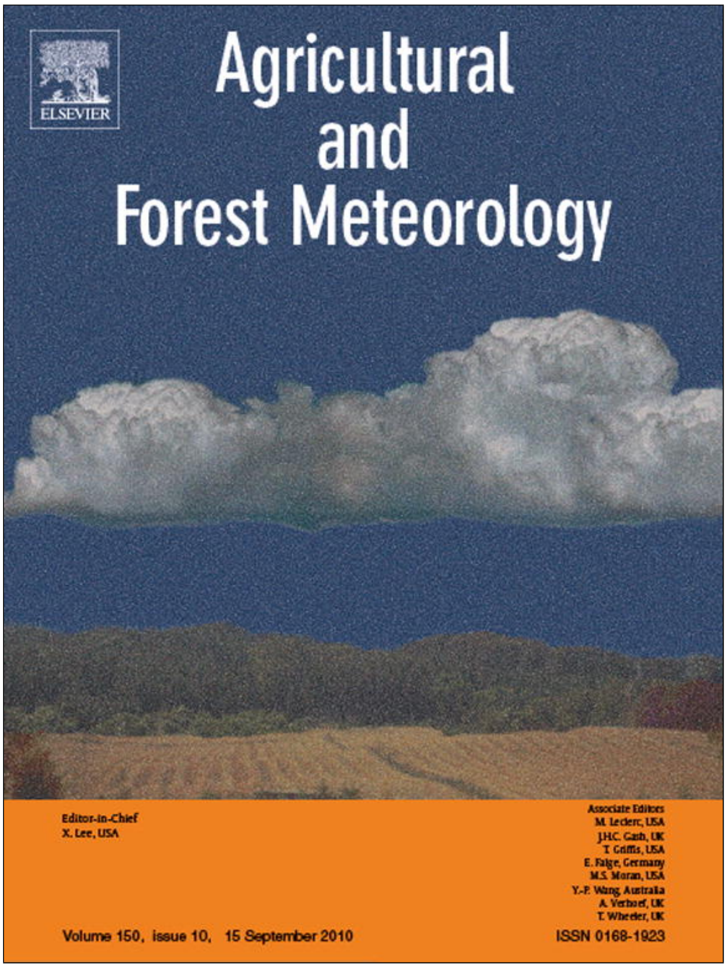
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Simulation of free air CO_2 enriched wheat growth and interactions with water, nitrogen, and temperature

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ABSTRACT

Agricultural system simulation models are key tools for assessment of possible impacts of climate change on crop production and environmental quality. In this study, the CERES-Wheat 4.0 module in the RZWQM2 model was calibrated and validated for simulating spring wheat grown under elevated CO_2 conditions in the FACE (Free Air CO_2 Enrichment) experiments conducted at Maricopa, Arizona, USA from 1992 to 1997. The validated model was then used to simulate the possible impacts of climate change on the crop for a 16-year period centered on 2050 with a projected atmospheric CO_2 concentration of 550 ppm. Sixteen General Circulation Model (GCM) projections of climate in response to this CO_2 concentration were used for this purpose. In the FACE experiment, the crops were grown under ambient (365–370 ppm) and elevated (∼550 ppm) CO_2 concentrations with two irrigation treatments (wet and dry) in 1992–1993 and 1993–1994, and two nitrogen (N) treatments (high and low N) in 1995–1996 and 1996–1997 crop seasons. The model simulated crop growth and grain yield, and soil water responses to CO_2 reasonably well, reproducing variations due to the treatments. Under ambient CO_2 in 1992–1993 and 1995–1996, biomass was simulated better in the dry and low N treatments with root mean square difference (RMSD) of 181 and 161 kg ha^{-1}, respectively, compared to the wet and high N treatments with RMSD of 259 and 268 kg ha^{-1}, respectively. The effects of water and N treatments were higher than those of CO_2, and the model reproduced these effects well. Elevated CO_2 effects on crop growth were counterbalanced by temperature effects, and projected precipitation had little effect on the simulated crop. The model results provide reasonable confidence for simulations of possible impacts of projected climate change on wheat crop growth in the region, within normal field data uncertainties.

1. Introduction

Global CO_2 emissions have increased by ∼80% from 1970 to 2004 and represent 77% of the total anthropogenic green house gases (GHG: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) (IPCC, 2007). Further, the CO_2 emissions between 2000 and 2030 from energy use alone are projected to increase by 40–110%. Historic records reveal that the increase of anthropogenic GHGs in the atmosphere resulted in an increase in global mean surface temperatures by 0.74 ± 0.18 °C over the last 100 years (1906–2005). For the next two decades, a warming of ∼0.2 °C per decade is predicted according to a range of IPCC Special Report on Emission Scenarios (SRES). The likely doubling of atmospheric CO_2 and associated warming within this century may affect agricultural production through changes in evapotranspiration, plant growth rates, plant litter composition, and nitrogen-carbon cycle (Long et al., 2006). However, the

Abbreviations: DSSAT, decision support system for agrotechnology transfer; *E*, model efficiency; ET_c, crop evapotranspiration; FACE, Free Air CO_2 Enrichment; GHG, green house gas; HFCs, hydrofluorocarbons; IPCC, intergovernmental panel on climate change; LAI, leaf area index; MRD, mean relative deviation; PFCs, perfluorocarbons; RMSD, root mean square difference; RZWQM, root zone water quality model; SD, standard deviation; SE, standard error; SRES, IPCC special report on emission scenarios; WUE, water use efficiency.

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Table 1
Summary of the cultural practices with the Free Air CO_2 Enrichment (FACE)-wheat experiment for different treatments and years.

Year	Treatment[a]	CO_2 level (μmol mol^{-1})	Seed to harvest (mm/dd)	Irrigation (mm)	N applied (kg ha^{-1})
1992–1993	A-CO_2 and dry	370	12/15–05/24	592	276.6
	A-CO_2 and wet	370	12/15–05/24	919	276.6
	E-CO_2 and dry	550	12/15–05/24	592	276.6
	E-CO_2 and wet	550	12/15–05/24	919	276.6
1993–1994	A-CO_2 and dry	370	12/08–06/01	287	260.6
	A-CO_2 and wet	370	12/08–06/01	629	260.6
	E-CO_2 and dry	550	12/08–06/01	287	260.6
	E-CO_2 and wet	550	12/08–06/01	629	260.6
1995–1996	A-CO_2 and HN	365	12/15–05/30	653	350.0
	A-CO_2 and LN	365	12/15–05/30	592	70.0
	E-CO_2 and HN	551	12/15–05/30	653	350.0
	E-CO_2 and LN	551	12/15–05/30	592	70.0
1996–1997	A-CO_2 and HN	365	12/15–05/29	621	350.0
	A-CO_2 and LN	365	12/15–05/29	548	135.0
	E-CO_2 and HN	551	12/15–05/29	621	350.0
	E-CO_2 and LN	551	12/15–05/29	548	135.0

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; LN: low nitrogen; HN: high nitrogen.

effect at any location will depend on the magnitude of change and response of the crops, forage or livestock species, and location-specific management. Soil–water-crop management practices that increase water use efficiency (WUE) and crop yield as well as add higher carbon residue to soil can potentially increase soil carbon and N storage to mitigate the GHG build-up in the atmosphere (Smith et al., 2007). In order to understand the potential effects of climate change on agriculture and recommend timely remedial measures, it is essential to study the impacts of a projected increase in anthropogenic GHG and consequent global climate change especially on the water-limited cropping and rangeland systems. Toward this goal, the large-scale Free Air CO_2 Enrichment (FACE) experiments in agriculture have been directed towards estimation of possible elevated CO_2 impacts (but without the temperature increases) on field crops under open-air conditions at different water and nitrogen levels (Ainsworth and Long, 2005; Kimball et al., 2002).

The FACE experiments exposed the crops to various elevated atmospheric CO_2 concentrations (e.g., 475–600 ppm) by injecting the gas around 8–30 m diameter ring pipes containing the crop plants. It is assumed that CO_2 effects on crops in the FACE experiments are more realistic in the representation of future climate conditions than those obtained in greenhouses and other controlled chamber experiments. The FACE experiments showed that yields of wheat and rice increased by an average of 12%, and yields of potatoes and cotton by ∼28% and 40%, respectively (Kimball et al., 2002). Production of C_3 plants showed substantial increase (∼20%) and of C_4 plants marginal increase (Long et al., 2006). In addition to the CO_2 fertilization effect, one of the reasons for the measured enhanced production under elevated CO_2 is the reduced stomatal conductance, which favored water saving by reducing transpiration at the leaf surfaces (Baldocchi and Wong, 2006; Leaky et al., 2004; Wall, 2001; Wall et al., 2000, 2006). Thus, the level of water availability to crops will influence their response to CO_2. Similarly, the level of nitrogen in the leaf tissue can affect response to both CO_2 and water (Grossman-Clarke et al., 2001).

In an agricultural system, plant growth and development are environmentally dependent upon the integrated responses of various interacting variables (temperature, CO_2, nutrients, water, and agronomic management) on various eco-physiological processes. It is impossible to incorporate all these variables and their interactions in field experiments (e.g., FACE) to study their impacts on agricultural production. Well calibrated and validated agricultural system models are essential tools for the integration of the various chemical, physical, and biological processes and their interactions in the system (Ahuja et al., 2000a,b; Kirschbaum, 2000). For example, a validated system model could be employed to explore how the temperature increases associated with enhanced CO_2 level in FACE studies will influence the response of crops to CO_2, water and nitrogen. The model could also be used to explore some adapta-

Table 2
Generic coefficients developed for simulation of spring wheat (cv. Yecora Rojo) using the RZWQM2-CROPSIM-CERES-Wheat model.

No.	Parameter	Value	
		Yecora Rojo	Spring-high Lat[a]
1	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars	5.0	5.0
2	Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h)	40.0	75.0
3	Relative grain filling duration based on thermal time (degree-days above a base temperature of 1 °C), where each unit increases above zero adds 20 degree-days to an initial value of 430 degree-days	530.0	450.0
4	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (1/g)	25.5	30.0
5	Kernel filling rate under optimum conditions (mg per day)	25.5	35.5
6	Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g)	1.1	1.1
7	Phyllochron interval (°C)	75.0	60.0

[a] Default values for the spring wheat varieties at high latitudes.

Table 3
Comparison between measured (M-SM) and simulated (S-SM) values of season-average soil moisture using the statistics of root mean square difference (RMSD) and mean relative deviation (MRD) at different depths for each treatment in the crop season 1992–1993 (calibration).

Soil depth (cm)	Treatment[a]	M-SM[b] ($cm^3\,cm^{-3}$)	S-SM ($cm^3\,cm^{-3}$)	RMSD ($cm^3\,cm^{-3}$)	MRD (%)
0–50	A-CO_2 and dry	0.254 ± 0.022	0.285	0.042	13.5
	A-CO_2 and wet	0.302 ± 0.025	0.330	0.041	9.4
	E-CO_2 and dry	0.263 ± 0.019	0.285	0.036	9.5
	E-CO_2 and wet	0.317 ± 0.020	0.335	0.032	5.8
50–110	A-CO_2 and dry	0.185 ± 0.035	0.215	0.031	16.1
	A-CO_2 and wet	0.214 ± 0.029	0.276	0.063	28.8
	E-CO_2 and dry	0.147 ± 0.031	0.213	0.068	45.7
	E-CO_2 and wet	0.199 ± 0.027	0.274	0.078	37.9
110–210	A-CO_2 and dry	0.202 ± 0.049	0.183	0.023	−9.8
	A-CO_2 and wet	0.202 ± 0.047	0.224	0.025	10.7
	E-CO_2 and dry	0.136 ± 0.045	0.182	0.048	33.1
	E-CO_2 and wet	0.163 ± 0.025	0.223	0.061	36.1

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2.
[b] Values after the ± symbol represent seasonal mean standard deviations.

tion strategies (e.g., Saseendran et al., 2000; Rosenzweig and Parry, 1994).

The RZWQM (Root Zone Water Quality Model) is a process-oriented agricultural system model that integrates various physical, chemical and biological processes and simulates the impacts of soil-crop-nutrient management practices on soil water, crop production, and water quality (Ahuja et al., 2000a). The crop simulation modules (CSM) in the DSSAT 4.0 package incorporate modules that facilitate detailed growth and development simulations of 16 different crops (Jones et al., 2003). The soil and water routines of RZWQM have been linked with the CSM-DSSAT 4.0 crop modules in the current RZWQM2 (Ma et al., 2009). It has the advantages of combining the detailed soil water and nitrogen modules of RZWQM with the detailed crop modules of DSSAT 4.0. RZWQM2 has been tested for crop production at various locations worldwide (Hu et al., 2006; Ma et al., 2005, 2006, 2008, 2009; Saseendran et al., 2007; Yu et al., 2006).

FACE experiments have been conducted to study the impacts of elevated CO_2 on spring wheat at two levels of irrigations, wet and dry (1992–1993, 1993–1994) and two levels of nitrogen (1995–1996, 1996–1997) at the USDA-ARS US Arid-Land Agricultural Research Center, Maricopa, Arizona, USA. Tubiello et al. (1999) used a modified version of CERES-Wheat with a simple leaf photosynthesis scheme for CO_2 effect to simulate the first two years of these data. They observed reasonable results, but also indentified a need for improvement of the model. Grossman-Clarke et al. (2001) used a detailed energy balance-plant growth model, DEMETER (Kartschall et al., 1995) to simulate green biomass and ET during the same first 2 years of experiments. The biomass was slightly over-predicted in early stages in both wet and dry treatments and years. Asseng et al. (2004) used the Australian APSIM-Nwheat model to simulate 4 years of the above FACE study. With modification in the model, the biomass tended to be overestimated, whereas the grain yields were predicted well. Some other recent studies also showed that the CERES model would be suitable for simulating climate change impacts on grain crop growth (Dhungana et al., 2006; Luo et al., 2003; Saseendran et al., 2000).

The objectives of the present study were to: (1) gain better understanding of the response of wheat to CO_2, water, and N interactions using the advanced CERES-Wheat v4.0 module in the RZWQM2 model to simulate all of the data from the above studies; and (2) use the validated model to assess the effect of changes in temperature and precipitation associated with elevated CO_2 (550 ppm) for the year 2050, as projected

Table 4
Comparison between simulated and measured final values of biomass, leaf area index (LAI), and grain yield using the statistics of root mean square difference (RMSD), mean relative deviation (MRD), and model efficiency (*E*) for each treatment in the crop season 1992–1993 (calibration).

Variable	Treatment[a]	Measured[b] ($g\,m^{-2}$)	M-E/A[c]	Simulated ($g\,m^{-2}$)	S-E/A[c]	RMSD ($g\,m^{-2}$)	MRD (%)	*E*
Biomass	A-CO_2 and dry	734.0 ± 84.5	–	747.1	–	71.0	1.12	0.97
	A-CO_2 and wet	840.6 ± 88.5	–	845.2	–	155.4	27.1	0.95
	E-CO_2 and dry	888.0 ± 90.2	1.210	870.8	1.166	155.2	5.4	0.96
	E-CO_2 and wet	945.7 ± 98.7	1.125	981.3	1.161	149.0	39.7	0.93
Variable	Treatment[a]	Measured[b] ($m^2\,m^{-2}$)	M-E/A[c]	Simulated ($m^2\,m^{-2}$)	S-E/A[c]	RMSD ($m^2\,m^{-2}$)	MRD (%)	*E*
LAI	A-CO_2 and dry	3.23 ± 0.56	–	2.40	–	1.11	−15.2	0.59
	A-CO_2 and wet	3.76 ± 0.67	–	3.21	–	1.10	5.9	0.71
	E-CO_2 and dry	3.26 ± 0.49	1.009	2.45	1.021	1.27	−11.3	0.49
	E-CO_2 and wet	3.86 ± 0.67	1.027	3.31	1.031	1.01	9.4	0.75
Variable	Treatment[a]	Measured[b] ($kg\,ha^{-1}$)	M-E/A[c]	Simulated ($kg\,ha^{-1}$)	S-E/A[c]	RMSD ($kg\,ha^{-1}$)	MRD (%)	*E*
Yield	A-CO_2 and dry	5954 ± 100	–	6018	–	–	1.1	–
	A-CO_2 and wet	8369 ± 424	–	6989	–	–	−16.5	–
	E-CO_2 and dry	7179 ± 595	1.206	6881	1.143	–	−4.2	–
	E-CO_2 and wet	9035 ± 562	1.080	7934	1.135	–	−12.2	–
	Mean	7634 ± 420	–	6955	–	895.8	−7.9	0.62

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; LN: low nitrogen; HN: high nitrogen.
[b] Values after the ± symbol represent seasonal mean standard deviations.
[c] Ratio of the value in elevated CO_2 to the value in atmospheric CO_2.

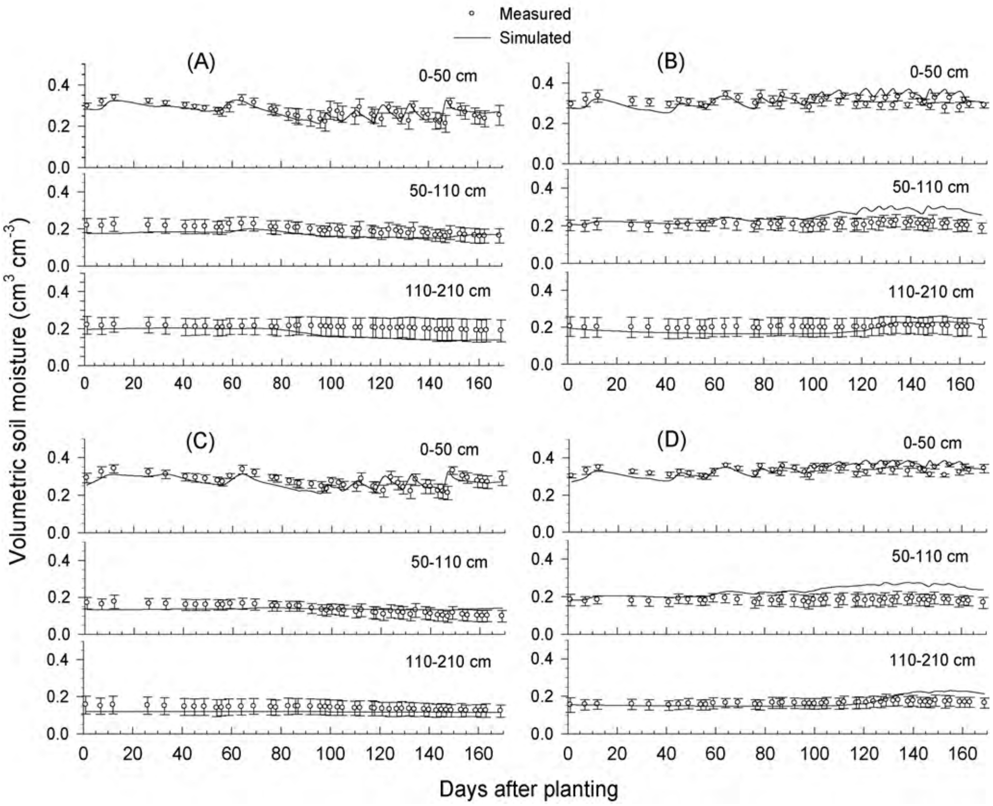

Fig. 1. Simulated and measured transient volumetric soil moisture during the season at three depths for the treatments of ambient CO_2 and dry (A), ambient CO_2 and wet (B), elevated CO_2 and dry (C), elevated CO_2 and wet (D) in 1993–1994. Vertical bars represent ±1 standard deviations ($n = 4$).

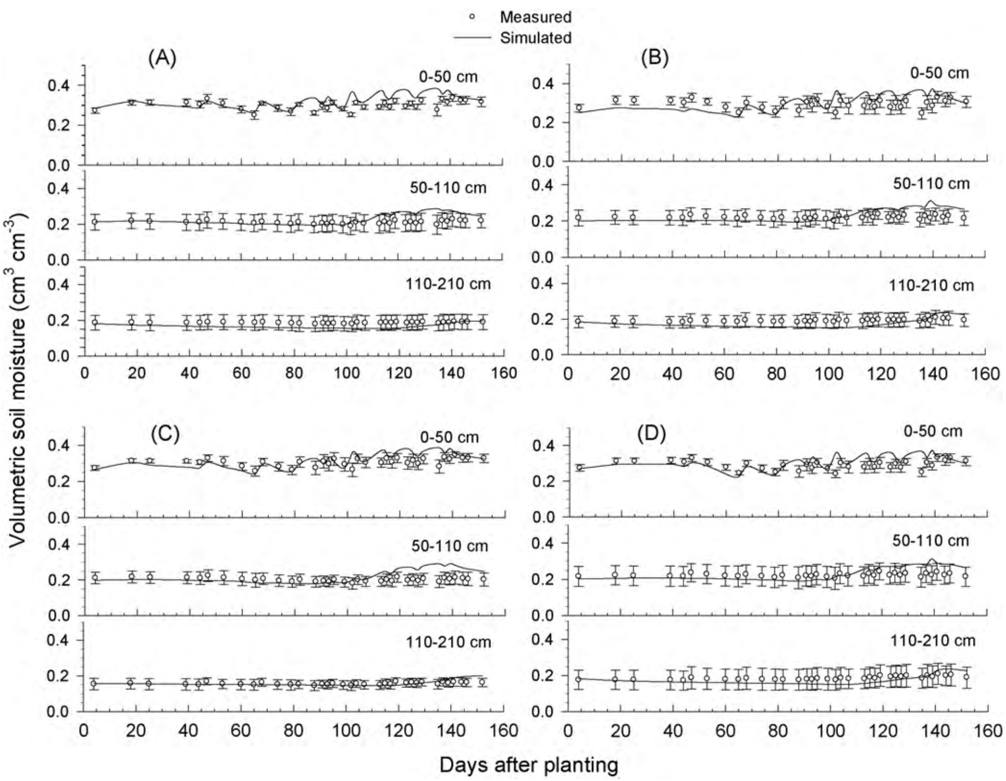

Fig. 2. Simulated and measured transient volumetric soil moisture during the season at three depths for the treatments of ambient CO_2 and low nitrogen (A), ambient CO_2 and high nitrogen (B), elevated CO_2 and low nitrogen (C), elevated CO_2 and high nitrogen (D) in 1996–1997. Vertical bars represent ±1 standard deviations ($n = 4$).

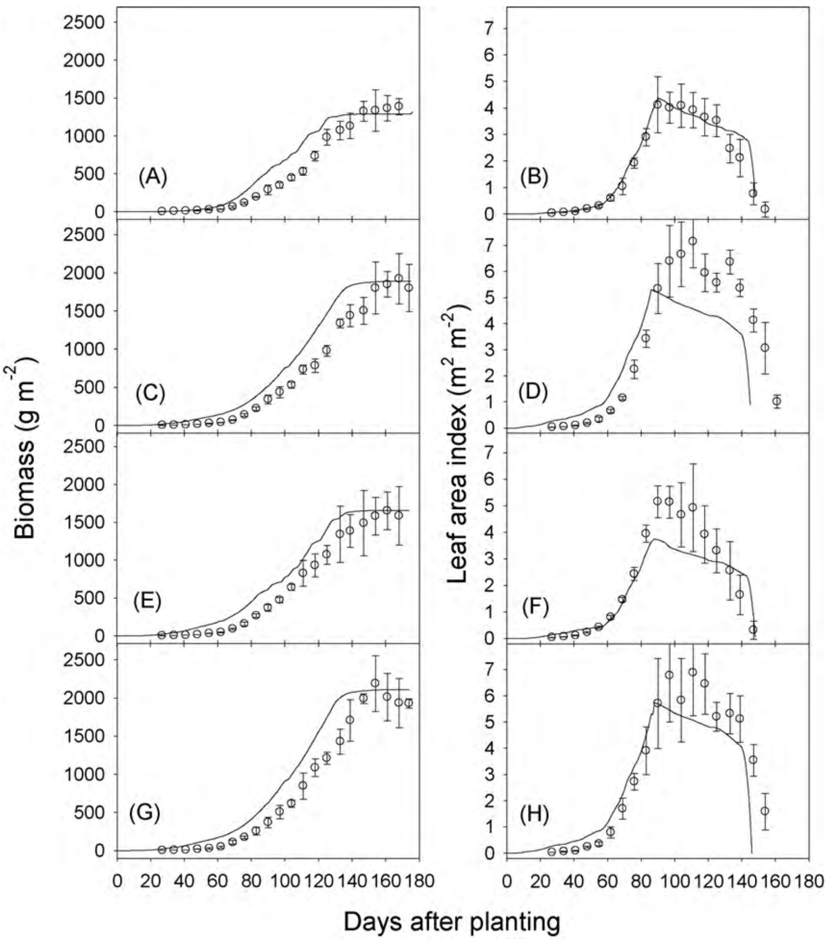

Fig. 3. Simulated (—) and measured (○) transient biomass (left) and leaf area index (right) as a function of days after planting for the treatments of ambient CO_2 and dry (A and B), ambient CO_2 and wet (C and D), elevated CO_2 and dry (E and F), elevated CO_2 and wet (G and H) in 1993–1994. Vertical bars represent ±1 standard deviations ($n = 4$).

by 16 general circulation models (GCMs), on the wheat crop production.

2. Materials and methods

2.1. Free air CO_2 enrichment (FACE) experiment

The experimental site was located in central Arizona, at the University of Arizona's Maricopa Agricultural Center (33.1°N, 112.0°W, 361 m above sea level). The FACE system was composed of four toroidal plenum rings of 25-m diameter, constructed from 0.305-m diameter irrigation pipes (Lewin et al., 1994). The rings had 2.5-m high vertical pipes with individual valves spaced every 2-m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations on the vertical pipes. The CO_2 concentration was continuously monitored at the center of each ring. The CO_2 flow rates were automatically adjusted using a computer control system to maintain the desired concentration at the center of each ring by compensating for wind direction and speed. In the experiment, the CO_2 concentrations inside the rings were elevated by 180 μmol mol^{-1} above the ambient concentration (~370 μmol mol^{-1}) during the growing seasons, except for a few brief periods when there were various mechanical problems. In 1995, blowers were installed in the four control rings in each replicate, so that for the 1995–1996 and 1996–1997 experiments, the control rings received ambient air similar to the FACE rings to assure identical microclimatic effects due to the FACE equipments (Pinter et al., 2000). However, for the 1992–1993 and 1993–1994 experiments, there was no forced air flow in the control plots, and some differences in microclimate and consequent crop growth were observed between FACE and control plots (Pinter et al., 2000).

A spring wheat cultivar (*Triticum aestivum* L., cv. Yecora Rojo) was cultivated from 1992 to 1997 in the FACE experiments (Table 1). The cultivar was selected because it was a recommended cultivar in the region and is still widely cultivated. In 1992–1993 and 1993–1994, irrigation was applied at two different amounts over the crop seasons, which were classified as 'dry' and 'wet'. In 1995–1996 and 1996–1997, nitrogen was also applied at two levels classified as ('low' and 'high' N) (Table 1). The soil at the FACE experimental site was classified as a Trix clay loam, fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents (Kimball et al., 1999). Daily weather data on maximum and minimum temperatures, solar radiation, precipitation, relative humidity, and wind speed were measured at the site. Measured crop growth data included time progressions of biomass and leaf area index (LAI) and grain yield. A minimum of 6 plants was sampled at 7–10-day intervals from 4 sampling zones in each FACE ring during the growing seasons (24 plants total). Plant phenology, green biomass, and green leaf area were then determined from a sub-sample of 12 median-sized plants per plot. All plants were oven-dried at 65–70 °C and determined dried biomasses for crown, stem, green leaf, non-green leaf, and head components. LAI was computed from the green leaf area and plant density. Final grain yields were determined by machine harvest of ~20 m^2 of each subplot. Soil moisture measurements were also made at various soil depths (0–2.1 cm).

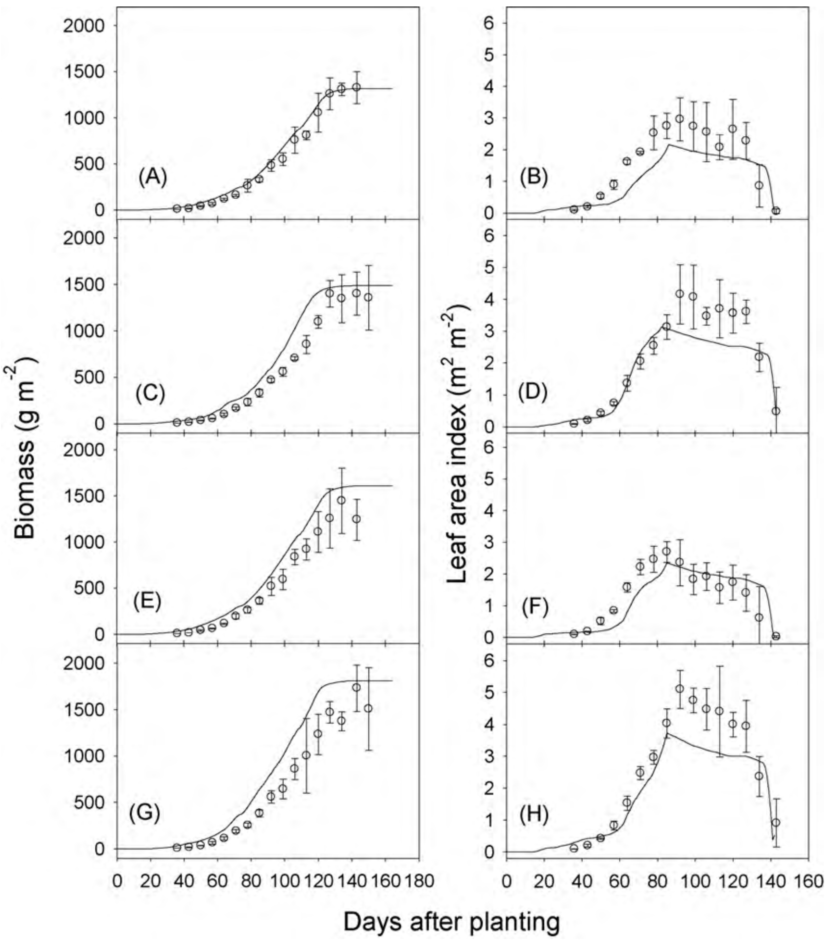

Fig. 4. Simulated (—) and measured (○) transient biomass (left) and leaf area index (right) as a function of days after planting for the treatments of ambient CO_2 and low N (A and B), ambient CO_2 and high N (C and D), elevated CO_2 and low N (E and F), elevated CO_2 and high N (G and H) in 1996–1997. Vertical bars represent ±1 standard deviations (n = 4).

Details of instruments used and data collection protocols are available elsewhere (Hunsaker et al., 1994, 2005).

2.2. RZWQM2 model

The DSSAT4.0-CERES-Wheat model in RZWQM2 was used in this study (Ma et al., 2009). RZWQM2 has a detailed soil–water balance module that uses the Green-Ampt equation for infiltration and the Richards' equation for redistribution of water among different soil layers (Ahuja et al., 2000a). Potential evapotranspiration is calculated using the extended Shuttleworth–Wallace equation modified to include the surface crop residue dynamics on aerodynamics and energy fluxes (Farahani and DeCoursey, 2000). The soil carbon/nitrogen dynamic module contains two surface residue pools, three soil humus pools and three soil microbial pools. N mineralization, nitrification, denitrification, ammonia volatilization, urea hydrolysis, methane production, and microbial population processes are simulated (Shaffer et al., 2000). Management practices simulated in the model include: tillage, applications of manure and fertilizers, planting and harvesting operations, irrigation, and surface crop residue dynamics (Rojas and Ahuja, 2000).

The DSSAT4.0-CERES plant growth module in RZWQM2 simulated crop yield components, leaf numbers, and phenological stages. The CERES-Wheat in RZWQM2 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 (Allen et al., 1987; Peart et al., 1989). They used a y-intercept term in a modified Michaelis-Menten equation to fit crop responses to CO_2 concentration:

$$\mathrm{RUE} = \frac{\mathrm{RUE_m} \cdot \mathrm{CO_2}}{\mathrm{CO_2} + K_\mathrm{m}} + \mathrm{RUE}_i \quad (1)$$

where $\mathrm{RUE_m}$ is the asymptotic response limit of ($\mathrm{RUE} - \mathrm{RUE}_i$) at high CO_2 concentration, RUE_i is the intercept on the y-axis, and K_m is the value of the substrate concentration, i.e., CO_2, at which ($\mathrm{RUE} - \mathrm{RUE}_i$) = $0.5\mathrm{RUE_m}$. Similar approaches are followed for simulations of CO_2 effects on cropping systems in EPIC (Williams et al., 1989), APSIM (along with nitrogen use efficiency and water use efficiency) (Reyenga et al., 1999), and Sirius (Jamieson et al., 2000) models. The CERES-Wheat model simulates effects of water stress on photosynthesis using empirically calculated factors, first computing canopy potential transpiration. The actual to potential evapotranspiration ratio must be relative to the actual reduction of biomass production (Ritchie, 1972). The model was enhanced to simulate the effect of elevated CO_2 on the potential evapotranspiration by increasing stomatal resistances in the Shuttleworth–Wallace (extended Penman–Monteith) equation (Allen et al., 1987; Acock and Allen, 1985).

2.3. Model parameterization and calibration

The 1992–1993 FACE wheat data from Arizona were used for model parameterization and calibration. The minimum driving variables for RZWQM2 simulations are daily solar radiation, maximum and minimum temperature, precipitation, soil physical and hydraulic properties, soil texture, and initial soil nitrogen

Table 5
Comparison between measured (M-SM) and simulated (S-SM) values of season-average soil moisture using the statistics of root mean square difference (RMSD) and mean relative deviation (MRD) at different depths for different treatments and years (validation).

Year	Treatment[a]	0–50 cm				50–110 cm				110–210 cm			
		M-SM ($cm^3 cm^{-3}$)	S-SM ($cm^3 cm^{-3}$)	RMSD ($cm^3 cm^{-3}$)	MRD (%)	M-SM ($cm^3 cm^{-3}$)	S-SM ($cm^3 cm^{-3}$)	RMSD ($cm^3 cm^{-3}$)	MRD (%)	M-SM ($cm^3 cm^{-3}$)	S-SM ($cm^3 cm^{-3}$)	RMSD ($cm^3 cm^{-3}$)	MRD (%)
1993–1994	A-CO_2 and dry	0.269 ± 0.030	0.229	0.054	−13.9	0.193 ± 0.036	0.157	0.038	−18.5	0.205 ± 0.052	0.139	0.066	−32.2
	A-CO_2 and wet	0.309 ± 0.020	0.324	0.041	5.4	0.207 ± 0.031	0.255	0.054	23.3	0.201 ± 0.050	0.195	0.024	−3.5
	E-CO_2 and dry	0.273 ± 0.027	0.226	0.061	−16.3	0.133 ± 0.031	0.137	0.024	6.5	0.138 ± 0.040	0.117	0.022	−14.8
	E-CO_2 and wet	0.334 ± 0.017	0.320	0.036	−4.1	0.181 ± 0.029	0.244	0.072	34.4	0.164 ± 0.028	0.178	0.032	8.1
1995–1996	A-CO_2 and HN	0.284 ± 0.024	0.316	0.048	11.7	0.218 ± 0.036	0.261	0.047	19.9	0.187 ± 0.035	0.203	0.025	8.4
	A-CO_2 and LN	0.300 ± 0.020	0.301	0.042	0.1	0.193 ± 0.036	0.231	0.054	19.1	0.187 ± 0.033	0.168	0.035	−11.1
	E-CO_2 and HN	0.285 ± 0.025	0.310	0.046	8.9	0.217 ± 0.054	0.244	0.037	12.2	0.166 ± 0.042	0.169	0.030	0.5
	E-CO_2 and LN	0.287 ± 0.018	0.300	0.051	4.5	0.201 ± 0.036	0.226	0.051	11.4	0.152 ± 0.026	0.150	0.032	−2.5
1996–1997	A-CO_2 and HN	0.293 ± 0.030	0.287	0.059	−1.6	0.221 ± 0.040	0.205	0.049	−7.2	0.191 ± 0.037	0.144	0.051	−25.0
	A-CO_2 and LN	0.300 ± 0.016	0.303	0.037	1.3	0.210 ± 0.046	0.234	0.034	11.5	0.187 ± 0.042	0.172	0.020	−7.9
	E-CO_2 and HN	0.291 ± 0.024	0.286	0.059	−1.3	0.222 ± 0.054	0.201	0.052	−10.0	0.185 ± 0.058	0.140	0.048	−24.6
	E-CO_2 and LN	0.306 ± 0.026	0.299	0.039	−2.4	0.202 ± 0.032	0.224	0.041	10.8	0.156 ± 0.025	0.160	0.016	2.2

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; LN: low nitrogen; HN: high nitrogen.

Table 6
Root mean square difference (RMSD), mean relative deviation (MRD), and model efficiency (E) for simulated and measured seasonal average values of biomass and leaf area index (LAI) for different treatments and years (validation).

Year	Treatment[a]	Biomass					LAI				
		Measured ($g m^{-2}$)	Simulated ($g m^{-2}$)	RMSD ($g m^{-2}$)	MRD (%)	E	Measured ($m^2 m^{-2}$)	Simulated ($m^2 m^{-2}$)	RMSE ($m^2 m^{-2}$)	MRD (%)	E
1993–1994	A-CO_2 and dry	542.9 ± 65.2	673.8	18.1	68.2	0.88	1.99 ± 0.39	1.80	0.43	15.8	0.92
	A-CO_2 and wet	725.7 ± 89.3	922.4	25.9	186.6	0.86	3.35 ± 0.45	2.92	1.33	127.8	0.76
	E-CO_2 and dry	664.8 ± 121.0	835.9	21.0	111.7	0.88	2.28 ± 0.50	1.91	0.84	45.9	0.81
	E-CO_2 and wet	839.0 ± 102.3	1063.5	28.6	185.6	0.87	3.36 ± 0.70	2.92	1.13	112.0	0.82
1995–1996	A-CO_2 and HN	690.9 ± 112.0	822.7	26.8	125.4	0.84	1.83 ± 0.57	2.27	0.69	37.8	0.85
	A-CO_2 and LN	782.2 ± 81.6	964.5	16.1	52.1	0.92	2.87 ± 0.53	2.75	0.54	32.0	0.73
	E-CO_2 and HN	779.1 ± 98.6	943.4	30.3	148.3	0.84	2.04 ± 0.50	2.26	0.89	41.6	0.80
	E-CO_2 and LN	879.3 ± 58.7	1099.2	19.6	123.4	0.90	3.08 ± 0.49	2.74	0.43	49.4	0.88
1996–1997	A-CO_2 and HN	534.8 ± 67.9	576.4	14.0	73.4	0.92	1.78 ± 0.40	1.24	0.37	−4.4	0.93
	A-CO_2 and LN	595.6 ± 80.1	712.1	8.0	3.8	0.97	2.23 ± 0.41	2.21	0.70	−18.5	0.48
	E-CO_2 and HN	561.2 ± 102.6	629.8	33.0	84.3	0.66	1.37 ± 0.35	1.41	0.98	1.5	0.68
	E-CO_2 and LN	673.6 ± 113.6	948.9	12.5	1.8	0.93	2.50 ± 0.42	2.06	0.46	4.8	0.69

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; LN: low nitrogen; HN: high nitrogen.

Table 7
Comparison between simulated (S) and measured (M) grain yield using the statistics of root mean square difference (RMSD), mean relative deviation (MRD), and model efficiency (*E*) for different treatments during 1993–1994, 1995–1996, and 1996–1997 (validation).

Year	Treatment[a]	M-Yield[b] ($kg\,ha^{-1}$)	M-E/A[c]	S-Yield ($kg\,ha^{-1}$)	S-E/A[c]	RMSD ($kg\,ha^{-1}$)	MRD (%)	*E*
1993–1994	A-CO_2 and dry	4744 ± 717	–	5421	–	–	14.3	–
	A-CO_2 and wet	7435 ± 871	–	7873	–	–	5.9	–
	E-CO_2 and dry	5918 ± 694	1.247	7023	1.296	–	18.7	–
	E-CO_2 and wet	8311 ± 270	1.118	9021	1.146	–	8.5	–
	Mean	6602 ± 420	–	7335	–	770.1	11.8	0.69
1995–1996	A-CO_2 and HN	7399 ± 299	–	6968	–	–	−8.5	–
	A-CO_2 and LN	5772 ± 568	–	6310	–	–	9.3	–
	E-CO_2 and HN	8494 ± 550	1.148	7704	1.138	–	−9.3	–
	E-CO_2 and LN	6457 ± 868	1.119	7089	1.123	–	9.8	–
	Mean	7031 ± 571	–	6968	–	654.1	0.3	0.61
1996–1997	A-CO_2 and HN	6126 ± 438	–	6420	–	–	4.8	–
	A-CO_2 and LN	5043 ± 567	–	4762	–	–	−5.6	–
	E-CO_2 and HN	7157 ± 681	1.168	7894	1.230	–	10.3	–
	E-CO_2 and LN	5306 ± 823	1.052	5564	1.168	–	4.9	–
	Mean	5908 ± 628	–	6160	–	440.2	3.6	0.87

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; LN: low nitrogen; HN: high nitrogen.
[b] Values following the ± symbols are standard deviations.
[c] Ratio of the value in elevated CO_2 to the value in atmospheric CO_2.

and soil water status. Typical crop management metadata include planting dates, planting depth, row spacing plant population, and amount and method of irrigation and fertilizer applications. To develop cultivar parameters (genetic coefficients) for simulations of the spring wheat cultivar 'Yecora Rojo' using the CERES-Wheat model, an iterative approach recommended by Godwin et al. (1989) was employed through trial-and-error to match the measured phenology, biomass, LAI, and yield with simulated values. The combination of cultivar parameters that gave the minimum RMSD were selected and used in further validation of the model (Table 2).

Water use efficiency (WUE) was quantified using simulated grain yield and transpiration (*T*) as follows:

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

2.4. Model sensitivity analysis

Model sensitivity to changes in atmospheric CO_2, temperature, and precipitation inputs were conducted. Simulations made use of 16 years of measured climate data as reference upon which the changes were superimposed, in order to allow inter-annual variability. The results were averaged and presented. The CO_2 concentrations of 100, 200, 300, 380, 475, 570, 700, 791, 995, and 1200 $\mu mol\,mol^{-1}$ or ppm were used. Temperature sensitivities were conducted by varying the measured daily maximum and minimum temperatures by −3, 0, 1, 3, and 5 °C, and precipitation sensitivities by modifying the measured values by −50, −20, 0, 20, and 50%.

2.5. Simulation of grain yield in 2050 with A2 scenario

Temperature and precipitation projections in response to the radiative forcing due to a 550 ppm atmospheric CO_2 concentration for possible climate conditions representing the 2050s (A2 scenario, IPCC, 2007) were obtained from 16 different GCMs for Maricopa, Arizona for a time (Appendix A). Average values from all ensemble members with each GCM were used. In order to include year-to-year natural variability, each GCM projection was made for a 30-year variation (2040–2069) centered on 2054 based on a 30-year baseline (1970–1999). In the 16 GCM projections, the models simulated the monthly mean temperatures for 2050 to be increased between 1.42 and 2.59 °C (Appendix B). Means of monthly total precipitation from the baseline varied from −22.9 to 15.3% (Appendix C). While the individual GCM projections differed from each other in their mean temperature and precipitation, the mean values over 16 GCMs for temperature increase (2.0 °C) and precipitation (−2.2%) matched well with the projections results for the Southwest of the USA reported earlier (Lenart, 2007).

The GCM projections of temperature and precipitation were then superimposed over a 16-year baseline of historical climate data (1987–2002) available at Maricopa Arizona, centered around the experimental years (1992–1997). We used the 1970–1999 model baseline period for comparison, and then adjusted changes by 6/7ths to account for the discrepancy between the model baseline period and the observed baseline period (6/7ths was the fraction of the time elapsed between the observed conditions and the future conditions compared to the time elapsed between the model baseline conditions and the future conditions). For example, a certain month's projected 1-degree change in temperature from the model baseline period to the future period would only be a 0.86-degree change between the observed conditions and the future period, and similarly a 10% decline in precipitation would be only an 8.6% decline. We also capped precipitation changes during dry months to be no more than 200%. The average temperature increase of each month was added equally to the daily minimum and maximum temperatures in the corresponding month. Likewise, the percent change in precipitation of each month was used to change the daily precipitation in the corresponding month. These projected climate data were used to simulate the climate change effects of CO_2, temperature, and precipitation on spring wheat using the validated model for the FACE data set conditions.

2.6. Model evaluation

Accuracy of the calibrated model was evaluated using the data from three crop seasons in 1993–1994, 1995–1996, and 1996–1997. Correlation analysis using PROC CORR and paired *t*-test using PROC TTEST (SAS version 9.2, Cary, NC) were conducted for comparisons between the simulated and measured data. Goodness-of-fit estimators used were *p* value from the paired *t*-test and correlation coefficient (*r*). In addition, four statistics were used to evaluate the model performance: (i) root mean square difference (RMSD), Eq. (3); (ii) mean relative deviation (MRD), Eq. (4); and (iii) model efficiency (E) (Nash and Sutcliffe, 1970), Eq. (5).

$$\mathrm{RMSD} = \left[\frac{1}{N}\sum_{i=1}^{n}(S_i - M_i)^2\right]^{1/2} \quad (3)$$

$$\mathrm{MRD} = \frac{1}{n}\sum_{i=1}^{n}\frac{(S_i - M_i)}{M_i}100\% \quad (4)$$

$$E = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_{avg})^2} \quad (5)$$

where S_i is the ith simulated value, M_i is the ith measured value, M_{avg} is the averaged measured value, and n is the number of data pairs. E values are equivalent to the coefficient of determination (R^2), if the values fall around a 1:1 line of simulated vs measured data, but E is generally lower than R^2 and can be negative when the predictions are very biased.

3. Results and discussion

3.1. Model calibration

Simulated and measured seasonal mean soil water over the wheat growing season ranged between 0.136 and 0.335 $cm^3\,cm^{-3}$ in the soil profiles (Table 3). Simulated soil water in different soil layers generally agreed well with the measured values. Most of the simulated values were within ±2 standard deviation (SD) about the measured mean, but a few were within ±3 SD.

The biomass was simulated within or close to ±1 SD about the measured mean, and the simulated leaf area index (LAI) values generally corresponded to their measured values within ±2 SD (Table 4). Measured yield enhancements due to elevated CO_2 relative to ambient CO_2 (E/A) ratios of 1.206 in the dry and of 1.080 in the wet treatments were reasonably reproduced at 1.143 and 1.135, respectively, in the simulations, within 0.062–0.083 coefficient of variation (CV) ranges of the measured data. The RMSD, MRD, and E of biomass simulations ranged from 71 to 155 $g\,m^{-2}$, 1.1 to 39.7%, and 0.93 to 0.97, respectively, and those of LAI were from 1.01 to 1.27 $m^2\,m^{-2}$, −15.2 to 9.4%, and 0.49 to 0.75, respectively. The simulated grain yield was in reasonable agreement with the measured values with RMSD of 896 $kg\,ha^{-1}$, MRD of −7.9%, and E of 0.62. The difference between simulated and measured grain yield was not significant (paired t-test with $p = 0.443$). All in all, even though some simulations of soil moisture and plant growth had high RMSD, the overall performance of the model was acceptable within the normal natural variability (±2 SD) associated with field measurements.

3.2. Model validation

Simulated transient soil water generally agreed with the measured values with most of the simulations falling within ±1 SD of the measured mean, the rest within ±2 SD (Figs. 1 and 2 for 1993–1994 and 1996–1997 data; 1995–1996 data were similar. see Table 5). On the whole, RMSD ranged from 0.016 to 0.072 $cm^3\,cm^{-3}$ and the MRD ranged from −32.2 to 45.7% (Table 5). The simulated and measured values of soil water were generally smaller under the elevated CO_2 condition than the ambient CO_2 condition. Soil water was simulated better in the low N treatment with the RMSD range of 0.016–0.054 $cm^3\,cm^{-3}$, compared to the high N treatment with the RMSD range of 0.025–0.059 $cm^3\,cm^{-3}$. Inter-annual variation in soil water was minimal between the corresponding soil depths and treatments (e.g., 1995–1996 vs 1996–1997). In summary, although there were some over- and under-simulations of soil water at certain times in some of the soil layers, the simulations in general responded to irrigation and N treatments under both ambient and elevated CO_2 conditions, within ±2 SD of the measured data.

Table 8
Simulated water use efficiency (WUE) for each treatment.

Treatment[a]	WUE ($kg\,ha^{-1}\,mm^{-1}$)		ΔWUE ($kg\,ha^{-1}\,mm^{-1}$)
	A-CO_2	E-CO_2	
Dry	11.74	14.96	3.22
Wet	10.01	11.48	1.47
High N	12.61	14.35	1.74
Low N	11.32	12.02	0.70

[a] A-CO_2: ambient CO_2; E-CO_2: elevated CO_2; ΔWUE: difference in WUE between E-CO_2 and A-CO_2.

In the high and low irrigation treatments under both the ambient and elevated CO_2 levels in 1993–1994, biomass was over-simulated between 40 and 140 days after planting (DAP) in the most treatments (Fig. 3). LAI values were under-simulated from 100 to 130 DAP in the dry treatments and after 100 DAP in the wet treatments. We assume that delicate changes of the partitioning from biomass to LAI in the actual system are not captured in the present simulation model. However, the seasonal average biomass values were within ±1 SD (Fig. 3; Table 6). The model also reasonably simulated variation in the measured biomass and LAI values due to the irrigation and CO_2 treatments. In the high and low N treatments in 1995–1996 and 1996–1997, most biomass and LAI simulations well reproduced the measured values within ±1 SD but some LAI values were underestimated (Fig. 4 for 1996–1997). However, simulations of biomass and LAI agreed reasonably with the measurements with most of the simulations falling within ±1 SD about the measured means (Table 6). Also, simulated values reproduced the smaller or larger measured values of biomass and LAI due to the N and CO_2 treatments well. The E values of biomass ranged from 0.84 to 0.92 in 1995–1996 and 0.66 to 0.97 in 1996–1997, and those of LAI ranged from 0.76 to 0.88 in 1995–1996 and 0.48 to 0.93 in 1996–1997 (Table 6). Simulation closely reproduced the measured inter-annual variations in relative magnitude and ranking of biomass and LAI for the corresponding treatments between 1992–1993 (Table 4), and 1993–1994 (Table 6), and between 1995–1996 and 1996–1997 (Table 6). Simulated biomass and LAI were better in the low N treatment than in the high N treatment under both ambient and elevated CO_2 conditions. In summary, the overall model performance was reasonably good with 11 out of 12 of the simulation E values ranging from 0.68 to 0.93 (Table 6). Simulations of biomass in the experiments are comparable with the previous simulations of part of this experiment using DEMETER (Grossman-Clarke et al., 2001), APSIM-Nwheat (Asseng et al., 2004), and CERES-Wheat (Tubiello et al., 1999). Those studies also overestimated biomass in some cases, similar to our results.

Simulated grain yields over all the treatments of CO_2, irrigation and N were in reasonable agreement with the measured values, with RMSD of 490 $kg\,ha^{-1}$, MRD of 1.3%, and E of 0.88 (Table 7; Fig. 5A). Also, seven of the 8 yield simulations (2-year average for each treatment for both simulated and measured) were within ±1 SD of the measured means. Simulated grain yield responses to elevated CO_2 relative to ambient CO_2 (E/A) were well reproduced within 0.032–0.155 CV ranges of measured responses (Table 7: CV data not shown). The simulated E/A ratios for wet and dry treatments in 1993–1994 were closer to the measured E/A values for yield (Table 7) than for similar comparisons in 1992–1993 (Table 4). Also, grain yield was simulated reasonably well for all individual treatments with RMSD between 440 and 770 $kg\,ha^{-1}$, MRD between −9.3 and 18.7% and E between 0.61 and 0.87. Table 7 also shows that simulations closely reproduced the measured inter-annual variations in magnitude and relative ranking of yield for different treatments and mean yields over treatments

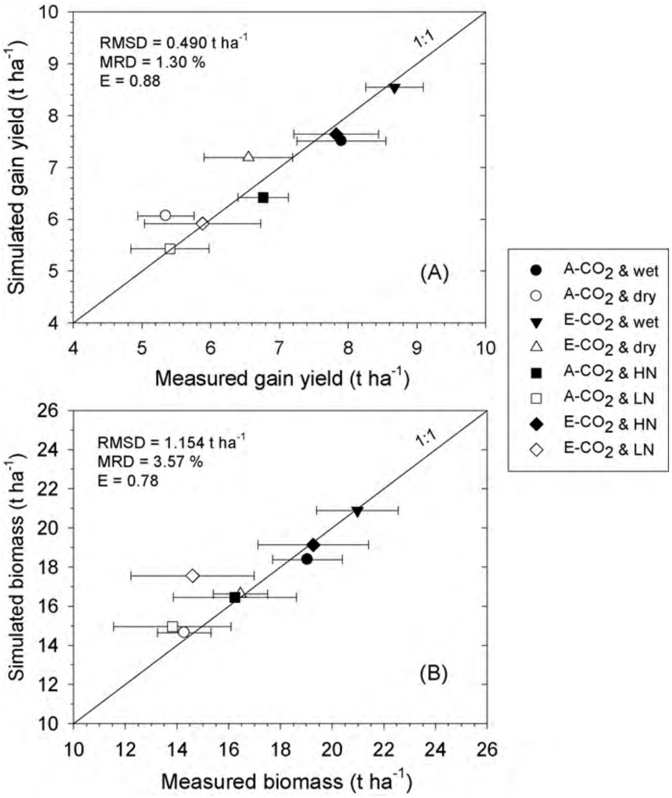

Fig. 5. Simulation vs measurement of grain yield (A) and biomass at maturity (B) for the different treatments (2-year average for each treatment), using data from 1992–1993 to 1996–1997. Horizontal bars represent standard deviations ($n = 4$).

between 1995–1996 and 1996–1997 seasons, as well as between 1992–1993 and 1993–1994 seasons (Tables 4 and 6). Simulated final biomass also agreed well with the measured values with RMSD of 1154 kg ha^{-1}, MRD of 3.57%, E of 0.78 (Fig. 5B). Paired t-tests demonstrate that there were no significant differences between simulated and measured grain yield treated with CO_2, irrigation, and N ($p = 0.443$) and final biomass ($p = 0.111$). It was previously reported that models are capable of simulating CO_2 effects of the FACE wheat on crop development and yield (Asseng et al., 2004; Grossman-Clarke et al., 2001; Tubiello et al., 1999). The present study also demonstrates this context using the full data set with the updated CERES-Wheat module in the RZWQM2 model. Meanwhile, simulated water use efficiencies (WUE) were higher in the elevated CO_2, low irrigation, and high N treatments compared to the ambient CO_2, high irrigation, and the low N treatments (Table 8). Furthermore, simulated plant phenology dates were in general agreement with the observed dates within an error range ±5 days (data not shown).

3.3. Model response to CO_2, temperature and precipitation

Simulated grain yield responses to various scenarios of CO_2 concentration, temperature, and precipitation were curvilinear (Fig. 6). Simulations were carried out with 16 years of climate data and the results averaged and presented. Grain yield response to CO_2 concentration showed a parabolic curve pattern, increasing rapidly to the current level of CO_2 (~380 ppm) with the rate of increase growing smaller as CO_2 increases. Grain yield response to temperature showed a cubic curve pattern, reaching a peak at the −3 °C change scenario from the current temperature and an almost linear decrease above the current temperature. This makes us hypothesize that the temperature was above optimum temperature range for the cultivar. Response of grain yield to precipitation has shown a threshold- or plateau-like pattern. The gentle-sloped curvilinear precipitation response can be attributed to the irrigation management conditions. It is considered that water was applied close to full irrigation even in the dry irrigation treatments. Meanwhile, the same curvilinear patterns were found in simulated WUE responses to various scenarios of CO_2 concentration, temperature, and precipitation (not shown). However, WUE reached a peak at the −4 °C change regime from the current temperature. Our sensitivity results are generally comparable with the report by Lugwig and Asseng (2006). They reported that effects of higher temperatures, elevated CO_2, and changed rainfall on wheat production were not linear and differed significantly among soil types and locations in a Mediterranean environment of Australia. The responses of net primary productivity and net ecosystem carbon exchange to the variables also showed nonlinear patterns (Zhou et al., 2008).

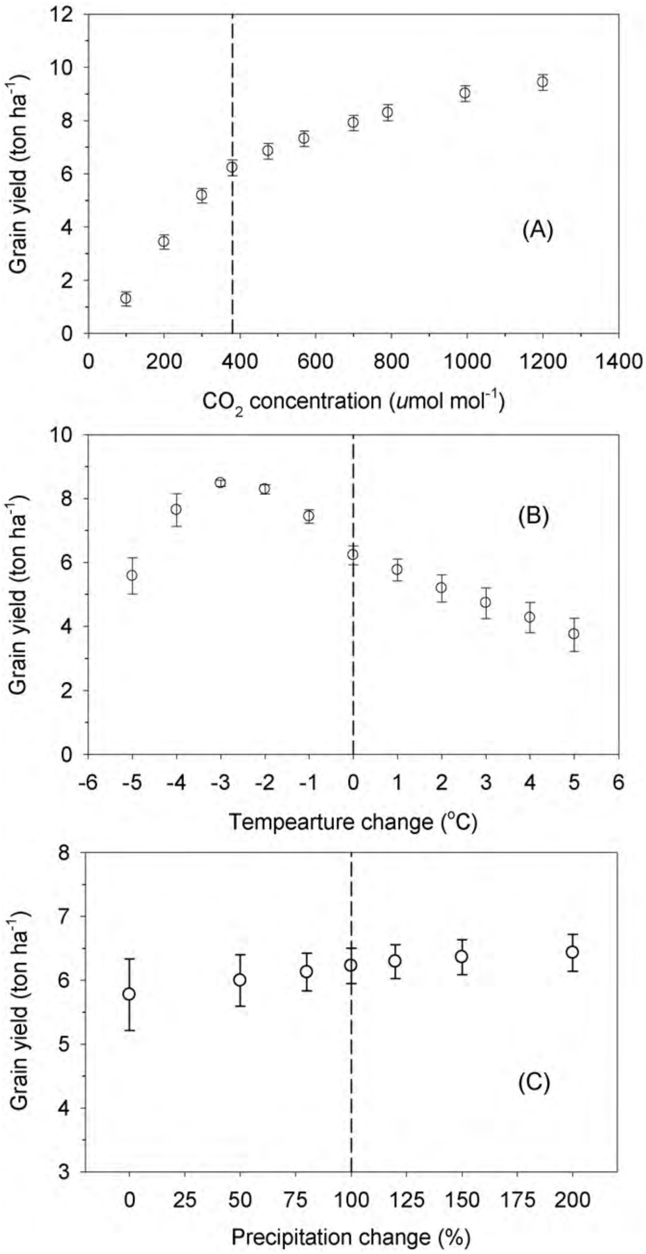

Fig. 6. Simulated grain yield responses to changes of CO_2 concentration (A), air temperature (B), and percentage of precipitation (C). Dotted lines and vertical bars represent the current status variables and ±1 SE ($n = 8$), respectively.

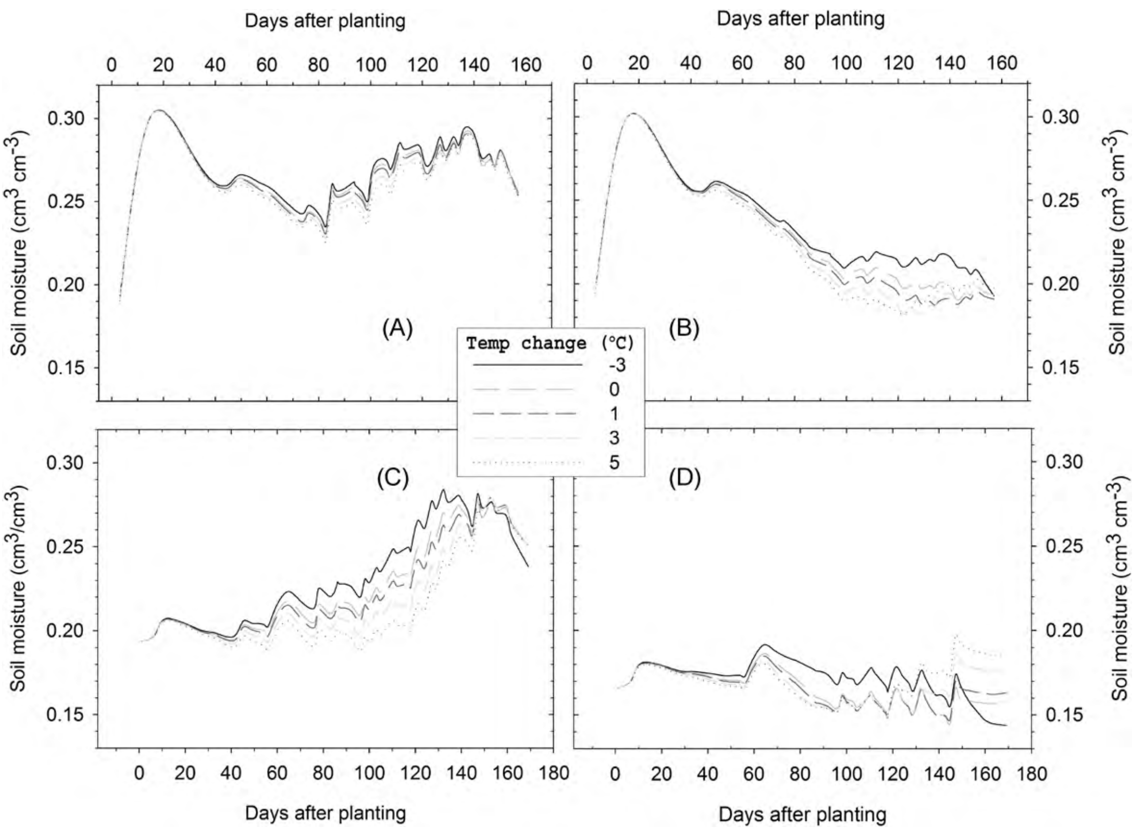

Fig. 7. Simulated profile-average soil moisture on various temperature change scenarios as a function of days after planting for the wheat crop seasons in 1992–1993 under wet (A) and dry (B) conditions and in 1993–1994 under wet (C) and dry (D) conditions.

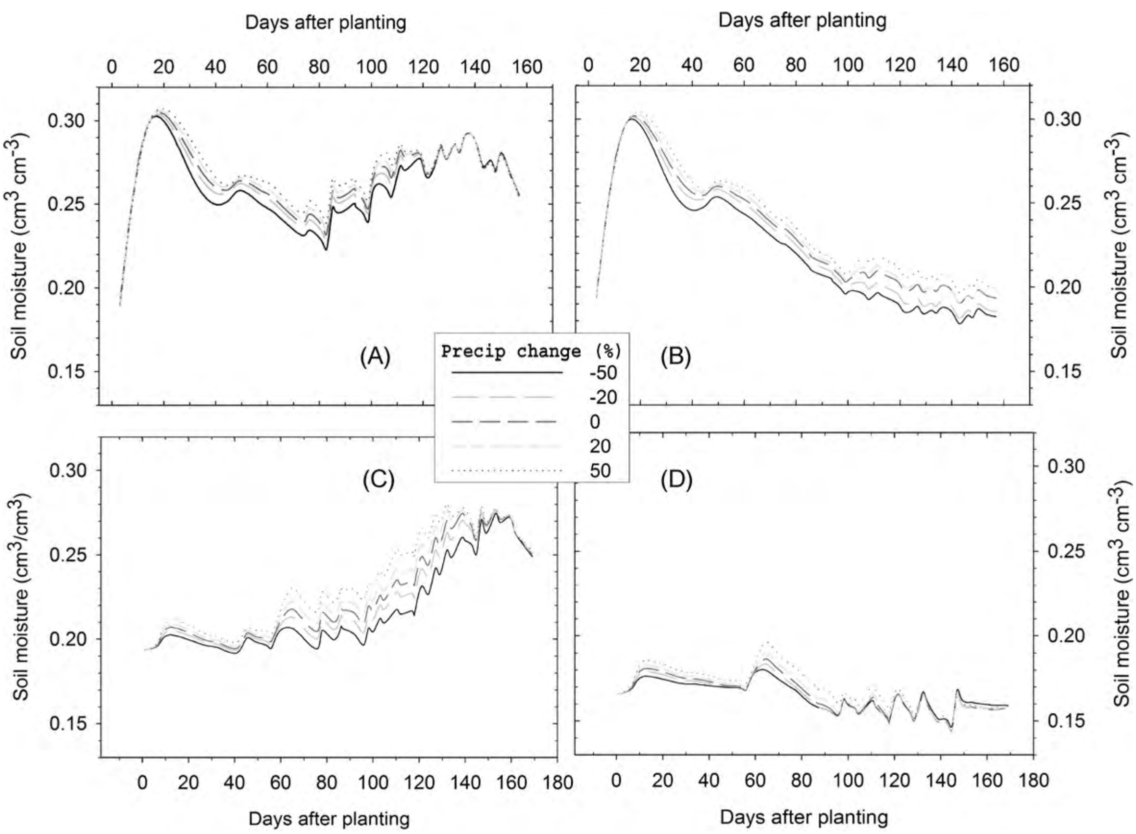

Fig. 8. Simulated profile-average soil moisture on various precipitation change scenarios as a function of days after planting for the wheat crop seasons in 1992–1993 under wet (A) and dry (B) conditions and in 1993–1994 under wet (C) and dry (D) conditions.

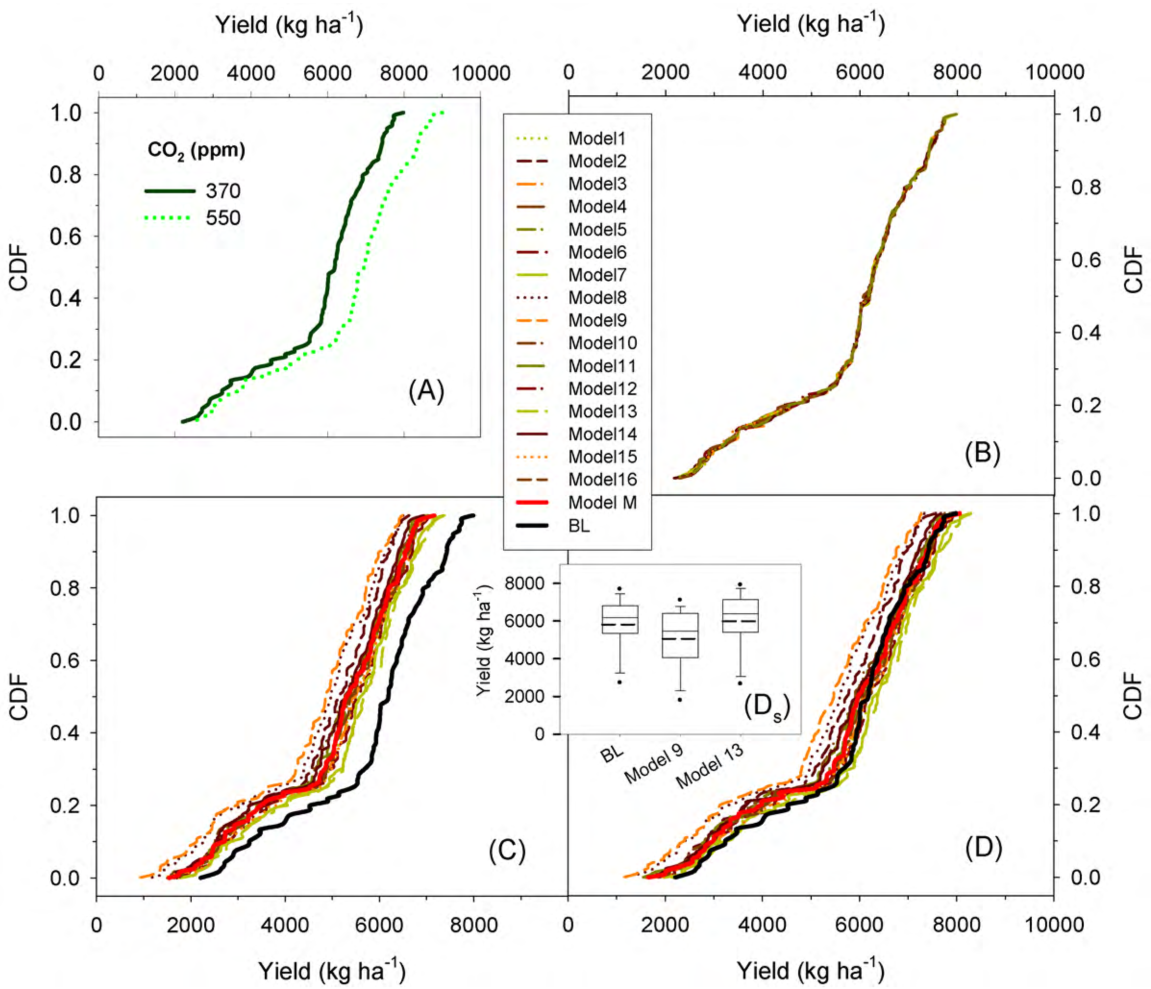

Fig. 9. Cumulative distribution function (CDF) of simulated wheat grain yields for the model projections of the year 2050 in response to just CO_2 (A), precipitation (B), and temperature (C), and the three factor combination (D), based on a 15 years base line (BL). The projections were based on the A2 scenario (IPCC, 2007) and 16 general circulation models (GCMs) and Model M = mean of the 16 models. The subplot D (Ds) shows the least and highest yields in comparison with the baseline yield, using points, error bars, and a box which represent the 5th, 10th, 25th, 75th, 90th, and 95th percentiles, showing the median (solid line) and mean (broken line) in the box.

Simulated soil moisture did not show much response to various scenarios of CO_2 concentrations (not shown) but responded to various scenarios of temperature and precipitation (Figs. 7 and 8). Soil moisture decreased as temperature increased and precipitation decreased, showing steeper variations under dry conditions in both scenarios. Since there was no appreciable difference in soil moisture between the CO_2 treatments while crop biomass and yield were greater in the elevated CO_2 treatment, effects of water conservation on the plants under elevated CO_2 were assumed to exist. Our sensitivity results also imply that, in the future climate change conditions (IPCC, 2007), wheat grain yield will be decreased due to the effects of temperature increases, but partial compensation for the yield loss is assumed to be present due to CO_2 fertilization effects. The information on sensitivity of the current model to climate change variables can be applied generally for describing responses of wheat grain yield, soil moisture, and WUE to CO_2, temperature, and precipitation.

3.4. Simulated grain yield response to the projected climate change in 2050

Simulated grain yield response to the projected climate change variables individually and in combination for the year 2050 are presented using a cumulative distribution function (CDF) in Fig. 9. The CDF combined data from effects on wet, dry, high N, and low N treatments studied in the FACE. The simulated yield increased with the elevated CO_2 concentration of 550 ppm in comparison with the baseline CO_2 concentration of 370 ppm (Fig. 9A). In simulations with 16 general circulation models (GCMs), CDFs of the yields as a function of the precipitation change scenarios were practically the same as the baseline (BL) (Fig. 9B). No effects of the precipitation change scenarios for the yield are attributed to the comparatively small precipitation changes (e.g., mean monthly average of −2.2% from the BL average of 291.5 mm). The yield decreased with temperature increase in comparison with the BL (Fig. 9C). CDFs of the simulated yields in relation to the combined effects of CO_2, temperature, and precipitation were the same as the BL for the mean and most of the GCMs, the yield decreased for some models, e.g., Model 9 or ipsl_cm4 (Fig. 9D). The lowest and highest grain yields were simulated for GCM Models 9 and 13, respectively, which also showed the extreme temperature changes (refer to Table 3). It appears that the yield increase due to the CO_2 elevation scenario compensated for the yield decreases due to the temperature increase scenarios. Adams et al. (1990) reported that future changes in temperature and precipitation can lead to increases in crop water demands and reductions in yield, while increased CO_2 enhances crop yield in the US agriculture.

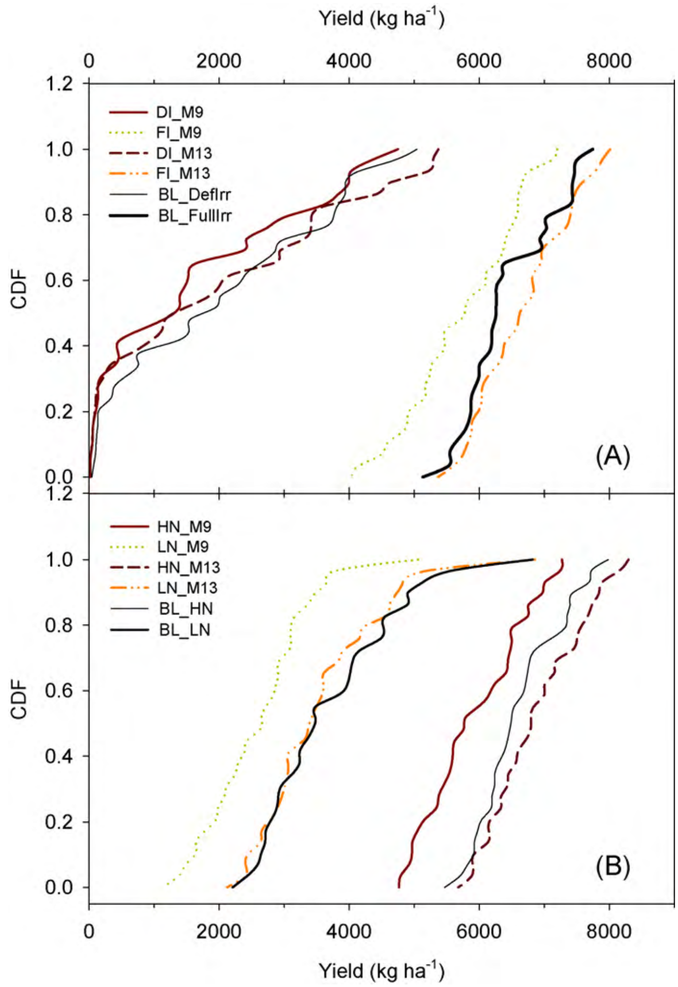

Fig. 10. Cumulative distribution function (CDF) of wheat grain yield in response to combined effect of all climate variables for 2050, for different field managements of irrigation (A) and nitrogen (B), simulated with Model 9 = ipsl_cm4 and Model 13 = mri_cgcm2_3_2a. DefIrr: deficit irrigation, FullIrr: full irrigation, HN: high nitrogen, and LN: low nitrogen, and BL: baseline.

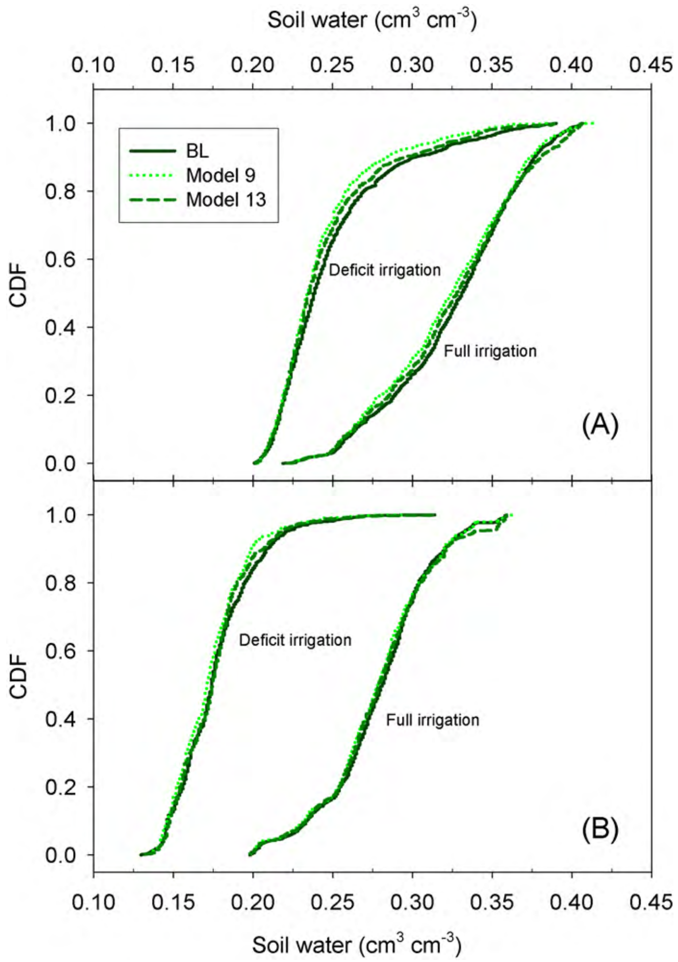

Fig. 11. Cumulative distribution function (CDF) of soil water at 0–30 cm (A) and 30–90 cm (B) over the crop season in response to combined effect of all climate variables for two 2050 projections (Model 9 = ipsl_cm4 and Model 13 = mri_cgcm2_3_2a) in comparison with the 15-year baseline (BL).

While the present results showed a general agreement with those by Adams et al. (1990), different climate change projections with maximum and minimum temperature variability might show different results. The results should also be affected by different atmospheric resolutions as well as origins of the GCMs (see Appendix A). Evaluation of the GCM models was not a scope of this study and we hypothesized that all the projections are probable. In addition, there are some uncertainties that validity of the projections of current crop models for future conditions may not be guaranteed by the validation under the current conditions. Therefore, further studies should be followed to address these issues with more advanced climate change projections and more process-based models of the agricultural system. We also believe that scientifically more advanced crop models would effectively simulate possible interactions of CO_2 effects with climate and other environment factors such as temperature, soil water, and N.

The management effects of irrigation and N on yield and soil water were investigated using the combined effects of all climate variables from Model 9 and 13 projections. There were significant differences in simulated grain yield between the full and deficit irrigation levels as well as the low and high N regimes similarly for the both projections (Fig. 10). The yield differences due to the irrigation and N managements ranged from ~1500 to 3500 kg ha^{-1} while those attributable to the different GCMs projections ranged between 0 and 1000 kg ha^{-1}. Meanwhile, simulated soil water during the season for the climate change scenarios (represented with Model 9 and 13) slightly decreased in comparison with that for the BL (Fig. 11). The variation between the different irrigation regimes was much greater than that between the climate change effects. The simulated soil water between the climate change effects varied more in the soil profile of 0–30 cm than that of 30–90 cm. In summary, we show that irrigation and N managements can dominate over climate change effects on yield and soil. Together with irrigation, timing of precipitation (especially under rainfed conditions) is also an important factor which has bigger effects than the total amount of seasonal precipitation (Baigorria et al., 2007).

4. Conclusions

CERES-Wheat4.0 in RZWQM2 was calibrated and validated for simulations of spring wheat grown in the Free Air CO_2 Enrichment (FACE) experiments at Maricopa, Arizona, USA. Soil moisture and plant growth were simulated with reasonable accuracy, within ±2 SD of measured data, for climate change impact assessments. The effects of water and N treatments were higher than those of CO_2, and the model reasonably simulated these effects. We also presented sensitivity of wheat to individual climate change variables for future model application as well as simulation with projections from 16 GCMs that include increased temperature and precipitation changes along with CO_2 for 2050. The beneficial effects of

CO_2 on yield were cancelled by negative effects of temperature increases, where precipitation changes had negligible effects. The irrigation and N effects were much higher than climate change effects. The simulations are comparable with some complex model simulations of photosynthetic carbon uptake in reproducing the dynamics of whole plant level crop growth (Tubiello and Ewert, 2002). A validated model is a good tool for analyzing possible impacts of climate change on wheat production in the region. The CERES-Wheat 4.0 module in the RZWQM2 model responded satisfactorily to the climate change deriving factors including CO_2, temperature, and precipitation. The results demonstrate the promise of the model for simulating climate change impacts on wheat production and soil water availability.

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Appendix A. General Circulation Models (GCMs) used for the climate change projections.

No.	GCM name	Host Center Institution	Atmospheric resolution (lat, long,°)
1	bccr_bcm2_0	Bjerknes Center for Climate Research, Norway	1.8 × 2.8
2	cccma_cgcm3_1_t63	Canadian Centre for Climate Modeling and Analysis, Canada	3.75 × 3.75
3	cnrm_cm3	CERFACS, National Weather Research Center, METEO-FRANCE, France	2.8 × 2.8
4	csiro_mk3_0	CSIRO Atmospheric Research, Australia	1.88 × 1.88
5	gfdl_cm2_0	Geophysical Fluid Dynamics Laboratory, USA	2 × 2.5
6	gfdl_cm2_1	Geophysical Fluid Dynamics Laboratory, USA	2 × 2.5
7	giss_model_e_r	NASA Goddard Institute for Space Studies, USA	4 × 5
8	inmcm3_0	Institute for Numerical Mathematics, Russia	4 × 5
9	ipsl_cm4	Pierre Simon Laplace Institute, France	2.5 × 3.75
10	miroc3_2_medres	Center for Climate Systems Research; National Institute for Environmental Studies; Frontier Research Center for Global Change, Japan	2.8 × 2.8
11	miub_echo_g	Meteorological Institute of the University of Bonn, Germany	3.75 × 3.75
12	mpi_echam5	Man Planck Institute for Meteorology, Germany	1.878 × 1.88
13	mri_cgcm2_3_2a	Meteorological Research Institute, Japan	2.8 × 2.8
14	ncar_ccsm3_0	National Center for Atmospheric Research, USA	1.4 × 1.4
15	ncar_ pcm1	National Center for Atmospheric Research, USA	2.8 × 2.8
16	ukmo_hadcm3	Hadley Centre for Climate Prediction, Met Office, UK	2.5 × 3.75

Appendix B. Monthly temperature changes (°C) for the year 2050 projected with 16 General Circulation Models (GCMs) and the corresponding 30-year baseline (BL) for Maricopa, AZ.

Model	January (°C)	February (°C)	March (°C)	April (°C)	May (°C)	June (°C)	July (°C)	August (°C)	September (°C)	October (°C)	November (°C)	December (°C)	Mean (°C)
1	1.20	1.03	1.82	1.49	1.54	1.46	1.36	1.49	1.79	1.89	1.82	1.58	1.54
2	1.37	2.23	2.49	1.92	2.38	1.53	2.77	3.22	2.61	2.26	1.85	1.82	2.20
3	1.43	1.20	1.66	2.23	1.69	2.10	2.15	2.17	1.97	2.47	2.09	1.46	1.89
4	1.37	1.45	1.88	1.10	1.36	1.65	1.38	1.32	2.09	2.89	1.23	1.15	1.57
5	2.00	1.63	1.59	3.20	2.83	2.63	2.87	3.28	2.65	2.89	2.52	1.37	2.45
6	1.06	1.36	1.33	1.83	2.47	2.49	2.86	2.89	3.18	1.95	1.66	1.46	2.04
7	0.84	0.82	1.34	1.20	1.94	2.39	2.29	1.92	2.46	2.09	0.70	0.97	1.58
8	2.66	2.57	2.13	2.11	2.28	3.01	2.97	2.36	2.35	2.07	2.42	3.17	2.51
9	3.15	2.81	2.12	2.86	1.96	2.69	2.64	2.79	3.11	2.00	2.18	2.74	2.59
10	1.81	2.04	1.66	2.65	2.72	2.44	2.48	2.65	2.88	2.93	2.79	2.33	2.45
11	1.77	2.04	1.66	2.36	1.65	1.66	1.43	1.69	1.83	2.18	1.80	1.69	1.81
12	1.60	1.25	2.06	1.54	1.82	2.01	1.95	2.57	2.83	2.81	2.84	1.89	2.10
13	0.68	0.86	1.11	0.97	1.43	1.64	1.59	1.57	1.71	2.29	1.89	1.15	1.41
14	1.97	1.79	1.96	2.24	2.99	2.83	2.53	1.74	2.71	2.87	2.58	1.86	2.34
15	1.04	1.13	1.67	1.16	1.32	1.71	1.88	1.77	1.46	1.13	0.89	0.86	1.34
16	1.56	1.32	1.77	2.06	2.37	3.44	1.90	2.50	2.60	2.53	1.95	1.75	2.15
Mean	1.60	1.59	1.77	1.93	2.05	2.23	2.19	2.25	2.39	2.33	1.95	1.70	2.00
BL	5.77	7.79	10.57	14.97	20.42	25.82	29.78	29.35	24.88	17.93	10.48	6.11	16.99

Appendix C. Monthly precipitation changes (%) for the year 2050 projected with 16 General Circulation Models (GCMs) and the corresponding 30-year baseline (BL) for Maricopa, AZ.

Model	January (%)	February (%)	March (%)	April (%)	May (%)	June (%)	July (%)	August (%)	September (%)	October (%)	November (%)	December (%)	Mean (%)
1	−22.8	−4.3	−50.8	−67.1	13.8	−37.8	69.6	59.4	−36.4	10.0	−20.7	44.1	−3.6
2	−28.6	−42.1	20.7	11.4	−36.8	9.5	−38.4	−45.0	13.8	6.0	−21.7	−24.5	−14.7
3	35.2	−39.7	−50.3	−67.4	−59.5	172.0	−1.2	−8.1	−10.8	−38.6	−2.9	−20.4	−7.6
4	−5.6	−6.9	−24.5	−0.1	−51.0	29.0	−8.2	17.8	−23.0	−21.0	−23.2	−4.7	−10.1
5	24.6	−1.6	−29.4	−63.4	−58.6	79.1	172.0	47.2	44.3	5.6	−23.0	−19.1	14.8
6	38.0	21.9	−10.9	−48.9	−67.0	98.3	−41.7	−21.6	2.4	39.5	97.6	−19.4	7.3
7	25.0	−3.4	−13.4	−2.7	−40.7	−25.1	−12.1	29.9	−20.2	16.4	23.6	34.5	1.0
8	29.2	36.3	20.1	13.4	1.8	16.3	19.9	0.2	6.2	10.8	1.1	−2.0	12.8
9	−13.2	−8.3	−15.8	−28.8	−3.1	−23.9	−33.7	−1.6	−16.1	−40.8	−10.6	10.9	−15.4
10	−30.9	−13.8	−35.1	−44.6	−24.7	−25.8	−14.2	2.2	−6.7	−20.6	−31.2	−29.9	−22.9
11	−10.9	12.0	−19.0	−23.0	−15.6	−76.4	−78.0	−17.7	172.0	−36.6	41.7	25.1	−2.2
12	−28.7	37.0	−13.1	−17.7	151.7	84.9	−31.8	−28.1	−29.9	8.7	1.1	9.5	12.0
13	−19.6	−10.9	−3.3	32.4	−43.5	−40.3	−20.0	20.5	−45.9	26.5	−41.2	16.7	−10.7
14	18.4	−11.1	−23.0	−30.6	−22.9	30.1	4.7	76.7	−19.3	−25.7	−27.9	−17.7	−4.0
15	13.4	−7.5	−4.8	4.3	−26.9	−52.0	−45.5	−32.8	19.2	22.0	22.7	11.8	−6.4
16	7.5	9.1	−15.9	−53.8	−68.4	117.4	20.8	−17.1	67.1	130.6	−8.3	−5.2	15.3
Mean	1.9	−2.1	−16.8	−24.2	−22.0	22.2	−2.4	5.1	7.3	5.8	−1.4	0.6	−2.2
BL (mm)	40.5	37.7	35.3	18.9	7.3	4.8	8.6	18.2	24.8	28.3	30.7	35.4	24.8

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