, and high temperatures are still the main limiting factors for corn and other agricultural production in the region (Halvorson et al., 1999; Norwood, 1999). Greater demand for freshwater resources by various human enterprises today necessitates even more judicial and efficient use of the limited available water for sustained crop production (Hsiao et al., 2007; Saseendran et al., 2008b; DeJonge et al., 2011).

In this context, agricultural system models are the potential tools for developing whole-system-based crop and water management practices for optimized use of limited precipitation and supplementary irrigation for crop production (Jackson et al., 1990; Saseendran et al., 2008b; DeJonge et al., 2011; Salazar et al., 2012). Accurate quantification of crop responses to water stress in agricultural system models is critical for their applications for this purpose. In most system models, the water stress effect is accounted for through specification of a "water stress factor," which is generally expressed as a supply/demand ratio to modulate the crop growth and development processes (Ritchie, 1981; Saseendran et al., 2008a), with slight variations in the form of this factor. All major crop system models, APSIM

Abbreviations: DOY, day of the year; ET, evapotranspiration; LAI, leaf area index; LIRF, Limited Irrigation Research Farm.

(McCown et al., 1996), CropSyst (Stockle et al., 2003), Daisy (Hansen et al., 1990, 1991), DSSAT (Jones et al., 2003; Ritchie, 1998; Woli et al., 2012), and STICS (Brisson et al., 1998), use the ratio of potential uptake to potential transpiration or actual to potential transpiration to represent water stress for modulating photosynthesis and leaf expansion growth in crop simulations. A notable exception is in the use of the fraction of plant-extractable water in the root-zone soil used as a water stress factor for modulating phenology and N_2 fixation in the APSIM model. The RZWQM2 model uses the DSSAT Version 4.0 (CSM-CERES and CROPGRO) crop models for the simulation of various crops and uses its water stress functions (Ahuja et al., 2000; Ma et al., 2009). Modifications of the CSM-CERES-Maize model have been reported recently for improved photosynthesis and leaf area simulation in the CSM-CERES-Maize 4.5 and CSM-IXIM-Maize 4.5 versions of the corn model within DSSAT 4.5 (Jones et al., 2003; Hoogenboom et al., 2010; Lizaso et al., 2011); however, these models still use the same water stress factors as Version 4.0. The need for better quantification of the water stress factors has been reported in several past studies (Cabelguenne et al., 1990; Castrignano et al., 1998; Ben Nouna et al., 2000; Faria and Bowen, 2003; Sau et al., 2004; Saseendran et al., 2008a; DeJonge et al., 2011). As we describe below, there is potential to improve the water stress factor from CERES Version 4.0 by improving the calculation of the potential root water uptake term. We also hypothesize that the inclusion of terms for canopy heating due to unused energy from potential soil evaporation in the quantifications of the water stress factors could improve simulations of crop responses to water.

In this study, we modified the current DSSAT-CSM stress factors in the RZWQM2 model in two different ways (WSI1 and WSI2), as explained below. Our main objective was to test these two water stress factors for simulating the detailed multilevel irrigation experiments in corn from 2008 to 2011 at Greeley, CO, using the RZWQM2 model with the embedded CSM-CERES-Maize 4.0 crop growth module. The model with modified water stress factors was also tested for simulating dryland and limited irrigation studies at Akron, CO, and another experiment in a sandy soil at Gainesville, FL, available in the DSSAT 4.5 database.

FORMULATION OF WATER STRESS FACTORS

As noted above, the RZWQM2 model uses the water stress functions of DSSAT based on the ratio of potential root water uptake (TRWUP) to potential plant transpiration (EP_o) (Ritchie, 1998), referred to hereafter as the default water stress factor (WSDef). In simulations under well-watered conditions, TRWUP is higher than EP_o and there is no water stress (Fig. 1). As the soil dries out due to root water uptake, TRWUP decreases. At a certain stage, a threshold is reached where the first water stress factor or turgor factor to modulate expansive leaf growth, called TURFAC, is activated. In both C_3 and C_4 plants, this point corresponds to the situation when the root water uptake combined with osmotic adjustments and cell wall extensibility (in meristematic cells) fail to maintain turgor pressure to sustain cell division (mitosis) and leaf expansion growth (Boyer, 1970; Cosgrove and Cleland, 1983; Neumann, 1995; Cosgrove, 1998). The TURFAC is defined as

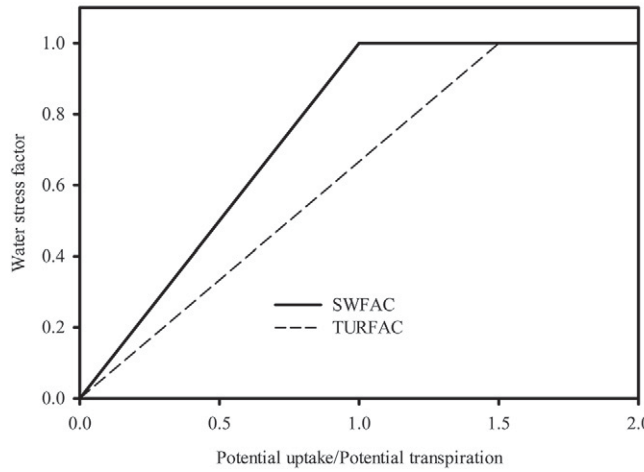

Fig. 1. Relationships used to calculate the soil water stress factors SWFAC and TURFAC in DSSAT-CSM models (Ritchie, 1998).

$$\mathrm{TURFAC} = \frac{\mathrm{TRWUP}}{\mathrm{RWUEP1} \times \mathrm{EP_o}} \quad [1]$$

where RWUEP1 is a species-specific parameter, used for emulating the water stress level in the plants below which turgor pressure in the plant leaf cells fails to sustain expansion growth at the potential level, which is currently set to 1.5 for corn. This suggests that the plants start experiencing water stress for expansion growth when TRWUP is 1.5 times EP_o.

When EP_o demand equals or exceeds the TRWUP, a second stress factor, called SWFAC, is activated:

$$\mathrm{SWFAC} = \frac{\mathrm{TRWUP}}{\mathrm{EP_o}} \quad [2]$$

The SWFAC mainly affects photosynthesis and other dry matter accumulation related processes. In plants, this stress sets in at a leaf water potential level that is significantly below the TURFAC level, when photosynthesis and other C assimilation processes are impaired due to water shortage. Both the TURFAC and SWFAC stress factors are used as direct multipliers on the leaf growth and dry matter accumulation rate that ranges from 1 for no stress to 0 for complete stress.

The TRWUP in the CSM-CERES-Maize module in RZWQM2 is computed using a simplified analytic solution of radial flow of water to plant roots in the soil profile (Ritchie, 1998). The EP_o is computed from potential evapotranspiration in the soil–residue–canopy system modeled using the extended Shuttleworth–Wallace ET model (Farahani and Ahuja, 1996; Farahani and DeCoursey, 2000).

The simplified closed-form equation of Ritchie (1998) used to calculate TRWUP in Eq. [1] and [2] above is

$$\mathrm{TRWUP} = \sum_{i=1}^{N} \frac{k_1 \exp\left[k_2\left(\mathrm{SW}_i - \mathrm{LL}_i\right)\right]}{k_3 - \ln\left(\mathrm{RLV}_i\right)} \mathrm{RLV}_i \Delta Z_i \quad [3]$$

where RLV_i is the root length density in the *i*th soil layer (cm cm^{-3}); $k_1 = 0.00132$; $k_2 = 45.0$ if the drained lower limit (LL) of the soil water (plant wilting point or soil water content at 1.5 MPa suction) in the soil layer is > 0.30 cm^3 cm^{-3}, and k_2 = 130 LL if the LL for the soil layer is <0.30 cm^3 cm^{-3}; k_3 = 7.01; SW_i and LL_i are the volumetric soil water content and the lower limit of plant-available water in the *i*th layer (cm cm^{-1}), respectively; and Z_i is the depth of the *i*th layer (cm).

The WSI1 Water Stress Factor

Equation [3] was derived from the theory of radial flow of water to a single root with several simplifying assumptions (Gardner, 1960). It assumes that the hydraulic conductivity of all soils is similar when normalized with respect to the lower limit soil water content (approximately corresponding to 1.5 MPa soil water tension). This assumption may be nearly correct when the soil water content is near the lower limit but has larger errors for higher soil water contents. The equation also assumes that the water potential gradient between the root and the soil remains constant even when the soil dries out; in fact, the water potential of the roots changes considerably throughout the day and so will the gradient. The equation of Nimah and Hanks (1973) solves the same radial flow of water to the roots numerically without these assumptions. Therefore, we explored the use of the Nimah–Hanks equation option in the RZWQM2 model for more rigorous computation of TRWUP.

In the RZWQM2 soil water routine, between rainfall or irrigation events the soil water is redistributed by using the Richards' equation (Ahuja et al., 2000):

$$\frac{\partial\theta}{\partial z}=\frac{\partial}{\partial z}\left[K\left(h,z\right)\frac{\partial h}{\partial z}-K\left(h,z\right)\right]-S\left(z,t\right) \quad [4]$$

where θ is the volumetric soil water content (cm^3 cm^{-3}); *t* is time (h); *z* is the soil depth (cm, assumed positive downward); *h* is the soil-water pressure head (cm); *K* is the unsaturated hydraulic conductivity (cm h^{-1}), a function of *h* and *z*; and the sink term *S*(*z*,*t*) includes the rates of root water uptake and the contribution to tile flow from a given soil depth. The root water uptake part of the sink term, $S_r(z,t)$ (cm h^{-1}), is computed using the Nimah and Hanks (1973) equation:

$$S_r\left(z,t\right)=\frac{\left[H_r+R_r z-h\left(z,t\right)-s\left(z,t\right)\right]R\left(z\right)K\left(\theta\right)}{\Delta x\Delta z} \quad [5]$$

where H_r is an effective root water pressure head (cm); R_r is a root resistance term, and the product ($R_r z$) accounts for gravity and friction loss in H_r (assumed = 1.05); *s*(*z*,*t*) is the osmotic pressure head (assumed = 0 cm); Δx is the distance from the plant roots to where *h*(*z*,*t*) is measured (assumed = 1 cm); Δz is the soil depth increment (cm); *R*(*z*) is the proportion of the total root activity in the depth increment Δz, obtained from the plant growth model.

The sum total of $S_r(z,t)$ across the transient root zone gives the total root water uptake TRWUP for any given time. The actual uptake cannot exceed the potential transpiration demand (EP_o) of the atmosphere; this is obtained by varying the value of H_r in Eq. [5] until the total uptake is equal to or less than the EP_o. The total potential uptake ($TRWUP_{NH}$) is calculated from the summation of Eq. [5] with H_r set equal to −1.5 MPa as the permanent wilting point (which can vary with crop species).

The WSI1 stress factors were then calculated as

$$\text{SWFAC}=\frac{\text{TRWUP}_{\text{NH}}}{\text{EP}_{\text{O}}} \quad [6]$$

and the formulation of TURFAC with the new SWFAC for corn is then

$$\text{TURFAC}=\frac{\text{SWFAC}}{1.5} \quad [7]$$

The WSI2 Water Stress Factor

In addition to the above computation of $TRWUP_{NH}$, we also realized that Eq. [1] and [2] neglect the water stress that the plants may experience due to heating of the canopy by the latent heat energy partitioned to potential soil evaporation but not used in soil evaporation when the surface soil water content is limiting. Therefore, we explored including stress due to additional canopy heating in the calculation of the water stress factors by changing their formulation.

We changed the formulation of SWFAC in Eq. [6] by replacing EP_o with the potential crop evapotranspiration, ET, in the denominator and adding the actual soil evaporation (E_S) for the day in the numerator:

$$\text{SWFAC}=\frac{\text{TRWUP}_{\text{NH}}+E_{\text{S}}}{\text{ET}} \quad [8]$$

where E_S is the amount of soil water available for evaporation, calculated by solving the Richards equation for upward vertical water flux at the soil surface subject to a boundary condition (upper limit) of the potential soil evaporation rate. The potential evaporation rate is obtained from the extended Shuttleworth–Wallace ET model (Farahani and Ahuja, 1996; Farahani and DeCoursey, 2000).

The formulation of TURFAC, using the new SWFAC, remained the same as in Eq. [8].

MATERIALS AND METHODS

Greeley, Colorado, Experiments

The field experiments for development of the water stress factors in this study were conducted at the Limited Irrigation Research Farm (LIRF) (40°26′ N, 104°38′ W, and 1428 m asl) of the USDA-ARS Water Management Research Unit, near Greeley, CO, during 2008 to 2011. A detailed description of the experiments was provided by Trout et al. (2010). In brief, the LIRF is a 16-ha field irrigation research facility for various crops (corn, winter wheat [*Triticum aestivum* L.], sunflower [*Helianthus annuus* L.], and dry bean [*Phaseolus vulgare* L.]) of the region. Soils at the farm include Nunn (fine, smectitic, mesic Aridic Argiustolls), Olney (fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). All three soils have a fairly uniform texture in the 200-cm profile, with an average of 74% sand, 17% clay, and 9% silt. Irrigation treatments were replicated four times in 9- by 40-m plots (0.76-m row spacing). Six water treatments were randomized within each replication (Table 1).

Table 1. Total seasonal irrigation and precipitation during the vegetative (VS) and reproductive (RS) stages of corn under six irrigation treatments from 2008 to 2011 in the limited irrigation experiments at Greeley, CO (LIRF).

Irrigation treatment†	Irrigation or precipitation							
	2008		2009		2010		2011	
	VS	RS	VS	RS	VS	RS	VS	RS
	mm							
Precipitation	39	191	135	94	145	55	138	38
T1 (100% of crop evapotranspiration, F)	289	149	202	216	201	164	255	230
T2 (85% of T1, V)	227	111	169	179	130	160	203	185
T3 (70% of T1, F)	202	80	146	154	114	133	182	147
T4 (70% of T1, V)	186	86	102	148	88	132	177	129
T5 (55% of T1, V)	136	45	68	100	61	98	129	92
T6 (40% of T1, V)	111	26	50	59	42	70	97	60

† V = variable, F = fixed. In the V treatments, 20% of the estimated weekly amounts of irrigation requirement during vegetative growth period were withheld and added to weekly amounts during the reproductive growth period; this was not done in the F treatments.

The six irrigation treatments were designed to meet certain percentages of the potential crop ET (ET_c) requirements during the growing seasons, starting 3 to 4 wk after planting: 100% (T1), 85% (T2), 70% (T3), 70% (T4), 55% (T5), and 40% (T6) of ET_c (Table 1). The amount of irrigation water for each treatment was estimated on a weekly basis based on the alfalfa (*Medicago sativa* L.) reference ET demand (ET_r; Allen et al., 2005), crop coefficient, rainfall, and soil water deficit (Trout et al., 2010; Bausch et al., 2011). For all the treatments except T1 and T3, 20% of the estimated weekly amounts during the vegetative growth period were withheld and added to the weekly amounts during the reproductive growth period. Crop rows had a north–south orientation.

DeKalb 52-59 field corn was planted on Day of the Year (DOY) 132, 131, 131, and 123 and harvested on DOY 310, 316, 292, and 310 in 2008, 2009, 2010, and 2011, respectively. A 2.0-cm irrigation was applied after planting in all plots to assure good germination. Fertilizer as urea–NH_4NO_3 was applied, based on soil sample analysis, before planting and then with the irrigation water during the growing seasons, to assure ample N for stress-free growth.

The soil water content was measured in each plot between the 30- and 200-cm depths with a neutron probe (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) in an access tube in the crop row near the center of each plot. The surface soil water content (0–15 cm) was measured with a MiniTrase portable time domain reflectometry system (Soil Moisture Equipment Corp.). These measurements were made before each irrigation and following an irrigation or precipitation event. Weather data were recorded on site (Colorado Agricultural Meteorological Network Station GLY04, available at http://ccc.atmos.colostate.edu/~coagmet/) were used in the calculation of ET_r.

Grain yield and crop biomass at harvest of the three crops were measured every year; however, biomass was measured in only a few plant samples, which may make these measurements less reliable than those of grain yield. Leaf area index measurements were not made systematically, and continuous full-season measurements were made (LI-3000C portable leaf area meter) only in 2010 in the T1, T3, T4, and T5 treatments; however, canopy cover (C_c) was estimated with a nadir-view digital camera (ADC, TetraCam) mounted on a “high boy” mobile platform and driven through the plots weekly. The C_c data were used to roughly calculate LAI using the Farahani and DeCoursey (2000) equation for corn and were used for comparative evaluation of LAI simulations by the model across different water levels. Phenology notes in terms of days to tasseling were available in 2008 and 2009.

Akron, Colorado, Experiments

One set of experiments was conducted in a silt loam soil (a fine, montmorillonitic, mesic Pachic Arguistoll) at Akron (40.15° N, 103.14° W, 1.38 km asl), CO, under both irrigated and rainfed conditions for a period of 8 yr. In the irrigation experiments, conducted during 1984, 1985, and 1986, Pioneer Brand 3732 hybrid corn (101-d relative maturity) was planted under a line-source gradient irrigation system, with maximum water application next to the irrigation line and linearly declining water application with distance from the line. In 1985, additional irrigation treatments were imposed through drip irrigation using four irrigation levels determined by different threshold values of the Crop Water Stress Index (Saseendran et al., 2008b). The corn hybrid Pioneer Brand 3732 used in the irrigation studies was also used in the rainfed corn experiments from 1993 to 1997 at the location; therefore, data during this period were used for simulations of the crop under rainfed conditions. Saseendran et al. (2008b) simulated the Akron experiments using the CERES-Maize Version 4.0 within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008b) were used as a starting point for calibration of the cultivar parameters in this study (Table 2). The Ma et al. (2011) protocol was adopted for calibration of the cultivar parameters. Grain yield data collected in the drip irrigation treatment (wettest, 213 mm applied) in 1985 were used in the calibration. The calibrated cultivar-specific coefficients were then used for simulating the crop in the 10 remaining irrigation treatments from 1984 to 1986 and five rainfed experiments from 1993 to 1997.

The DSSAT Data Sets

The DSSAT suite of cropping system models has been used extensively for simulations of various crops around the world (Jones et al., 2003). In this study, the enhanced RZWQM2 was further tested for simulations of corn in an irrigation experiment, distributed with the DSSAT 4.5 package, in a sandy soil conducted at Gainesville (29.63° N, 82.37° W, 0.01 km asl), FL, in 1982 (UFGA experiments) (Hoogenboom et al., 2010). The experiment consisted of corn under (i) rainfed

Table 2. Plant parameters calibrated for RZWQM2-CERES simulations of corn hybrids in the LIRF, UFGA, and Akron experiments using the WSDef, WSI1, and WSI2 water stress factors.

Trait	LIRF	UFGA	Akron
P1: Degree days (base temperature of 8°C) from seedling emergence to end of juvenile phase, °C d	260	260	290
P2: Day length sensitivity coefficient (the extent [d] that development is delayed for each hour increase in photoperiod above the longest photoperiod [12.5 h] at which development proceeds at maximum rate)	0.60	0.30	0.80
P5: Degree days (base temperature of 8°C) from silking to physiological maturity, °C d	620	910	615
G2: Potential kernels per plant, no.	1000	980	690
G3: Potential kernel growth rate, mg kernel^{-1} d^{-1}	6.90	7.1	9.3
PHINT: Degree days required for a leaf tip to emerge, °C d	43.0	43.0	38.9

with low N, (ii) rainfed with high N, (iii) irrigated with low N, (iv) irrigated with high N, (v) water stress in the vegetative stage with low N, and (vi) water stress in vegetative stage with high N conditions in 1982.

The RZWQM2 Model

The agricultural system model, RZWQM2 (Root Zone Water Quality Model), is process oriented and combines the biological, physical, and chemical processes for simulation of the impacts of agricultural management practices (tillage, water, agricultural chemicals, and crop) on soil water, crop production, and water quality (Ahuja et al., 2000). Plant transpiration is computed in RZWQM2 as the amount of water taken up by the plant that was not allowed to exceed the potential plant transpiration demand. The potential demand is calculated using the extended Shuttleworth–Wallace ET model (Farahani and Ahuja, 1996; Farahani and DeCoursey, 2000). This model extends the Penman–Monteith approach to include the effect of incomplete canopy cover and canopy height in the potential evaporation and transpiration estimations. The CSM-CERES-Maize 4.0 module is embedded within the RZWQM2 for simulation of corn growth (Ma et al., 2009). The RZWQM2 and its previous versions have been used extensively for simulating corn growth under various conditions in the Great Plains of the United States (Ma et al., 2003; Saseendran et al., 2004, 2005, 2008b, 2009, 2010).The advantages of using the RZWQM2 model come from combining the detailed simulations of soil surface residue dynamics, tillage, and other soil management practices and detailed soil water and soil C and N processes of RZWQM with the detailed crop-specific plant growth modules of the DSSAT 4.0 suite of crop models. Ma et al. (2005, 2006, 2009) reported comparable simulation results of soybean [*Glycine max* (L.) Merr.] and corn production using the RZWQM–DSSAT (RZWQM2) hybrid models as the original CROPGRO and CERES models within DSSAT. Ma et al. (2012) simulated the LIRF experiments for corn from 2008 to 2010 using the CSM-CERES-Maize Version 4.0 module in RZWQM2.

Input Data for the Simulations and Calibration of RZWQM2

The RZWQM2 model needs inputs of daily weather (daily solar irradiance, maximum and minimum temperature, wind speed, relative humidity, and precipitation as breakpoint rainfall data), soil and crop management (planting dates, planting depth, row spacing, and plant population; amount, dates, and methods of irrigation and fertilizer applications; and dates and methods of tillage operations). It also requires soil physical properties (soil profile depth and horizons or layers, soil texture, and bulk density), the soil water retention curve (SWRC), soil hydraulic conductivity, and organic matter content in the profile by horizon. Excepting the SWRC, these input data were available for the LIRF (Ma et al., 2012), Akron (Ma et al., 2002), and UFGA (Hoogenboom et al., 2010) experiments. In RZWQM2, the SWRC and saturated hydraulic conductivity of each soil horizon are represented in the form of the Brooks and Corey equations (Ahuja et al., 2000). The SWRC for the model soil water balance were obtained from the available soil bulk density and field capacity water content (33.3-kPa soil water content) data (Ahuja et al., 2000). The Brooks–Corey equation was fitted to these data for each of the soil layers to obtain the SWRC (Brooks and Corey, 1964; Ma et al., 2011). If not available, soil hydraulic conductivity values were obtained from soil texture and the SWRC using the default tables or empirical equations in the model (Ahuja et al., 2000).

Measured rainfall and irrigation varied markedly among the crop seasons from 2008 to 2011 in the LIRF experiments (Table 1). Unfortunately, the initial soil water at planting was not measured. In earlier studies at Akron, CO, we found that if we started the model a few months ahead of planting, on 1 January of each year, the precipitation during this early period tended to equilibrate the soil water and reproduce close to the initial soil water at planting. The initial soil water content on 1 January was assumed to be at field capacity in the upper 450 mm of soil and at half the plant-available water below this depth, which reproduced a few measured values at Akron. This scheme was followed by Ma et al. (2012) for the Greeley data as well, and we followed the same scheme for this study. We followed the same calibration procedures and used the same initial conditions of the model for simulations of the experiments using all three (WSDef, WSI1, and WSI2) stress factors.

Because various process interactions in an agricultural production system are highly complex, the model parameters required for reliable simulation of the system need careful calibration based on measured results (Ma et al., 2011). The RZWQM2 requires careful iterative calibration of its parameters for the soil water component, followed by the N and plant growth components. If the simulation of crop growth at a calibration step is not satisfactory, the whole sequence of calibration is repeated to obtain more accurate simulations (Ma et al., 2011). The calibration procedure included matching the simulation results with measured soil water, transpiration, ET, anthesis and maturity dates, maximum LAI, and final

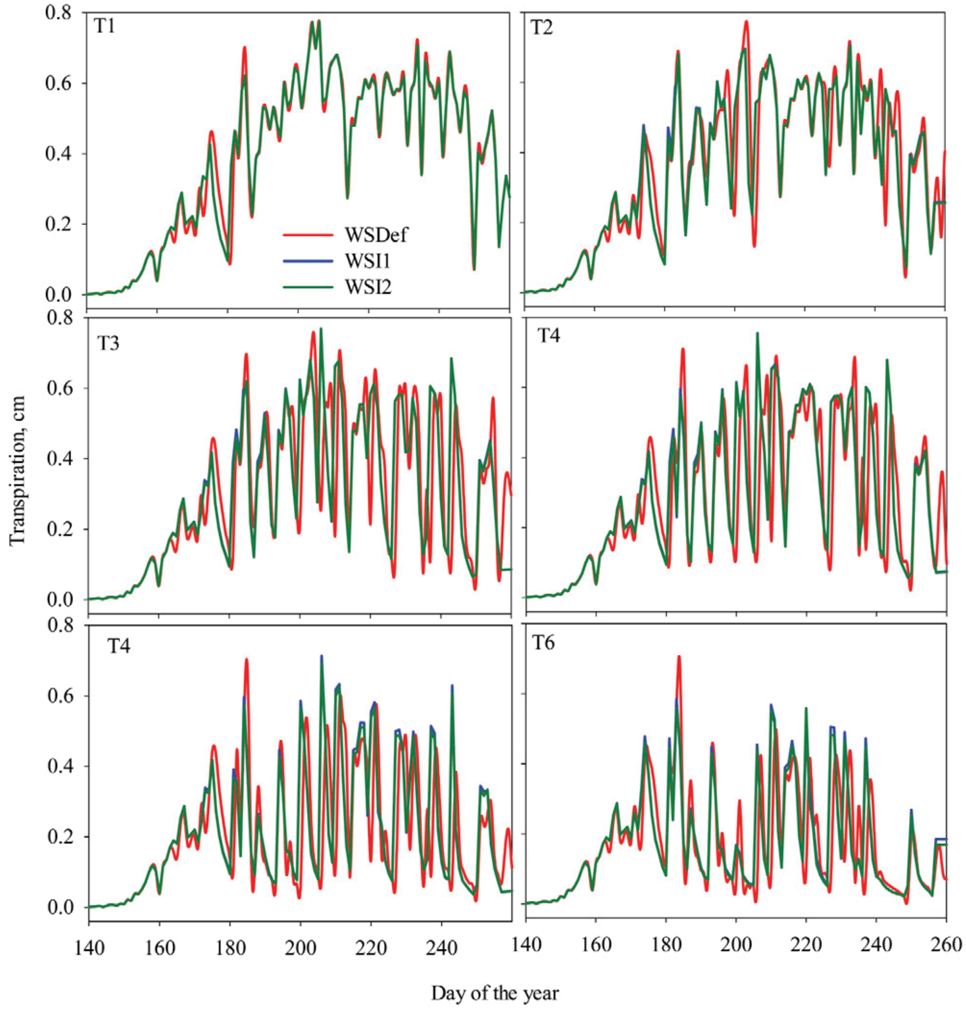

Fig. 2. Comparison between daily corn transpiration simulated in response to the WSDef, WSI1, and WSI2 water stress factors in 2010 under six irrigation levels (T1–T6, highest to lowest).

biomass and yield. Ma et al. (2012) initially calibrated the model for plant and soil parameters using data collected in 2008 and then simulated the experiments in 2009 and 2010. The cultivar parameters found by Ma et al. (2012) for the LIRF experiments were fine tuned for the best possible simulations, using the WSDef water stress factor, of the measured grain yield, biomass, and LAI when the experimental data for 2011 were used in simulations.

The model was calibrated manually following Ma et al. (2011) to achieve the best possible match between the simulated and measured available soil water component and the plant growth components (grain yield, biomass, and LAI) in the LIRF, Akron, and UFGA experiments using the WSDef water stress factor in RZWQM2 for simulation of corn using the embedded CSM-CERES-Maize 4.0 model (Table 2). The calibrated models were used without further change for simulating the effects of the WSI1 and WSI2 water stress factors in simulations of corn in the three experiments. Experimental data from the highest water treatment in each experiment was used only for calibration, and the remaining treatments were used for validation. Simulated phenology dates were compared with available field notes. In general, the anthesis and physiological maturity dates in the simulations were off by 2 to 7 d from the field-estimated dates in simulations from 2008 to 2011 with the three water stress factors.

Statistics for Model Calibration and Evaluations

We evaluated the simulation results using: (i) the root mean squared error (RMSE) between simulated and observed values; (ii) the relative RMSE (RRMSE), which varies between 0 and 100%, and (iii) the index of agreement (d) between measured and simulated parameters (Willmott, 1981), which varies between 0 (poor model) and 1 (perfect model):

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i-O_i\right)^2} \quad [9]$$

$$\mathrm{RRMSE}=\frac{\mathrm{RMSE}}{O_{\mathrm{avg}}} \quad [10]$$

$$d=1.0-\frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i-O_{\mathrm{avg}}\right|+\left|O_i-O_{\mathrm{avg}}\right|\right)^2} \quad [11]$$

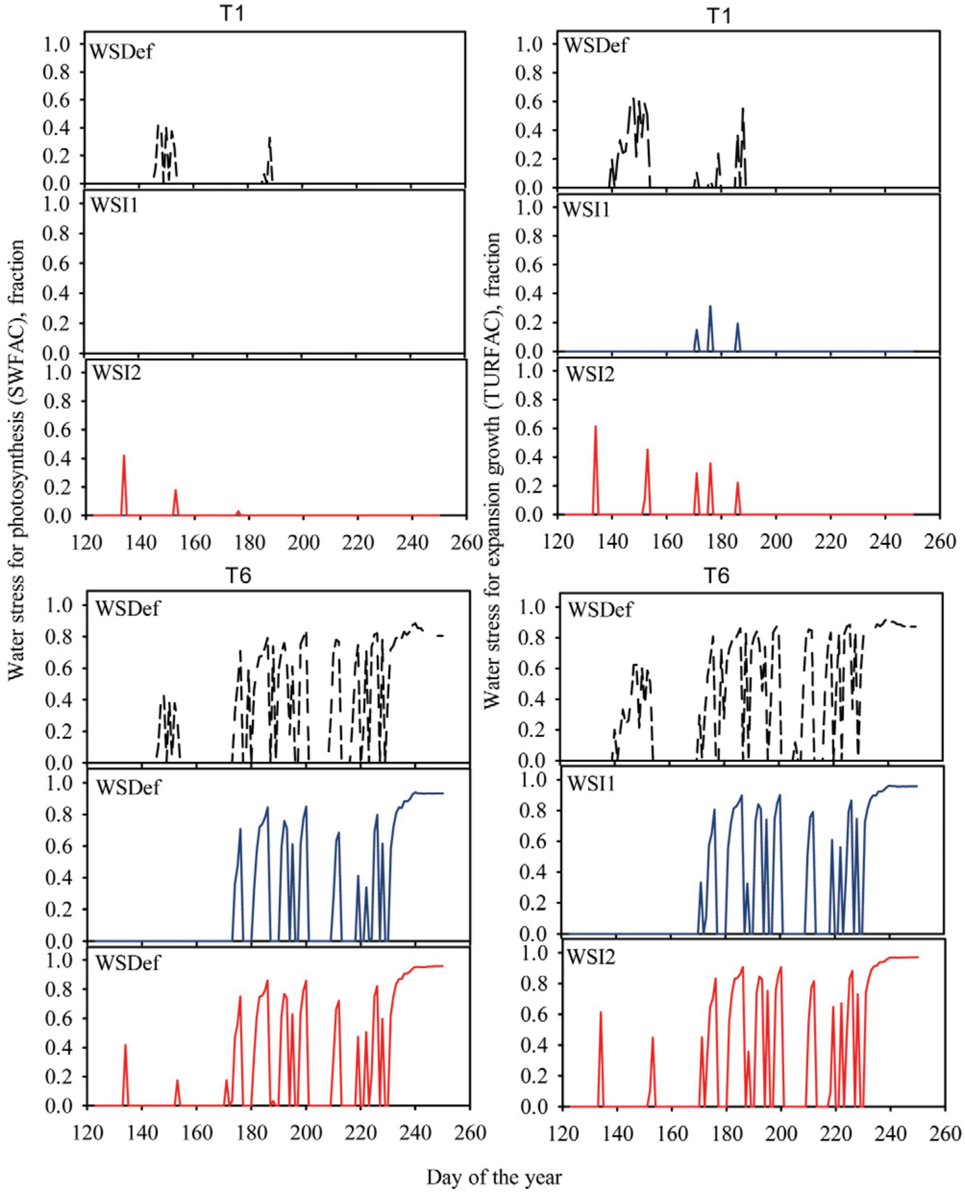

Fig. 3. Comparison between the water stress factors for corn growth (SWFAC and TURFAC) simulated in response to the stress factors WSDef, WSI1, and WSI2 in 2010 under T1 (highest water treatment) and T6 (lowest water treatment). The stress factors range from 0 for no stress to 1 for complete stress.

where P_i is the ith simulated value, P_{avg} is the average of the simulated values, O_i is the ith observed value, O_{avg} is the average of the observed values, and n is the number of data pairs.

RESULTS AND DISCUSSION

Greeley, Colorado, Experiment

Comparison of Plant Transpiration Simulated in Response to WSDef, WSI1, and WSI2

Seasonal total crop transpiration simulated using WSDef with Eq. [3] (Ritchie, 1998) and WSI1 and WSI2 with Eq. [5] (Nimah and Hanks, 1973) for root water uptake did not differ appreciably under the six irrigation treatments (T1–T6) (Fig. 2). Although the same Nimah and Hanks (1973) equation was used in computations of water uptake when the WSI1 and WSI2 factors were used, the computed uptake (transpiration) differed slightly between them because the different water stress factors impacted the crop growth and subsequent transpiration slightly differently. Seasonal plant transpiration simulated using WSDef, WSI1, and WSI2 were 57.0, 55.7, and 55.5 cm, respectively, under T1 and 23.4, 24.3 and 24.0 cm, respectively, under T6 (Fig. 2). Compared with WSDef, transpiration values simulated using WSI1 and WSI2 were closer to each other because both used the same equation for root water uptake (Eq. [5]). Under T1, while the simulated daily transpiration differed slightly between WSDef and WSI1/WSI2 during the initial growth stages of the crop (up to about DOY 190), they were similar during the remaining crop growth period (T1 in Fig. 2). Under T1, until about DOY 190, the irrigation fell short of completely meeting the transpiration demand of the crop, resulting in some water stress to the crop (Fig. 3). No water stress was simulated after about DOY 190. The daily transpiration simulated with WSDef and WSI1/WSI2 differed, and the difference remained more or less constant with deficit irrigations in the T2, T3, T4, T5, and T6 treatments (Fig. 2). These results demonstrate that both Eq. [3] and [5] for root water uptake simulate similar plant transpiration when transpiration demand is fully met with

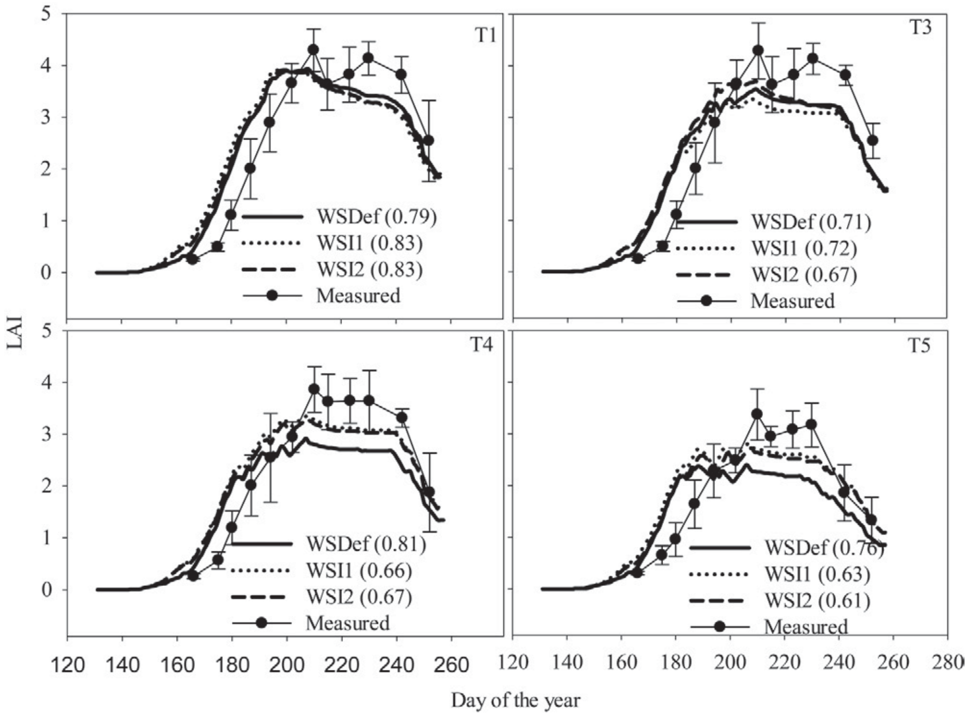

Fig. 4. Comparisons of measured and simulated corn leaf area index (LAI) using stress factors WSDef, WSI1, and WSI2 in 2010 under the T1, T3, T4 and T5 irrigation treatments, where T1 is the lowest water treatment and T5 the highest. Error bars show one standard deviation of the measurements. The RMSE values are given in parentheses in the legends. The average RMSE values of the LAI simulations across treatments were 0.77, 0.71, and 0.69 for the WSDef, WSI1, and WSI2 stress factors, respectively.

irrigation but begin to differ slightly when irrigation falls short of meeting the full transpiration demand.

Comparison of the Changes in Different SWFAC and TURFAC Stress Factors

In general, appreciable differences in simulated water stress between WSDef and the two new water stress factors were in the beginning of the crop season when the soil was not fully covered by the crop. Average (arithmetic mean of daily stress factors calculated) TURFAC values simulated using WSDef, WSI1, and WSI2 under T1 were 0.12, 0.00, and 0.03, respectively, until the simulated crop LAI reached a value of 1.00 on DOY 166 (Fig. 3 and 4). Corresponding SWFAC values simulated were 0.05, 0.0, and 0.01, respectively. The simulated TURFAC and SWFAC values after the crop LAI exceeded a value of 3.50 on DOY 192 were 0.00 for all four water stress factors under T1 (Fig. 4). The difference in the stress factors simulated by WSI2 in the early phases of crop development was due to the fact that in the WSDef (Eq. [1] and [2]) and WSI1(Eq. [6] and [7]), water demand and supply are based on the potential plant water uptake and potential plant transpiration; both neglect the heating of the canopy (sensible heat) due to unmet soil evaporation demand. When the crop does not cover the soil completely and the soil evaporation demand is not met, the heat load developed in the soil is transmitted to the plants, causing an enhancement in the water stress experienced by the plants. To account for this effect, in WSI2, we have the default potential transpiration demand replaced with ET demand (Eq. [8]). However, WSI1 is simply a ratio of the actual $TRWUP_{NH}$ to EP_o (Eq. [6] and [7]). Additionally, WSI2 has actual soil evaporation (E_S) added to the $TRWUP_{NH}$ in the numerator of the equation (Eq. [8]) to account for the portion of the soil evaporation demand actually met by rain and irrigation in the experiments.

Soil Water Simulations

In addition to management (soil–water–crop), water stress experienced by plants is directly related to the water storage capacity of the soil and its depletion and replacement (Ritchie, 1981). Therefore, adequate calibrations of the model for soil water simulations are important for the correct estimation of water stress factors that affect crop growth and development. Soil water simulations under all the treatments in response to the three stress factors (WSDef, WSI1, and WSI2) were reasonably accurate in 2008, 2010, and 2011. In these years, the RRMSE of the total profile (180 cm) soil water simulations was between 11.1 and 15.7% and the *d* index between 0.47 and 0.79 (RMSE 4.1– 5.7 cm) (Table 3). Error statistics for soil water simulations in 2009 were higher, with RRMSE between 17.4 and 19.1% (RMSE 5.7 and 6.3 cm and *d* index of 0.69–0.72) (Table 3). Differences in error statistics across the years occurred due to the fact that there were differences in the soil properties across plots in the LIRF experiment, as corn was planted in different plots in different years (2008–2011). Because no initial soil N and water in each plot were measured at planting, however, a single set of average soil properties was used in the simulations. Nonetheless, differences in error statistics in soil water simulations between the three water stress factors were not appreciable.

Leaf Area Index Simulations

As noted above, in the LIRF experiment, continuous direct measurements of LAI were available only for one crop season in 2010 in the T1, T3, T4, and T5 treatments (Fig. 4). Overall, in 2010, the LAI (estimated from canopy cover data) was

Table 3. Evaluation statistics of root mean square error (RMSE), relative RMSE (RRMSE), and index of agreement (*d*) for simulations of total profile soil water, leaf area index (LAI, estimated from canopy cover data), biomass, and grain yield (0% moisture) using the three stress factors (WSDef, WSI1, and WSI2) against measured values at six irrigation levels in each of the 2008, 2009, 2010, and 2011 LIRF experiments.

Year	Total profile (0–180 cm) soil water			LAI			Biomass			Grain yield		
	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*
	cm	%			%		kg ha^{-1}	%		kg ha^{-1}	%	
						WSDef						
2008	3.9	13.0	0.84	0.81	54.7	0.88	1002	9.6	0.97	523	10.6	0.97
2009	6.3	19.1	0.69	1.13	56.0	0.75	1475	8.1	0.96	935	11.3	0.95
2010	5.3	14.6	0.47	0.66	39.3	0.96	2078	13.8	0.97	645	8.3	0.98
2011	4.2	13.7	0.57	0.73	29.0	0.97	1263	7.5	0.98	1613	19.3	0.91
						WSI1						
2008	3.6	12.6	0.84	0.82	55.1	0.90	1544	9.1	0.92	566	6.7	0.95
2009	5.7	17.5	0.72	1.18	58.7	0.75	827	4.6	0.99	260	3.1	0.99
2010	5.3	14.6	0.46	0.77	45.4	0.80	2873	19.2	0.84	488	6.3	0.98
2011	4.1	13.2	0.58	0.88	34.7	0.99	1599	3.5	0.99	1085	13.0	0.94
						WSI2						
2008	3.6	12.8	0.82	0.78	38.4	0.79	1166	5.7	0.96	382	6.0	0.98
2009	5.7	17.4	0.72	1.17	57.8	0.75	876	4.8	0.98	448	5.4	0.99
2010	5.7	15.7	0.46	0.75	44.4	0.84	2076	13.9	0.90	449	5.7	0.99
2011	4.1	13.1	0.58	0.79	31.2	0.98	1195	10.5	0.99	1002	12.0	0.96

best simulated with WSI2, with RRMSE of 36.4% and *d* of 0.95 (Table 3). However, detailed treatmentwise comparisons showed that the LAI simulations in T1 (highest water treatment) using WSDef with RMSE of 0.79 and WSI1 and WSI2 with RMSE of 0.83 did not differ appreciably (Fig. 4). Notwithstanding, in the lower water treatments (T3, T4, and T5 in Fig. 4), simulations using WSI1, with RMSE between 0.63 and 0.66, and using WSI2, with RMSE between 0.61 and 0.69, were appreciably better than simulations with WSDef, with RMSE between 0.71 and 0.81. Taking into account the measured deviations in LAI between replications (standard deviations plotted in Fig. 4), overall, the simulations using the three stress factors (WSDef, WSI1, and WSI2) reasonably followed the measured crop LAI in the field. It should also be noted that the measurements with the LI-3000C portable leaf area meter had large uncertainties because the measurements were made directly on the plant without removing the leaves from the plant. Attempts to improve the LAI simulations further by changing the plant species and cultivar parameters, including the phyllochron and senescence parameters, in the model did not yield better results. We are looking further into improving both the measurements and simulations.

Grain Yield and Biomass Simulation

Measured grain yields in 2008 in response to the six irrigation levels ranged from 11,071 to 7546 kg ha^{-1}, with a maximum gain of 3615 kg ha^{-1} due to the applied irrigation between the highest and lowest treatments (Fig. 5a). A similar gain in biomass due to irrigation in this year was 7781 kg ha^{-1} (Fig. 6a). Using the WSDef stress factor, the simulated grain yields ranged between 10,988 kg ha^{-1} under T1 and 6408 kg ha^{-1} under T6, with a gain of 4580 kg ha^{-1} due to applied irrigation among the treatments, underestimating the measured gain by 965 kg ha^{-1}. Simulations with WSI1 underestimated the maximum yield gains due to applied irrigation by 762 kg ha^{-1}, while WSI2 overestimated the yield gain by 135 kg ha^{-1}. Similarly, simulations of maximum biomass gain due to applied irrigation with the three stress factors (WSDef, WSI1, and WSI2) were 9089, 5792, and 7334 kg ha^{-1}, respectively, compared with the measured gain of 7781 kg ha^{-1}. For 2008, the RMSE of grain yield simulations using WSDef (523 kg ha^{-1}) and WSI1 (566 kg ha^{-1}) did not differ appreciably (Table 3) compared with the RMSE of 382 kg ha^{-1} achieved using the WSI2 water stress factor (Table 3; Fig. 5a). Biomass simulations using WSDef, WSI1, and WSI2 were 1002, 1544, and 1166 kg ha^{-1}, respectively (Table 3; Fig. 6a). The RMSE of LAI simulations, with values ranging between 0.78 for WSI2 and 0.90 for WSI1, did not differ appreciably among the three stress factors. In general in 2008, simulations using WSI2 were better than using WSI1 or WSDef in RZWQM2; however, biomass simulations with WSDef showed slightly better accuracy than with the other stress factors (Table 3; Fig. 5a and 6a).

For 2009, in simulations of grain yield and biomass across the six irrigation treatments, those using WSI1 and WSI2 showed lower RMSE, RRMSE, and higher *d* than those using WSDef (Table 3; 5b and 6b). Unlike in 2008, however, grain yield simulations with WSI1 were more accurate than with WSI2, and biomass simulations were comparable; however, the RMSE values for the LAI simulations (1.13, 1.18, and 1.17 for WSDef, WSI1, and WSI2, respectively) were comparable to each other. In summary, for 2009, both WSI1 and WSI2 fared equally well in simulations of the crop and more accurately than WSDef.

For 2010, the highest measured grain yield and biomass under the maximum irrigation treatment (T1 at 100% ET) was 9436, which was 15, 8, and 20% lower than the measured highest grain yields underT1 in 2008, 2009, and 2011, respectively (Fig. 5c); however, the measured grain yield under T6 for this year was lower than in 2008 and 2009 by 38 and 7%, respectively, but more than in 2011 by 35%. Grain yield simulations with all three stress factors (WSDef, WSI1, and WSI2) for this year were reasonably accurate, with RMSE values ranging between 449 kg ha^{-1} (for WSI2) and 645 kg ha^{-1} (for WSDef) (Table 3; Fig. 5c). Biomass simulations using the three water stress factors were also comparable to each other, with RMSE values ranging between 2076 kg ha^{-1} using WSI2 and 2873 kg ha^{-1} using WSI1 (Table 3; Fig. 6c). In summary, taking into account both

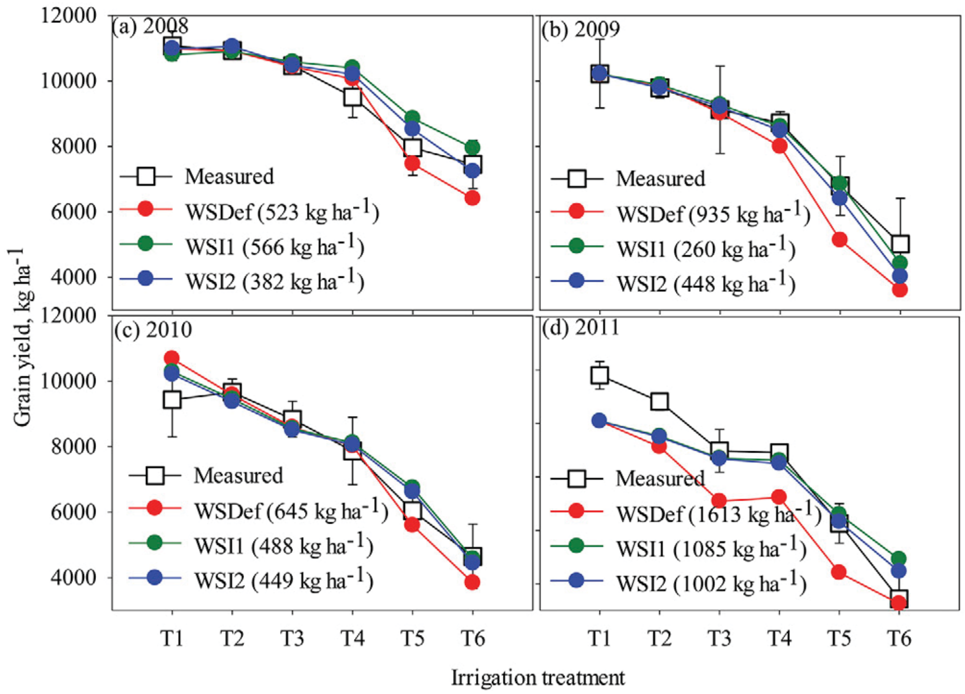

Fig. 5. Comparison between measured and simulated corn grain yield (0% moisture) in six irrigation treatments (T1–T6, highest to lowest) from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSDef, WSI1, and WSI2. Error bars indicate one standard deviation of the measured data. The RMSE values are given in parentheses in the legends; the RMSE values across years were 1021, 672, and 623 kg ha^{-1} for the WSDef, WSI1, and WSI2 stress factors, respectively.

grain yield and biomass simulations, in 2010, WSI2 simulations were more accurate than WSDef and WSI1.

The crop season in 2011 was markedly different from the previous 3 yr, with the highest measured maximum grain yield of 11,809 kg ha^{-1} (the highest in 4 yr of experiments) due to the highest irrigation level (T1, at 100% ET) and the lowest grain yield of 3434 kg ha^{-1} (the lowest in 4 yr of experiments) in response to the lowest irrigation level (T6, at 40% ET). The measured grain yield in response to T1 for this year was 7, 15, and 25% higher than those measured in 2008, 2009, and 2010, respectively (Fig. 5). Also, equally conspicuous was the lowest measured grain yield due to the lowest irrigation level, which was lower by 54, 32, and 26%, respectively. Similar differences were also reflected in the measured biomass (Fig. 6). Simulated grain yield differences

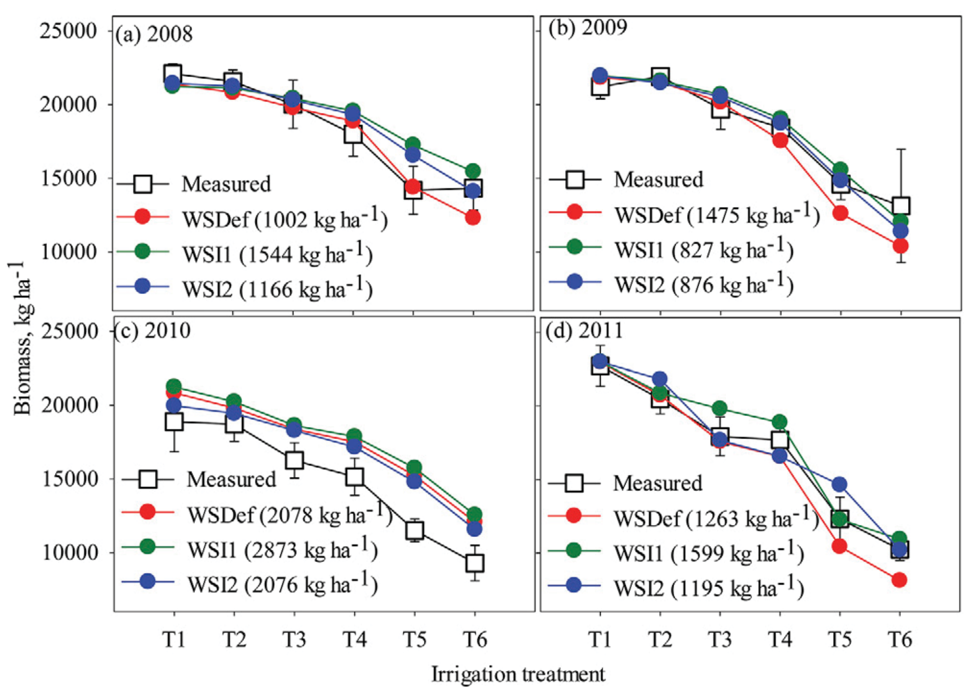

Fig. 6. Comparison between measured and simulated corn biomass in six irrigation treatments (T1–T6, highest to lowest) from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSDef, WSI1, and WSI2. Error bars indicate one standard deviation of the measured data. The RMSE values are given in parentheses in the legends; RMSE values across years were 1665, 1694, and 1401 kg ha^{-1} for the WSDef, WSI1, and WSI2 stress factors, respectively.

Table 4. Evaluation statistics of root mean square error (RMSE), relative RMSE (RRMSE), and index of agreement (*d*) for simulations of grain yield (0% moisture) and biomass using the three stress factors (WSDef, WSI1, and WSI2) against measured values for pooled data from six irrigation treatments in each of the four crop seasons of 2008, 2009, 2010, and 2011 in the LIRF experiments.

Stress factor	Biomass			Grain yield		
	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*
	kg ha^{-1}	%		kg ha^{-1}	%	
WSDef	1665	9.6	0.94	1021	12.0	0.92
WSI1	1694	9.8	0.94	672	7.9	0.97
WSI2	1401	8.1	0.97	623	7.3	0.98

between the highest and lowest irrigation treatments for this year using the WSDef, WSI1, and WSI2 stress factors were 6843, 5180, and 5631 kg ha^{-1}, respectively, against the measured value of 8375 kg ha^{-1}. In response to the six irrigation treatments, however, simulations of grain yield with WSI1 and WSI2 were comparable to each other, with RMSE values of 1002 and 1085 kg ha^{-1}, respectively, and were considerably more accurate than WSDef, with RMSE of 1613 kg ha^{-1} (Table 3; Fig. 5d and 6d). Nonetheless, WSI1 simulations of biomass for this year, with RMSE of 1599 kg ha^{-1}, was less accurate than simulations with WSI2 and WSDef, with RMSE values of 1195 and 1263 kg ha^{-1}, respectively (Table 3; Fig. 6d).

In summary, in simulations of the LIRF experiments, across 2008 to 2011 data, simulations of corn grain yield with RMSE of 623 kg ha^{-1} and biomass with RMSE of 1401 kg ha^{-1} using WSI2 were more accurate than using WSDef and WSI1 water stress factors in RZWQM2 (Table 4).

Akron Experiments

There were 5, 11, and 10 irrigation events in 1984, 1985, and 1986, respectively, in the irrigation trials in the Akron experiments (Saseendran et al., 2008b). When both WSI1 and WSI2 simulated grain yields and biomass in these experiments better than WSDef, WSI1 simulations were slightly better than WSI2 simulations (Table 5; Fig. 7). Grain yields of these experiments (total of 26) were simulated with RMSE values of 657, 370, and 436 kg ha^{-1} using the WSDef, WSI1, and WSI2 water stress factors, respectively (Table 5; Fig. 7a). Biomass harvested at the end of the season (total of 25 data points) were simulated with RMSE values of 2158, 1460, and 1833 kg ha^{-1}, respectively (Table 5; Fig. 7).

In general, accuracies of grain yield simulations in the rainfed experiments were also best with WSI2 compared with the other two water stress factors (Table 5; Fig. 7a). The RMSE values for grain yield were 929, 835, and 634 kg ha^{-1}, respectively, using the WSDef, WSI1, and WSI2 factors in RZWQM2. While simulating the Akron experiments, Saseendran et al. (2008b) noted an outlier in the rainfed measured grain yield in 1997

Table 5. Evaluation statistics of root mean square error (RMSE), relative RMSE (RRMSE), and index of agreement (*d*) for simulations of grain yield (0% moisture) and biomass using the three stress factors (WSDef, WSI1, and WSI2) against measured values for pooled data from rainfed experiments from 1993 to 1997 and irrigation trials with line source and drip systems from 1984 to 1986 at Akron, CO.

Stress factor	Treatment	Biomass			Grain yield		
		RMSE	RRMSE	*d*	RMSE	RRMSE	*d*
		kg ha^{-1}	%		kg ha^{-1}	%	
WSDef	rainfed	2158	17.2	0.56	657	8.4	0.97
	irrigated	2168	48.0	0.68	929	48.8	0.73
WSI1	rainfed	1460	11.7	0.81	370	4.7	0.99
	irrigated	1450	32.2	0.53	835	43.8	0.74
WSI2	rainfed	1833	14.6	0.64	436	5.6	0.99
	irrigated	1556	34.5	0.79	634	33.3	0.88

(Fig. 7a). This year, the lowest grain yield of 357 kg ha^{-1} was obtained when rainfall and other weather conditions during the crop growing season were comparable to other years in which measured grain yield ranged from 1611 to 3689 kg ha^{-1}. Neglecting this value, the RMSE of grain yield simulated in the rainfed trials using WSI2 was 57 kg ha^{-1} and using WSI1 was 377 kg ha^{-1}. Using the WSDef factor in the model, grain yields were simulated with RMSE of 500 kg ha^{-1}. Taking into account the standard errors in the measurements (266–1850 kg ha^{-1}), biomass simulations in the rainfed trials using WSI1 with RMSE of 1450 kg ha^{-1} and WSI2 with RMSE of 1556 kg ha^{-1} did not differ appreciably. In general, in both rainfed and irrigated experiments at Akron, simulations using both WSI1 and WSI2 were comparable and considerably more accurate than using WSDef (Table 5; Fig. 7).

The DSSAT Data Sets

The UFGA experiment conducted in a sandy soil at Gainesville, FL, in 1982 distributed with the DSSAT 4.5 package consisted of six different combinations of water and N applied differentially in the vegetative and reproductive growth stages of corn. It stands out in the database for its complexity in the water treatments. Measured grain yields reported in this experiment ranged from 2929 to 11,881 kg ha^{-1}. Using the two new stress factors in RZWQM2, we simulated this experiment exactly with the same initial water and N conditions as was done using the CSM-CERES-Maize model available within the DSSAT 4.5 for simulations of corn (Hoogenboom et al., 2010). Grain yield, end-of-season biomass, and seasonal maximum LAI in the simulations of this experiment using the three water stress factors (WSDef, WSI1, and WSI2) were comparable to each other, with RMSE values for grain yield varying between 525 and 726 kg ha^{-1}, RMSE of biomass varying between 1151 and 1285 kg ha^{-1}, and RMSE of LAI varying between 0.52 and 0.55 (Table 6; Fig. 8). The lowest RMSE for grain yield (525 kg ha^{-1}),

Table 6. Evaluation statistics of root mean square error (RMSE), relative RMSE (RRMSE), and index of agreement (*d*) for simulations of grain yield (0% moisture) and biomass using the three stress factors (WSDef, WSI1 and WSI2) against measured values for pooled data from the UFGA82 experiment in a sandy soil at Gainesville, FL, distributed with DSSAT version 4.5.

Stress factor	LAI			Biomass			Grain yield		
	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*	RMSE	RRMSE	*d*
		%		kg ha^{-1}	%		kg ha^{-1}	%	
WSDef	0.52	16.1	0.98	1285	9.8	0.99	726	10.8	0.99
WSI1	0.55	16.8	0.98	1275	9.7	0.99	525	7.8	0.99
WSI2	0.55	16.7	0.98	1151	8.8	0.99	625	9.2	0.99

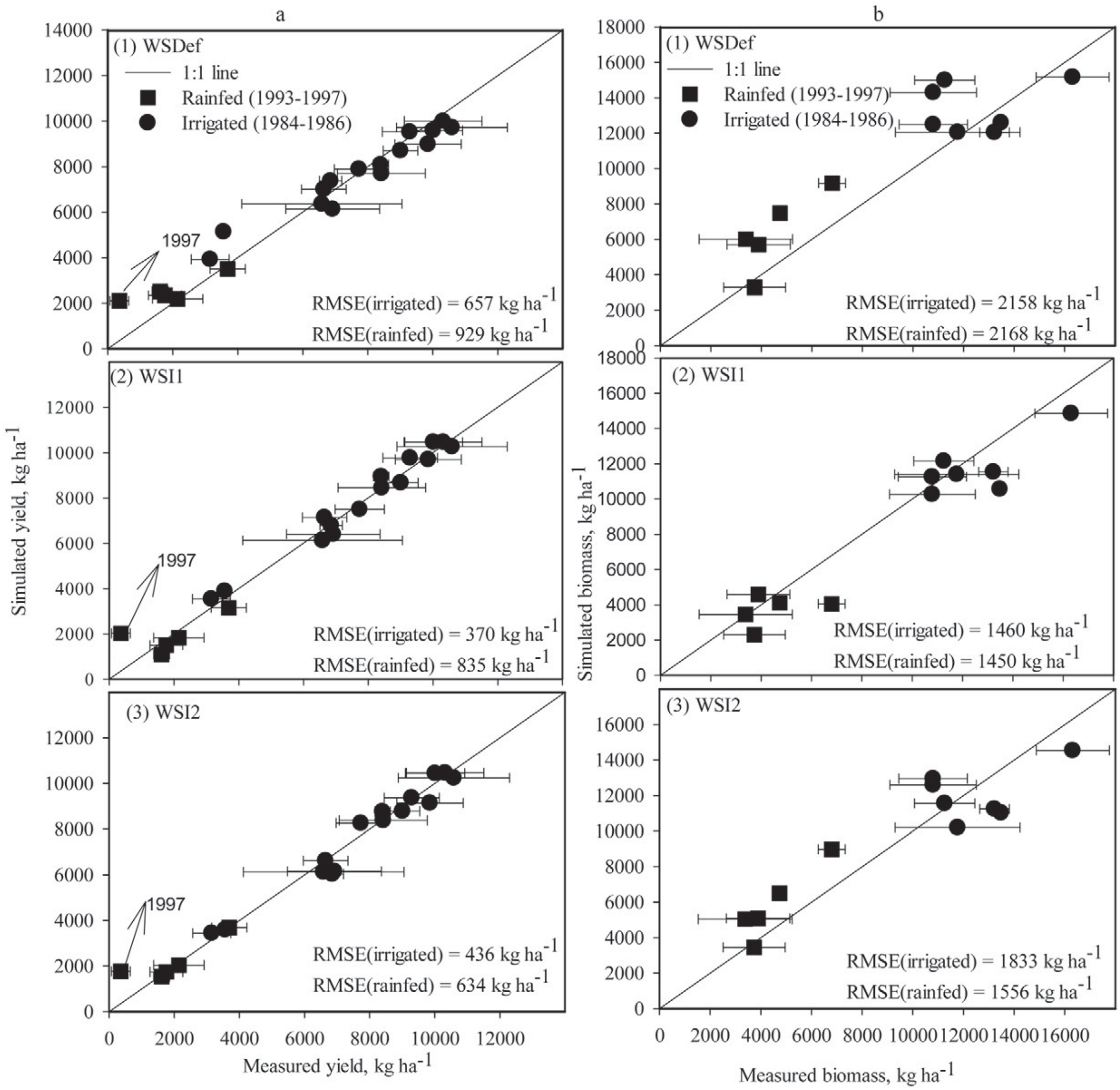

Fig. 7. Measured and simulated (a) corn grain yield (0% moisture) and (b) biomass in the irrigated (1984–1986) and rainfed experiments (1993–1997) at Akron, CO. Simulations used the WSDef, WSI1, and WSI2 water stress factors in RZWQM2. Error bars indicate one standard deviation about the mean of the treatment replications.

however, was obtained using WSI1, and the lowest for biomass (1151 kg ha^{-1}) was obtained using WSI2.

CONCLUSIONS

For applications in limited irrigation management, agricultural system models require enhancements for more accurate crop responses to soil water deficit stress. Limited irrigation experiments for corn conducted at the USDA-ARS LIRF near Greeley, CO, during 2008 to 2011 gave us a unique opportunity to quantify and test two water stress factors (WSI1 and WSI2) for the simulation of corn using the CSM-CERES-Maize 4.0 module with the soil water and N routines in RZWQM2. The default water deficit stress factor (WSDef) in RZWQM2 was based on the ratio of water available for plant uptake (water supply) and the potential transpiration demand (demand for water). We used the Nimah and Hanks (1973) approach for calculation of root water uptake and introduced soil evaporation in both the supply and demand terms in the water stress quantifications. In the simulations, the crop responses to water levels at Greeley varied from year to year, but overall the responses were improved with the new stress factors. In general, both WSI1 and WSI2 were found to be better than WSDef in simulations of corn grain yield than for biomass and LAI. The WSI2 simulations of the LIRF experiments were superior to those using WSI1. The new stress factors also improved the overall responses for the data from the Akron and UFGA experiments; the results from WSI1 and WSI2 were comparable. Superior or comparable simulations of corn using RZWQM2 modified with WSI1 and WSI2 over WSDef under irrigated conditions in the LIRF experiments at Greeley, CO, both rained and irrigated conditions in the experiments at Akron, CO, and in N and irrigation experiments in a sandy soil at Gainesville (UFGA), FL, verified the capability of the modified model for simulations across soils and climates. Notwithstanding, similar testing across locations in the world will facilitate building further confidence in the robustness of these stress factors in RZWQM2 for simulation of corn and other crops across climates and soils.

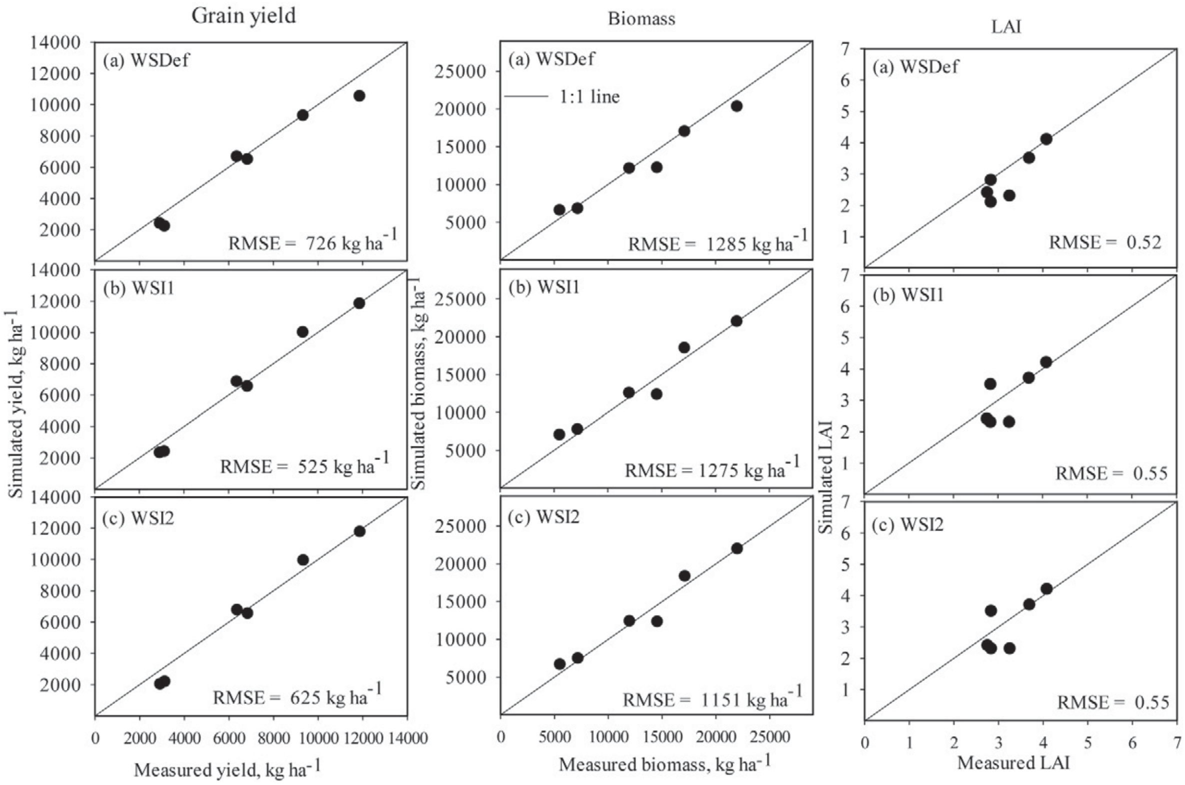

Fig. 8. Simulations of grain yield (0% moisture), biomass, and maximum seasonal leaf area index (LAI) in the UFGA82 experiment distributed with DSSAT 4.5 using RZWQM2 with (a) WSDef, (b) WSI1, and (c) WSI2 stress factors.

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