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Simulation of climate change impacts on grain sorghum production grown under free air CO_2 enrichment**

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A b s t r a c t. Potential impacts of climate change on grain sorghum (*Sorghum bicolor*) productivity were investigated using the CERES-sorghum model in the Decision Support System for Agrotechnology Transfer v4.5. The model was first calibrated for a sorghum cultivar grown in a free air CO_2 enrichment experiment at the University of Arizona, Maricopa, Arizona, USA in 1998. The model was then validated with an independent dataset collected in 1999. The simulated grain yield, growth, and soil water of sorghum for the both years were in statistical agreement with the corresponding measurements, respectively. Neither simulated nor measured yields responded to elevated CO_2, but both were sensitive to water supply. The validated model was then applied to simulate possible effects of climate change on sorghum grain yield and water use efficiency in western North America for the years 2080-2100. The projected CO_2 fertilizer effect on grain yield was dominated by the adverse effect of projected temperature increases. Therefore, temperature appears to be a dominant driver of the global climate change influencing future sorghum productivity. These results suggest that an increase in water demand for sorghum production should be anticipated in a future high-CO_2 world.

K e y w o r d s: climate change, crop simulation, FACE, grain yield, sorghum

INTRODUCTION

According to the Fifth Assessment Report (5AR) of Intergovernmental Panel on Climate Change (IPCC), global CO_2 concentration is projected to range between 421 and 936 ppm and to be accompanied by an increase in mean global surface temperature between years 2000 and 2100 (IPCC, 2013). The global warming trend might continue with likely increases in the ranges of 0.3 to 1.7°C representative concentration pathways (RCP 2.6), 1.1 to 2.6°C (RCP 4.5), 1.4 to 3.1°C (RCP 6.0), and 2.6 to 4.8°C (RCP 8.5) for 2081-2100 relative to 1986-2005. Consequently, the issue of climate change impacts on agriculture has been highlighted recently by many scientists. Global climate changes in atmospheric CO_2, air temperature, and precipitation have already occurred through the past 50 years. The atmospheric CO_2 concentration was recorded at 280 parts per million by volume (ppm) in the pre-industrial period and had risen to approximately 395 ppm by 2012 (NOAA, 2013). The major sources of CO_2 emission were from the burning of fossil fuels, which led to a direct promotion of the greenhouse effect. Many global datasets of global mean near-surface temperature indicate that there has been a 0.3 to 0.9ºC warming of the earth surface since the 1970s (Hansen *et al*., 2005). Average precipitation in the contiguous 48 states of the U.S. has been reported to have increased by 5.0% from 1900 to 2010 (NOAA, 2013). Even though global climate change has already been observed, most of the projected future climate scenarios show more severe situations.

During 2012, the United States harvested 6.3 million t of sorghum on approximately 2 million planted ha (Food and Agriculture Organization of the United Nations (FAO), http://faostat3.fao.org; verified 16/01/15). In the face of changing global climate, a challenge exists to elucidate the impacts of climate change on global food security. To investigate the impacts of global climate change on agricultural

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productivity, to develop appropriate strategies to mitigate any adverse effects of global climate change, and to ensure local and global food security, numerous studies have been conducted to investigate crop responses to potential global climate change. MacCarthy *et al.* (2010) investigated the response of sorghum yield to potential climate change in a smallholder farming system, semi-arid regions of Ghana. They reported that crop yield would be changed dramatically under global climate change conditions. However, different views exist on the effects of elevated CO_2 on sorghum growth. Some studies have reported that elevated CO_2 enhances plant growth of many C_4 species (Amthor *et al*., 1994; Poorter, 1993), whereas others have reported no effects (Carter and Peterson, 1983; Cousins *et al*., 2003) or an elevated-CO_2-based effect that occurred only when elevated CO_2 was accompanied by drought stress (Samarakoon and Gifford, 1996; Wall *et al*., 2001).

Currently, the two most predominant methods for CO_2 enrichment of vegetation experiments are open-top chambers (OTCs) (Hendry *et al.*, 1993) and free air CO_2 enrichment (FACE) (Kimball *et al*., 2002). Because there are no artifacts introduced by chamber walls, FACE is generally considered a more realistic approach for studying crop response to elevated CO_2, although some concerns exist with regard to whether the fluctuating, as opposed to steady, CO_2 concentrations in FACE plots could result in smaller responses (Kimball, 2011). Prior FACE experiments showed yield enhancements due to 550 ppm CO_2 of 12% for rice, 13% for wheat, and 14% for soybean (Kimball *et al*., 2002). However, yields of sorghum and maize were barely affected by that level of CO_2 elevation in a well-irrigated environment (Leaky *et al*., 2006; Ottman *et al*., 2001) or only affected when elevated CO_2 was accompanied by drought stress (Ottman *et al*., 2001; Samarakoon and Gifford, 1996; Wall *et al.*, 2001). The different photosynthetic pathways between C_3 and C_4 species likely explain the observed differences in CO_2 response (Ward *et al*., 2000).

The CERES models in DSSAT v4.5 have been used widely by many agriculturalists and ecologists to study crop growth under various environmental conditions (White *et al.*, 2011). Chipanshi *et al*. (2003) used CERES-Sorghum to study and examine the sensitivity of sorghum to global warming in Botswana. Grossi *et al*. (2013) used it to investigate the effects of global climate change on the sowing window of sorghum in Brazil. The model was also proven to be a highly efficient one for simulating sorghum growth under different nutrient regimes and different photoperiods (Folliard *et al*., 2004). According to our current knowledge, there is no report that evaluated the model for simulating sorghum growth under CO_2 enrichment associated with different irrigation management strategies. There is neither report that evaluated the simulation of projected global climate change impacts on sorghum growth in the western region of the United States.

The objectives of this study were to:

– calibrate the CERES-Sorghum model in DSSAT v4.5 for simulations of sorghum grown in the FACE experiments conducted at the University of Arizona, Maricopa, Arizona, USA, with a dependent dataset collected during 1998 and validate the model with an independent dataset collected during 1999 and
– apply the well calibrated (1998) and validated (1999) model to simulate grain sorghum yield and water use efficiency (*WUE*) variations due to changes in temperature and precipitation associated with elevated CO_2 in western North America from 2080 through 2100.

MATERIALS AND METHODS

The FACE experiments conducted at the University of Arizona, Maricopa Agricultural Center, Arizona, USA (33.05°N, 12.01°W), during 1998 and 1999 were used to investigate the interactive effects of elevated CO_2 and drought on grain sorghum (Wall and Kimball, 1993; Conley *et al*., 2001; Ottman *et al*., 2001; Wall *et al*., 2001). The main plots consisted of controls at ambient CO_2 (*c*. 370 μmol mol^{-1}) and elevated CO_2 plots that were exposed to a CO_2 treatment of *c*. 200 μmol mol^{-1} above ambient for 24 h per day. Each of the main circular FACE and control plots was divided into semicircular halves. Level-basin flood irrigation was utilized to supply each half of the main plot (divided plot) with either an ample (wet) or a water stress (dry) irrigation regime. Irrigation was applied to the dry treatment at planting and mid-season, whereas crops in the wet treatment were irrigated every two weeks (Conley *et al.*, 2001; Wall *et al.*, 2001) based on rates of evapotranspiration (Triggs *et al.*, 2004). In 1998, 1255 mm and 476 mm of irrigation were applied to the wet and dry plots, respectively, and rainfall was 35 mm (Table 1). In 1999, 766 mm and 338 mm were applied to wet and dry plots, respectively, and rainfall was 126 mm.

Grain sorghum seeds (*cv*. Dekalb Hybrid DK54) were sown on 16 July and 15 Juny in 1998 and 1999, respectively. Emergence occurred on 31 Jul. and 1 Jul, with a final plant population of 223,100 and 259,500 plants ha^{-1} during 1998 and 1999, respectively (Ottman *et al.*, 2001). The variety was selected based on its wide cultivation in the southwestern region of the United States and because it has desirable traits of drought tolerance, high yield potential, and early maturity. Base fertilizers (93 kg ha^{-1} of N and 41 kg ha^{-1} of P) were incorporated to both the dry and wet treatments on 10 June 1998 and 1 June 1999. A second application of N fertilizer was made to the dry plots at mid-season to give a rate of 186 kg ha^{-1}, whereas the wet plots received 124 kg ha^{-1} on the same date and received another 62 kg ha^{-1} on the next scheduled irrigation date. The rationale for this fertilization management strategy was to prevent soil nitrogen leaching due to the more frequent irrigation of the wet plots. Daily climate data that included

Table 1. Climate conditions and irrigation regimes during the sorghum growing season in 1998 and 1999

Year	Climate condition		Irrigation regime	
	Average temperature (°C)	Accumulated precipitation (mm)	Treatment	Total amount* (mm)
1998	24.0	35.0	Dry	476.0
			Wet	1255.0
1999	29.0	126.0	Dry	338.0
			Wet	766.0

*Dry treatments were applied on day of year (DOY) 209 (281 mm) and DOY 254 (195 mm) in 1998 and on DOY 178 (153 mm) and DOY 218 (185 mm) in 1999. The wet treatments were applied on DOY 209 (281 mm), 226 (352 mm), 240 (154 mm), 254 (120 mm), 268 (120 mm), 282 (120 mm), and 296 (108 mm) in 1998 and on DOY 153 (153 mm), 204 (161 mm), 218 (185 mm), 232 (138 mm), and 246 (129 mm) in 1999.

solar radiation, temperature, precipitation, and wind speed were collected continuously by an on-site weather station (Triggs *et al.*, 2004). Plants were sampled weekly from the three to four leaf stage until final harvest for each treatment to record plant height, green leaf area, and dry weight of leaf, stem, and panicle for at least three replications (n=3). Final grain yields were determined from a non-traffic area composed of six rows of 3 m length. Heads were removed from the plants to obtain grain weight (Ottman *et al.*, 2001).

The CERES-Sorghum model in DSSAT v4.5 is a process-based, management-level model developed for simulations of sorghum grain yield, development, and soil water and soil nutrient balance associated with the growth of sorghum. Compared with the previous version (DSSAT v4.0), two genetic coefficients of sorghum phenology were added to the CERES-Sorghum model (Hoogenboom *et al.*, 2012). The model is dominated by two main processes:

– the resource capture process where photosynthate produced by photosynthesis is determined by multi-climate and environment factors including solar radiation, CO_2, temperature, and soil water status and
– distributions of metabolites to organs that have different functions.

The CERES-Sorghum model calculates net biomass production using the radiation use efficiency (*RUE*) approach. The effects of elevated CO_2 on *RUE* are modeled empirically using curvilinear multipliers based on a look-up function to fit crop responses to CO_2 concentration. The potential daily biomass production per plant, *PCARB*, is calculated using the following equation (White *et al.*, 2015):

$$PCRB = RUE\ PCO_2\ (PAR/PPOP)\ [1.0 - \text{EXP}(-e\ LAI)], \quad (1)$$

where: PCO_2 is a factor to adjust *RUE* for atmospheric CO_2 concentration, *PPOP* is plant population, and EXP(x) specifies exponentiation. The arguments of EXP(x) determine the fraction of *PAR* that is intercepted by the crop as a function of e, the light extinction coefficient, which is adjusted for effects of row spacing and population, and *LAI*, the leaf area index. The model also simulates effects of water stress on photosynthesis using empirically calculated factors, first computing canopy potential transpiration. The actual to potential transpiration ratio must be relative to the actual reduction of biomass production (Ritchie, 1972). The CERES-Sorghum model was enhanced to simulate the effect of elevated CO_2 on the potential evapotranspiration by increasing stomatal resistances in the Penman–Monteith equation (Acock and Allen, 1985; Allen *et al.*, 1987). More detailed information about the CERES-Sorghum model has been described previously (White *et al.*, 2015).

The 1998 FACE sorghum data were used for model parameterization and calibration (dependent dataset). Because minimum requirements of available weather, soil, field management, and variety-specific genetic input are required, weather data, soil properties data, and field management data in the FACE experiments were developed into a model-identifiable format. Climate variables used in this study were solar radiation (MJ m^{-2} day^{-1}), maximum and minimum temperatures (°C), and precipitation (mm). Soil parameters applied for the simulations are presented in Table 2. To develop genetic coefficients for simulations of the grain sorghum cultivar 'Dekalb DK54' using the CERES-Sorghum model, an iterative approach recommended by Ritchie *et al.* (1989) was employed through trial-and-error to match the measured phenology, biomass, *LAI*, and yield with simulated values. The combination of genetic coefficients that gave the minimum root mean square difference (RMSD) and the maximum model efficiency (E) (Nash and Sutcliffe, 1970) were selected and used in further validation of the model (Table 3).

To conduct an independent test of the calibrated model which was based on the 1998 FACE data, it was applied for simulations of the sorghum FACE experiment in 1999. Simulated grain yield, biomass, *LAI*, and transient volumetric soil-water content were compared with their corresponding measured values. In both the calibration and validation processes, three statistical indices were used for model evaluation:

– RMSD,
– mean relative deviation (MRD),
– and E. Values of E are equivalent to the coefficient of determination (R^2).

A sensitivity test was conducted to estimate the sensitivity of the calibrated and validated CERES-Sorghum model to changes in CO_2, temperature, and precipitation. Climate data for 25 years (between 1987 and 2012) were obtained from the Arizona Meteorological Network (http://ag.arizona.edu/AZMET/) and used as a baseline to

T a b l e 2. Soil parameters applied for the simulation of sorghum grown at the free air CO_2 enrichment facility using CERES-Sorghum

Variable*	Value									
SALB	0.22									
SLU1	45.0									
SLDR	0.6									
SLRO	75.5									
SLB	5	15	30	45	60	90	120	150	180	208
SLLL	0.111	0.111	0.111	0.115	0.105	0.050	0.029	0.022	0.028	0.028
SDUL	0.280	0.279	0.279	0.261	0.261	0.250	0.210	0.170	0.150	0.150
SSAT	0.307	0.301	0.301	0.294	0.296	0.276	0.268	0.258	0.258	0.258
SRGF	1.000	1.000	0.707	0.540	0.400	0.240	0.110	0.030	0.001	0.001
SBDM	1.31	1.27	1.27	1.30	1.47	1.47	1.57	1.57	1.57	1.57
SLOC	0.41	0.35	0.27	0.24	0.16	0.16	0.10	0.10	0.10	0.10
SLHW	8.5	8.5	8.5	8.6	8.6	8.6	8.6	8.6	8.6	8.6

SALB – Albedo (fraction), SLU1 – evaporation limit (cm), SLDR – drainage rate (fraction day^{-1}), SLRO – runoff curve number, SLB – depth, base of layer (cm), SLLL – lower limit (cm^3 cm^{-3}), SDUL – upper limit, drained (cm^3 cm^{-3}), SSAT – upper limit, saturated (cm^3 cm^{-3}), SRGF – root growth factor (g cm^{-3}), SBDM – bulk density, moist (%), SLOC – organic carbon (%), SLHW – pH in water.

T a b l e 3. Genetic coefficients developed for the simulations of grain sorghum (*Sorghum bicolor* (L.) Möench cv. Dekalb DK54) using the CERES-Sorghum model

Variable	Parameter	Value
P1	Thermal time from seedling emergence to the end of the juvenile phase (degree days above base temperature)	480.0
P2	Thermal time from the end of the juvenile stage to panicle initiation	122.0
P2O	Critical daylength above which development slows (short day response)	15.0
P2R	Photoperiod sensitivity as the extent to which development is delayed for each hour of photoperiod above P2O	25.0
PANTH	Thermal time from the end of panicle initiation to anthesis (degree days above base temperature)	875.5
P3	Thermal time from the end of flag leaf expansion to anthesis (degree days above base temperature)	152.5
P4	Thermal time from the end of anthesis to beginning grain filling (degree days above base temperature)	171.5
P5	Thermal time from beginning of grain filling to maturity (degree days above base temperature)	350.0
PHINT	Phylochron interval: the interval in thermal time between successive leaf tip appearances (degree days)	65.0
G1	Scalar for relative leaf size	10.0
G2	Scalar for partitioning of assimilates to the panicle (head)	5.7

determine sensitivity in biomass and grain yield responses to 12 levels of CO_2 (100, 200, 300, 380, 475, 538, 570, 700, 800, 950, 1,000, and 1,200 ppm), 21 levels of temperature (-5, -4, -3, -2, -1, +0, +1, +1.1, +2, +2.6, +3, +3.1, +3.4, +4, +4.2, +4.3, +5, +6.1, +7, +7.7 and +8°C), and 14 levels of precipitation (-50, -20, -4, -2, 0, +2, +3, +4, +6, +8, +14, +20, +25, and 50% of the precipitation amount). These regimes were also designed in order to reflect all possible combinations of CO_2, temperature, and precipitation for western North America according to the climate change scenarios of RCP 4.5 and RCP 8.5 using 39 global models (IPCC, 2013). For these simulations, the amounts of irrigation were employed with those used in the model calibration and validation for the 25 years, which were 476 and 1,255 mm for 1998 and 338 and 766 mm for 1999, respectively, at Maricopa, AZ.

Following the sensitivity analyses, the CERES-Sorghum model was used to simulate the potential impacts of global climate change on sorghum production for the future years of 2080 to 2100 (centered at 2090). The specific regional

T a b l e 4. Average temperature and precipitation projections for western North America according to the climate change scenarios of RCP 8.5 using 39 global models (IPCC, 2013). The area mean temperature and precipitation responses were first averaged for each model over all available projections for the 1986 to 2005 period from the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations and the 2081 to 2100 period

Division* (%)	Annual temperature response (°C)	Annual precipitation response (%)
Min	+3.1	-2
25	+4.2	0
50	+5.0	+3
75	+6.2	+8
Max	+7.7	+25

*Computing the difference between these two periods, the table shows the minimum, maximum, median (50%), and 25% and 75% quartiles among the 21 models for temperature (°C) and precipitation (%) changes.

climate change in western North America was taken as reference for the estimation of the climate change at Maricopa, Arizona. Climate change variables (Table 4) were projected by a set of 39 global circulation models in the multi-model set associated with a CO_2 concentration of 936 ppm based on the RCP 8.5 scenario (IPCC, 2013). In order to include the inter-year climate variability, simulated growth parameters of sorghum for the past 20 years (1990 to 2010) were used as a baseline and compared with those of sorghum projected for 2080 to 2100. The projected climate variations for each combination of temperature and precipitation were superimposed over the past 20-year baseline: changes in temperature were added in the environmental modification section of the model, those in precipitation were entered as ratio, and the CO_2 concentration was replaced by 936 ppm. Consequently, potential future climatic environments were formulated.

The results for each scenario were expressed as cumulative distribution functions (CDFs) to present the inter-year crop yield and water use efficiency (*WUE*, kg ha^{-1} mm^{-1}; Eq. (2)) responses to the 25 combined climatic environments:

$$WUE = \frac{\text{grain yield}}{T}, \qquad (2)$$

where: *T* is transpiration (mm). To obtain a CDF, the yearly simulated grain yields were ordered according to value from smallest to largest. Then, the probability of obtaining a yield of less than or equal to each simulated grain yield value was computed as the ratio of its serial number to the total number of values in the set (cumulative probabilities vary between zero and one). The mean values of the CDFs for different projection years were tested statistically for the significance of the differences between the baseline CDF and the CDF of each of the projection years using a non-parametric test, PROC NPAR1WAY (SAS Institute, 2009). The differences of mean and variance for the baseline CDF and the CDF of each of the projection years were analyzed using the Wilcoxson two-sample test and the Kolmogorov-Smirnov test, respectively.

RESULTS

Grain yields of sorghum grown in different treatments in 1998 were simulated within ±0.5 standard deviation (SD) about the corresponding measured means in the calibration (Fig. 1). The simulated grain yields of sorghum agreed with the measurements with an RMSD of 0.43 t ha^{-1}, MRD of -6.7%, and *E* of 0.79, respectively. The ratio of measured yield due to elevated CO_2 relative to that of ambient CO_2 (enriched/ambient) was 1.09 in the dry treatments and was reproduced at 1.06 and that of 1.03 in the wet treatments was reproduced at 1.08. Most of the differences between simulated and measured biomass and *LAI* were within ±1.5 SD about the measured means (Fig. 2). The values of RMSD, MRD, and *E* for biomass ranged from 1.142 to 1.641 t ha^{-1}, 89.3 to 114.2%, and 0.91 to 0.97, whereas values for *LAI* ranged from 0.93 to 1.52 m^2 m^{-2}, -2.9 to 13.2%, and 0.52 to 0.70, respectively (Table 5). Transient soil moistures during the sorghum growing season were also generally simulated well within statistically acceptable errors (Fig. 3). Most of the simulated values were within ±2 SD about the measured means (Fig. 3). The values of RMSD, MRD, and *E* ranged from 0.01 to 0.06 mm^3 mm^{-3}, -46.21 to -0.05%, 0.15 to 0.95, respectively.

The simulated grain yields of sorghum in the validation agreed with the measurements with an RMSD of 0.73 t ha^{-1}, MRD of 33.6%, and *E* of 0.80 (Fig. 4). The enriched/ambient ratios of 1.33 in the dry treatments and of 0.89 in the

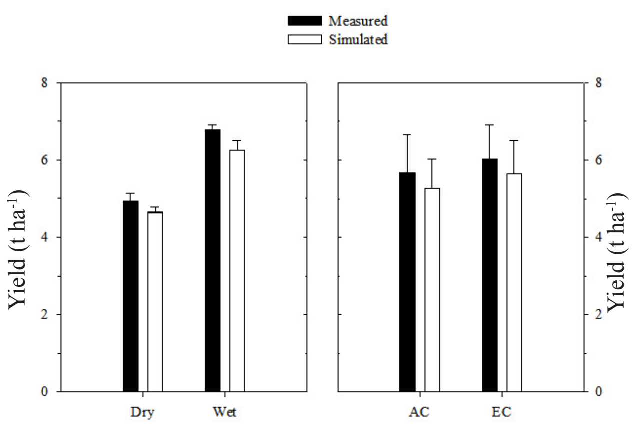

Fig. 1. Simulated and measured grain yield of sorghum under different irrigation management conditions (dry and wet) and different CO_2 concentrations (ambient CO_2, AC, and elevated CO_2, EC) in 1998 for parameterization. Horizontal bars represent ±1 standard deviation (*n* = 6).

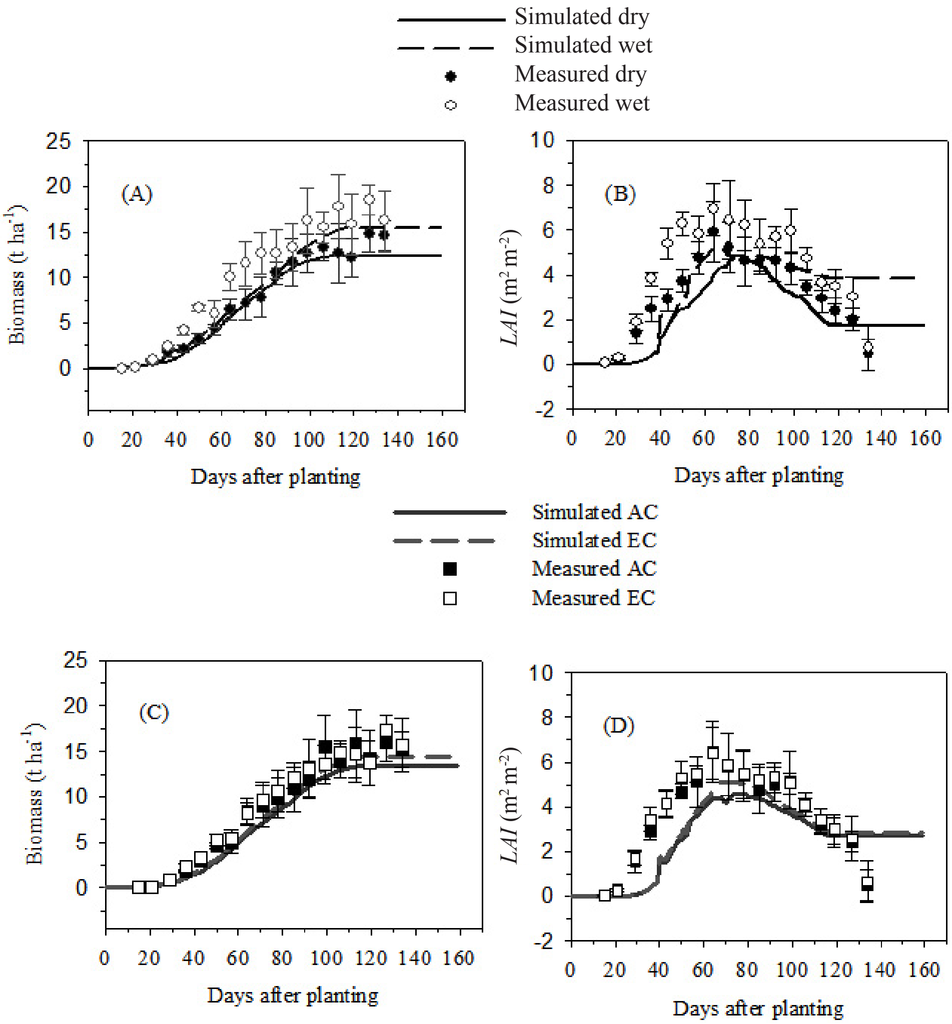

Fig. 2. Simulated and measured seasonal biomass (A and C) and leaf area index, *LAI*, (B and D) of sorghum under different irrigation management conditions (dry and wet) and different CO_2 concentrations (ambient CO_2, AC, and elevated CO_2, EC) in 1998 for parameterization. Explanations as in Fig. 1.

wet treatments were also generally reproduced at 1.02 and 1.03, respectively. Even though some values of simulated biomass and *LAI* were somewhat overestimated compared with the measurements, the trends in sorghum growth dynamics were generally well reproduced by the model (Fig. 5). Values of RMSD, MRD, and *E* of biomass ranged from 2.230 to 4.565 t ha^{-1}, 192.0 to 329.2%, and 0.17 to 0.50, whereas those for *LAI* ranged from 1.23 to 1.88 m^2 m^{-2}, 23.1 to 101.3%, and 0.40 to 0.60, respectively (Table 5). The simulated transient volumetric soil-water content values agreed with the corresponding measurements within ±1.5 SD (Fig. 6). Values of RMSD, MRD, and *E* ranged from 0.02 to 0.08 mm^3 mm^{-3}, -27.54 to 39.41%, and 0.33 to 0.86, respectively. The simulated crop growth parameters in the dry treatments were generally smaller than those in the wet treatments, which agreed well with the measurements.

Simulations of sorghum grain yield for model sensitivity to the drivers of climate change effects were conducted to investigate the independent responses to CO_2 and temperature of the grain yield using 25 years of climate data as the baseline (Fig. 7). The individual effects of projected climate changes in CO_2 and temperature for the year 2100 are also presented in comparison with the current condition. The response of crop yield to atmospheric temperature change showed a non-linear parabolic curve pattern (Fig. 7A). The yield reached a peak at -1ºC from the current temperature and then decreased as the temperatures increased. As temperature increases by 2.6 to 5.0ºC for the future year of 2100, grain yields are projected to decrease with a range from 0.7 to 1.89 t ha^{-1} under the dry condition and from 1.08 to 3.14 t ha^{-1} under the wet condition. Grain yield responses to varying CO_2 concentration showed a negative exponential curve pattern (Fig. 7B). As CO_2 concentration increased from 200 to

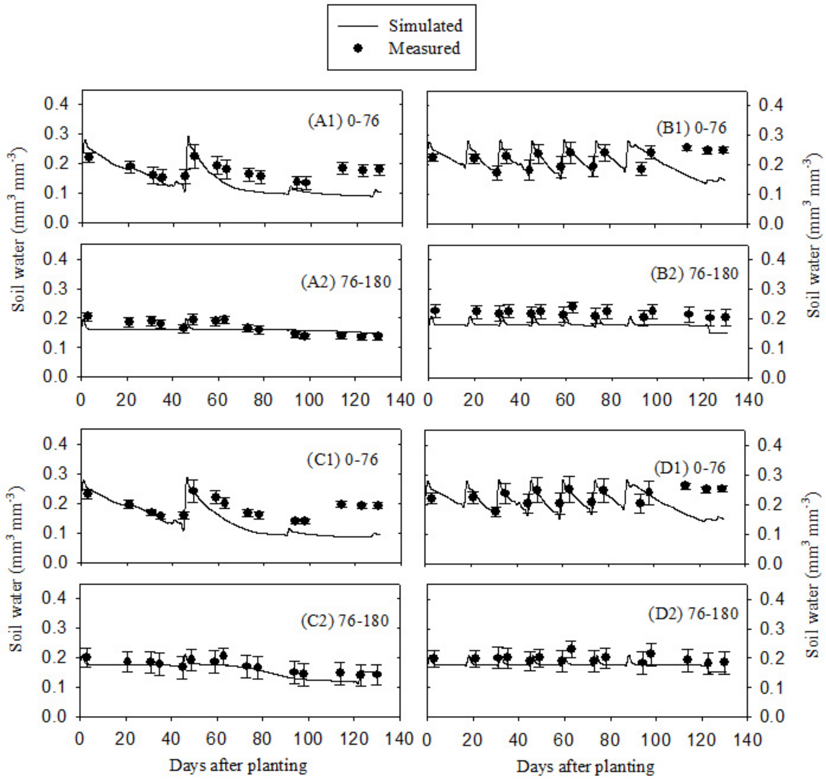

Fig. 3. Simulated and measured volumetric soil-water content in the different irrigation conditions [dry (A) and wet (B)] and in the different CO_2 concentration regimes [ambient CO_2 (C) and elevated CO_2 (D)] at the soil depths of 0-76 cm (A1, B1, C1, and D1) and 76-180 cm (A2, B2, C2, and D2) in 1998 for parameterization. Vertical bars represent ±1 standard deviation (n = 6).

400 ppm (~ 50 ppm higher than the current value of 395 ppm), the simulated yield increased rapidly, but the grain yield maintained a plateau from 500 to 1 200 ppm. Relatively small enhancement effects (0.25 to 0.65 t ha^{-1}) on crop yield were projected with elevated CO_2 of 538 and 936 ppm for the year 2100 in comparison with the current CO_2 concentration of 395 ppm.

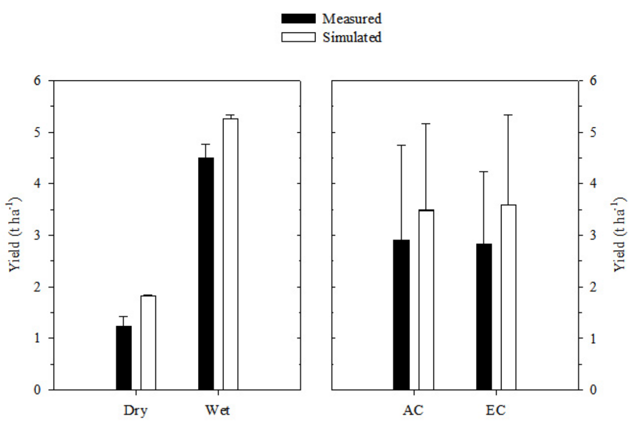

Fig. 4. Simulated and measured grain yield of sorghum under different irrigation management conditions (dry and wet) and different CO_2 concentrations (ambient CO_2, AC, and elevated CO_2, EC) in 1999 for validation. Explanations as in Fig. 1.

The combined effects of projected climate changes in CO_2, temperature, and precipitation for the year 2100 in association with the full and deficit irrigation regimes are presented using box and whisker plots in Figs 8 and 9. In simulations using two climate change combinations of the temperature and precipitation projections, crop yields decreased significantly in both irrigation management options (Fig. 8). Furthermore, statistically significant differences of grain yield were shown between the full and deficit irrigation regimes. The average grain yield difference due to the different irrigation regimes was about 2.2 t ha^{-1}, whereas the grain yield differences between the different combinations in each irrigation regime ranged from 0.02 to 2.2 t ha^{-1}. The responses of *WUE* to the combined climate variables were comparable to those of grain yield to the combined climate variables in each irrigation regime (Fig. 9). Comparatively, lower *WUE*s were projected in the combinations of higher temperature.

DISCUSSION

The model reproduced sorghum grain yield and growth dynamic variables including seasonal biomass, leaf area index, and transient volumetric soil-water content reasonably well. Nevertheless, simulated biomass and *LAI* were somewhat overestimated in 1999. This could have been attributable to the model inability to simulate the tattered upper leaves that occurred because of a hailstorm

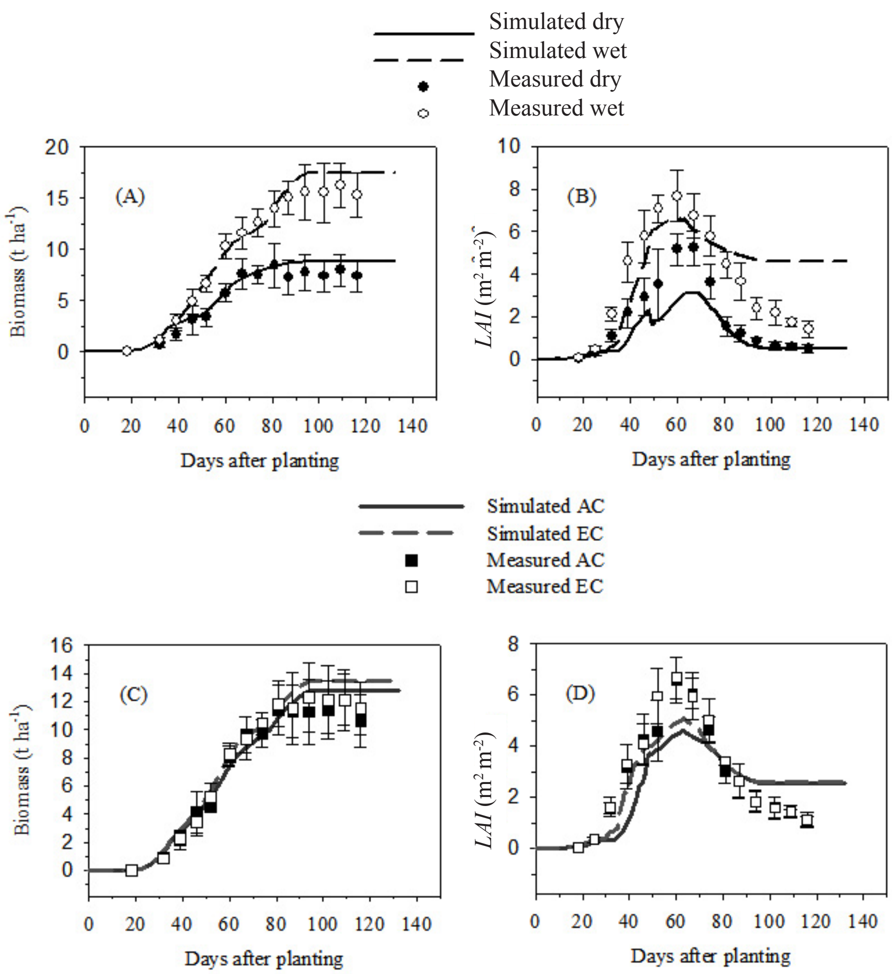

Fig. 5. Simulated and measured seasonal biomass (A and C) and leaf area index, *LAI*, (B and D) of sorghum under different irrigation management conditions (dry and wet) and different CO_2 concentrations (ambient CO_2, AC, and elevated CO_2, EC) in 1999 for validation. Explanations as in Fig. 1.

during the heading stage (sorghum heads appeared unscathed; Ottman *et al.*, 2001). Thus, future development of the model is required to account for physical damage due to abiotic stresses such as hail damage. However, in all the treatments, the statistical analysis of model performance showed an acceptable range of *E* values between 0.17 and 0.97 for biomass and between 0.40 and 0.70 for *LAI*, respectively (Table 4). The *E* values range within the acceptable levels of model performance according to Moriasi *et al*. (2007). The model also simulated sorghum grain yield well. Previous studies showed that the CERES models are capable of reproducing growth and yield of sorghum (and other cereal crops) grown under an elevated CO_2 environment (Gangadhar *et al.*, 1995; Grossi *et al.*, 2013; Ko *et al.*, 2010; Tubiello *et al.*, 1999). The simulations of growth variables and yield of sorghum in this study also reached a relatively satisfactory precision.

The model sensitivity (Fig. 7) demonstrated that sorghum grain yield would decrease at temperatures lower or higher than -1ºC from the current temperature. Thus, we assume that the optimum temperature regime for sorghum growth is around this temperature level (max 26.8 and min 11.3ºC). We also projected effects of precipitation in association with a range of irrigation amount (Fig. 10). Deficit irrigation conditions (less than 50% from the baseline) significantly affected sorghum yield. Therefore, it appears that both irrigation and precipitation can play a significant role with regard to the effects of climate change on sorghum yield in Arizona. Varying CO_2 from 200 to 480 ppm increased grain yield rapidly with an increment of 1.7 t ha^{-1}, but only a 0.2 t ha^{-1} increment was observed between 480 to 950 ppm. Our results are generally comparable with those reported by Brown and Rosenberg (1995). They reported that sorghum yield would diminish with elevated temperature and would be enhanced by elevated CO_2 from 350 to 550 ppm.

The simulated grain yields and *WUE*s of sorghum under the projected climate variable combinations were diminished (Figs 8 and 9). The grain yield and *WUE* of sorghum were more sensitive to temperature than to precipitation. It appears that elevated temperature is negatively correlated to grain yield and *WUE* of sorghum. For simulations based on

T a b l e 5. Root mean square difference (RMSD, t ha^{-1}), mean relative deviation (MRD, %), and model efficiency (*E*, dimensionless) for the measured and simulated seasonal average values of biomass and LAI of sorghum for different treatments in 1998 for calibration and in 1999 for validation

Variable	Year	Treatment*	Measured	Simulated	RMSD	MRD (%)	*E* dimensionless
				(t ha^{-1})			
Biomass	1998	D-ACO_2	7.34	7.79	1.54	108.5	0.91
		W-ACO_2	10.03	9.22	1.64	103.1	0.93
		D-ECO_2	7.80	8.23	1.50	114.2	0.92
		W-ECO_2	10.06	9.92	1.14	89.3	0.97
	1999	D-ACO_2	5.14	6.41	2.39	327.5	0.17
		W-ACO_2	10.23	12.07	4.55	232.1	0.33
		D-ECO_2	5.67	7.12	2.23	329.2	0.46
		W-ECO_2	10.02	12.61	3.74	192.0	0.50
			$m^2 m^{-2}$	$m^2 m^{-2}$	$m^2 m^{-2}$	%	dimensionless
LAI	1998	D-ACO_2	2.94	2.39	0.93	6.5	0.70
		W-ACO_2	4.21	3.45	1.52	13.2	0.52
		D-ECO_2	3.29	2.60	1.07	-2.9	0.64
		W-ECO_2	4.20	3.77	1.24	11.1	0.66
	1999	D-ACO_2	1.81	1.15	1.23	23.1	0.43
		W-ACO_2	3.89	4.33	1.50	55.0	0.60
		D-ECO_2	2.09	1.33	1.33	30.9	0.46
		W-ECO_2	3.59	4.64	1.88	101.3	0.40

*D-ACO_2 – dry and ambient CO_2, D-ECO_2 – dry and elevated CO_2, W-ACO_2 – wet and ambient CO_2, W-ECO_2 – wet and elevated CO_2.

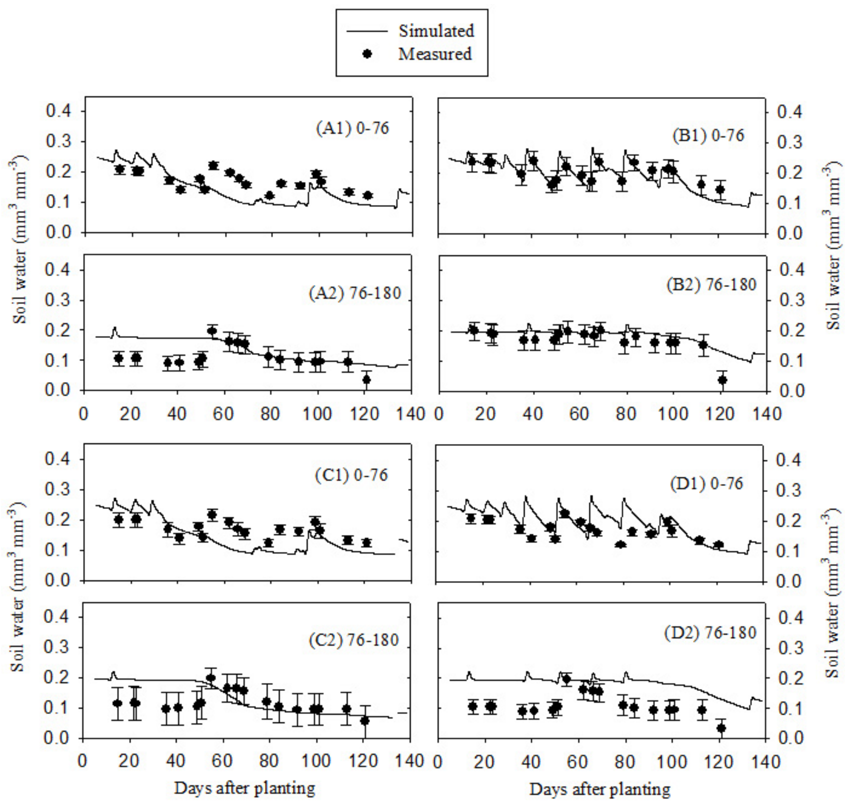

Fig. 6. Simulated and measured volumetric soil-water content in the different irrigation conditions [dry (A) and wet (B)] and in the different CO_2 concentration regimes [ambient CO_2 (C) and elevated CO_2 (D)] at the soil depths of 0-76 cm (A1, B1, C1, and D1) and 76-180 cm (A2, B2, C2, and D2) in 1999 for validation. Vertical bars represent ±1 standard deviation (*n* = 6).

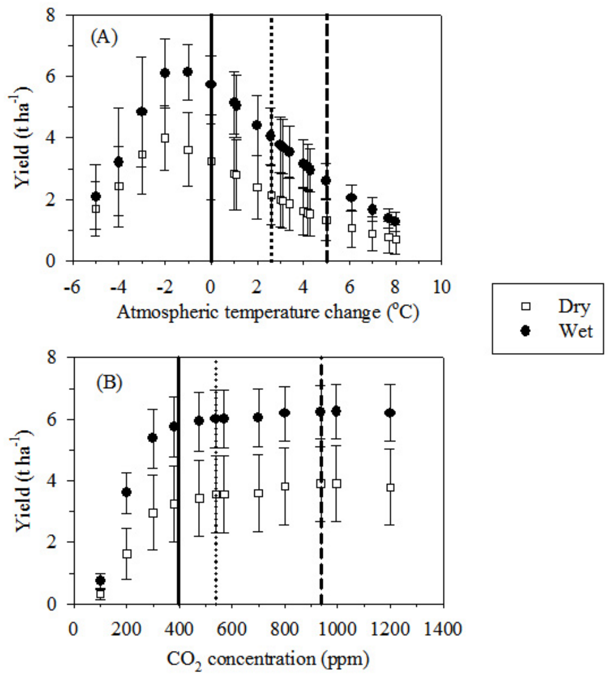

Fig. 7. Sorghum grain yields as a function of variations in temperature (A) and CO_2 concentration (B). Vertical bars and lines represent ±1 SD (n = 25) and the current (solid line) and future (dotted and dashed lines) climate conditions. The dotted and dashed vertical lines represent the RCP 4.5 and RCP 8.5 scenarios (IPCC, 2013) derived from the potential regional climate changes for western North America.

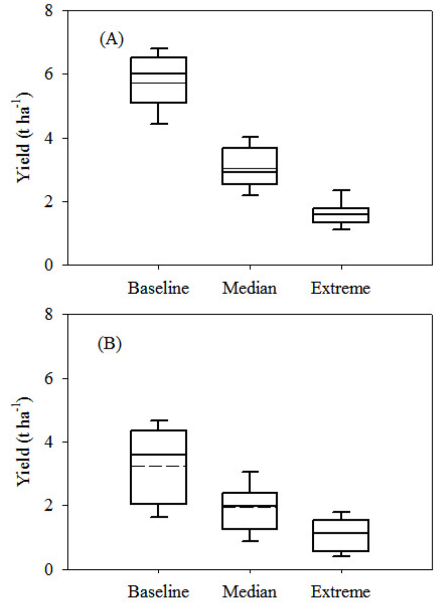

Fig. 8. Simulated grain yields of sorghum for the climate change projections (median and extreme) from 2081 to 2100 in comparison with the current status (baseline) under full (A) and deficit (B) irrigation regimes. The climate data were projected in response to the climate change combination of temperature, precipitation, and CO_2 (median), including each extreme condition of max temperature and min precipitation (extreme), according to the RCP 8.5 scenario (IPCC, 2013). Error bars and peripheral box represent the 10th, 25th, 75th, and 90th percentiles of the yield data, showing the median (inner box) and mean (solid line) in the outer box.

individual variables of climate change (Fig. 7), we found that sorghum grain yield would be enhanced at a range of 0.25 to 0.65 ton ha^{-1} with elevated CO_2 but diminished at a range of 0.7 to 3.14 ton ha^{-1} with elevated temperature. When these climate variables were combined, grain yield was projected to decrease by between 1.29 and 4.12 t ha^{-1}. This implies that interactive effects between precipitation and temperature that affected sorghum productivity occurred, but that compared with other climate variables, temperature dominated. Chen *et al.* (2004) investigated the effects of various climate variables on the main crops in the USA and reported that elevated temperature could significantly reduce yields and yield variability in comparison with other climate variables. Our results were also comparable to those reported by Chipanshi *et al.* (2003). They concluded that the yield enhancement due to enriched CO_2 could not compensate for the yield decrease due to elevated temperature for most C_4 crops in Botswana.

Grain yield variation between different irrigation regimes was much greater than that between combinations/scenarios of climate change. In order to ensure future global food security, it seems that irrigation water demands would be increased in semiarid regions such as Arizona. Adam *et al*. (1990) also reported that there would be an increase in irrigation water demand in US agriculture due to projected climate changes.

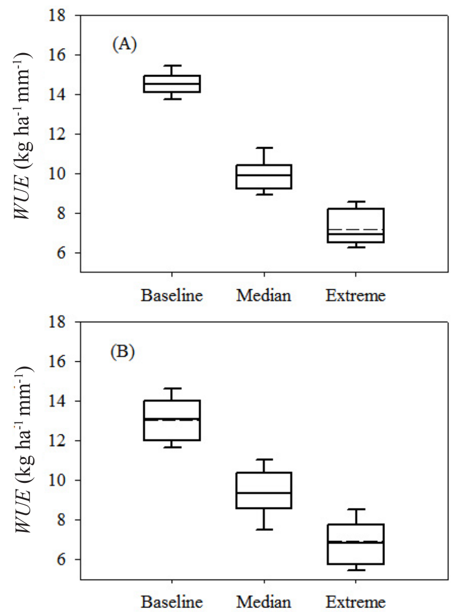

Fig. 9. Simulated water use efficiency of sorghum for the climate change projections (median and extreme) from 2081 to 2100 in comparison with the current status (baseline) under full (A) and deficit (B) irrigation regimes. Explanations as in Fig. 8.

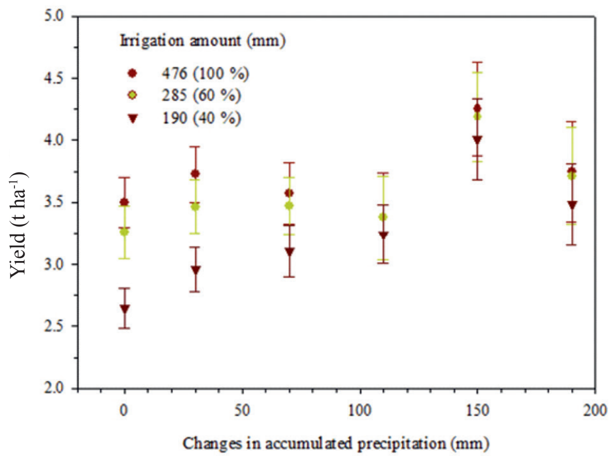

Fig. 10. Simulated sorghum grain yield in response to changes of precipitation and irrigation under the future climate condition projected from 2081 to 2100 according to the RCP 8.5 scenario (IPCC, 2013). The irrigation amount represents the 25-year average of the seasonal total irrigations for each design of both irrigation and precipitation. Vertical bars represent ±1 SE ($n = 25$).

CONCLUSIONS

1. The CERES-Sorghum module in DSSAT v4.5 was successfully calibrated and validated for simulations of grain sorghum grown in the FACE experiments at the University of Arizona, Maricopa Agricultural Research Center, Maricopa, Arizona, USA. The simulated crop growth variables, including soil moisture, seasonal *LAI*, and biomass, matched well with the measurements within statistically acceptable errors.

2. We found that sorghum grain yields under changing climate for the very arid Maricopa, Arizona, would be more sensitive to temperature than to precipitation or CO_2.

3. The projected grain yields in full irrigation were significantly enhanced compared with those in deficit irrigation. To ensure global food security in the future, a corresponding increase in water demand may have to be satisfied.

4. The CERES-Sorghum model provided a valuable preview of sorghum crop response to potential climate change forcing factors including CO_2 temperature, and precipitation, and it proved its capability to simulate the impacts of global climate change on sorghum production.

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