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Quantifying crop water stress factors from soil water measurements in a limited irrigation experiment

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ABSTRACT

A correct simulation of crop responses to water stress is essential for a system model. In this study, we investigated three methods of quantifying water deficit stresses based on soil water measurements and their effects on simulating grain yield, biomass and canopy cover of corn (*Zea Mays* L.). Experimental data were collected for six irrigation treatments designed to replace 40 to 100% of potential crop evapotranspiration (ETc) losses during the growing season, from 2008 to 2011 near Greeley, Colorado in a sandy loam soil (Limited Irrigation Research Farm, LIRF). Water available for plant uptake (PAW, plant available water) and the maximum PAW (MAW) in the soil were calculated for a constant 1 m soil profile from 45 days after planting till maturity. Water deficit stress factors were calculated as ratios of (1) PAW to alfalfa reference crop evapotranspiration (ETr) (WSF1), (2) PAW to MAW (WSF2), and (3) WSF2 to ETr (WSF3). Average WSF1, WSF2 and WSF3 over the growing season were related to end of the season grain yield, biomass, and fraction canopy cover measurements. These stress factors were implemented in the RZWQM2 cropping system model and the calibrated results compared with those obtained from using current stress factors in CERES-maize module in RZWQM2. The best simulation of the measured grain yields, biomass and LAI was obtained using WSF3. The modified model was also tested for simulating dryland and limited irrigation studies at Akron, CO, and irrigated corn in a sandy loam soil at Zaragoza, Spain and in a sandy soil at Gainesville, Florida, USA. In general, WSF3 gave slightly better simulations of grain yields, biomass and LAI than WSF2, WSF1 and the original stress factor.

1. Introduction

With competing demands for fresh water from various sectors of the burgeoning human enterprises, increasing productivity of the water allocated for irrigation is required for sustained food security on the earth. The United Nations, Food and Agricultural Organization calls for all-around efforts from scientists for increasing water use efficiency (WUE) in irrigated agriculture (FAO (Food and Agriculture Organization of the United Nations), 2002) for a hunger free world. Owing to our inadequate understanding of the biological mechanisms regulating WUE in plants, little advances have been made so far through the traditional genetic approaches to modify WUE in crop plants (De Pascale et al., 2011). There is a need and possibility for making agriculture water use less wasteful and more efficient through enhancing and applying the existing irrigation science and technologies (Hsiao et al., 2007).

Considerable research is being conducted to see if we can enhance WUE through the implementation of 'limited irrigation' water management practices for various crops in the Great Plains of the USA (Hergert, 2010; Hergert et al., 1993; Klocke et al., 2004; Schneekloth et al., 1991, 2001). However, like other agro-management practices, the transfer of the developed location-specific short-term limited irrigation technologies across locations has been difficult due to varying precipitation regimes, soils and landscapes (Hergert, 2010).

Field experiments that encompass all the multi-year and multi-location variability in climate and soils are practically unfeasible. Simulation models can synthesize and integrate data collected from available limited-term field studies, and present a way to extrapolate results to long-term weather conditions and to other soils and climates (Knisel and Turtola, 2000; Mathews et al., 2002). Using CSM-CERES-maize model in DSSAT (decision support system for agricultural technology transfer) v4.0 (Jones et al., 2003), Saseendran

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et al. (2008a) demonstrated how a comprehensive agricultural system simulation model can be integrated with field experiments and long-term climate data to identify beneficial limited water irrigation management practices in the Great Plains of USA.

Innovative decision support systems developed with reliable cropping system models help in the efficient allocation of limited water resources, and its management by the farmers of the region. However, adequacy of agricultural system models for this application, especially in limited irrigation water management, depends upon accurately simulating the imposed soil water stress effects on crop growth and yield. Water stress decreases plant growth primarily by reducing cell division and expansion growth. Other known processes modulated by water stress are plant developmental rates, leaf initiation, photosynthesis, carbon allocation and partitioning, and root length and density in soil layers, resulting in reduced biomass and grain yield (Chartzoulakis et al., 1993; Chaves et al., 2002; Chen and Reynolds, 1997; Passioura, 1994; Pereira and Chaves, 1993; Saini and Lalonde, 1998; Saseendran et al., 2008b). In general, these effects are simulated in the current cropping system models, by describing a 'water stress factor' that modifies the simulated plant growth and development processes.

Plants experience water stress when water supply available in the soil fails to meet the evapotranspiration demand. Although it is easy to define the concept, accurate quantification and representation of a 'water stress factor' in crop models have been a challenge in system modeling (Ritchie, 1981; Saseendran et al., 2008b). Ritchie (1981) analyzed practical difficulties in using several plant parameters (e.g., stomatal conductance and leaf water potential) as 'water stress factors' in the system models, and felt that empirical quantifications of crop growth and development processes as related to the soil water deficits such as fraction of plant available water in the root zone of the crop are viable options. Following Ritchie (1981), Brisson et al. (1992), Sinclair (1986) and McCree and Fernandez (1989) developed and implemented stress factors based on plant water availability in the soil relative to atmospheric evaporative demands into crop models. The cropping system models widely in use today [e.g., APSIM (McCown et al., 1996), CropSyst (Stockle et al., 2003), DSSAT-CSM (Jones et al., 2003; Woli et al., 2012), and RZWQM2 (Ahuja et al., 2000; Ma et al., 2009)] use the ratio of potential water uptake to potential transpiration or actual to potential transpiration (supply-demand ratio) to represent water stress for modulating dry matter synthesis and expansion growth in crop simulations. Notable exceptions are the APSIM cropping system model that uses a 'fraction plant extractable water in the root zone soil' as water stress factor for modulating phenology and N fixation, and the AquaCrop model that uses a water stress coefficient based on the root zone water depletion affecting canopy expansion and senescence, transpiration, harvest index and root growth (http://www.fao.org/nr/water/docs/aquacropv31pluschapter1.pdf). The RZWQM2 model has DSSAT-CSM crop modules for simulations of various crops and uses its water stress functions.

Inadequate crop growth simulations and the need to improve the water stress quantifications in many cropping system models including DSSAT and RZWQM2 have been reported in the literature (Cabelguenne et al., 1990; Castrignano et al., 1998; Faria and Bowen, 2003; Nouna et al., 2000; Saseendran et al., 2008a; Sau et al., 2004). Some of the recent crop models used 'soil water content' based 'water stress indices' for simulations. For instance, Sepaskhah et al. (2006) used a ratio of actual PAW (soil water above the wilting point) to the fraction of PAW that is not readily available for plant extraction, as defined by Allen et al. (1998), for modulating simulated yields of wheat, corn and sugarbeet under water stress; Casadebaig et al. (2011) used the ratio of actual to maximum possible water content in the plant root zone as an index of water stress for simulating sunflower in the SUNFLO model. These examples indicate the possibility that the water is not equally available to plants within the entire PAW range.

In 2008, a field study was initiated at the Limited Irrigation Research Farm (LIRF) at Greeley in the central Great Plains of Colorado, USA to collect information on response of field corn (*Zea mays* L.) to limited irrigation (Greeley experiments) (Bausch et al., 2011; Trout et al., 2010). A wide range of irrigation levels from fully irrigated (100% of ET demand) to about 40% of full irrigation was being tested. Using the corn growth data from the Greeley experiments, Saseendran et al. (2014) developed and tested two modifications (WSI1 and WSI2) of the default water stress factor (WSDef) in RZWQM2 for simulation of corn using the embedded DSSAT-CSM-CERES-Maize model. WSI1 was a modification of SWFAC factor for photosynthesis related processes using the daily potential root water uptake (TRWUP) calculated

Table 1
Experimental sites, years and types of data used in the calibration validation of RZWQM2. ET is potential crop evapotranspiration.

Treatments	Year and data for modeling
LIRF, Greeley (Colorado, USA)	
T1: Irrigations at 100% of crop ET, fixed[1]; T2: 85% of T1, variable; T3: 70% of T1, fixed; T4: 70% of T1, variable; T5: 55% of T1, variable; and T6: 40% of T1, variable. [1]T1 in 2008 only was used in model calibration.	Grain yield, biomass, soil water and LAI data collected in 24 irrigation treatments from 2008 to 2011. Soil water data measured in this experiment were used for developing water stress functions.
UFGA82 experiments (Gainesville, Florida, USA)	
U1: Rainfed with low N[1]; U2: rainfed with high N; U3: irrigated with low N; U4: Irrigated with high N; U5: water stress in vegetative stage with low N; and U6: Water stress in vegetative stage with high N. [1]U1 only was used in model calibration.	Grain yield, biomass and maximum LAI measured in 1982. These data were accessed from the DSSAT 4.5 database.
SIAZ96 experiments (Zaragoza, Spain)	
S1: Full irrigation to meet ET demand[1]; S2: 50% of full irrigation; S3: one-third of full irrigation; S4: full irrigations was from seedling emergence to tassel emergence (phase 1) and from tassel emergence to milk stage of grain (phase 2); S5: Full irrigation in phases 1 and from milk stage to physiological maturity (phase 3); S6: Full irrigation in phases 2 and 3; S7: full irrigation in phase 1; S8: full irrigation in phase 3; and S9: full irrigation in phase 2. [1]S1 only was used in model calibration.	Grain yield, biomass and maximum LAI measured in 1996. These data were accessed from the DSSAT 4.5 database.
Akron experiments (Akron, Colorado, USA)	
A1: Four line-source irrigation treatments each in 1984[1], 1985, and 1986. A2: Four drip irrigation treatments in 1985 (irrigation levels were based on different threshold values of the Crop Water Stress Index (Nielsen and Gardner, 1987); and A3: Rainfed experiments from 1993 to 1997. [1]Highest irrigation treatment in 1984 was only used in model calibration.	Grain yield and biomass data collected in 16 irrigation treatments during 1984, 1985 and 1986; and 6 dryland (rainfed) treatments from 1993 to 1997.

Variable: 20% of irrigation (ET) demand during the vegetative stage was withheld and added to irrigations during the reproductive state. Fixed: Water applied uniformly based on ET demands.

Table 2
Total seasonal irrigation and precipitation during the vegetative (V) and reproductive (R) stages of corn under six irrigation treatments during 2008 to 2011 in the limited irrigation experiments at Greeley, Colorado (LIRF).

Irrigation treatment	Irrigation/precipitation, mm							
	V	R	V	R	V	R	V	R
Corn (cv. Dekalb 52–59)	2008		2009		2010		2011	
Precipitation	39	191	135	94	145	55	138	38
T1	289	149	202	216	201	164	255	230
T2	227	111	169	179	130	160	203	185
T3	202	80	146	154	114	133	182	147
T4	186	86	102	148	88	132	177	129
T5	136	45	68	100	61	98	129	92
T6	111	26	50	59	42	70	97	60

by the Nimah and Hanks (1973) approach, and WSI2 was a ratio of actual crop evapotranspiration to potential crop evapotranspiration. They found, in general, WSI2 simulations of the crop were either comparable or more accurate than WSI1 and WSDef simulations. In this study, we explored the relationships between plant available water in the soil, crop evapotranspiration, and measured grain yield, biomass, and fraction canopy cover of corn, and use those as the basis for quantifying crop responses to water stress in the RZWQM2 model. The soil water content based stress factors have an advantage in that the farmers commonly track soil water levels in rainfed or irrigated fields and can thus relate them to effect on expected yield, or control them for a targeted yield. Thus, the objectives of the study were (1) to derive three water stress factors (i) PAW to alfalfa reference crop evapotranspiration (ETr) (WSF1), (ii) PAW to maximum PAW (MAW) (WSF2), and (iii) WSF2 to ETr (WSF3) for quantification of water stress effects on plant growth and yield; and (2) test the performance of these stress factors in RZWQM2 model for simulations of (i) corn growth and yield in the Greeley experiments, (ii) dryland and limited irrigation studies at Akron, CO and (iii) two experiments in contrasting soils (sandy and sandy loam soils) available in the DSSAT 4.5 database.

2. Materials and methods

2.1. Data for quantification of water stress factors (Greeley experiments)

The data for this study were collected from experiments conducted by the USDA-ARS at their Limited Irrigation Research Farm (LIRF) (40° 26′ N, 104° 38′ W, and 1428 m msl) near Greeley, Colorado during 2008–2011 (Greeley experiments; Table 1). LIRF is a 16 ha field research facility developed to conduct research on crop responses related to irrigation. Experimental plots were distributed across three types of soils observed at the site viz. Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids) and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). Plots are 12 rows wide (0.76 m row spacing) by 40 m long and are replicated four times for each specific water treatment. Crop rows have a north/south orientation. Six water treatments are randomized within each replication. The six irrigation treatments were designed to meet certain percentages of potential crop ET (ETc) requirements during the growing seasons: 100% (T1), 85% (T2), 70%F (T3), 70% (T4), 55% (T5), and 40% (T6) of ETc. The amount of irrigation water for each treatment was estimated on a weekly basis based on reference ET demand (ETr), crop coefficient (Allen et al., 2005), rainfall, and soil water deficit. Flow rates and water treatments were measured with turbine flow meters. In order to provide more water during the reproductive stages of growth of corn, for all treatments except for T1 and T3, 20% of the estimated weekly amounts during vegetative growth period (V7-R1) were withheld and added to weekly amounts during the reproductive growth period. So, in T3 (in contrast to T4), there were no transfer of 20% of the irrigation demand during the vegetative stages to the reproductive stages.

Corn (cv. Dekalb 52–59) was planted on day of the year (DOY) 132, 131, 132 and 123 in 2008, 2009, 2010 and 2011, respectively, and harvested on DOY 310, 316, 292 and 310. Interannual variability in precipitation during the vegetative (39 to 145 mm) and reproductive (38 to 191 mm) stages of growth of the crop were observed; consequently the applied irrigation amounts in different irrigation treatments also varied (Table 2). Fertilizer as UAN was applied, based soil sample analysis, before planting and then with irrigation water during the growing seasons, to assure ample N for stress free growth.

Weather data recorded on site (Colorado Agricultural Meteorological Network, GLY04) and available at http://ccc.atmos.colostate.edu/~coagmet/ were used in calculation of ETr. Soil water content was measured in each plot between 30 and 200 cm depth with neutron attenuation (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) in an access tube in the crop row near the center of each plot. A depth control stand (Evett et al., 2003) was used to control probe depth relative to the soil surface. Surface soil water content (0–15 cm) was measured with a MiniTrase portable TDR system (SoilMoisture Equipment Corp.). These measurements were made prior to each irrigation and following irrigation or major precipitation events. When PAW near the soil surface was inadequate at planting time, the plots were sprinkler irrigated to assure good germination. Canopy cover (C_c, also referred to in literature as: ground cover or canopy cover) was estimated with a photosynthetically

Table 3
Plant parameters calibrated for CSM-CERES-Maize simulations of corn hybrids in the Greeley, SIAZ96, UFGA82 and Akron experiments using the WSDef, WSF1, WSF2 and WSF3 water stress factors within RZWQM2.

Acronyms used and definitions of traits	Parameter values			
	Greeley experiments (cv. Dekalb 52–59)	UFGA82 experiments (cv. McCurdy 84)	SIAZ96 experiments (cv. Prisma)	Akron experiments (cv. Pioneer Brand 3732)
P1 – Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (thermal degree days).	260	260	280	300
P2 – Day length sensitivity coefficient [the extent (days) 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	0.22	0.60
P5 – Degree days (base temperature of 8 °C) from silking to physiological maturity (thermal degree days)	620	910	779	595
G2 – Potential kernel number	990	980	709	720
G3 – Potential kernel growth rate (mg/(kernel d)	7.80	7.10	7.27	9.90
PHINT – Degree days required for a leaf tip to emerge (phyllochron interval) (thermal degree days)	40.0	43.0	49.0	51.0

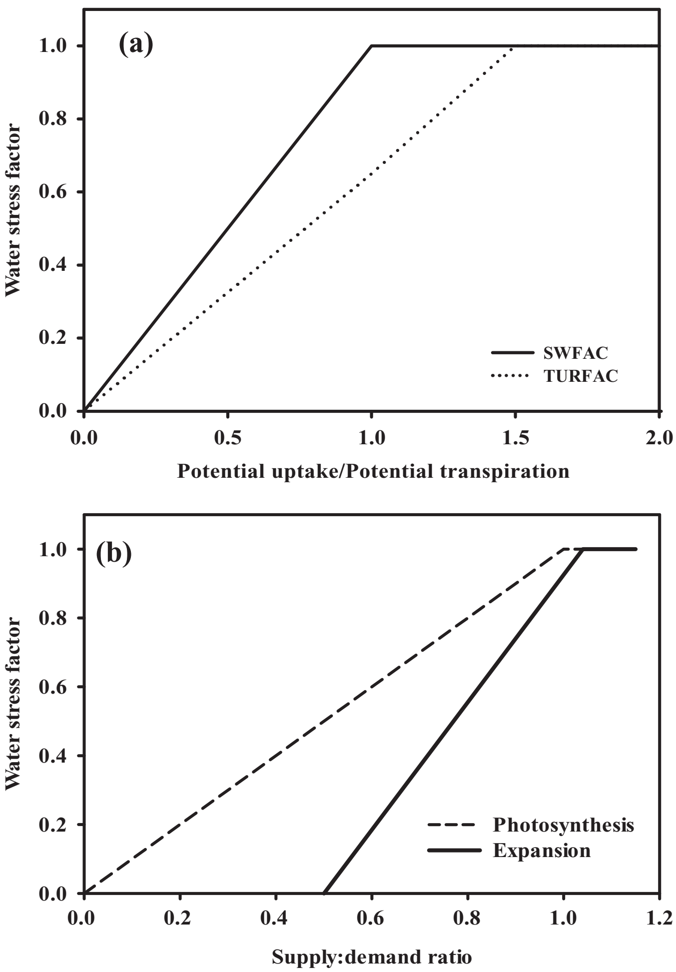

Fig. 1. Relationships used to calculate soil water stress factors, SWFAC and TURFAC in (a) RZWQM2, and (b) APSIM (Maize) (Saseendran et al., 2008b).

active radiation sensor (AccuPAR LP-80, Decagon Devices, Inc.) from above and below canopy measurements and from analysis of images acquired with a digital camera (RGB) mounted on a "high boy" mobile platform and driven through the plots weekly. Grain yield and crop biomass at harvest of the crops were measured every year.

2.2. Data for testing the performance of the modified RZWQM2 in other soils and climates

To test the robustness of the new stress factors in RZWQM2 for simulations across soils and locations, the following three studies in which corn was grown either under irrigated or rainfed conditions combined with or without varying N rates were used (Table 1).

As noted above, the CSM-CERES-Maize 4.0 was used with the soil water and N routines of RZWQM2 in the simulations. The DSSAT suite of cropping system models were used extensively for simulations of various crops across the world (Jones et al., 2003). In this study, for testing the modified RZWQM2, two irrigated corn experiments distributed with the DSSAT 4.5 package, one in a sandy loam soil conducted at Zaragoza (41.432009°N, 0.49°W, 0.23 km amsl), Spain in 1996 (SIAZ96 experiments) and another in a sandy soil at, Gainesville (29.63°N, 82.37°W, 0.01 km amsl), Florida, USA in 1982 (UFGA82 experiments) were used (Hoogenboom et al., 2010). The SIAZ96 experiment conducted in the year 1996 consisted of (1) full irrigation to meet the consumptive use demand of corn (cv. Prisma), (2) 50% of full irrigation, (3) one-third of full irrigation, (4) full irrigations in phases 1 and 2 (phase 1 was from seedling emergence to tassel emergence and phase 2 was from tassel emergence to milk stage of grain), (5) full irrigation in phases 1 and 3 (phase 3 was from milk stage to physiological maturity), (6) full irrigation in phases 2 and 3, (7) full irrigation in phase 1, (8) full irrigation in phase 3, and (9) full irrigation in phase 2. The UFGA82 experiment consisted of corn (cv. McCurdy 84) under (1) rainfed with low N, (2) rainfed with high N, (3) irrigated with low N, (4) irrigated with high N, (5) water stress in vegetative stage with low N, and (6) water stress in vegetative stage with high N. The soil and plant parameters supplied with the DSSAT package were used as a starting point for calibration (plant parameters) and testing the new stress factors.

The third experiment was conducted over a period of eight years at the Central Great Plains Research Station, USDA-ARS at Akron (40.15°N, 103.14°W, 1.38 km amsl), Colorado, USA in a silt loam soil (fine montmorillonitic mesic Pachic Arguistoll) under both irrigated and rainfed conditions (Akron experiments). The irrigation experiments were during 1984, 1985, and 1986 in which corn hybrid 'Pioneer Brand 3732' 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 (Nielsen and Gardner, 1987). 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 was used for simulations of the crop under rainfed conditions. Saseendran et al. (2008a) simulated the Akron experiments using the CERES-Maize v4.0 within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008a) were used as starting point for calibration of the cultivar parameters in this study (Table 3).

Ma et al. (2011) protocol was adopted for calibration of the cultivar parameters in Greeley, SIAZ96, UFGA82 and Akron experiments in this study. Grain yield data collected in the maximum irrigation treatment of the experiments in 2008 was used in the calibration and the remaining treatments in the same year and all treatments in 2009, 2010 and 2011 for validation. However, to be brief, the calibration and validation treatments are not discussed separately in the results and discussions below.

2.3. Water stress factors

The following 'water stress factors' based on plant available water (PAW) status of the soil profile (plant water supply) and ETr (plant water demand) were computed on a daily basis:

Table 4
Quantitative relationships for the relative responses of corn relative grain yield (RGY) and canopy cover (RC_c) to the three soil water stress factors (WSF1, WSF2, and WSF3).

RGY	RC_c
WSF1	**WSF1**
RGY = 0.06 WSF1 + 0.28 for 5.1 < WSF1 < 10.4.	RC_c = 0.09 WSF1-0.16 for 3.1 < WSF1 < 11.6.
RGY = 0.11 WSF1 for WSF1 < 5.1.	RC_c = 0.0 for WSF1 < 3.1.
RGY = 1 for 10.4 < WSF1.	RC_c = 1 for 11.6 < WSF1.
WSF2	**WSF2**
RGY = 1.24 WSF2 + 0.2 for 0.3 < WSF2 < 0.50.	RC_c = 1.93 WSF2-0.17 for 0.23 < WSF2 < 0.53.
RGY = 1.8 WSF2 for WSF2 < 0.3.	RC_c = 0.0 for WSF2 < 0.23.
RGY = 1 for 0.50 < WSF2.	RC_c = 1 for 0.53 < WSF2.
WSF3	**WSF3**
RGY = 0.68 WSF3 + 0.27 for 0.29 < WSF3 < 1.10.	RC_c = 0.99 WSF3-0.002 for 0.23 < WSF3 < 1.22.
RGY = 1.8 WSF3 for WSF3 < 0.29.	RC_c = 0.0 WSF3 for WSF3 < 0.23.
RGY = 1 for 1.10 > WSF3.	RC_c = 1 for 1.22 < WSF3.

$$TURFAC = \frac{TRWUP}{RWUEP1 * EPo}$$

$$WSF1 = \frac{PAW}{ETr} \quad \text{(unitless)} \tag{1}$$

$$WSF2 = \frac{PAW}{MAW} \quad \text{(unitless)} \tag{2}$$

$$WSF3 = \frac{WSF2}{ETr} \quad (\text{cm}^{-1}) \tag{3}$$

where *PAW* is the plant available water in the soil root zone profile on a given day, and *MAW* is the maximum possible *PAW*, and *ETr* is the alfalfa reference crop ASCE 'standardized' evapotranspiration for the day, calculated using the Allen et al. (2005) procedure. Whereas, for a given duration of a day in the study, WSF1 and WSF2 are unitless, WSF3 has the unit of cm^{-1}. The logic behind the use of the ratio of PAW to MAW in WSF2 and WSF3 was that the water may not be equally available in the entire PAW range.

PAW and MAW are defined as:

$$PAW = \theta - PWP \tag{4}$$

$$MAW = FC - PWP \tag{5}$$

where θ is the measured water content for a measured soil layer, and FC and *PWP* are field capacity (drained upper limit) and permanent plant wilting point (lower limit) water contents of the same layer of the soil, respectively. We used the measured drained upper limit of soil water in each layer during the experiment (2008 to 2011) as an estimate of *FC*, and *PWP* was assumed to be half of the *FC*. This was found to be a reasonable approximation for the soil, as average pressure chamber measured 1.5 MPa water content for the soil was about 50% of its 0.03 MPa water content (Ma et al., 2012). The PAW in the soil of each replication of the six irrigation treatments was calculated separately using the FC information representing those plots. The PAWs calculated across the replications were averaged for each treatment and used for calculation of stress factors. As the crops in the experiments were uniformly irrigated at planting to assure adequate germination and establishment of crop stands, for delineation and analysis of treatment effects, we used the soil water data for the period approximately between 45 days after planting to crop physiological maturity for calculation of stress factors.

Ma et al. (2012) simulated the Greeley experiments for corn from 2008 to 2010 using the CSM-CERES-Maize v4.0 in RZWQM2. For calculation of PAW in the root zone of corn, from 45 days after planting to maturity, we initially used the rooting depth simulated by Ma et al. (2012). However, we could not get enough PAW responses to the six irrigation treatments following the dynamic rooting depth with time; the different levels of irrigations did not result in different PAW levels in the soil profile. This indicated that the entire modeled rooting depth was not the effective depth of water uptake by the plants under the above irrigated conditions. Soil water measurements indicated negligible water extraction below the 1 m profile; however, we tried various constant effective rooting depths of 0.5, 1.0, 1.5 and 2.0 m and selected 1 m rooting depth to best represent PAW responses due to irrigations that can be quantitatively related to observed crop responses in the experiments for the time duration of 45 days after planting to physiological maturity.

In the experiments, all the treatments had the same irrigation schedule through the season. The stress factors (daily basis) were first calculated for each plot on each day that coincided with a soil water measurement. Since the biomass and grain yield were measured only at harvest, the calculated daily stress factors for each plot

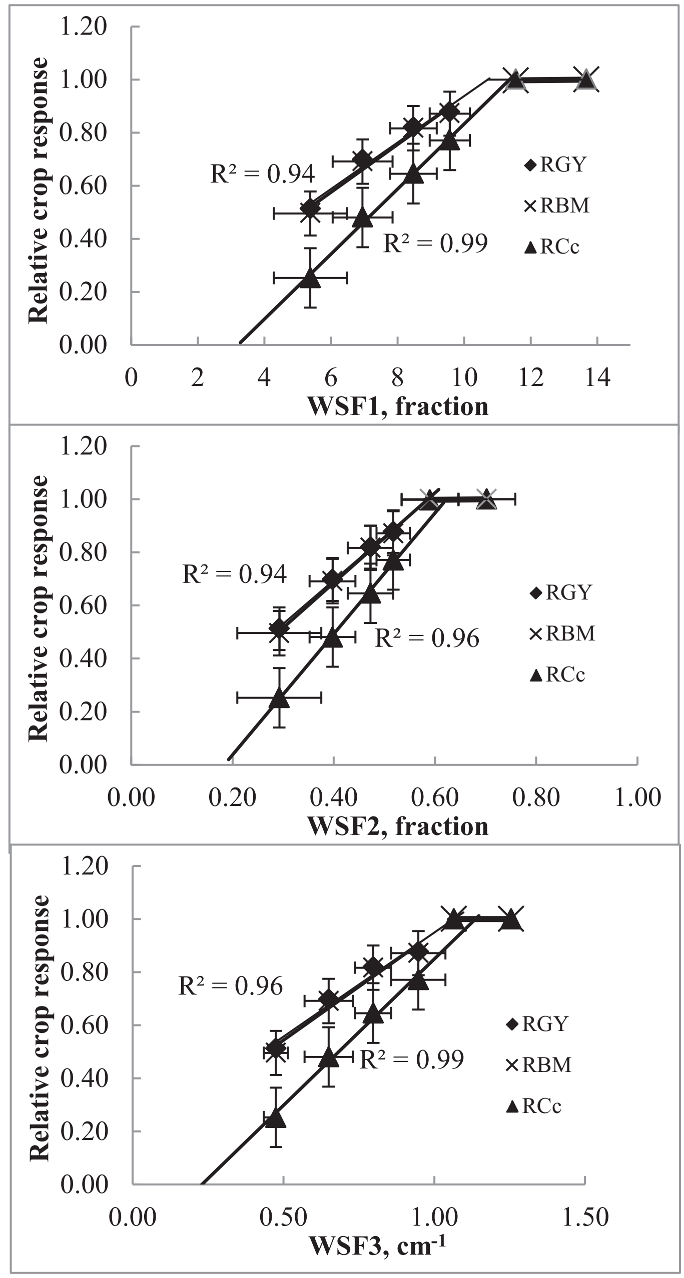

Fig. 2. Piecewise linear relationships between the three water stress factors (average daily WSF1, WSF2 and WSF3) and the three relative crop response variables (RGY, RBM and RC_c) of corn, averaged across the four crop seasons of 2008–2011. R^2 shown is for the dark fitted sloping line which has values less than 1 on the y-axis. Complete set of the piecewise linear relationships are presented in Table 4. Error bars indicate one standard deviation from the mean.

were averaged for each season. For consistency with the biomass and grain yield measurements, the C_c measurements coinciding with the physiological maturity was only used in the analysis. Treatment averages and standard deviations (across the 4 replications) of WSF1, WSF2 and WSF3 for each year as well as over the 4 years were calculated.

Measured crop growth (LAI, grain yield and biomass) differed between locations due to many factors that include genetic, weather, and water availability and distribution. In order to bring those values to a common base for comparison across locations, we normalized the measurements by dividing the individual measurements at a location by their maximum values obtained in the highest

Table 5
Evaluation statistics for simulations of total profile soil water, leaf area index (LAI), biomass and grain yield against measured values in the 2008, 2009, 2010, and 2011 in the Greeley experiments.

Year	Total profile(180 cm) water					LAI					Biomass					Grain yield				
	No. of data	RMSE (cm)	RRMSE %	R^2	d		RMSE	RRMSE %	R^2	d	No. of data	RMSE (kg ha^{-1})	RRMSE %	R^2	d	No. of data	RMSE (kg ha^{-1})	RRMSE %	R^2	d
WSDef																				
2008	144	3.1	10	0.73	0.90	90	1.0	55	0.49	0.82	6	2502	13	0.80	0.82	6	1598	16	0.70	0.65
2009	180	2.5	8	0.75	0.94	168	1.1	58	0.72	0.76	6	1695	10	0.90	0.92	6	1372	16	0.90	0.93
2010	142	3.9	11	0.46	0.70	96	0.7	46	0.84	0.88	6	3506	23	0.96	0.78	6	1208	15	0.97	0.91
2011	234	3.8	12	0.07	0.86	148	0.9	35	0.73	0.90	6	2549	15	0.93	0.92	6	1007	12	0.93	0.96
WSF1																				
2008	144	3.9	13	0.75	0.85	90	1.3	70	0.68	0.68	6	3792	20	0.92	0.76	6	1042	10	0.90	0.91
2009	180	2.3	7	0.73	0.97	168	1.0	53	0.43	0.76	6	2028	11	098	0.92	6	891	10	0.95	0.96
2010	142	3.2	8	0.49	0.76	96	1.0	61	0.74	0.91	6	1736	11	0.93	0.95	6	1167	15	0.84	0.92
2011	234	4.8	15	0.07	0.80	148	1.2	47	0.69	0.99	6	3514	20	0.93	0.86	6	1718	20	0.89	0.89
WSF2																				
2008	144	3.3	11	0.73	0.89	90	0.9	50	0.63	0.82	6	1456	13	0.89	0.95	6	572	5	0.92	0.96
2009	180	2.4	7	0.73	0.95	168	0.9	49	0.55	0.76	6	2166	11	0.97	0.93	6	1398	16	0.95	0.91
2010	142	3.7	10	0.45	0.72	96	0.6	36	0.87	0.96	6	1755	11	0.99	0.95	6	1168	15	0.94	0.93
2011	234	4.0	13	0.06	0.84	148	0.9	32	0.60	0.98	6	1666	9	0.97	0.97	6	1351	16	0.92	0.94
WSF3																				
2008	144	3.3	13	0.74	0.89	90	0.9	55	0.64	0.78	6	2054	11	0.90	0.91	6	491	5	0.96	0.98
2009	180	2.4	7	0.72	0.95	168	0.9	49	0.54	0.76	6	1345	7	0.95	0.96	6	1178	14	0.97	0.92
2010	142	3.7	10	0.45	0.72	96	0.6	36	0.85	0.96	6	1860	12	0.99	0.94	6	952	12	0.94	0.95
2011	234	4.0	13	0.06	0.84	148	0.8	32	0.58	0.98	6	1614	5	0.99	0.99	6	1166	9	0.95	0.94

RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

irrigation treatments in each season at the same location. Linear regression relationships were developed between the average stress factors, and average relative grain yield (*RGY*), relative biomass (*RBM*) and relative canopy cover (RC_c) responses:

$$RGY = f\,(WSF1\,or\,WSF2\,or\,WSF3) \tag{6}$$

$$RBM = f\,(WSF1\,or\,WSF2\,or\,WSF3) \tag{7}$$

$$RC_c = f\,(WSF1\,or\,WSF2\,or\,WSF3) \tag{8}$$

where f is the piecewise linear function.

RGY, RBM and RC_c were calculated as:

$$RGY = \frac{GY}{GY_{max}} \tag{9}$$

$$RBM = \frac{BM}{BM_{max}} \tag{10}$$

$$RC_c = \frac{C_c}{C_{cmax}} \tag{11}$$

where *GY, BM* and C_c are measured values of grain yield, biomass and fraction canopy cover for each of the various irrigation levels in each crop season; and GY_{max}, BM_{max} and C_{cmax} represent their measured values in response to the maximum irrigation treatment (T1) for that season.

Comparisons of the stress factors for their effectiveness in explaining observed values of RGY, RBM and RC_c over different irrigation levels were based on the R^2 of the linear regression relationships between them (only the sloping section).

In our measurements, C_c was defined as the percentage of the green crop canopy cover projected vertically onto the ground. Leaf area index (LAI) of a crop can be reasonably estimated from C_c by expressing C_c as an exponential function of LAI following the Beer–Lambert's law of light transmission through the plant canopy and inverting the equation (Gonsamo, 2010) as:

$$1 - F_c = e^{-kLAI} \tag{12}$$

$$LAI = -\frac{\ln(1 - C_c)}{k} \tag{13}$$

where k is the extinction coefficient which is related to leaf spectral properties and leaf angles in the canopy. A k value of 0.594 for the location was used based on Farahani and DeCoursey (2000).

As we did not have measurements of k in the study, C_c data were not converted into LAI for the analysis. The C_c data were used as a surrogate for LAI, an indicator for leaf expansion growth in the crop plants (Eq. 13). All the crop response variables (GY, BM and C_c) expressed relative to their maximum values as measured in the T1 were used in the analysis, hence non-availability of absolute values of LAI should not affect the interpretations presented in terms of water stress effects on expansion growth in the study.

2.4. RZWQM2 model

The RZWQM2 (Root Zone Water Quality Model), is a process-oriented agricultural system model that simulates the impacts of physical, biological and chemical processes for simulation of impacts of tillage, water, agricultural chemical and crop management practices on crop production and water quality (Ahuja et al., 2000). The CSM-CERES-maize 4.0 model of the DSSAT 4.0 package (Jones et al., 2003) linked to the soil water and nitrogen modules of RZWQM2 is used for simulation of corn in this study (Ma et al., 2009). Adequacies of RZWQM2 and its earlier versions for simulating corn growth under various agroclimatic conditions in the Great Plains of USA have been reported (Ma et al., 2003; Saseendran et al., 2004, 2005, 2008b, 2009, 2010a). Ma et al. (2009) reported comparable simulation results of corn production using the CSM-CERES-Maize 4.0 model in RZWQM2 as the original CSM-CERES-Maize 4.0 model within DSSAT.

For quantification of soil water stress, RZWQM2 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 hereafter as default WS factors (WSDef) (Fig. 1a). When there is adequate water available in the soil for plant uptake, TRWUP is greater than EP_o and there is no water stress. However, as the soil dries due to root water uptake, TRWUP decreases until a threshold is reached

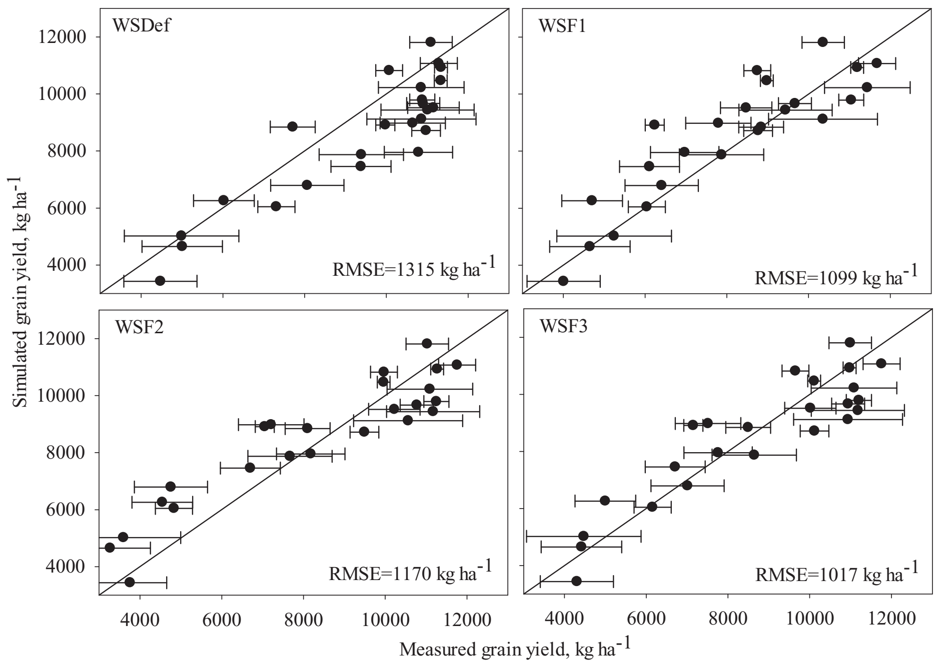

Fig. 3. Comparison between measured, and simulated corn grain yields in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSDef, WSF1, WSF2 and WSF3. Error bars indicate one standard deviation in the measured data.

where the first WS factor or turgor factor (TURFAC) is activated to modulate expansive leaf growth. In both C3 and C4 plants, this point corresponds to the plant water level when the root water uptake combined with osmotic adjustments and cell wall extensibility fail to maintain turgor pressure to sustain cell division (mitosis) and expansion growth (Boyer, 1970; Cosgrove, 1998; Cosgrove and Cleland, 1983; Neumann, 1995). The first stress factor, TURFAC is defined as:

$$TURFAC = \frac{TRWUP}{RWUEP1 * EPo} \quad (14)$$

where $RWUEP1$ is a species-specific parameter, used for emulating the water stress level in the plants above which turgor pressure in the plant leaf cells fail to sustain expansion growth at the potential level, which was set to 1.5 for corn.

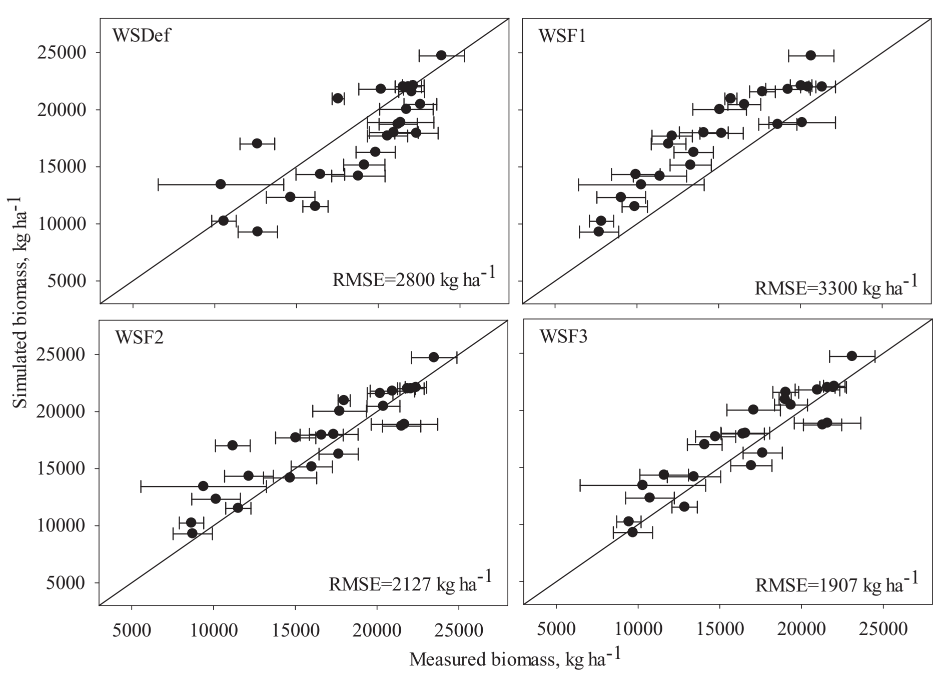

Fig. 4. Comparison between measured, and simulated final biomass in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSDef, WSF1, WSF2 and WSF3. Error bars indicate one standard deviation in the measured data.

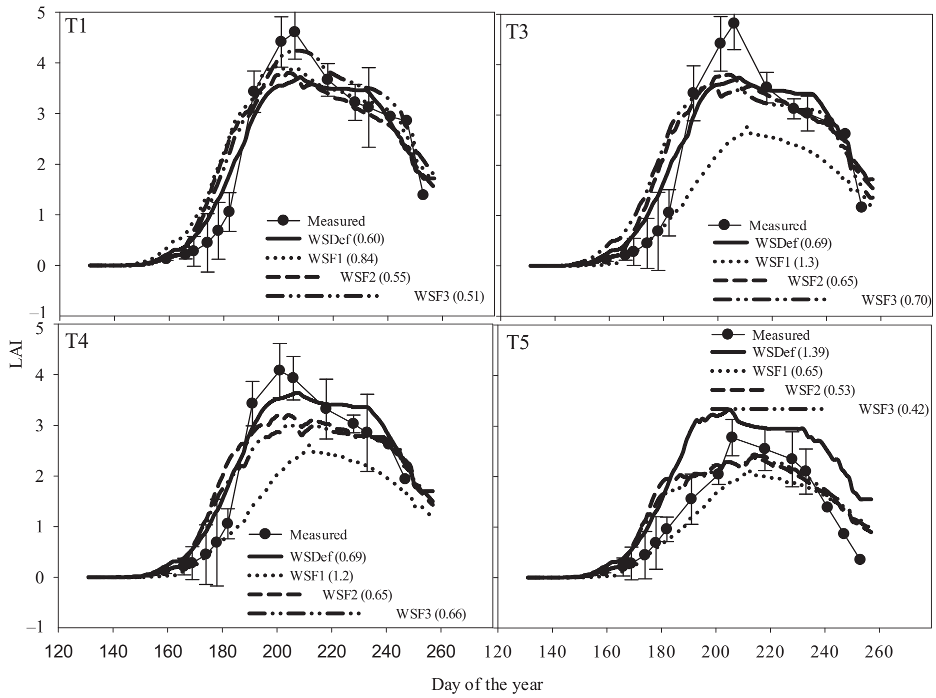

Fig. 5. Comparisons of measured and simulated corn LAI using stress factors WSDef, WSF1, WSF2 and WSF3 in 2010 in the T1, T3, T4 and T5 treatments. Error bars show one standard deviation in the measurements. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSEs of LAI simulations across the four treatments were 0.84, 1.00, 0.59 and 0.57 for the WSDef, WSF1, WSF2 and WSF3 stress factors, respectively.

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

$$SWFAC = \frac{TRWUP}{EPo} \tag{15}$$

SWFAC mainly affects photosynthesis and other dry matter assimilation related processes. This stress sets in at a leaf water potential level that is significantly below the *TURFAC* level, when the photosynthesis and other carbon assimilation processes are impaired due to water shortage. In the model, both stress factors are used as a direct multiplier on growth or dry matter accumulation rate that ranges from 1 for no stress to 0 for complete stress.

In this study, the expressions in CSM-CERES-Maize module in RZWQM2 for TURFAC (Eq. 14) was replaced with the equation developed between RC_c and the three soil water stress factors (i.e., Eq. 8). The expression for SWFAC (Eq. 15) was replaced with equations developed between RGY, and the three stress factors (i.e., Eq. 6) (as discussed below, the relationships developed between RGY and RBM with the three stress factors were found to be similar, so the

Table 6
Evaluation statistics (pooled data from SIAZ96 experiment in a sandy loam soil at Zaragoza, Spain and UFGA82 experiment in a sandy soil at Gainesville, Florida distributed with DSSAT 4.5) for simulations of grain yield and biomass using the three stress factors (WSF1, WSF2 and WSF3) and the default stress factor (WSDef) against measured values.

LAI					Biomass					Grain yield (kg ha^{-1})				
No. of data	RMSE kg ha^{-1}	RRMSE %	R^2	d	RMSE (kg ha^{-1})	No. of data	RRMSE %	R^2	d	No. of data	RMSE	RRMSE %	R^2	d
SIAZ96 experiments														
WSDef														
9	0.88	20.9	0.19	0.61	4061	9	22.9	0.47	0.74	9	1833	20.5	0.63	0.86
WSF1														
9	0.75	17.8	0.32	0.66	4620	9	26.1	0.13	0.53	9	1971	21.5	0.24	0.60
WSF2														
9	0.74	17.7	0.22	0.67	3196	9	18.1	0.54	0.81	9	1771	19.3	0.67	0.87
WSF3														
9	0.63	15.0	0.64	0.68	3591	9	20.3	0.46	0.75	9	1341	14.6	0.65	0.89
UFGA82 experiments														
WSDef														
6	0.29	8.9	0.72	0.98	1386	6	10.6	0.96	0.98	6	547	8.4	0.98	0.99
WSF1														
6	0.83	25.8	0.74	0.91	1982	6	15.2	0.99	0.98	6	313	4.6	0.99	0.99
WSF2														
6	0.26	8.0	0.80	0.99	1584	6	12.1	0.96	0.99	6	456	6.8	0.98	0.99
WSF3														
6	0.36	11.1	0.59	0.97	1329	6	10.4	0.96	0.99	6	449	6.6	0.98	0.99

RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

relationships between RGY and the stress factors were only used for further analysis).

2.5. Input data for the simulations and calibration of RZWQM2

RZWQM2 needs inputs of weather (daily solar irradiance, maximum and minimum temperature, wind speed, relative humidity, and precipitation as break point 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). Soil physical properties, soil profile depth and horizons (layers), soil texture, bulk density, and organic matter content are also needed. For simulation, the RZWQM2 requires careful iterative calibration of its soil water component, followed by the nitrogen (N) and the 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 simulation results with measured soil water, anthesis and maturity dates, maximum LAI, and final biomass and yield.

The RZWQM2 with the WSDef factors and crop/cultivar parameters calibrated by Ma et al. (2012) for simulating the Greeley experiment from 2008 to 2010 were initially used in the study. Yet, as various process interactions in the agricultural production system are highly complex, the model parameters obtained from calibration are not totally independent of the stress factor used. Therefore, for simulation of the crop using the three new water stress factors developed in this study, we recalibrated the cultivar parameters to get reasonable match between the grain yield, biomass, LAI and soil water. Calibration was performed only for the highest water level treatment in 2008, and these parameters were used for model validation runs of all other irrigation treatments in 2008, 2009, 2010 and 2011. One set of cultivar parameters was used for all the three factors, WSF1, WSF2, WSF3 (Table 3); further improvements in simulations were not obtained through calibration for unique sets of parameters for each factor.

Saseendran et al. (2008a) simulated the Akron experiments using the CERES-Maize v4.0 within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008a) were used as starting point for calibration of the cultivar parameters in this study (Table 3). For calibration of the cultivar parameters in the SIAZ96 and UFGA82 experiments, the cultivar parameters available in the DSSAT 4.5 database were used as a starting point (Table 3). In all the calibrations, only the highest water level treatment in the experiments was used to calibrate parameters for all treatments.

2.6. Statistics for model calibration and evaluations

We evaluated the simulation results using: (i) Root Mean Squared Error (RMSE), Eq. (16), between simulated and observed values; (ii) relative RMSE (RRMSE) that varies between 0 and 100%, Eq. (17), (iii) the index of agreement (d) between measured and simulated parameters (Willmont, 1981) which varies between 0 (poor model) and 1 (perfect model), Eq. (18); and (iv) coefficient of determination (R^2), Eq. (19).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{16}$$

$$\mathrm{RRMSE} = \frac{RMSE}{O_{avg}} \tag{17}$$

$$\mathrm{d} = 1.0 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|Pi - O_{avg}| + |Oi - O_{avg}|)^2} \tag{18}$$

$$\mathrm{R}^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})\right]^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2} \tag{19}$$

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.

3. Results and discussion

3.1. Greeley experiments

3.1.1. Plant available water (PAW) in the soil profile

Across the crop growth period, in general, the soil water content of the soil profile increased following the irrigation events and decreased following active crop water uptake (data not shown). Highest PAWs were generally in the T1 treatment, due to larger irrigation amounts, followed by T2, T3, T4, T5 and T6 treatments with lower irrigation levels. However, some large rain events like the 86.0 mm on DOY 229 in 2008 increased soil water content (SWC) to FC in all the treatments in that year. Similarly, SWC of all the treatments came close to FC for all treatments in 2010 on DOY 200 for corn.

3.1.2. Water stress factors

Patterns in the relationships between RGY, RBM and RC_c and the three soil water content-based stress factors (WSF1, WSF2 and WSF3) emerge when the average values for each treatment across crop seasons were plotted together (Fig. 2). When the overall pattern of these observed relationships deviated from the default pattern in RZWQM2 (Fig. 1a), the pattern matched better with those used in APSIM model (Saseendran et al., 2008b) (Fig. 1b). We assumed piecewise linear as a reasonable approximation of the relationships between the computed water stress factors and crop responses in terms of RGY, RBM and RC_c. As the number of data points (six) was not enough for a rigorous piecewise linear regression analysis, we assumed a threshold through the points with relative crop response greater or equal to 1.0 (horizontal line parallel to the x-axis in Fig. 2). A linear regression was fitted to the remaining data points to get the sloping line in the figure with relative crop responses below 1.0. A third line was used to connect the lower end of the fitted sloping line (at the lowest WSF value) representing the grain yield and biomass responses to the origin (0, 0). Thus, we assumed that the relative biomass and grain growth stops when there is no PAW in the soil for plant uptake. However, expansion growth response (RC_c) of plants cease at PAW levels well above zero (Boyer, 1970; Cosgrove, 1998; Cosgrove and Cleland, 1983; Neumann, 1995); therefore these regression lines were extended downward to meet the x-axis.

The slopes of the lines representing the responses of corn to water stress factors in the figure are steeper for RC_c compared to RGY and RBM. The RGY and RBM responses to the three stress factors were similar enough to assume them as identical. The results clearly show an early (in stress onset) response in expansion growth (canopy cover as surrogate for LAI) of the plant due to water stress before dry matter assimilation processes are affected. These results are in line with the observation that the chemical signals from the roots of plants subjected to water deficit stress modulate cell expansion rate at lower stress values and more strongly than net carbon assimilation and translocation rates, and depending on the stress level, this can continue even after the plants have been re-watered (Boyer, 1970; Granier and Tardieu, 1999; McCoy et al., 1990; Tardieu et al., 1999, 2000). In corn, Boyer (1970) and Sobrado (1986) observed reductions in both leaf area and dry matter accumulation with soil water deficits;

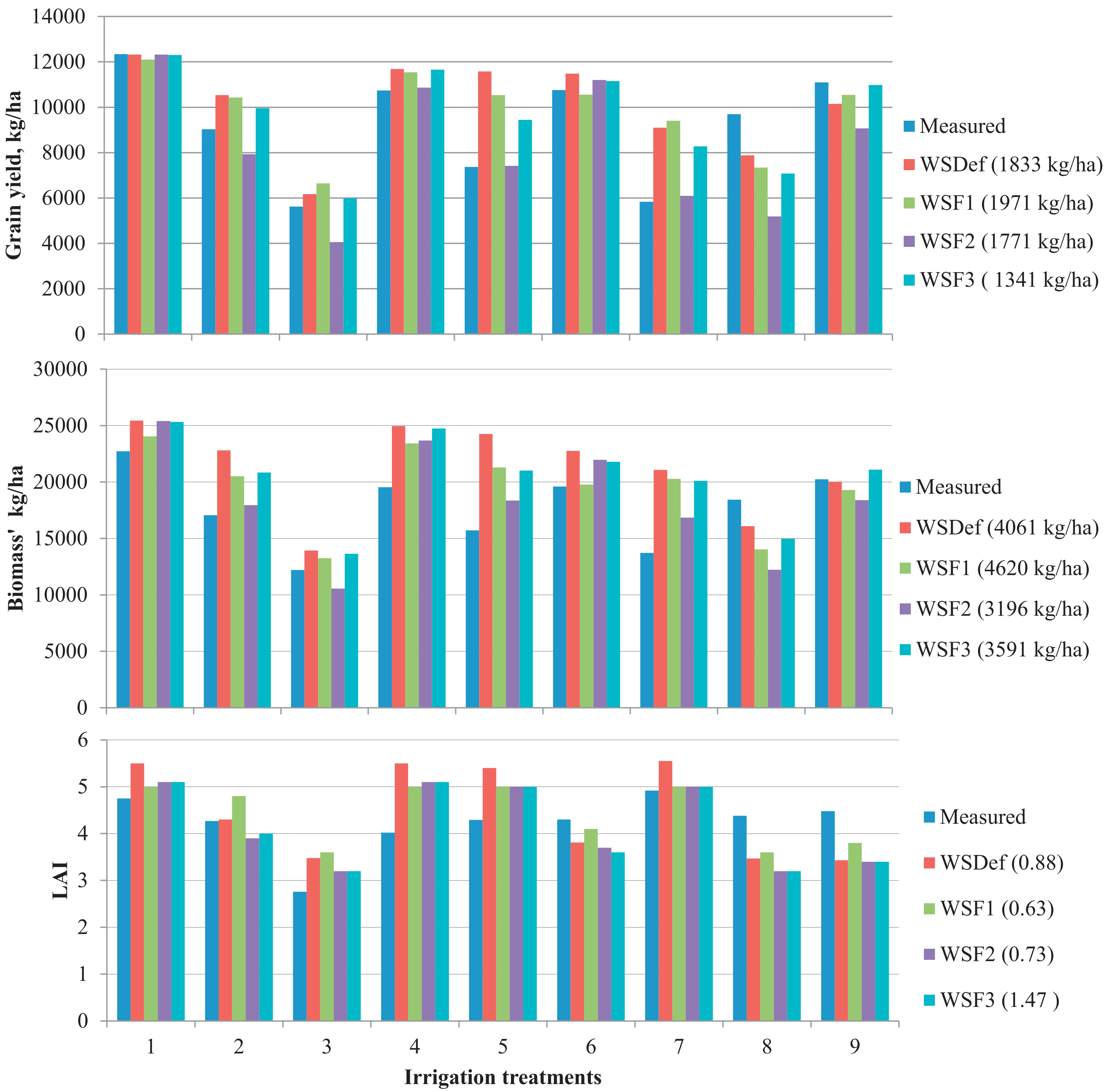

Fig. 6. Simulations of grain yield, final biomass, and seasonal maximum LAI in the SIAZ96 experiment distributed with DSSAT 4.5 using RZWQM2 modified with WSF1, WSF2 and WSF3 stress factors. Enclosed in parenthesis of the legends are root mean square errors (RMSE).

however the leaf expansion rate was observed to be more sensitive to low turgor, and the expansion ceased when turgor reached 0.2 MPa. These observed responses of plants to water stress has also been incorporated in crop simulation models by making the simulated expansion processes (leaf area) more sensitive to water stress than the biomass assimilation processes (photosynthesis) (McCree and Fernandez, 1989; Ritchie, 1998; Saseendran et al., 2008b). The results of differential effects of irrigation treatments on RGY and RBM in corn did not disagree from the reported relative enhanced sensitivity of leaf expansion growth to water deficit (Boyer, 1970).

3.1.3. Comparisons of water stress factors

In general, the R^2 of linear relationships between WSF2 and crop responses were slightly less than WSF3 with values between 0.94 and 0.98 (Fig. 2). Relatively least accurate linear fit was between WSF1 and the three crop response variables (R^2 between 0.92 and 0.99). Quantitative, piecewise linear relationships between WSF1, WSF2 and WSF3 and RGY, RBM and RC_c responses for the crop are useful for modeling the impacts of crop water stress on corn growth and development (Table 4). Overall ranking of the three stress factors based on the variances explained (R^2) by them in the average RGY and RBM, and RC_c data during 2008–2011 was in the order WSF3 > WSF2 > WSF1.

3.1.4. Performance of WSF1, WSF2 and WSF3 in simulations of corn using RZWQM2

For simulation of corn, the default TURFAC (Eq. 14) and SWFAC (Eq. 15) stress factor computation procedures in CSM-CERES-Maize in RZWQM2 were replaced with relationships derived between RC_c and RGY, respectively, with each of the three stress factors (WSF1, WSF2 and WSF3) (Eqs. 6, 7 and 8) as given in Table 4. TURFAC or the new substitute modifies leaf, stem, ear and grain growth, and SWFAC or the substitute modifies photosynthesis and carbon portioning, rooting depth, leaf senescence and N mobilization to grains in the model. All the simulations across the four years (2008 to 2011) and six irrigation treatments (T1 to T6) using the three water stress factors used the same initial soil water and nutrient conditions on the first day of the year as used in Ma et al. (2012) using the WSDef. In earlier studies at Akron, CO, we found that if we started the model, on January 1 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 January 1 was assumed to be at field capacity in the upper 450 mm of soil and half the plant available water (PAW) above the plant wilting point below this depth 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. Simulated phenology dates were compared with measured growth stages. In general, the anthesis and physiological maturity dates in the simulations were within 3 to 6 days of the field measured dates in simulations from 2008 to 2011 with the four water stress factors.

Average value of the TURFAC or substitute simulated for WSDef, WSF1, WSF2 and WSF3 under T1 treatment in 2010 were 0.00, 0.41, 0.03, and 0.09, respectively, until the simulated crop LAI reached a value of 1.00 on DOY 173 (for discussion, the stress factors are shown to range from 0 for no stress to 1 for complete stress). However, appreciable differences in simulated WS between WSDef and the three WS factors were in the beginning of the crop season when the soil was not fully covered by the crop. The simulated TURFAC values after the crop LAI exceeded a value of 3.50 (DOY 200) were 0.00, 0.01, 0.00 and 0.01, respectively. This difference was mainly due to the fact that with WSDef [Eq. (14) and (15)], water demand and supply is 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 (Ritchie and Basso, 2008). 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 WSF1 and WSF3, the default potential transpiration demand is replaced with ETr demand [Eq. (1) and (3)]. However, WSF2 is only a ratio of the actual to potential PAW in the soil [Eq. (2)].

In general, soil water simulations across the four crop seasons (2008 to 2011) in response to WSF1, WSF2 and WSF3 were comparable to WSDef simulations. RMSEs of the simulated 2 m soil profile water ranged from 2.3 to 4.8 cm across four years and the three stress factors (Table 5). Simulations with WSF1 were relatively less accurate (Table 5).

Measured grain yields in 2008 in response to the six irrigation levels ranged from 11,071 to 7546 kg ha^{-1}. Simulated yield gains were underestimated by an average of 1953 kg ha^{-1} using the WSDef factor and overestimated by 1953, 1443 and 1434 kg ha^{-1} with WSF1, WSF2 and WSF3 stress factors, respectively. Overall, in 2008, WSF3 was found to simulate the crop better than WSDef and WSF1 in grain yield, LAI and biomass simulations (Table 5; Fig. 3 and 4). In 2009, in simulations of biomass and LAI across the six irrigation treatments, simulations with WSF3 showed lowest RRMSEs and highest d values (Figs. 3 and 4). Nonetheless, grain yield predicted by WSF1 with an RMSE of 891 kg ha^{-1} was more accurate than others. In 2010, simulations of grain yield using the WSF3 factor had the lowest RRMSE of 12%. Biomass simulations using WSF1, WSF2 and WSF3 this year were comparable with RMSEs 11, 11 and 12%, respectively (Table 5; Fig. 4). As noted earlier, in the Greeley experiment, continuous direct measurements of LAI were available only for one crop season in 2010 in the T1, T3, T4 and T5 treatments (Fig. 5). Overall, among the three stress factors WSF1, WSF2 and WSF3, estimate of LAI was best simulated with WSF3 with RRMSE of 36% and d of 0.96 (Table 5). Taking into account the measured deviations in LAI between replications [standard deviations (SD) plotted in Fig. 5], overall, the simulations using stress factors WSDef and WSF3 reasonably followed the measured crop growth in the field.

In 2011, simulations of grain yield using WSF3 and WSDef factors were comparable in accuracies with RMSEs 1166 and 1007 kg ha^{-1}, respectively. The simulations of LAI and biomass this year were more accurate than the previous three years (2008, 2009 and 2010) using the WSF3 factor compared to the WSDef, WSF1 and WSF2 factors (Table 5, Fig. 4). Overall, in simulations of the crop, averaged across the four years, WSF3 was found to simulate the crop better than the other two WS factors (WSF1 and WSF2), especially in grain yield and biomass simulations (Figs. 3 and 4). Nonetheless, using a ratio of actual crop ET to potential crop ET as the water stress factor in RZWQM2, Saseendran et al. (2014) simulated corn in the Greeley experiments appreciably better than WSF3.

3.2. Simulations of the SIAZ96 and UFGA82 experiments from the DSSAT database

Measured grain yields reported in the SIAZ96 experiments ranged from 5620 to 12,340 kg ha^{-1} (Fig. 6; Table 6). We simulated this experiment using the modified RZWQM2 with the same initial water and N conditions as was done using the CSM-CERES-Maize and -IXIM-maize models available within the DSSAT 4.5 for simulations of corn (Hoogenboom et al., 2010; Jones et al., 2003; Lizaso et al., 2011). The full irrigation treatment to meet the consumptive use demand of corn was used for calibration of the cultivar parameters. In general, the anthesis and physiological maturity dates in the simulations were within 0 to 3 days of the field measured dates. Grain yield, biomass and LAI simulations of RZWQM2 using the WSF3 had lower RMSE than simulations using the WSDef, WSF1 and WSF2 (Fig. 6, Table 6). The RRMSE of grain yield simulations ranged between 14.6% with WSF3 and 21.5% with WSF1 stress factors. These results were significantly better than Saseendran et al.'s (2014) simulations of the same experiment using a ratio of actual crop ET to potential crop ET as the water stress factor in RZWQM2.

The UFGA82 experiment had complex treatments with six different combinations of water and N applied differentially in the vegetative and reproductive stages of growth. Using the modified RZWQM2, we simulated this experiment also with the same initial water and N conditions as was done using the CSM-CERES-Maize and -IXIM-maize models available within the DSSAT 4.5 for simulations of corn.

The anthesis and physiological maturity dates in the simulations were within 1 to 4 days of the field measured dates. Grain yield and biomass simulations of this experiment using the four WS factors (WSDef, WSF1, WSF2 and WSF3) were comparable to each other with RMSE of grain yield varying between 313 and 547 kg ha^{-1} (Table 6, Fig. 7). The RMSE of biomass varied between 1329 and 1982 kg ha^{-1}. However, the lowest RMSE for grain yield (313 kg ha^{-1}) was obtained using WSF1, and lowest RMSE for biomass (1329 kg ha^{-1}) was obtained using WSF3. The RMSE of LAI simulations with the four WS factors were also comparable to each other varying between 0.26 and 0.83, with the lowest value obtained using WSF2 and the highest with WSF1. Collectively, simulations of the SIAZ96 experiment with

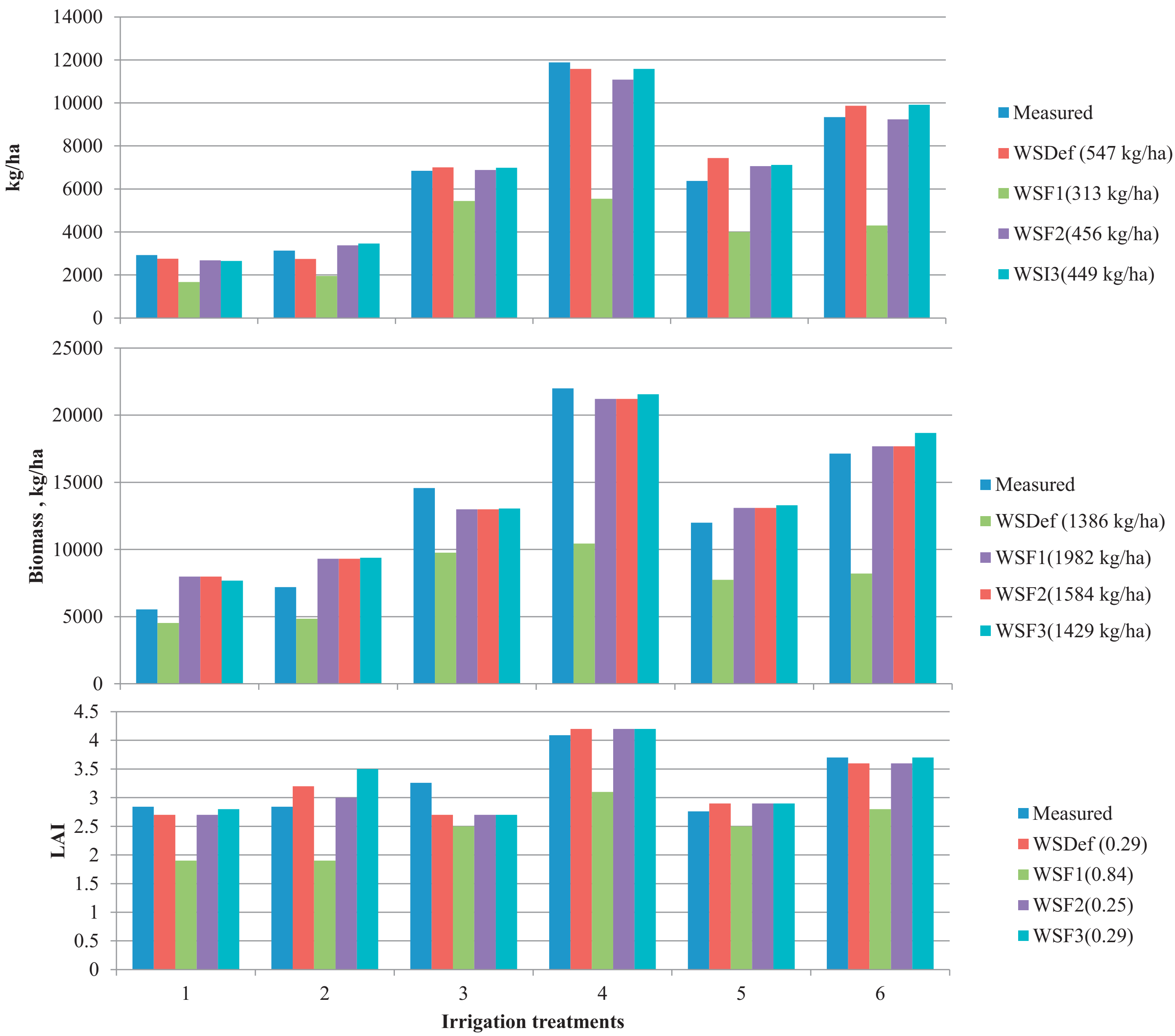

Fig. 7. Simulations of grain yield, final biomass, and seasonal maximum LAI in the UFGA82 experiment distributed with DSSAT 4.5 using RZWQM2 modified with WSF1, WSF2 and WSF3 stress factors. Enclosed in parenthesis of the legends are root mean square errors (RMSE).

RZWQM2 modified with the WSF3 stress factor (RMSE of 449 kg ha^{-1}, 1329 kg ha^{-1} and 0.36, respectively, for grain yield, biomass and LAI) were more accurate than simulations with the other three WS factors. These results were also appreciably better than Saseendran et al. (2014) simulations of the same experiments using a ratio of actual crop ET to potential crop ET as the water stress factor in RZWQM2.

3.3. Simulations of Akron experiments

Grain yields in the irrigation studies of the Akron experiments (total of 26 grain harvests across three years) were simulated with RMSE of 669, 846, 1300, and 326 kg ha^{-1} using the RZWQM2 with WSDef, WSF1, WSF2 and WSF3 stress factors, respectively (Table 7, Fig. 8). Biomass harvested at the end of the season were simulated with RMSE of 1699, 2064, 4983 and 1685 kg ha^{-1}, respectively (Table 7). Both grain yield and biomass in the irrigation studies were simulated best by WSF3.

In general, accuracies of grain yield simulations in the rainfed experiments also were best using WSF3 compared to the other WS factors (Table 7, Fig. 8). RMSE of grain yields were 837, 521, 409 and 231 kg ha^{-1}, respectively, using the WSDef, WSF1, WSF2 and WSF3 factors in RZWQM2. While simulating the Akron experiments, Saseendran et al. (2008a) identified an outlier in the rainfed measured grain yield in 1997 (Fig. 8). This year, the lowest grain yield of 357 kg ha^{-1} was obtained when the 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 varied between 125 kg ha^{-1} using WSF3 and 504 kg ha^{-1} using WSF1. Using the WSDef factor in the model, grain yields (excluding the 1997 data) in the rainfed studies were simulated with an RMSE of 331 kg ha^{-1}. The RMSE of biomass simulations in the rainfed trials (including 1997) using the four water stress factors were similar varying between 1015 kg ha^{-1} using WSDef

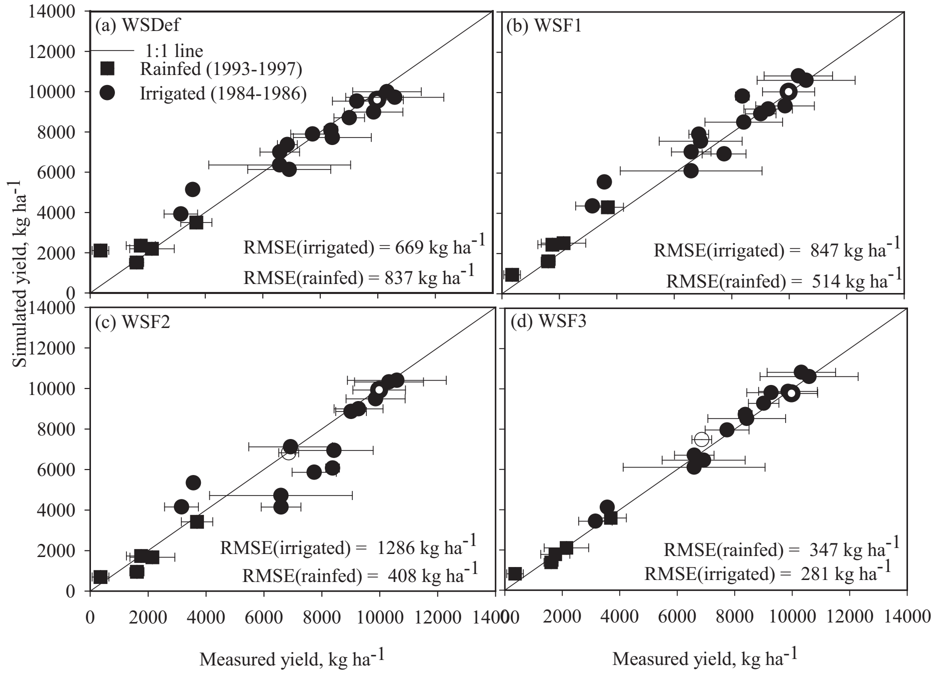

Fig. 8. Measured and simulated corn grain yield in the irrigated (1984 to 1986) and rainfed experiments (1993 to 1997) at Akron, Colorado. Error bars indicate 1 standard deviation about the mean of the treatment replications. RMSE = Root Mean Square Error.

and 1049 kg ha^{-1} using WSF1. In summary, in the Akron experiments, simulations using WSF3 in RZWQM2 was more accurate than simulations using WSDef, WSF1 and WSF2. These results were also more or less similar in accuracy of Saseendran et al. (2014) simulations of the same experiments using a ratio of actual crop ET to potential crop ET as the water stress factor in RZWQM2. Accurate quantifications of the soil water based WS factors in RZWQM2 for simulation of specific crops will demand accurate measurements and specification of water in the root zone soil profile at planting, sometimes limiting its applications in experiments where these are not measured.

Table 7
Evaluation statistics (pooled data from rainfed experiments from 1993 to 1997, and irrigation trials with line source and drip systems from 1984 to 1986 at Akron, Colorado, USA) for simulations of grain yield and biomass using the three stress factors (WSF1, WSF2 and WSF3) and the default stress factor (WSDef) against measured values in the Akron experiments.

	Biomass					Grain yield				
	No. of data	RMSE (kg ha^{-1})	RRMSE %	R^2	d	No. of data	RMSE (kg ha^{-1})	RRMSE %	R^2	d
					WSDef					
Rainfed	5	1699	13.5	0.21	0.61	5	669	8.5	0.97	0.97
Irrigated	16	1015	22.5	0.49	0.99	16	837	8.5	0.86	0.97
					WSF1					
Rainfed	5	2064	16.5	0.22	0.68	5	846	10.8	0.87	0.95
Irrigated	16	1049	23.3	0.68	0.91	16	521	27.4	0.68	0.92
					WSF2					
Rainfed	5	4983	39.7	0.05	0.26	5	1300	16.6	0.99	0.91
Irrigated	16	1027	22.7	0.84	0.99	16	409	21.5	0.94	0.99
					WSF3					
Rainfed	5	1685	13.3	0.38	0.63	5	326	4.2	0.99	0.99
Irrigated	16	1017	22.6	0.62	0.99	16	231	12.3	0.94	0.99

RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

4. Summary and conclusions

In this study, our initial interest were focused on the development of water stress factors that have potentials for explaining corn growth responses to varying water inputs in limited irrigation experiments. The three water stress factors developed were ratios of PAW to ETr (WSF1), PAW to MAW (WSF2), and WSF2 to ETr (WSF3). Out of these three stress factors, WSF3 explained corn grain yield responses to water levels in the Greeley experiments better than the other two factors. Nevertheless, we implemented all the three stress factors in the RZWQM2 and tested their abilities in simulating the corn growth responses to various irrigation and N levels in the Greeley, SIAZ96, UFGA82 and Akron experiments. From these investigations, we conclude that simulations of corn growth response to water by the three new stress factors were not appreciably better than the default water stress factor (WSDef) currently available in the model. However, WSF3 was relatively better than WSDEef, WSF1 and WSF2 in simulations of corn grain yield, biomass and LAI in the Greeley, SIAZ96, UFGA82 and Akron experiments. But, accuracy of the WSF3 simulations of the Greeley experiments were lower, SIAZ96 experiments were better and Akron experiments were similar to Saseendran et al.'s (2014) simulations of the same experiments using a ratio of actual crop ET to potential crop ET as the water stress factor in RZWQM2. Potential for adaptation of this stress factor for simulation of corn and other crop species in RZWQM2 across soils and climates need to be verified in further studies.

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