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Modeling maize production under growth stage-based deficit irrigation management with RZWQM2

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ABSTRACT

Farmers are challenged to maintain yield and economic productivity with declining water resources and climatic variability in semi-arid regions worldwide. Growth stage-based deficit irrigation has been suggested as a feasible approach to maintain yields with less water. Experiments were conducted in 2012, 2013, and 2015 in which maize (*Zea mays* L.) was irrigated under twelve treatments with varied levels of deficit irrigation during the late vegetative (Lveg) and maturation (Mat) growth-stage periods in Northern Colorado. The Root Zone Water Quality Model 2 (RZWQM2)-CERES-Maize model was used to simulate the effects of growth stage-based deficit irrigation on maize production and yield components. The results showed that RZWQM2 could simulate the impact of temperature on maize phenology but did not simulate the impact of water stress on maize maturity. Both simulated and observed aboveground biomass, grain yield, and kernel weight decreased with the decrease of irrigation water amount during Lveg and Mat periods. In general, the simulated aboveground biomass and grain yield showed larger errors in terms of root mean squared error (RMSE), relative RMSE, and Nash–Sutcliffe efficiency, than those reported in the previous modeling studies where deficit irrigation was applied uniformly throughout the growing seasons in the same field. Future efforts to improve the effects of deficit irrigation on kernel development will likely make RZWQM2 a better tool for optimizing irrigation management in semi-arid regions.

1. Introduction

Irrigation water in semi-arid northern Colorado has declined due to factors such as growing population, increasing industrial water needs, and declining aquifer recharge. Increasing temperature has resulted in increased evaporative water loss in watersheds and reduced river flows (Finley, 2018). Therefore, farmers are facing a challenge of maintaining yield and economic productivity with declining irrigation water supplies. Maize is a major crop for human consumption and an important feed for livestock both regionally and globally. More irrigated land is planted to maize than any other crop in the USA, and this trend is increasing (Wright and Wimberly, 2013; Derner et al., 2015). Many studies have been conducted on water management strategies that maximize maize production, such as agronomic practices and irrigation systems, and growth stage-based deficit irrigation (Kirda, 2002; Walthall et al., 2013).

Growth stage-based deficit irrigation allocates a limited water supply in response to plant's varying sensitivity to water stress during different growth stages. Water deficit during reproductive stages (from tassel emergence to the beginning of grain filling) might reduce yield significantly by decreasing grain number due to poor pollination and fertilization (Bolanos and Edmeades, 1996; NeSmith and Ritchie, 1992a; Saini and Westgate, 2000; Çakir, 2004). Studies have shown a 20–40% reduction in maize yield by water stress during grain-filling period, with kernel weight being the most affected yield component (NeSmith and Ritchie, 1992b; Çakir, 2004). It has also been reported that maize is relatively insensitive to water stress imposed during vegetative growth stages (from emergence to tasseling) and that water deficit during vegetative growth stages does not reduce maize yield significantly (Abrecht and Carberry, 1993; Çakir, 2004). However, much of the previous research on maize has focused on the impact of water deficit during a single growth stage (Otegui, et al., 1995; Bolanos and Edmeades, 1996; Çakir, 2004), and more recent research (Comas et al., 2019; Zhang et al., 2019) has provided a more complex understanding of

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maize response to deficit irrigation.

There may be opportunities to improve water productivity (yield per unit water consumed) in maize by applying deficit irrigation during specific periods of both vegetative and maturation stages but full irrigation during key reproductive stages. By studying crop water use as well as crop yield under deficit irrigation during the late vegetative (Lveg, V8-VT) and maturation (Mat, R4-R6) growth-stage periods, Comas et al. (2019) suggested that greater water productivity could be achieved by deficit irrigation during Lveg than Mat periods. Zhang et al. (2019) evaluated the impact of deficit irrigation on maize during Lveg and Mat periods in terms of phenology, dry leaf weight, aboveground biomass, yield, kernel number, 1000 kernel weight, and grain filling rate. Their results suggested that water deficit during Lveg decreased the kernel number and dry leaf weight, and thus decreased the potential grain filling rate, whereas deficit during Mat directly reduced the grain filling rate and duration, and thus had the strongest effect on grain yield.

Modeling studies have also evaluated maize responses to non-water-stressed and limited-irrigation management. Anothai et al. (2013) evaluated the capability of the Cropping System Model (CSM)–CERES–Maize model to simulate the impact of different irrigation regimes (100%, 85%, 70%, 55% and 40% of full crop water requirements) throughout the season on maize growth and development under semi-arid conditions in northern Colorado. Their results showed that the CSM–CERES–Maize model simulated both grain yield and final biomass fairly well for all irrigation levels. Trout and DeJonge (2017) found that water productivity of maize in Colorado might be relatively insensitive to small decreases in crop evapotranspiration (ETc) (<25%) when deficit irrigation was applied uniformly through the season but was partially relieved during early reproduction, which was supported by modeling studies (Ma et al., 2012a, 2016) using the Root Zone Water Quality Model - Decision Support System for Agrotechnology Transfer (RZWQM2-DSSAT). Zhang et al. (2018) demonstrated that the DayCent model could simulate maize canopy development, biomass production, soil water dynamics, and grain yields under water deficit conditions as well as those achieved using models with greater complexity in crop growth–production submodels (e.g., CERES and RZWQM2) using the same dataset as the above-mentioned studies (Ma et al., 2012a, 2016). Qi et al. (2016) reported that RZWQM2 adequately simulated overall corn growth stages in northern Colorado under constant deficit irrigation (water stress) conditions. Saseendran et al. (2014) modified the water stress factors for simulating dryland and limited irrigated corn using RZWQM2 model with the embedded CSM-CERES-Maize module. Their results show that overall simulation of crop responses to water stress was improved, especially in simulation of corn grain yield.

Most agricultural system models have been evaluated under uniform water stresses throughout the whole growing season. Few studies have reported on model performance under growth stage-based irrigation management, especially the response of yield components to deficit irrigation applied during Lveg and/or Mat periods. A recent study conducted in northern Colorado has developed an agro-economic model to connect plant growth-stage-specific evapotranspiration targets with farm profitability, suggesting that deficit irrigation can become optimal both during Lveg or Mat periods depending on output price and production costs (Manning et al., 2018). Therefore, it is necessary to further evaluate agricultural system models for simulating growth stage-based irrigation management on crop production.

The purpose of this study was to evaluate the performance of RZWQM2 in simulating maize yield and yield components under growth stage-based deficit irrigation management with three-years of experimental data and investigate the best growth stage-based irrigation strategies under conditions of limited water availability.

2. Materials and methods

2.1. Field experiment

The field experiment was conducted on maize (*Zea mays* L., Dekalb DCK52-59, 102-day relative maturity class maize hybrid designed for use in the northern Colorado) at the USDA-ARS Limited Irrigation Research Farm (LIRF), in Greeley, Colorado, USA (40°26′57″N, 104°38′12″W, elevation 1427 m). The site contains three soil types, Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). The soil is a sandy loam and is fairly uniform throughout the 200 cm soil profile. Maize was planted on Apr 30/May 1 (2012), May 15 (2013), and June 1 (2015), with seeding rate of 80,000–84,000 seeds ha^{-1}. The same study was conducted in 2014, but these data were not included because above-average precipitation prevented water-stress conditions in some deficit-irrigation treatments. Plants emerged on May 14 (2012), May 23 (2013), and June 10 (2015). Plant-stand density was evaluated for each treatment plot, and the final populations per hectare were found to be 80,496 (2012), 77,665 (2013), and 82,570 (2015). Fertilizers were applied at planting and in-season with the irrigation water to avoid nutrient deficiencies on all treatments.

Total applied nitrogen (N, UAN 32%) ranged between 266 and 349 kg ha^{-1} in 2012, 230–294 kg ha^{-1} in 2013, and 242–290 kg ha^{-1} in 2015, depending on the treatment. A liquid starter N of 41 kg ha^{-1} was applied at planting each year with approximately 170 kg ha^{-1} applied as fertigation over four irrigation events in 2012, 160 kg ha^{-1} applied over five irrigation events in 2013 (Comas et al., 2019), and 167 kg ha^{-1} applied as fertigation over four irrigation events in 2015 in July prior to tasseling. The remainder of N (97–175 kg ha^{-1} in 2012, 74–127 kg ha^{-1} in 2013, 38–120 kg ha^{-1} in 2015) was applied through the season with the well water used for irrigation, which contained high nitrate content (approximately 25 mg kg^{-1} N).

The experimental field was divided into two equal sections, and maize was rotated with sunflower (*Helianthus annuus* L.) with the same irrigation treatment design. Each section was divided into four replicated blocks, and each block was divided into twelve 9-m × 43-m plots containing twelve crop rows oriented north-south (with 0.76-m spacing). During the growing seasons in 2012, 2013, and 2015, twelve irrigation treatments with varying levels of regulated deficit irrigation (RDI) were arranged in a randomized block design with four replications (Table 1). Irrigations (Trout and DeJonge, 2017) were scheduled using FAO-56 dual crop coefficient methodology (Allen et al. 1998) with basal crop coefficients adapted from Table E-2 in Jensen and Allen (2016) and adjusted for measured crop canopy growth and senescence (Allen and Pereira, 2009). At the beginning, all plots were irrigated the same to ensure good germination. Deficit irrigation was applied during the late vegetative (Lveg, V8-VT) and/or maturation (Mat, R4-R6) growth-stage periods (Abendroth et al., 2011). All treatments were irrigated fully to

Table 1
Twelve irrigation treatments[a] in 2012, 2013, and 2015 growing seasons at the Limited Irrigation Research Farm at Greeley, CO. Irrigation amount in each treatment is defined as a percentage of crop evapotranspiration (ETc) during late vegetative (Lveg, V8-VT) and maturation (Mat, R4-R6) growth-stage periods.

		Target percentage of ETc in Lveg				
		100	80	65	50	40
Target percentage of ETc in Mat	100	x			x	
	80		x	x	o	x
	65		x	x	x	x
	50				x	
	40		Δ			x

[a] o – Treatment only conducted in 2012 and 2013; Δ – Treatment only conducted in 2015. x – Treatment conducted all three years.

meet ETc demand during the reproductive period (Rep, R1-R3). Each treatment was targeted to meet a percentage of potential non-stressed ETc (Allen et al., 1998; Jensen and Allen, 2016) during Lveg and Mat growth-stage periods (e.g., "100/50″ treatment would indicate a target of 100% of maximum ETc during Lveg and 50% of maximum ETc during Mat). Treatment 80/50 (T80/50) in 2012 and 2013 was replaced with T40/80 in 2015 to further investigate the effect of water deficit during the Mat period. All measurements were taken from the middle six (of twelve) rows to avoid edge effects.

During each growing season, irrigation water was applied through a surface drip irrigation system with 16-mm diameter drip tubing that was placed along each crop row. Meteorological data were recorded from an on-site CoAgMet weather station GLY04 (Colorado Agricultural Meteorological Network, http://ccc.atmos.colostate.edu/~coagmet/), including hourly air temperature, relative humidity, incoming shortwave solar radiation, horizontal wind speed taken at 2 m above a grass reference surface, and daily precipitation (Table 2).

Neutron attenuation (neutron moisture meter, CPN-503 Hydroprobe, InstroTek, San Francisco, CA, USA) was used to measure soil water content at 30 cm depth increments to 2 m, in the crop row near the middle of each plot. Soil water content at the 0–15 cm layer was measured with a portable time domain reflectometer (MiniTrase, Soilmoisture Equipment Corp, Santa Barbara, CA, USA). Soil water content measurements were taken before and/or after irrigation for a total of two or three times a week, from Lveg to the end of the growing season. The total irrigation and actual ET amount (mm) for each treatment in experimental years are given in Table 3 (Comas et al., 2019, Zhang et al., 2019).

Maize phenology was measured weekly during each growing season, from five plants in each treatment plot, or a total of 20 plants for each treatment. Aboveground biomass and leaf area index (LAI) were measured at the beginning of deficit irrigation (ca. V7), the end of vegetative deficit irrigation (VT), and the end of growing season. For each biomass sampling, leaves, stems, cob and grain were measured separately for each of the five plants collected from each plot. All biomass samples were oven dried to constant mass at 60 °C. Grain was removed from the ear after being dried and then both grain and cob were re-dried and weighed. The dry weight sum of leaves, stems, cob, and grain was considered the total aboveground biomass and was calculated for each plot. Once grain moisture in the plots fell to approximately 16%, grain yield was measured by hand-harvesting the ears from the center 23 m of the center four rows of each plot. Grain was threshed with a stationary thresher (Wintersteiger Classic ST, Wintersteiger AG, Ried, Austria), weighed and subsampled for moisture content determination. Grain moisture content at harvest was measured with a DICKEY-john GAC500-XT Moisture Tester (DICKEY-john Corp, Aubern, Ill, USA). Grain yield was normalized to 0% moisture content. The weight of 1000 kernels of oven dried grain were measured and average number of kernels per plant was estimated from grain yield per plant and average kernel weight. Full details of plant data collection are found in Comas et al. (2019) and Zhang et al. (2019).

Table 3
The total irrigation and actual ET amount (mm) for each treatment in experimental years.

Treatments	2012 ET (mm)	Applied irrigation amount (mm)	2013 ET (mm)	Applied irrigation amount (mm)	2015 ET (mm)	Applied irrigation amount (mm)
100/100	771	575	659	427	621	481
100/50	653	430	565	334	457	289
80/80	676	488	581	349	517	380
80/65	611	407	566	328	472	311
80/50	586	377	505	297		
80/40	601	372	493	268	407	236
65/80	641	444	559	329	492	354
65/65	565	369	541	307	398	265
65/50	551	353	494	277	383	221
65/40	545	335	450	249	383	199
50/50	531	326	454	262	369	191
40/40	477	281	422	216	323	153
40/80					434	300

2.2. Description and calibration of RZWQM2 model

The Root Zone Water Quality Model 2 (RZWQM2) is a continuous time, physically based, deterministic, whole-system model developed by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) with detailed soil C/N dynamics, plant growth, water and solute transport, and heat flow (Ahuja et al., 2000; Ma et al., 2012a). Specifically, the Green–Ampt equation is used for water infiltration and the Richards' equation is solved for water redistribution between rainfall/irrigation events. The CERES-Maize crop model is incorporated from the DSSAT model and used in this study. Potential evapotranspiration, estimated from the Shuttleworth–Wallace equations, is partitioned between potential evaporation and potential transpiration. Actual evaporation is calculated by solving the Richards' equation for upper boundary water flux, and actual transpiration is estimated from root length density and soil water content (Ma et al., 2006, 2012a).

Fang et al. (2017) calibrated the model with measured data (end-of-season crop yield and aboveground biomass, soil water content in the 0–120 cm depth, and growth stage data, including emergence, anthesis, and maturity) from the full irrigation (100/100) and lowest irrigation (40/40) treatments in 2012 and 2013, and the calibrated soil parameters for 2013 were used without further calibration, since the same plots were planted to maize in 2013 and 2015, and these values were close to those used by Ma et al. (2012b) on the same site (Table 4). However, we did recalibrate the plant parameters to improve crop simulation, because Fang et al. (2017) found inadequacy in their model calibration in response to irrigation for some treatments. In addition, Ma et al. (2012b) demonstrated the dependence of calibrated plant parameters with calibration datasets due to the non-uniqueness of model calibration. Therefore, some recalibration of the plant parameters was warranted. The maize cultivar parameters were calibrated using the Parameter estimation (PEST) software optimization algorithm in RZWQM2 based on the previous simulation study in Fang et al. (2017) who used soil water content, plant biomass, final yield, and N uptake in

Table 2
Average daily temperature (Mean T, °C), relative humidity (RH, %), solar radiation (Rs, MJ m^{-2}), wind speed (Ws, m s^{-1}) and precipitation (Precip, mm) during the late vegetative (Lveg, V8-VT), reproductive (Rep, R1-R3), and maturation (Mat, R4-R6) growth-stage periods in 2012, 2013 and 2015.

Year	2012			2013			2015		
Growth stage	Lveg	Rep	Mat	Lveg	Rep	Mat	Lveg	Rep	Mat
Mean T	20.3	23.2	18.3	20.4	20.0	19.5	21.0	21.4	15.4
RH	53.0	52.1	54.3	59.5	61.2	62.4	58.5	57.4	58.8
Rs	25.2	23.2	18.9	24.8	20.5	17.7	22.9	25.0	16.2
Ws	2.0	1.7	1.5	2.2	1.4	1.5	1.6	1.3	1.5
Precip	88	6	30	54	27	112	80	16	33

Table 4
Soil hydrological parameters used in RZWQM2, from prior calibration (Fang et al., 2017).

Soil depth (cm)	Soil bulk density (g cm^{-1})	ksat[a] (cm h^{-1})	$\theta_{1/3}$ (cm^3 cm^{-3})	θ_{15} (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	θ_r (cm^3 cm^{-3})
0–15	1.49	1.95	0.274	0.12	0.437	0.035
15–30	1.49	2.79	0.256	0.12	0.437	0.035
30–60	1.49	5.08	0.219	0.12	0.437	0.035
60–90	1.57	6.31	0.176	0.10	0.408	0.035
90–120	1.57	7.14	0.167	0.10	0.408	0.035
120–150	1.62	5.46	0.167	0.13	0.390	0.035
150–200	1.62	3.71	0.192	0.15	0.390	0.035

[a] ksat – saturated soil hydraulic conductivity (cm h^{-1}); $\theta_{1/3}$ – field capacity (cm^3 cm^{-3}); θ_{15} – wilting point (cm^3 cm^{-3}); θ_s – soil water contents at saturation (cm^3 cm^{-3}); θ_r – residue soil water content (cm^3 cm^{-3}).

their objective function for optimization. In this study, we also looked into kernel number and kernel weight although they are not included in the objective function. The final calibrated maize cultivar parameters were similar to the previous results for the study site (Table 5).

2.3. Statistics for model calibration and evaluation

The simulation performance was evaluated with the root mean squared error (RMSE, Eq. 1), the relative RMSE (RRMSE, Eq. 2), Nash-Sutcliffe efficiency (NSE, Eq. 3, Nash and Sutcliffe, 1970), and the coefficient of determination (R^2, Eq. 4):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(P_i - O_i)^2} \quad (1)$$

$$\mathrm{RRMSE} = \frac{\mathrm{RMSE}}{\overline{O}} \quad (2)$$

$$\mathrm{NSE} = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2} \quad (3)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{p}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}(P_i - \overline{p})^2} \quad (4)$$

where p_i is the ith simulated value, O_i is the ith observed value, $\overline{O}$ and $\overline{P}$ are the mean observed and simulated values, respectively, and n is the number of data pairs. The statistical analyses were conducted in R (R Core Team, 2016). Interpretation and assessment of performance statistics followed standard methods and guidelines (Moriasi et al., 2007; Harmel et al., 2014, 2018).

Table 5
Initial and range of crop cultivar parameter values (Fang et al., 2017) for calibrating the CERES-Maize model in Root Zone Water Quality Model (RZWQM2) and final values as calibrated with PEST in this study.

Parameters-description	Initial	Range	Final
P1 – Thermal degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase	245.6	230–270	245.6
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]	0.1562	0.10–0.5	0.1560
P5 – Thermal degree days (base temperature of 8 °C) from silking to physiological maturity	704.4	550–890	890
G2 – Potential kernel number	994.1	850–1150	868.1
G3 – Potential kernel growth rate (mg $kernel^{-1}$ d^{-1})	6.239	4–15	5.7510
PHINT – Thermal degree days required for a leaf tip to emerge	52.89	40–55	52.88

3. Results and discussion

3.1. Soil water

The simulated and observed soil water storage (SWS) in 0–200 cm depth in all treatments of each year ranged from 240 to 420 mm (Fig. 1). Simulated SWS in 0–200 cm was, on average, lower than measured values in 2012 and 2013. But the RMSE of SWS of each year was smaller than average measurement error of 50 mm among replicates, indicating that the simulated SWS was reasonable with a RMSE of 18–34 mm. These simulation errors were also comparable with previous simulation results. Ma et al. (2012b) found RMSE = 37 mm for 0–200 cm soil depth. Fang et al. (2017) found overall RMSE for model evaluation treatments were 22.2 mm in 2012 and 24.8 mm in 2013 for 0–120 cm soil depth, respectively, at the same experiment site. The model underpredicted total SWS in 2012 and 2013, which was also reported by Fang et al. (2017). Soil water measurement in the field depends on TDR sensor location; measurements of SWS were taken near the drip line and may have given higher readings than the modeled SWS based on a homogeneous one-dimensional layer (Fang et al., 2017).

Compared with simulation results in upper soil layer (0–90 cm), soil water content was better simulated in 90–200 cm with smaller RMSE and RRMSE values (Table 6). In general, soil water content was overestimated in the 120–200 cm layers but underestimated in the 0–120 cm layers. However, overall, the RMSE, RRMSE, NSE, and R^2 values of the simulated soil water content in all layers across three years were 0.025 cm^3 cm^{-3}, 15.2%, 0.39, and 0.47 respectively. This is similar to that reported in a previous study at the same site (Saseendran et al., 2014). Although standard model performance criteria have not been developed for assessing soil moisture simulation, applying standard surface-flow-based criteria (Harmel et al., 2018) suggests that these results were marginally satisfactory (NSE and $R^2 \approx 0.5$ or greater) only for surface soil layers (0–30 cm) and overall (R^2, 0–200 cm) (Table 6).

Both simulated and calculated seasonal evapotranspiration (ET) from soil water balance decreased with decreasing total irrigation amount. For example, seasonal ET values decreased from treatment 80/80, 80/65, to 80/40, increased for treatment 65/80 and then decreased again for treatment 40/40; and treatment 40/80 showed a higher seasonal ET value than treatment 40/40 in 2015 (Fig. 2). Seasonal ET was overestimated in 2013 but was closer to measured data in 2012 and 2015. The overall RMSE was 29.2 mm and R^2 was 0.92 for simulated seasonal ET across the three years. The simulated seasonal ET ranged from 350 to 825 mm across the treatments, which was close to the estimated range of 323–771 mm from the soil water balance, with RMSE and R^2 values of 22.6 mm and 0.94 (2012), 19.6 mm and 0.88 (2013), and 18.8 mm and 0.97 (2015), respectively. The RMSE and R^2 of simulated SWC and seasonal ET were comparable with previous simulation results in the same field using the 2008–2011 data (Ma et al., 2012a, 2016; Fang et al., 2017).

3.2. Maize phenology and water stress simulations

Table 7 shows the days after planting (DAP) when maize reached anthesis (R1) and physiological maturity (R6) in each treatment in 2012, 2013, and 2015. DAP data to reach beginning of grain filling (R3) were not shown in Table 7, but the observed and simulated values agreed well for all treatments in the three years. As shown in Table 7, the simulated maize phenology for R1 and R6 was close to the observed values in 2012 and 2013 but not in 2015. Both simulated and observed R1 stage DAP decreased with increasing mean air temperature (Table 2 and 7). For example, mean air temperature in Lveg increased from 20.3 °C in 2012–21.0 °C in 2015 (Table 2), thus requiring fewer days to reach R1

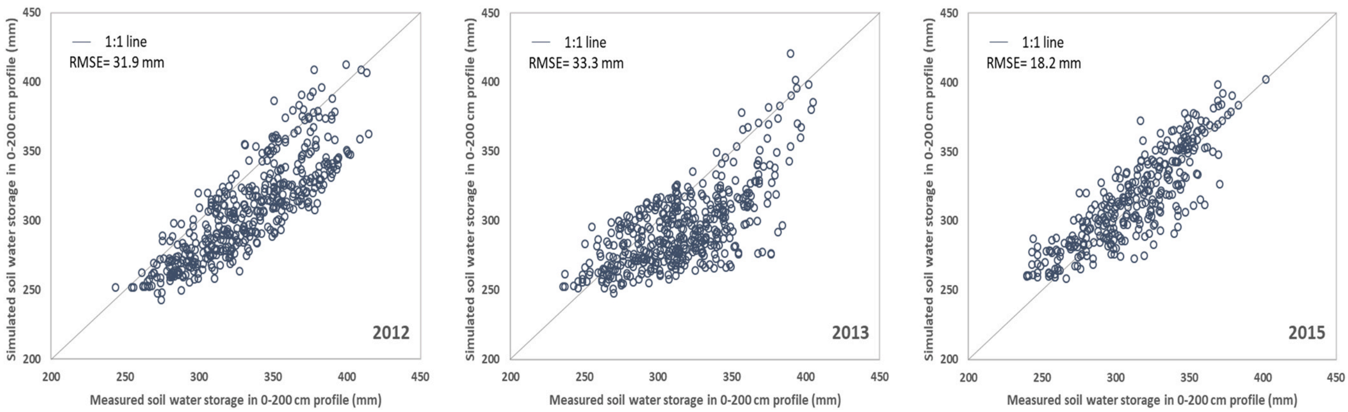

Fig. 1. Root Zone Water Quality Model (RZWQM2) simulated vs. measured soil water storage in 0–200 cm profile in 2012, 2013 and 2015.

Table 6
Statistical comparison† between observed and RZWQM2 simulated soil water content (SWC).

Soil depth (cm)	Measured average SWC (cm^3 cm^{-3})	Simulated average SWC (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})	RRMSE (%)	NSE	R^2	P-value
0–15	0.184	0.179	0.027	14.7	0.46	0.47	<0.0001
15–30	0.187	0.181	0.027	14.4	0.50	0.55	<0.0001
30–60	0.180	0.156	0.028	15.6	−0.54	0.26	<0.0001
60–90	0.148	0.128	0.018	12.2	−0.33	0.29	<0.0001
90–120	0.142	0.124	0.011	7.8	−0.13	0.39	<0.0001
120–150	0.143	0.147	0.012	8.4	0.33	0.36	<0.0001
150–200	0.165	0.172	0.012	7.3	0.38	0.45	<0.0001
0–200	0.164	0.155	0.025	15.2	0.39	0.47	<0.0001

† Statistically significant at p-value = 0.05

stage for both observed data and simulated values. Also, the simulated maize phenology for R6 was up to 40 days longer than the observed values for deficit treatments in 2015, which corresponded with mean air temperature during the Mat stage being about 3–4 °C cooler in 2015 than in the other two years. The CSM-CERES-Maize model simulated crop development mainly based on thermal time, so it did not incorporate water stress effects in determining maturation days. In all three years, the simulated phenology was not sensitive to irrigation treatment, so it did not reflect the fact that water stress accelerated maize development to reach R6 in the Mat period (Table 7). Results from previous studies also reported that water stress during Mat would shorten the grain maturation period (NeSmith and Ritchie, 1992a, 1992b; Abrecht and Carberry, 1993; Farré and Faci, 2006; Aydinsakir et al., 2013;). Thus, the CSM-CERES-Maize model was able to address the impact of temperature on maize phenology but could not reflect the impact of water stress on maize maturation. Many studies have shown plant responds to water stress differently at different growth stage (Sudar et al. 1981); however, the CSM-CERES-Maize model uses the same water, nitrogen, and temperature stresses factor throughout the growing season. The empirical equation itself in the model may be outdated due to the new cultivars developed in the past decades. New approaches are needed to include water stress in plant phenology development (McMaster et al., 2019).

In 2013, RZWQM2 did not simulate water stress during Rep but did simulate water stress during Lveg and Mat for the deficit irrigation treatments (Table 8). In 2012 and 2015, maize showed water stress not only during Lveg and Mat, but also some degree of stress during Rep, especially in 2012. In 2012, it was a dry year with average air temperature during Rep being higher than those in 2013 and 2015, which could be the reason for water stress during the period; even resuming full irrigation later could not relieve the accumulated stress from Lveg. There was about 80 mm more precipitation during Mat in 2013 than the other two years (Table 2), so lower water stress was observed after rain interfered with the designed deficit treatments. In 2015, the observed Rep (R1-R3) was between 61 and 86 days after planting (DAP), while the simulated Rep was between 72 and 86 DAP, thus the water stress effect ranging from 61 to 71 DAP (actual deficit irrigation applied) was accounted into the simulated stress value for Rep. Overall, the simulated water stress increased with decreasing irrigation amount during both Lveg and Mat. For example, for treatments 40/80 and 40/40 in 2015, similar stress levels were observed during Lveg, but the stress level in treatment 40/40 was higher than for 40/80 due to receiving less irrigation during Mat.

3.3. Leaf area index

Destructive direct measurements of leaf area index (LAI) for all treatments were only taken four times in 2012 (Comas et al., 2019). During early growth stages, LAI was overpredicted when LAI was low, especially for lowest irrigation treatments (50/50 and 40/40) and underpredicted when LAI was moderate to high (Fig. 3), with RMSE of 0.51 cm^2 cm^{-2}, RRMSE of 16.4% and NSE of 0.89. Similar simulation errors were reported for CSM-CERES-Maize model in previous studies (Ma et al., 2016, Saseendran et al., 2014). The treatments to meet 65% of ETc or above during Lveg reached similar LAI values by the beginning of Mat, especially treatment 100/50. This indicated that water stress during Mat had little impact on vegetative growth.

3.4. Yield and yield component simulation

The statistical comparison between model simulated and observed grain and biomass yield, kernel number and 1000 kernel weight are shown in Table 9.

Both simulated and observed grain yield decreased with decreasing irrigation amount during Lveg and Mat (Fig. 4). As stated previously, in CERES-Maize, water stress during Lveg might have impacted yield in two ways: (1) by its effect on potential daily growth rate, which affects kernel number, and (2) by its effect on LAI and the carbon assimilation process. The water stress has direct impacts on daily kernel growth rate during Mat. The RMSE, RRMSE, R^2 and NSE values of simulated yield

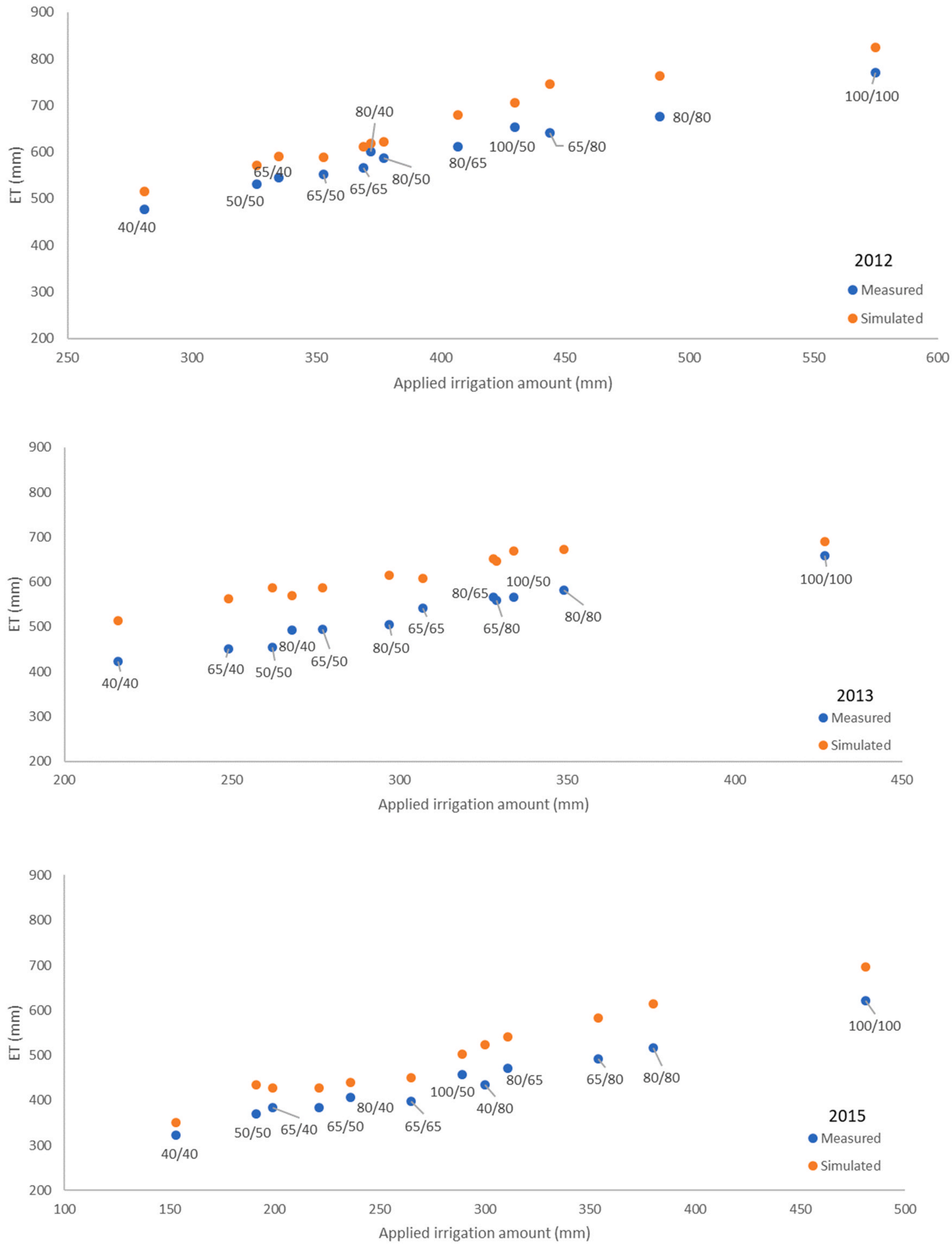

Fig. 2. Comparisons between measured and simulated seasonal evapotranspiration (ET) across all irrigation treatments in 2012, 2013 and 2015.

were 1193 kg/ha, 11%, 0.75 and −0.75 (2012), 551 kg/ha, 5%, 0.77 and 0.23 (2013), and 1148 kg/ha, 15%, 0.84 and 0.74 (2015), respectively.

The simulation errors in grain yield were higher than the values in previous studies at the same experimental site (Ma et al., 2012a, 2016; Fang et al., 2017), which suggested that the model performed better for a crop under uniform water stress conditions throughout the season than that under stage-based stress conditions. The response of both simulated and observed grain yield to water stress during Mat and Lveg varied in different years. Both simulated and observed grain yield showed an obvious decreasing trend with decreasing irrigation amount during Lveg and Mat in 2012 and 2015, due to high crop water stress. In 2013, simulated grain yield was less responsive to the treatments due to less water stress in Mat (although maize in 2013 still suffered high water stress in Lveg), which indicated that enough irrigation in Mat might relieve the impact of water stress in Lveg on maize yield. Based on both simulated and observed results in 2012 and 2013, water stress during Lveg and Mat showed similar effect on grain yield reduction. However, in 2015, the simulated grain yield reduction was more significant with the decrease of irrigation amount during Mat. Nonetheless, the model

Table 7
Day after planting when maize reached anthesis (R1) and physiological maturity (R6) in each treatment in 2012, 2013, and 2015. Number in parentheses are simulated values by RZWQM2. Irrigation amount in each treatment is defined as a percentage of crop evapotranspiration (ETc) during late vegetative (Lveg, V8-VT) and maturation (Mat, R4-R6) growth-stage periods.

Irrigation treatment (% of ETc)		Mat														
		2012					2013					2015				
		100	80	65	50	40	100	80	65	50	40	100	80	65	50	40
Lveg	100	84, 156 (84, 147)			84, 143 (79, 147)		75, 140 (76, 154)			75, 135 (76, 155)		61, 152 (72, 157)			61, 117 (72, 159)	
	80		84, 156 (79, 147)	(84, 143) (79, 147)	84, 143 (79, 147)	84, 143 (79, 147)		75, 137 (76, 155)	75, 135 (76, 156)	75, 134 (76, 154)	75, 127 (76, 155)		61, 138 (72, 158)	61, 125 (72, 158)		61, 117 (72, 157)
	65		84, 156 (79, 147)	84, 143 (79, 147)	84, 143 (79, 147)	84, 143 (79, 147)		75, 137 (76, 155)	75, 134 (76, 156)	75, 137 (76, 154)	75, 134 (76, 155)		61, 138 (72, 159)	61, 125 (72, 158)	61, 117 (72, 158)	61, 117 (72, 157)
	50				84, 143 (79, 147)					75, 137 (76, 154)					61, 117 (72, 159)	
	40					84, 143 (79, 147)					75, 127 (76, 155)		61,154 (72, 158)			61, 117 (72, 158)

Table 8
RZWQM2 simulated crop average water stress across all irrigation treatments in late vegetative (Lveg, V8-VT), reproductive (Rep, R1-R3) and maturation (Mat, R4-R6) growth-stage periods in 2012, 2013 and 2015. (0 = no stress, 1 = maximum stress). Irrigation amount in each treatment is defined as a percentage of crop evapotranspiration (ETc) during Lveg and Mat periods.

Growth- stage Period	Year		2012					2013					2015				
	Irrigation treatment (% of ETc)		Mat														
			100	80	65	50	40	100	80	65	50	40	100	80	65	50	40
Lveg	Lveg	100	0.00			0.00		0.00				0.01	0.00				0.00
		80		0.00	0.00	0.07	0.03		0.08	0.10	0.11	0.17		0.00	0.00		0.03
		65		0.05	0.16	0.19	0.15		0.20	0.26	0.23	0.24		0.07	0.22	0.11	0.09
		50				0.21					0.28					0.14	
		40					0.29					0.38		0.21			0.28
Rep		100	0.00				0.00	0.00				0.00	0.00				0.00
		80		0.00	0.00	0.05	0.04		0.00	0.00	0.00	0.00		0.00	0.00		0.11
		65		0.16	0.20	0.20	0.20		0.00	0.00	0.00	0.00		0.00	0.12	0.11	0.14
		50				0.26					0.00					0.09	
		40					0.31					0.00		0.01			0.06
Mat		100	0.00				0.23	0.00				0.00	0.00				0.50
		80		0.07	0.38	0.48	0.47		0.00	0.06	0.11	0.2		0.24	0.40		0.56
		65		0.15	0.41	0.45	0.49		0.01	0.03	0.09	0.15		0.26	0.43	0.53	0.55
		50				0.41					0.07					0.52	
		40					0.47					0.14		0.27			0.54

adequately simulated the effect of water deficits in Lveg and Mat on maize yield.

Simulation of final aboveground biomass yield (ABY) was good in 2015 and fairly good in 2012 and 2013 (Fig. 5). There was significant over-estimation of ABY in treatment 100/50 in 2012 and 2013 and 40/80 in 2015, which might indicate that the model could not simulate the ABY for large contrasts of irrigation amount between Lveg and Mat. The RMSEs of simulated ABY (Table 9) were larger than those reported in previous studies in the same field using data from 2008 to 2011 uniformly irrigated treatments (Ma et al., 2012a, 2016).

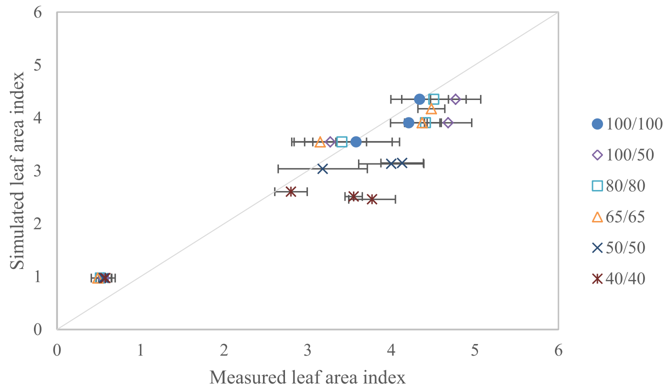

Fig. 3. RZWQM2 simulated vs. measured leaf area index of treatment 100/100, 100/50, 80/80, 65/65, 50/50, 40/40 in 2012. The horizontal bars are 1 SD from the mean.

Table 9
Statistical comparison between grain and biomass yields, kernel number, and 1000 kernel weight for all treatments in 2012, 2013 and 2015†.

Variable	Year	RMSE	RRMSE	R^2	NSE	P-value
Grain yield ($kg\ ha^{-1}$)	2012	1193	11%	0.75	−0.75	0.0003
	2013	551	5%	0.77	0.23	0.0002
	2015	1148	15%	0.84	0.74	<0.0001
Biomass yield ($kg\ ha^{-1}$)	2012	2046	10%	0.77	0.28	0.0002
	2013	1710	9%	0.57	0.42	0.0044
	2015	1260	8%	0.89	0.88	<0.0001
Kernel number ($kernels\ plant^{-1}$)	2012	42.3	8%	0.72	−5.52	0.0005
	2013	31.5	6%	0.3	−4.37	0.0648
	2015	15.4	3%	0.7	−0.67	0.0007
1000 Kernel weight (g)	2012	9.82	4%	0.86	0.71	<0.0001
	2013	6.74	3%	0.72	−4.63	0.0005
	2015	9.48	4%	0.98	0.60	<0.0001

† Statistically significant at *p*-value = 0.05

Given the same irrigation amount during Lveg, both simulated and observed 1000 kernel weight decreased with decreasing irrigation amount in Mat in all three years. In RZWQM2, the daily growth rate during Mat was calculated by adjusting the potential daily growth rate (G2 in Table 5 × actual kernel number) based on temperature and water stresses (Ma et al., 2002, 2006; Jones et al., 2003). The 1000 kernel weight (g per 1000 kernels) was determined by dividing grain yield ($g\ ha^{-1}$) by kernel number ($kernels\ ear^{-1} \times ears\ ha^{-1}$) times 1000. Previous research also indicated that water stress during Mat might result in decreased 1000 kernel weight, caused by early leaf senescence and a shortened grain filling period (Grant et al., 1989; NeSmith and Ritchie, 1992b; Mansouri-Far et al., 2010). The simulated values agreed well with observed 1000 kernel weight in 2012 and 2015 but over-estimated observed values in 2013. The RMSE, RRMSE, R^2 and NSE values were 9.82 g, 4%, 0.86 and 0.71 (2012) and 9.48 g, 4%, 0.98 and 0.60 (2015), respectively. The simulated 1000 kernel weight values of treatment 40/40 were inversely related to the simulated water stress values during the Mat stage (Table 7 and Fig. 6). Across the three years, both observed and simulated kernel weight showed a decreasing trend with decreasing irrigation amount during Mat, especially, the ability to repeat the small bumps on the curves for treatment 65/80 and 50/50, suggesting that RZWQM2 adequately simulated the effect of water stress in Mat on kernel weight.

Given the same irrigation amount in Mat stage, both observed and simulated kernel number decreased with the decrease of irrigation amount in Lveg in all three years (Fig. 7). Simulated kernel numbers were similar for these treatments meeting 80% of ETc or above in Lveg. Treatment 40/80 also had similar kernel number as treatment 40/40 in 2015, which indicated that, as expected, water stress during Lveg has much more impact on kernel number than water stress in Mat. If the crop

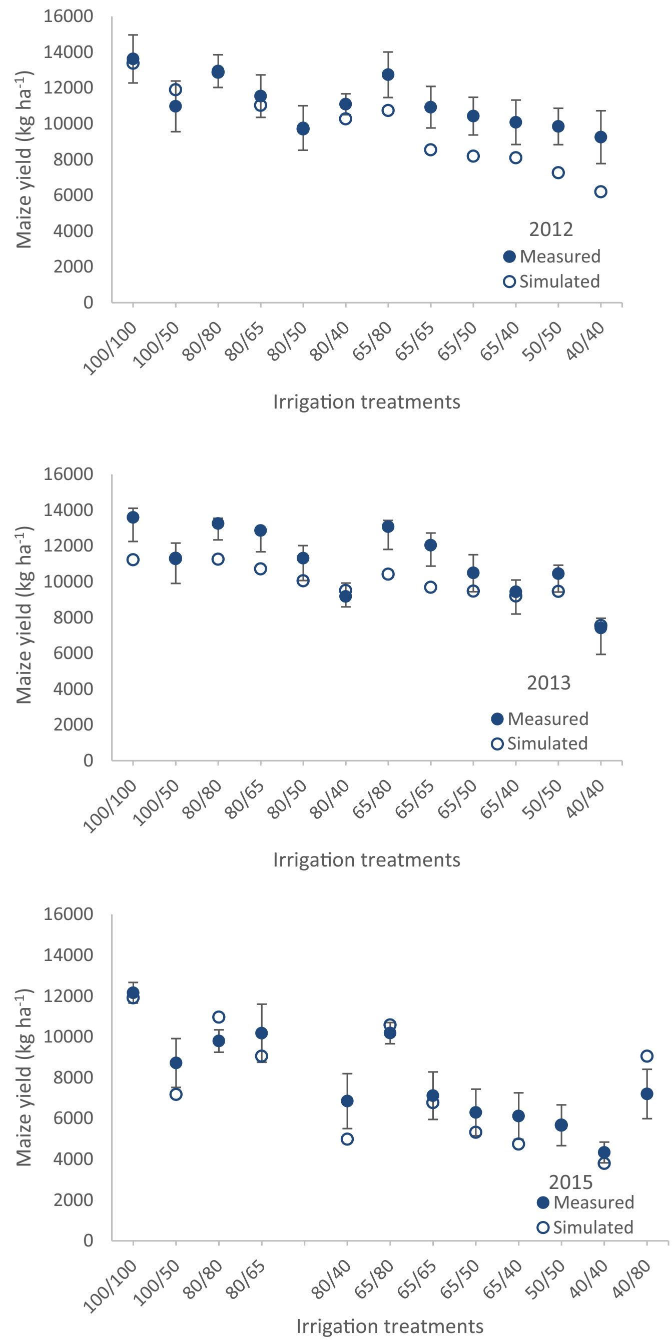

Fig. 4. RZWQM2 simulated vs. measured maize yield in each treatment in 2012, 2013 and 2015. The vertical bars are 1 SD from the mean.

suffered moderate to severe water stress during Lveg, water stress effects on kernel number might not be recovered even with more irrigation in Rep and Mat. In CERES-Maize, kernel number per plant is determined in the flowering (VT-R1) period, based on a potential kernel number (G2 in Table 5), canopy weight, daily carbohydrate accumulation, as well as stress during this period (Ma et al., 2002, 2006; Jones et al., 2003). Thus, in the CERES-Maize, water stress before VT stage might cause the decrease of kernel number by decreasing the leaf weight and then decreasing carbohydrate accumulation during the flowering period. Previous studies also suggested that the actual kernel number was determined at R1, and any factors that influence the ovules fertilization processes might affect the actual kernel number (Kiniry and Ritchie, 1985; Ritchie and Hanway, 1989; NeSmith and Ritchie, 1992a). Experimental studies indicate that water stress at V12 and V17 stages

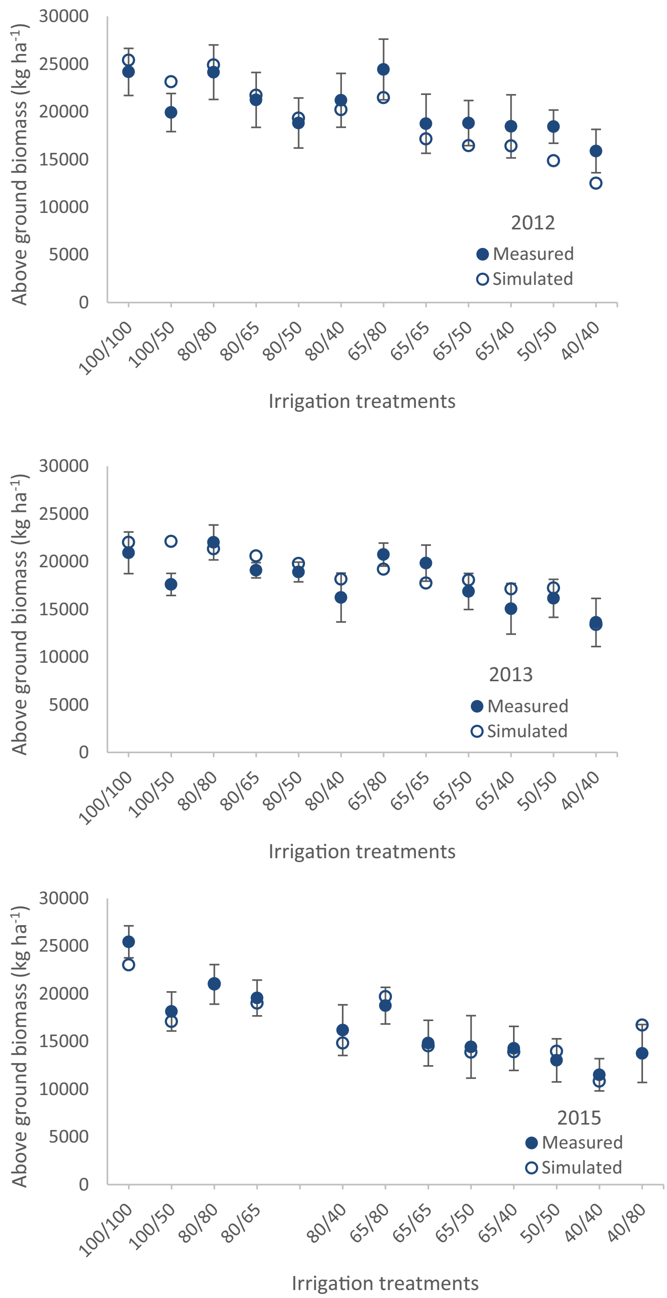

Fig. 5. RZWQM2 simulated vs. measured end of growing season aboveground biomass yield in each treatment in 2012, 2013 and 2015. The vertical bars are 1 SD from the mean.

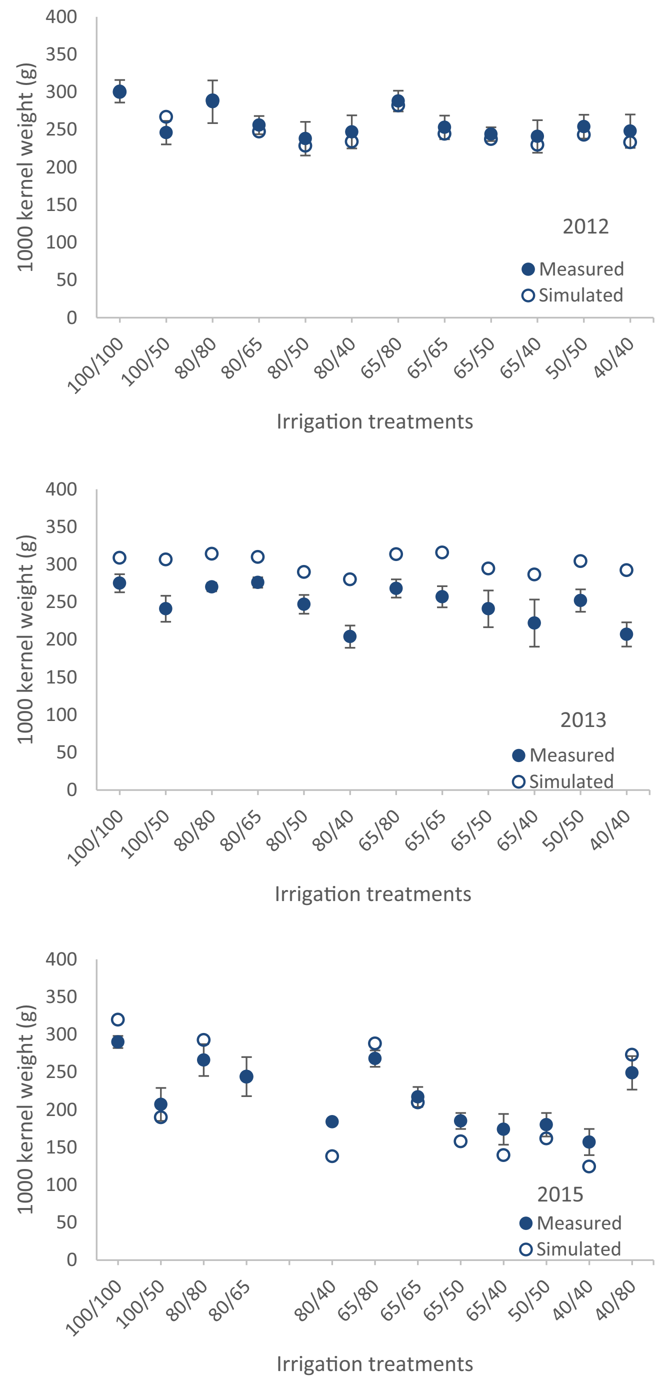

Fig. 6. RZWQM2 simulated vs. observed 1000 kernel weight in 2012, 2013 and 2015. The vertical bars are 1 SD from the mean.

also have direct impact on kernel number by influencing the ear size and number of ovules (potential kernels) (Ritchie and Hanway, 1989). The CERES-Maize model underestimated the kernel number in all three years (Fig. 7), which suggested high water stress effects on kernel number, simulated in the model as kernel number, were reduced significantly from the potential G3 of 890 to less than 500. Overall, the CERES-Maize model in the RZWQM2 successfully simulated the impact of water stress during Lveg on kernel number. The corresponding RMSE, RRMSE, NSE and R^2 ranged 15.4–42.3, 3–8%, −5.52 to −0.67, and 0.3–0.72 in three years, respectively (Table 9).

4. Conclusion

The study used CERES-Maize model in RZWQM2 to simulate the effects of growth stage-based deficit irrigation on maize (*Zea mays* L., Dekalb DCK52–59) growth and yield components. The results showed that the impact of temperature on maize phenological development was simulated adequately but the impact of water stress on maize phenology was not accurately simulated. Both simulated and observed above-ground biomass yield, grain yield, and kernel weight decreased with decreasing irrigation water amount during Lveg and Mat periods. In general, the simulation errors of aboveground biomass and grain yield were higher in terms of RMSE, RRMSE, and NSE than those reported previously where deficit irrigation was applied uniformly throughout the growing seasons in the same field. The simulated and observed 1000 kernel weight in 2012 and 2015 agreed well, with RMSE, RRMSE, R^2 and

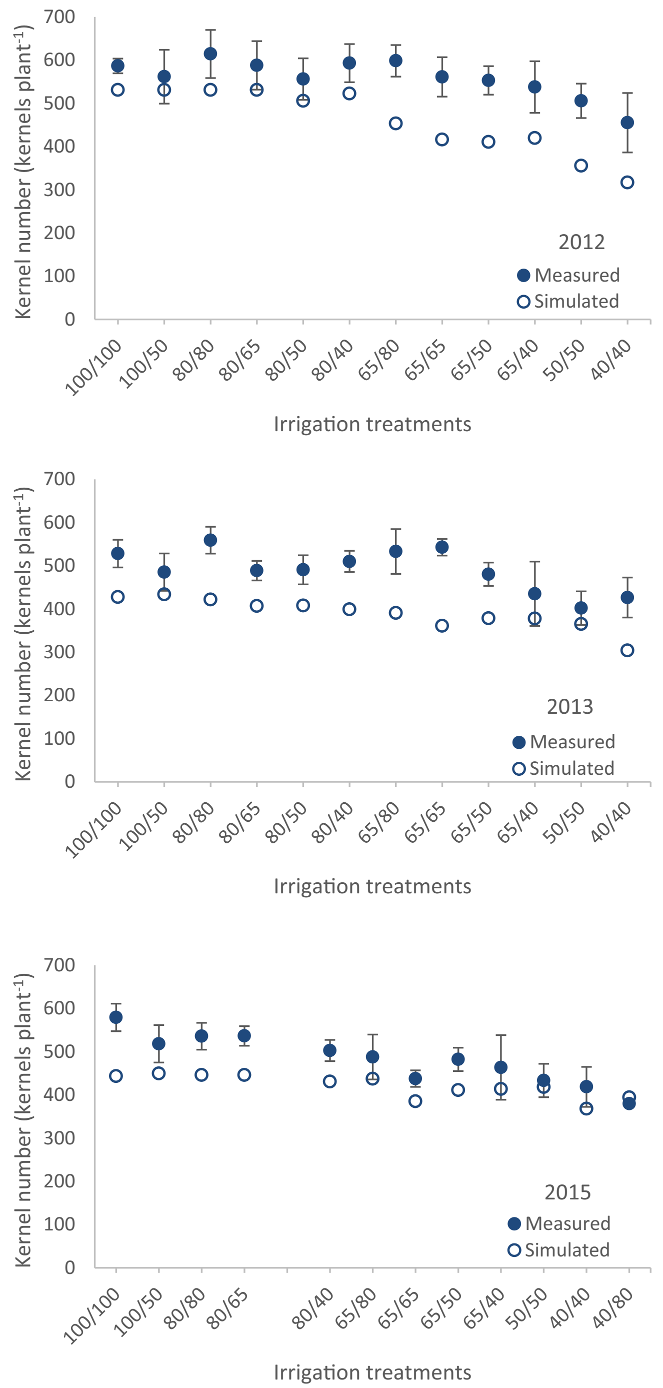

Fig. 7. RZWQM2 simulated vs. measured kernel number per plant in 2012, 2013 and 2015. The vertical bars are 1 SD from the mean.

NSE values of 9.82 g, 4%, 0.86 and 0.71 (2012), and 9.48 g, 4%, 0.98 and 0.6 (2015), respectively. The study also revealed the knowledge gaps in CERES-Maize model in terms of water stress effects on kernel number and maturity dates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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