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Abstract Agricultural systems models are essential tools to assess potential climate change (CC) impacts on crop production and help guide policy decisions. In this study, impacts of projected CC on dryland crop rotations of wheat-fallow (WF), wheat-corn-fallow (WCF), and wheat-corn-millet (WCM) in the U.S. Central Great Plains (Akron, Colorado) were simulated using the CERES V4.0 crop modules in RZWQM2. The CC scenarios for CO_2, temperature and precipitation were based on a synthesis of Intergovernmental Panel on Climate Change (IPCC 2007) projections for Colorado. The CC for years 2025, 2050, 2075, and 2100 (CC projection years) were super-imposed on measured baseline climate data for 15–17 years collected during the long-term WF and WCF (1992–2008), and WCM (1994–2008) experiments at the location to provide inter-annual variability. For all the CC projection years, a decline in simulated wheat yield and an increase in actual transpiration were observed, but compared to the baseline these changes were not significant ($p>0.05$) in all cases but one. However, corn and proso millet yields in all rotations and projection years declined significantly ($p<0.05$), which resulted in decreased transpiration. Overall, the projected negative effects of rising temperatures on crop production dominated over any positive impacts of atmospheric CO_2 increases in these dryland cropping systems. Simulated adaptation via changes in planting dates did not mitigate the yield losses of

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the crops significantly. However, the no-tillage maintained higher wheat yields than the conventional tillage in the WF rotation to year 2075. Possible effects of historical CO_2 increases during the past century (from 300 to 380 ppm) on crop yields were also simulated using 96 years of measured climate data (1912–2008) at the location. On average the CO_2 increase enhanced wheat yields by about 30%, and millet yields by about 17%, with no significant changes in corn yields.

Abbreviations

CT	conventional tillage
DSSAT	decision support system for agrotechnology transfer
E	model efficiency
FACE	free air CO_2 enrichment
GCM	General Circulation Model
GHG	green house gas
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change Special Report on Emission
SRES	special emission scenarios
IPCC	intergovernmental panel on climate change
LAI	leaf area index
NT	no-tillage
PFCs	Perfluorocarbons
RMSD	root mean square difference
RZWQM	root zone water quality model
SD	standard deviation
WCF	wheat-corn-fallow
WCM	wheat-corn-millet
WF	wheat-fallow
WUE	water use efficiency
SF_6	Sulphur hexafluoride

1 Introduction

Global CO_2 emissions represent 77% of the total anthropogenic greenhouse gases (GHG: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6). CO_2 emissions have increased by approximately 80% from 1970 to 2004 and are projected to increase by 40 to 110% between 2000 and 2030 from energy use alone (IPCC 2007). The build-up of anthropogenic GHGs in the atmosphere have resulted in increased global mean surface temperatures by 0.74°C±0.18°C over the last 100 years (1906–2005)and for the next two decades, a warming of approximately 0.2°C per decade is predicted according to the IPCC Special Report on Emission Scenarios (IPCC 2007). The likely doubling of atmospheric CO_2 and associated warming within the next century may affect agricultural production through changes in evapotranspiration, plant growth rates, plant litter composition, and nitrogen-carbon cycling (Long et al. 2006). In the semi-arid regions of the world, increased in crop demand for water due to higher temperatures could seriously affect crop production in these already water stressed areas. However, the effect at any given location will depend on the choice of crops and location-specific management. In order to understand the effects and recommend remedial measures, it is important to study the impacts of a projected increase in CO_2 and consequent global climate change on water-limited cropping systems.

In earlier studies, investigators measured responses of various crops to elevated CO_2 and temperature in enclosed chambers (e.g., Kimball 1983; Allen et al. 1987). These studies showed relatively large fertilization effect of CO_2 on both C3 and C4 crops, averaging about 31-32% for wheat and soybean and 18% for corn and other C4 crops at 550 ppm CO_2 concentration (Long et al. 2006). More recently, 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 more realistic, open-air field conditions at different water and nitrogen levels (Ainsworth and Long 2005; Kimball et al. 2002). 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 corn and sorghum were not affected, except under drought conditions (Leaky et al. 2006; Ottman et al. 2001). 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. 2006). Thus, the level of water availability to crops will influence their responses to CO_2. Similarly, the level of nitrogen in the leaf tissue can affect responses to both CO_2 and water (Grossman-Clarke et al. 2001). Most importantly, the concurrent increase in temperatures may have negative effects on yield, which counteract the positive effects of CO_2.

In an agricultural system, plant growth and development are products of the integrated effects of the various interacting environmental variables (temperature, CO_2, nutrients, water, and agronomic management) on eco-physiological processes. It is impossible to incorporate all of these variables and their interactions in a field experiment (e.g., FACE) to study their impacts on agricultural production. Well-calibrated and tested agricultural system models are essential tools for integration of the various chemical, physical, and biological processes and their interactions in the system (Ma et al. 2009). A validated system model could be employed to study how the temperature and precipitation changes associated with enhanced CO_2 level will influence the responses of crops to CO_2, water and nitrogen. Adams et al. (1990) reported that climate changes in temperature and precipitation projected by the GCMs led to reductions in yields and increased crop water demands, mitigating some or all of the CO_2 enhanced crop yields. Saseendran et al. (2000) used the CERES-rice model to study the impact of climate change on rice production in a humid tropical environment characterized by suboptimal temperatures during the growing season (June to August—summer monsoon) and showed that rice crop yields can increase from improvement in day time temperatures predicted by GCMs. Anderson et al. (2001) used CERES-Maize, SOYGRO, and DAFOSYM crop models to identify impacts of historical climate on corn, soybean, and alfalfa productions at 13 sites in the Great Lakes region using long-term (1895–1996) climatological series. They found that low precipitation and high moisture stress were chief limitations to simulated crop yields in the region. Parry et al. (2004) reported potential impacts of climate change on global crop production using different SRES emissions and socio-economic scenarios (i.e., A1FI, A2, B1, and B2, see IPCC 2007). These scenarios are based on different assumptions about the GHG emissions in the future. They predicted that regional differences in crop production are likely to grow stronger through time, especially under A1FI and A2 scenarios. Tubiello et al. (2002) evaluated the projected climate change effects on US crop production of wheat, potato, corn, and citrus, based on two GCM scenarios. According to their study, climate change resulted in significant reductions of grain yield (30 to 40%) in some rainfed production areas, accompanied by increased year-to-year variability. Thompson et al. (2005) also summarized a US national assessment of dryland production of grain (corn, soybean, and winter wheat) and two forage (alfalfa and clover hay) crops based on climate change scenarios from three GCMs at two levels of CO_2 concentrations (365 and 560 ppm). They projected overall national production of the crops to change by ±25% from present levels and to vary regionally by greater than ±50%. Agricultural system simulation models have also been used to explore some adaptation strategies (e.g., Lobell et al. 2008; Rosenzweig and Parry 1994). Lobell et al. (2008) opined that in some regions, one possible adaptation strategy can be to switch from highly impacted to less impacted crops. Until now, most assessment studies have been focused on single crops such as wheat or corn, while much less is known about potential effects of climate change on crop production under various cropping rotation systems.

Field experiments on several no-till dryland cropping systems of increasing cropping intensity (i.e., reduced fallow frequency) involving winter wheat in rotation with various summer crops (e.g., corn, proso-millet, sunflower, canola) have been conducted since 1991 at the USDA-ARS Central Great Plains Research Station at Akron, Colorado, USA (Anderson et al. 1999). Some results from these experiments were effectively simulated using the DSSAT-CERES models in RZWQM earlier (Saseendran et al. 2005, 2008, and 2009). Saseendran et al. (2010) successfully simulated the crop rotations experiments in this study (WF under both CT and NT, and WCF and WCM under NT) using RZWQM2 (described in the next section). The objectives of this study were to use the calibrated and validated wheat, corn and proso millet crop modules in RZWQM2 (Saseendran et al. 2010) to: (1) simulate the impacts of GCM projected CO_2 and climate change scenarios for the years 2025, 2050, 2075, and 2100 on wheat, corn, and millet crop production in the above rotations representing the Central Great Plains; and (2) for comparison, simulate the possible impact of CO_2 increases in the past century with measured climate conditions on crop yields in these rotations.

2 Materials and methods

2.1 RZWQM2 modeling package

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 under different climates (Ahuja et al. 2000b). 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 are linked with the CSM-DSSAT 4.0 crop modules in the current version, RZWQM2 (Ma et al. 2009). It has the advantages of combining the detailed soil water, nitrogen, and management 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 and 2009; Saseendran et al. 2007; Yu et al. 2006).

The DSSAT4.0-CERES crop simulation modules for wheat, corn, and proso millet modules in RZWQM2 were used (Saseendran et al. 2009; Ma et al. 2009) in this study. 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, and microbial population processes are simulated in detail (Shaffer et al. 2000). Management practices simulated in the model include: tillage, applications of irrigation, manure and fertilizer at different rates and times by different methods, planting and harvesting operations, and surface crop residue dynamics (Rojas and Ahuja 2000).

The DSSAT4.0-CERES plant growth module in RZWQM2 simulates phenological stage, vegetative and reproductive growth, and crop yield and its components. This module 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:

$$RUE = \frac{RUE_m \cdot \ CO_2}{CO_2 + K_m} + RUE_i \tag{1}$$

where RUE_m is the asymptotic response limit of (RUE—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 (RUE—RUE_i)=0.5 RUE_m. Similar approaches were followed for simulations of CO_2 effects on cropping systems in EPIC (Williams et al. 1989), APSIM, the Agricultural Production System Simulator model, (along with nitrogen use efficiency and water use efficiency) (Reyenga et al. 1999), and Sirius (Jamieson et al. 2000). Water stress effects on photosynthesis are simulated by CERES using empirically calculated stress factors, with respect to potential transpiration and crop water uptake (Ritchie and Otter-Nacke 1985). Enhancement in CO_2 concentration also decreases stomatal conductance (increases stomatal resistance) in the equation for calculating potential transpiration in DSSAT-CERES, based on the literature (Allen 1986, 1990; Rogers et al. 1983). In RZWQM2, the same algorithm is used to reduce potential transpiration due to CO_2 effect with the Shuttleworth-Wallace equation. The decrease in potential transpiration demand, in turn, decreases root water uptake and actual transpiration, and reduces plant water stress. Ko et al. (2010) showed that RZWQM2 simulated the Arizona FACE yield data well for two levels of CO_2 at two levels each of water and N.

2.2 Cropping system data

Field data used in this study were obtained from the long-term dryland Alternative Crop Rotation (ACR) experiments at the Central Great Plains Research Station (CGPRS), USDA Agricultural Research Service at Akron, Colorado, USA (40^o 09' N, 103^o 09' W; 1,384 m) since 1991. The CGPRS receives about 420 mm of mean annual precipitation. These experiments were carried out on a Weld silt loam soil in plots (9.1 m×30.5 m) laid out in an east–west direction with three replications in a randomized complete block design. Twenty crop rotations were initially established, which include combinations of six crops and fallow, and three tillage treatments. Bowman and Halvorson (1997) and Anderson et al. (1999) reported detailed cultural practices, plot area, and experiment design. In this study, we used data from the wheat-fallow (WF), wheat-corn-fallow (WCF), and wheat-corn-millet (WCM) cropping systems. The WF and WCF data were available for 17 years from 1992 to 2008 and WCM for 15 years from 1994 to 2008. The WF cropping system was conducted under both conventional tillage (CT) and no tillage (NT) while the WCF and WCM were practiced under NT only. All phases of all the crop rotations were included every year in the experiments comprising 10 data sets: 1) WF(CT)-W (beginning wheat phase), 2) WF(CT)-F (beginning fallow phase), 3) WF(NT)-W (beginning wheat phase), 4) WF(NT)-F (beginning fallow phase), 5) WCF-W (beginning wheat phase), 6) WCF-C (beginning corn phase), 7) WCF-F (beginning fallow phase), 8) WCM-W (beginning wheat phase), 9) WCM-C (beginning corn phase), 10) WCM-M (beginning millet phase).

Three winter wheat cultivars, 'TAM 107' from 1991 to 1995', 'Akron' from 1996 to 2005, and 'Danby' from 2006 to 2008, were planted. Five corn hybrids used were 'Pioneer Hybrid 3732' from 1992 to 1997, 'DK493 BT' from 1998 to 1999, 'DKC49-92' in 2000, 'NK4242 BT' from 2001 to 2003, and 'N42B7' from 2004 to 2008. Two proso millet cultivars planted were 'Sunup' from 1995 to 2000, and from 2002 to 2005, and 'Huntsman' in 2001, 2006, 2007, and 2008. Detailed descriptions of cultural practices for simulations using RZQM2 are available in Saseendran et al. (2010).

2.3 Model parameterization and calibration

The minimum driving variables for RZWQM2 simulations are daily solar radiation, maximum and minimum temperature, precipitation, soil texture, and initial soil nitrogen and soil water status. Typical crop management practices include planting dates, planting depth, plant population, and amount and method of irrigation and fertilizer applications. Cultivar parameters for the cultivars used in the simulations were calibrated for the location as described in Saseendran et al. (2010).

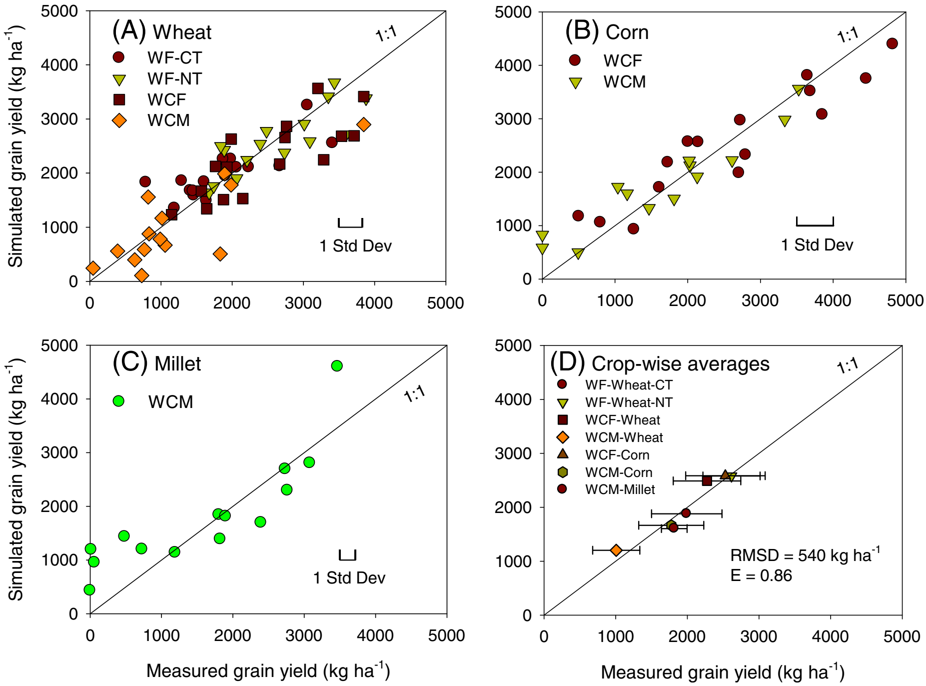

Fig. 1 Simulated vs. measured grain yields of **a** wheat, **b** corn, **c** millet, and **d** all the crops in wheat-fallow (*WF*) under conventional tillage (*CT*) and no tillage (*NT*), wheat-corn-fallow (*WCF*) under NT, and wheat-corn-millet (*WCM*) under NT. The horizontal bars represent ±1 standard deviation. (Saseendran et al. 2010)

Summary results of the model calibration/validation for wheat, corn, and millet grain yields under the different cropping systems are reproduced from Saseendran et al. (2010) in Fig. 1. Simulated grain yields of wheat (A), corn (B), and millet (C) corresponded to the measured grain yields mostly within ±1 Root Mean Squared Difference (RMSD), with value less than 540 kg ha^{-1}, and model efficiency (E) 0.86 (Nash and Sutcliffe 1970) for all the three crops. These statistics are frequently used to evaluate the model performance using the following formulas:

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

$$E = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_{avg})^2} \tag{3}$$

where S_i is the i^{th} 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 versus measured data, but E is generally lower than R^2 and can be negative when the predictions are very biased relative to measured variance.

2.4 Projected climate change impacts for the years 2025, 2050, 2075, and 2100

In the IPCC SRES document (IPCC 2007), only three scenarios of B1, A1B, and A2 were studied intensively by climate modeling centers, and the implications of the three scenarios are similar to one another for a 25- to 50-year planning and adaptation horizon (Ray et al. 2008). The climate changes for Colorado projected by Ray et al. (2008) comprise a synthesis of multiple realization GCM runs, which means that our climate drivers can be viewed as ensemble average climate projections for each projection period. Based on the three scenarios, the CO_2 concentration is projected to increase from 380 ppm in 2005 to 550 ppm in 2050 (Table 1), and by assuming a linear increase we interpolated the 2025 CO_2 concentration of 415 ppm. Based on the SRES A2 scenario, CO_2 is projected to increase from 550 ppm in 2050 to 836 ppm in 2100. Assuming a linear increase in CO_2 with time from 2050 to 2100 the 2075 concentration will be 693 ppm.

Table 1 Climate change scenarios in Colorado superimposed on the baseline experimental period, based on the synthesis of multiple GCM projections by Ray et al. (2008)

Year	CO_2 (ppm)	Temp increase (°C)		Precipitation change (%)	
		Apr-Sep	Oct-Mar	Apr-Sep ($-\Delta P_w$)	Oct-Mar
2025	415	1.9	0.8	−10%	$+\Delta P_w$
2050	550	2.7	1.6	−20%	$+\Delta P_w$
2075	693	3.5	2.4	−30%	$+\Delta P_w$
2100	836	4.3	3.2	−40%	$+\Delta P_w$

Climate models project that Colorado will warm by 1.4°C (1.5 to 3.5°C) by 2025, relative to the 1950–99 baseline, and 2.2°C (2.5 to 5.5°C) by 2050 (Ray et al. 2008). Based on the report by Ray et al. (2008), it is assumed that the 2025 temperatures will increase by 1.9°C in summers and 0.8°C in winters. In 2050, 2075, and 2100, summer temperatures are expected to increase by 2.7°C, 3.5°C, and 4.3°C, and the winter temperatures are increased by 1.6°C, 2.4°C, and 3.2°C, respectively (Table 1).

Ray et al. (2008) also reported that there are no consistent long-term trends in mean annual precipitation for Colorado. However, a seasonal shift in precipitation amounts was reported with a decrease in late spring and summer, and an increase in fall and winter precipitation. Following this seasonal shift, we assumed that the precipitation will decrease by 10% per 25 years in the warm ("summer") season (April to September) and increase by the same amount in the cold ("winter") season (Table 1). The numerical procedure for this projection is described in the following equations.

$$P_S = \sum_{i=1}^{N} p_i(\text{summer}) \tag{4}$$

$$P_w = \sum_{i=1}^{M} p_i(\text{winter}) \tag{5}$$

$$\Delta P_s = fP_s \tag{6}$$

$$\widehat{p}_i(summer) = p_i(summer) - \frac{\Delta P_s}{N}, i = 1, \ldots N \tag{7}$$

$$\widehat{p}_i(\text{winter}) = p_i(\text{winter}) + \frac{\Delta P_s}{M}, 1, \ldots, M \tag{8}$$

In the above equations, P is the cumulative seasonal precipitation for half-year periods called summer (P_s) or winter (P_w), ΔPs is the total decrease in P_s in a given year and is also the corresponding increase in P_w, f is the fraction of P_s that decreases yearly, p_i is daily precipitation that occurs on N days in summer and M days in winter, and $\widehat{p}_i$ is the modified daily precipitation resulting from the proportional reduction during summer and increase during winter. The fraction f is assumed equal to 0.1, 0.2, 0.3, and 0.4 for years 2025, 2050, 2075 and 2100, respectively. These changes are probably on the high side and may represent an extreme case we wished to explore. Thus there is no change in annual P, and daily p_i is modified by a constant for each season, which assumes no changes to within season variability in precipitation. Such detailed changes cannot be projected with any known confidence. So we used this relatively simple "delta" method.

To simulate the projected CC impacts on the cropping systems, the temperature and precipitation changes corresponding to the CC scenarios (see Table 1) were superimposed on the measured climate data for a number of baseline years in order to allow year to year variability in projections. Baseline years used in this study corresponded to the time span of the experimental periods for each of the three cropping systems (i.e. 17 years from 1992 to

2008 for WF and WCF and 15 years from 1994 to 2008 for the WCM). These baseline years encompassed included both above normal and below normal rainfall years, so we thought these baseline periods were sufficient. The initial conditions for the soil water and nitrogen levels for the simulations were set equal to an average value for the field measured baseline years. Each year was simulated separately starting the average initial conditions, not in a continuous simulation for all years, to minimize correlation among the results among the years. Simulations were made for effects on crop yield of the individual climate change factors (i.e., CO_2, temperature, and precipitation) as well as their combinations. The results for 17 or 15 years in each case were expressed as cumulative distribution functions (CDFs). To obtain a CDF, the yearly simulated yields are ordered according to their value from the smallest to the largest. Then, the probability of obtaining a yield or less than or equal to each simulated yield value is computed as the ratio of its serial number to the total number of values in the set. Thus, the cumulative probabilities vary between zero and one.

2.5 Simulation of the effects of past measured climate and CO_2 changes on the cropping systems

We simulated wheat, corn and proso millet yields in three rotations (WF, WCF, and WCM) to see how historical increases in CO_2 (from 300 to 380 ppm) and associated weather as recorded at the station from 1912 to 2008 may have affected the yields. Three separate simulations were run with three CO_2 concentrations (300, 340 and 380 ppm). In this case, each combination of the crop rotation and CO_2 concentration was run continuously for 96 years, starting with an average initial condition in 1912. The crop cultivars and other management practices were based on current experiments. The simulated crop yields over the 96 years are presented as cumulative distribution functions (CDFs).

2.6 Statistical evaluation of simulations

The mean values of the CDFs for different projection years as described in Section 2.4 were tested statistically for significance of differences from the mean of baseline CDF using the Duncan's Multiple Range Test (DMRT 1955) using PROC GLM (SAS version 9.2, Cary, NC). We also performed a nonparametric test for the CDF as a whole, the Kolmogorov-Smirnov (K-S) test, using PROC NPAR1WAY (SAS version 9.2, Cary, NC) between the baseline CDF and each of the projection year's CDF. For this purpose, we assumed that year to year values within a CDF were statistically independent, as we simulated each year separately (not in a continuous simulation for all years) that minimized the dependence among years. The DMRT was applied to the total CDF mean, as well as to mean values for upper and lower halves of the CDFs. All significance testing used a 95% confidence level for both DMRT and K-S test, so differences are reported below as 'significant' based on this criterion.

3 Results and discussion

3.1 Effects of projected climate change on the WF under NT and CT

Cumulative distribution function (CDF) of simulated wheat yield in WF-CT for the baseline years were compared with the projections for 2025, 2050, 2075, and 2100 for effects of individual factors, as well as their combinations (Fig. 2). With increasing CO_2

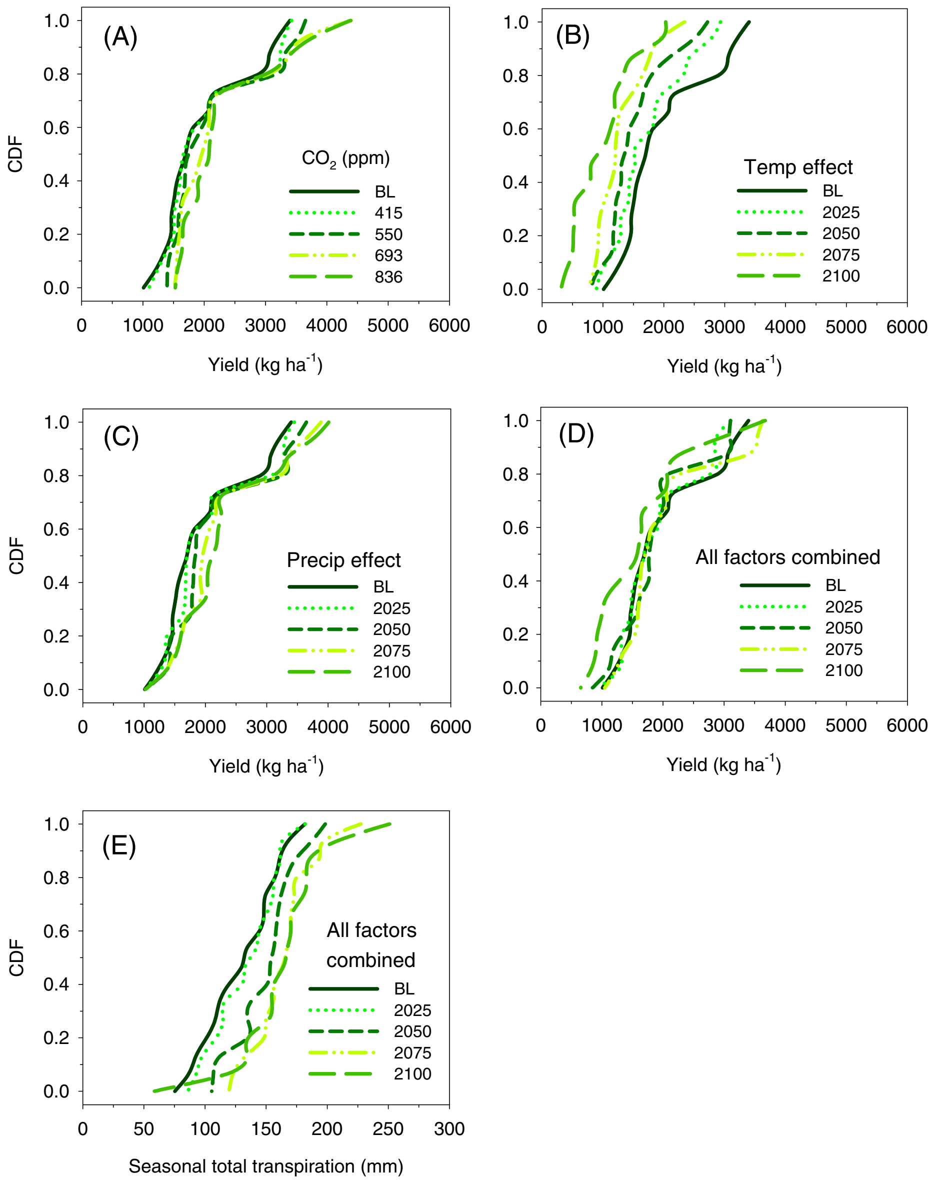

Fig. 2 Cumulative distribution function (*CDF*) of wheat grain yield in conventional tillage (*CT*) under the wheat-fallow (WF) cropping system, comparing simulated yield for the 17 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

concentrations alone (i.e., 415 ppm for 2025, 550 ppm for 2050, 693 ppm for 2075, and 836 ppm for 2100), the yield increased (Fig. 2a). However, this yield increase was mostly not significantly different in both K-S test and DMRT at 95% confidence intervals (Table 2). With increasing temperatures (e.g., S1.9-W0.8=1.9°C in summers and 0.8°C in winters for

Table 2 Statistical analysis for the simulation data (Fig. 2) of the future climate change impacts on winter wheat yield (A) and on transpiration (B) in wheat-fallow (WF) under conventional tillage

			Yield[#]		
		K-S test	CDF average	Higher CDF	Lower CDF
(A)		*p*		kg ha^{-1}	
CO_2 (ppm) effect	Baseline	-	1974[a]	2546[a]	1403[c]
	415	0.999	2026[a]	2609[a]	1442[c]
	550	0.699	2138[a]	2720[a]	1555[bc]
	693	0.210	2257[a]	2859[a]	1656[ab]
	836	0.210	2320[a]	2900[a]	1739[a]
Temperature effect	Baseline	-	1974[a]	2546[a]	1403[a]
	2025	0.699	1724[ab]	2199[ab]	1249[ab]
	2050	0.093	1512[bc]	1894[bc]	1130[bc]
	2075	0.012	1290[cd]	1610[c]	969[c]
	2100	0.001	981[d]	1415[c]	548[d]
Precipitation effect	Baseline	-	1974[a]	2546[a]	1402[a]
	2025	0.941	2036[a]	2617[a]	1456[a]
	2050	0.415	2135[a]	2724[a]	1546[a]
	2075	0.415	2220[a]	2824[a]	1616[a]
	2100	0.415	2275[a]	2891[a]	1660[a]
All factors combined[##]	Baseline	-	1974[a]	2546[a]	1403[a]
	2025	0.941	1901[a]	2417[a]	1385[a]
	2050	0.941	1881[a]	2365[a]	1397[a]
	2075	0.941	2007[a]	2555[a]	1458[a]
	2100	0.415	1627[a]	2232[a]	1021[b]
(B)		*p*		mm	
All factors combined[##]	Baseline	-	129.4[b]	155.5[b]	103.3[c]
	2025	0.999	133.5[b]	157.0[b]	110.0[bc]
	2050	0.210	149.9[ab]	170.2[ab]	129.6[ab]
	2075	0.036	163.9[a]	184.1[a]	143.8[a]
	2100	0.036	161.9[a]	189.5[a]	134.4[a]

[#] Yield and transpiration data were analyzed with both Kolmogorov-Smirnov (K-S) test and Duncan's Multiple Rage Test (DMRT). The data were divided into the averages of all CDF data (CDF 0–1), upper CDF (data higher than CDF 0.5), and lower CDF (data lower than CDF 0.5)

[##] Combination of CO_2, temperature, and precipitation projections

[a,b,c] The values with the same superscript letters are not significantly different (DMRT at 95% confidence intervals)

2025), the yield decreased (Fig. 2b) with a statistically significant differences (Table 2). With precipitation change scenarios, yield increase was not statistically significant (Fig. 2c, Table 2). With all three factors-combined the yield generally decreased, but the yield decreases were not significant (Fig. 2d, Table 2). The CDFs of transpiration changes showed an overall significant increase with time, even though the yield decreased (Fig. 2e, Table 2). This suggests that demands on transpiration would increase due to the temperature increase even at some lower yield.

Using climate projections from a set of GCMs in EPIC crop growth models, Thompson et al. (2005) reported that over the conterminous USA, the universal effect of the increase in global mean temperature from +1 to +2.5°C was a decline in crop production, which was partially offset by the positive impact of CO_2 fertilization. The present study using a synthesis of several GCMs predicted the similar potential yield decreases in wheat production in the Central Great Plains. Similar results were reported by Adams et al. (1990), Favis-Mortlock et al. (1991), Nonhebel (1996), Brown and Rosenberg (1999), Tubiello et al. (1999) and Hatfield et al. (2008), although results with individual GCM projection may vary (Tubiello et al. 2002).

Climate change impacts on the wheat yield and transpiration in WF-NT (Fig. 3) were similar to those in WF-CT (Fig. 2). The impacts of CO_2, temperature, precipitation, and all these three factors-combined on grain yield simulated are comparable between the two rotations (WF-CT and WF-NT) except the yield decrease in year 2100 for WF-NT was significant. The crop yield was higher under no tillage for baseline and 2025–2075 years, but the temperature effect in 2100 negated this advantage causing a greater reduction. Nonetheless, NT is a good adaptation strategy over CT.

3.2 Effects of projected climate change on the WCF-NT

Simulated wheat yield increased with CO_2 concentration (Fig. 4a) but a significant difference was found only for the lower part of the CDF (Table 3). Simulations with temperature increase alone showed statistically significant yield decreases (Fig. 4b and Table 3), and projected seasonal changes in precipitation alone resulted in insignificant yield increases (Fig. 4c, Table 3). When precipitation, temperature and CO_2 factors were combined in the crop model simulations, in general, marginal or no yield changes were simulated (Fig. 4d). However, these scenarios caused transpiration to increase significantly (Fig. 4e, Table 3). The simulated grain yields under the WCF were consistently lower than those in WF-NT but higher than those in WF-CT. In comparison with the WF-CT, the WCF-NT rotation was reported to improve soil quality through enhanced soil carbon sequestration with increased residue return to the soil (Anderson et al. 1999; Dhuyvetter et al. 1996; Smika and Unger 1986).

Corn yields in the present study for the Central Great Plains were projected to have small non-significant changes with the increasing CO_2 concentrations alone (Fig. 5a, Table 4). As a typical C_4 crop, similar response was reported by Long et al. (2006). Yields decreased with the elevated temperature in the climate change scenarios (Fig. 5b, Table 4), and this was statistically significant for the average and upper part of the CDF of the yield. A small yield decrease was also simulated with changes in precipitation alone (Fig. 5c), that was not statistically significant. Effects of all the three factors-combined scenarios resulted in statistically significant reductions in yield (Fig. 5d, Table 4) as well as transpiration (Fig. 5e, Table 4). However, the effect on transpiration was significant only for the upper CDF. Thompson et al. (2005) reported that the national production of dryland corn could potentially change by −20 to +10% depending upon the location under the scenarios of temperature increases at +1 and +2.5°C and of elevated CO_2 at 560 ppm.

3.3 Effects of projected climate change on the WCM-NT

Impacts of the climate change scenarios on wheat yield and transpiration in WCM were generally similar to those in WCF (Fig. 6). However, yields and transpiration

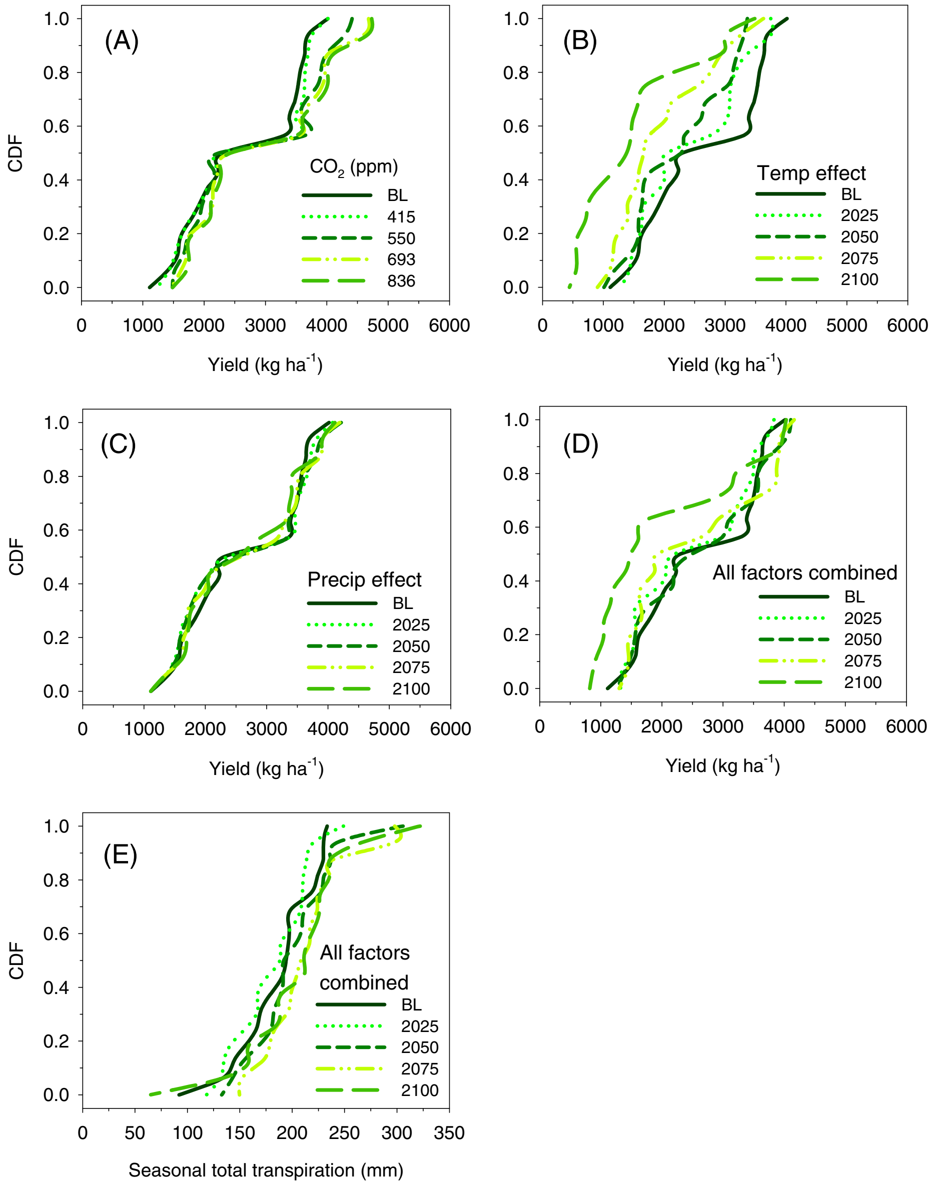

Fig. 3 Cumulative distribution function (*CDF*) of wheat grain yield in no tillage (*NT*) under the wheat-fallow (*WF*) cropping system, comparing simulated yield for the 17 baseline years (1992–2007) with the projections of yield caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

amounts in WCM were significantly lower than those in WCF and WF. Also, the seasonal precipitation change scenarios did not affect wheat yields in the WCM rotation. Differences in the yield between the scenarios were relatively small. Significant

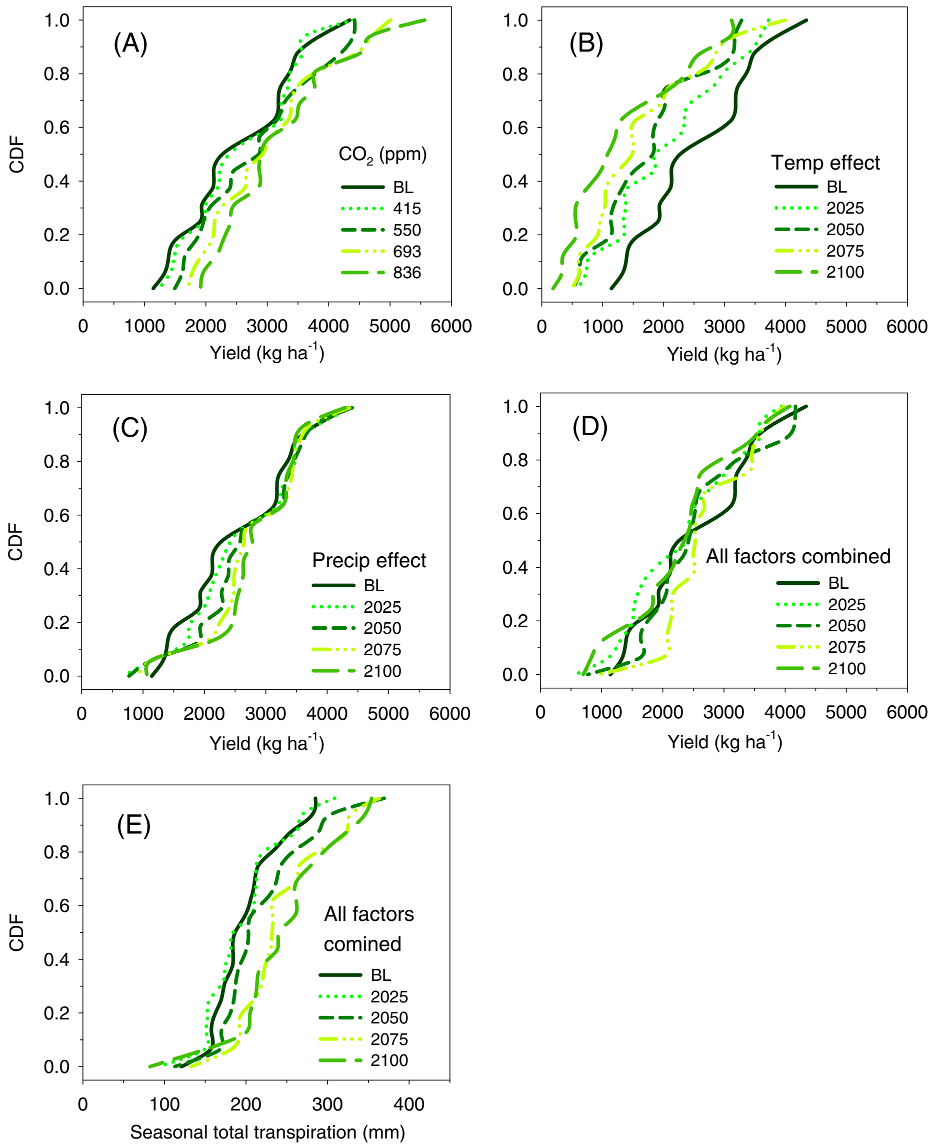

Fig. 4 Cumulative distribution function (*CDF*) of wheat grain yield under the wheat-corn-fallow (*WCF*) cropping system, comparing simulated yield for the 17 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

differences in the yields were found between the CDFs for the 'temperature alone increase' scenarios and only between the average and the upper parts of the CDFs for the three factors-combined scenarios. Significant differences in the transpiration amounts were found between all of the average, upper, and lower CDFs for the three factors-combined scenarios.

Table 3 Statistical analysis for the simulation data (Fig. 4) of the future climate change impacts on winter wheat yield (A) and on transpiration (B) under the wheat-corn-fallow (WCF)

			Yield[#]		
		K-S test	CDF average	Higher CDF	Lower CDF
(A)		*p*		kg ha^{-1}	
CO_2 (ppm) effect	Baseline	-	2530[a]	3279[a]	1687[b]
	415	0.999	2591[a]	3320[a]	1771[b]
	550	0.953	2828[a]	3614[a]	1945[ab]
	693	0.734	3026[a]	3796[a]	2224[a]
	836	0.240	3185[a]	3913[a]	2293[a]
Temperature effect	Baseline	-	2530[a]	3279[a]	1687[a]
	2025	0.454	2046[ab]	2816[ab]	1179[b]
	2050	0.112	1769[b]	2442[bc]	1012[b]
	2075	0.046	1652[b]	2352[bc]	865[bc]
	2100	0.005	1344[b]	2064[c]	534[c]
Precipitation effect	Baseline	-	2530[a]	3279[a]	1687[a]
	2025	0.999	2588[a]	3345[a]	1736[a]
	2050	0.454	2681[a]	3371[a]	1893[a]
	2075	0.454	2747[a]	3381[a]	2028[a]
	2100	0.240	2789[a]	3387[a]	2134[a]
All factors combined[##]	Baseline	-	2530[a]	3279[a]	1687[ab]
	2025	0.953	2292[a]	3055[a]	1433[b]
	2050	0.953	2519[a]	3182[a]	1773[ab]
	2075	0.454	2647[a]	3169[a]	2061[a]
	2100	0.734	2276[a]	2967[a]	1498[b]
(B)		*p*		mm	
All factors combined[##]	Baseline	-	199.0[b]	230.6[b]	163.4[ab]
	2025	0.734	195.3[b]	232.4[b]	153.7[b]
	2050	0.734	219.6[ab]	259.8[ab]	174.4[ab]
	2075	0.046	242.3[a]	281.8[a]	198.0[a]
	2100	0.046	243.7[a]	291.7[a]	189.6[ab]

[#] Yield and transpiration data were analyzed with both Kolmogorov-Smirnov (K-S) test and Duncan's Multiple Rage Test (DMRT). The data were divided into the averages of all CDF data (CDF 0–1), upper CDF (data higher than CDF 0.5), and lower CDF (data lower than CDF 0.5)

[##] Combination of CO_2, temperature, and precipitation projections

[a,b,c] The values with the same superscript letters are not significantly different (DMRT at 95% confidence intervals)

Effects of the climate change scenarios on corn yield and transpiration in the WCM rotation was qualitatively similar to those in the WCF rotation (Fig. 7). However, the average yields and transpiration amounts in WCM were significantly lower than those in WCF. Yield and transpiration decreased with the climate change scenarios of temperature alone, precipitation alone, and the three factors-combined change scenarios. Significant differences were found between the upper part of the CDFs of the yield for the 'increasing temperature' scenarios and between the average and upper CDFs of the yields for the 'three

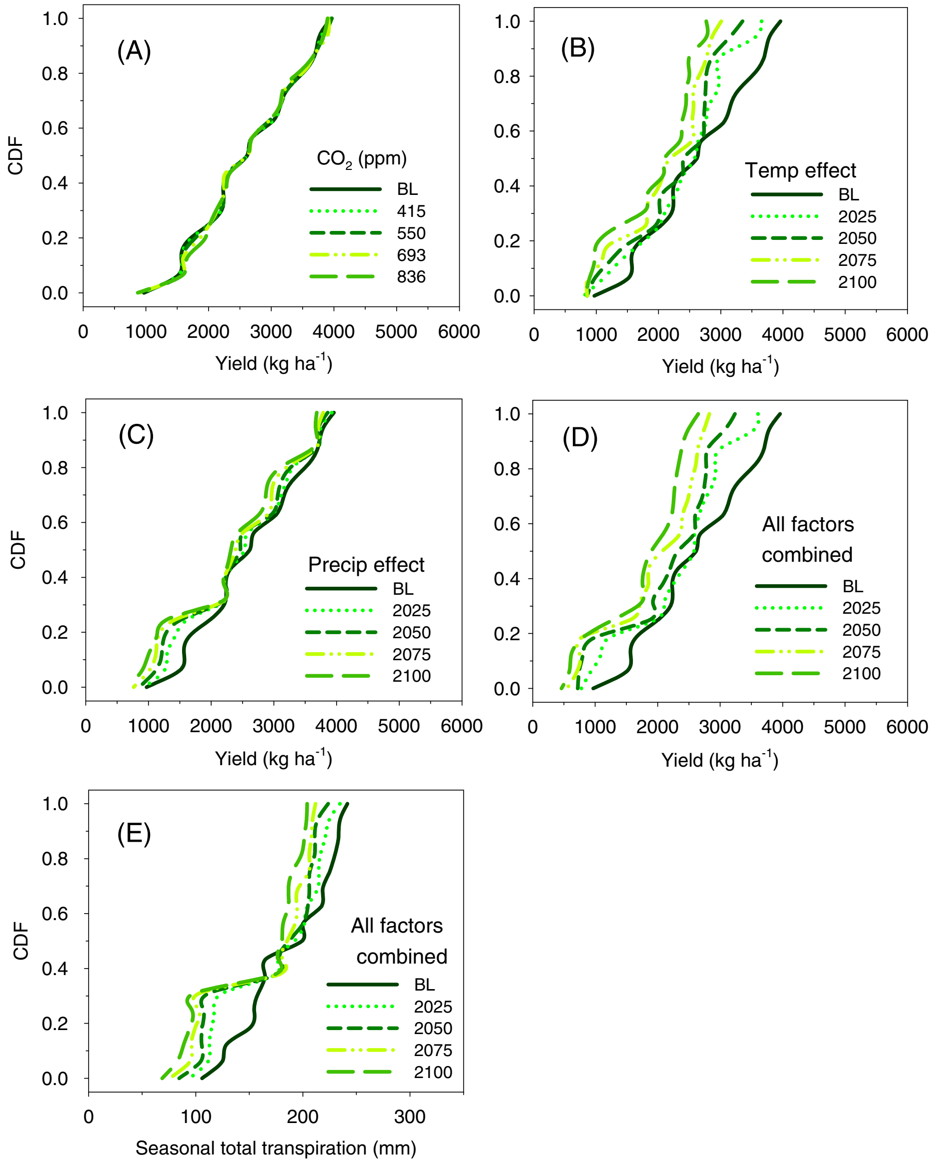

Fig. 5 Cumulative distribution function (*CDF*) of corn grain yield under the wheat-corn-fallow (*WCF*) cropping system, comparing simulated yield for the 17 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

factors-combined' scenarios . There was a significant difference between the upper CDFs of the transpiration for the 'three factors-combined' scenarios.

Increases in proso millet grain yields with the elevated CO_2 concentrations (Fig. 8a) were not statistically significant (Table 5). CO_2 fertilization effect on the yield was relatively higher than the effect on the corn yield but lower than that on the wheat yield.

Table 4 Statistical analysis for the simulation data (Fig. 5) of the future climate change impacts on corn yield (A) and on transpiration (B) under the wheat-corn-fallow (WCF)

		K-S test	Yield[#] CDF average	Higher CDF	Lower CDF
(A)		*p*		kg ha^{-1}	
CO_2 (ppm) effect	Baseline	-	2603[a]	3305[a]	1813[a]
	415	1.000	2606[a]	3310[a]	1814[a]
	550	1.000	2607[a]	3306[a]	1822[a]
	693	0.999	2608[a]	3302[a]	1824[a]
	836	0.999	2609[a]	3283[a]	1851[a]
Temperature effect	Baseline	-	2603[a]	3305[a]	1813[a]
	2025	0.454	2392[ab]	2988[b]	1723[a]
	2050	0.454	2257[ab]	2827[bc]	1616[a]
	2075	0.112	2077[ab]	2635[cd]	1450[a]
	2100	0.112	1938[b]	2470[d]	1340[a]
Precipitation effect	Baseline	-	2603[a]	3305[a]	1813[a]
	2025	0.953	2496[a]	3234[a]	1666[a]
	2050	0.953	2437[a]	3189[a]	1592[a]
	2075	0.734	2377[a]	3134[a]	1526[a]
	2100	0.734	2303[a]	3051[a]	1461[a]
All factors combined[##]	Baseline	-	2603[a]	3305[a]	1813[a]
	2025	0.454	2314[ab]	2949[b]	1599[ab]
	2050	0.454	2129[ab]	2760[bd]	1420[ab]
	2075	0.112	1910[b]	2518[cd]	1225[ab]
	2100	0.046	1745[b]	2288[d]	1133[b]
(B)		*p*		mm	
All factors combined[##]	Baseline	-	185.6[a]	222.1[a]	144.5[a]
	2025	0.734	173.5[a]	213.6[ab]	128.5[a]
	2050	0.240	167.0[a]	207.0[bc]	122.0[a]
	2075	0.112	161.1[a]	200.9[cd]	116.4[a]
	2100	0.112	153.7[a]	192.5[d]	110.1[a]

[#] Yield and transpiration data were analyzed with both Kolmogorov-Smirnov (K-S) test and Duncan's Multiple Rage Test (DMRT). The data were divided into the averages of all CDF data (CDF 0–1), upper CDF (data higher than CDF 0.5), and lower CDF (data lower than CDF 0.5)

[##] Combination of CO_2, temperature, and precipitation projections.

[a,b,c] The values with the same superscript letters are not significantly different (DMRT at 95% confidence intervals)

The CO_2 fertilization effect of millet is statistically insignificant, generally corresponding to the findings for C_4 crops (Long et al. 2006). Millet yields decreased with the climate change scenarios of temperature, precipitation, and the three factors-combined and transpiration also decreased with the three factors-combined scenarios (Fig. 8b-e). All of these effects were statistically significant (Table 5). Climate change impacts on proso millet have not been reported elsewhere to our knowledge.

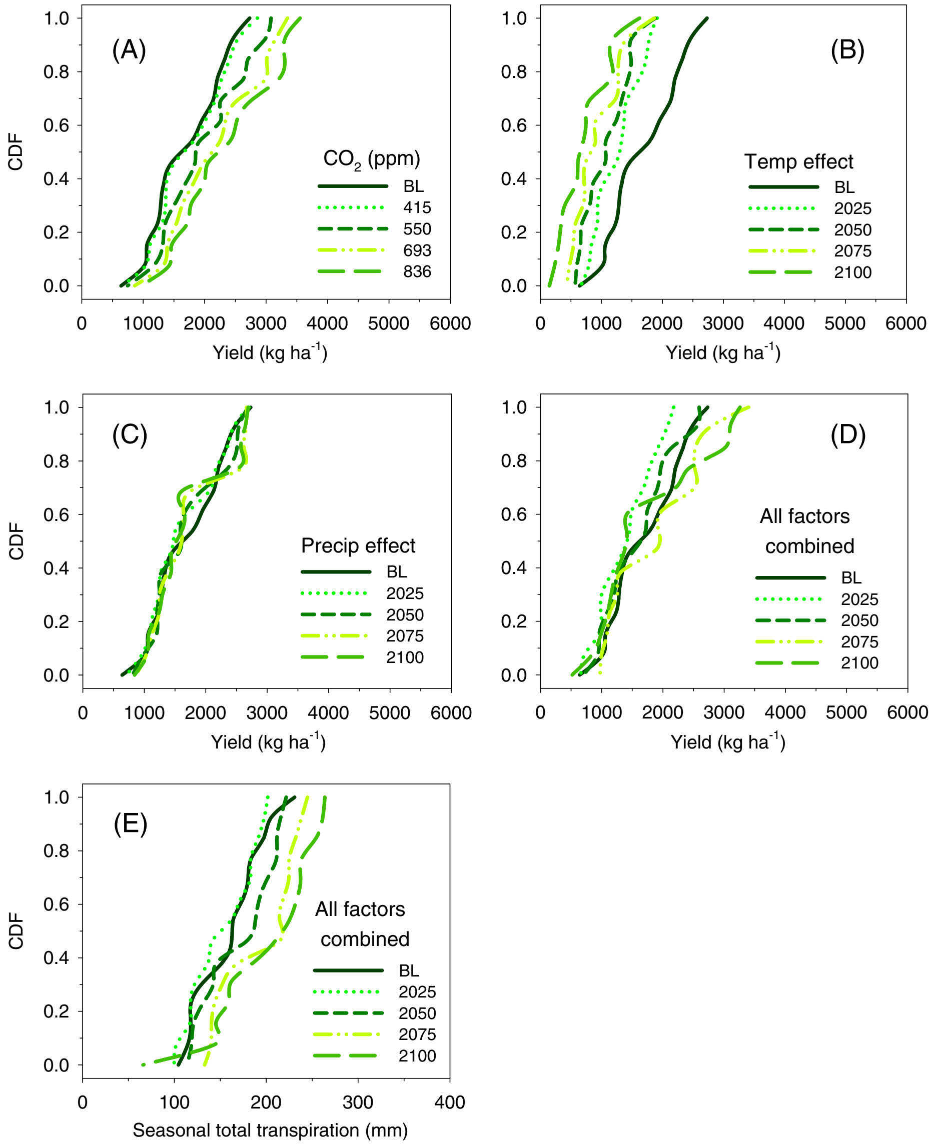

Fig. 6 Cumulative distribution function (*CDF*) of wheat grain yield under the wheat-corn-millet (*WCM*) cropping system, comparing simulated yield for the 15 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

3.4 Effects of past CO_2 increases on wheat and corn production

Simulated winter wheat yields in wheat-fallow (WF) rotation with conventional tillage (CT) and no tillage (NT) practices during 96 years (1912–2078) at the current 380 ppm CO_2 level varied from 988 to 4,057 kg ha^{-1} (data not shown). The cropping systems were simulated continuously without re-initialization between crop seasons in a sequential

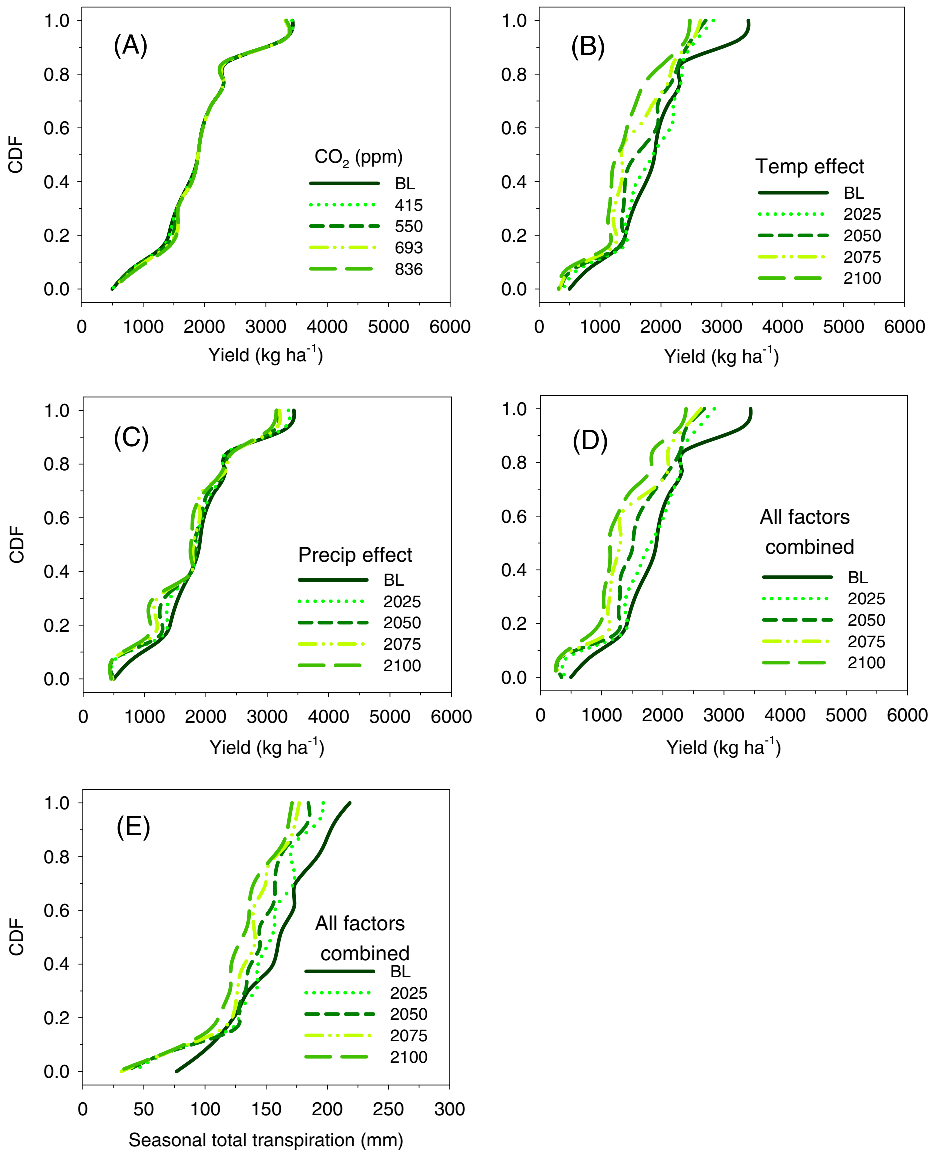

Fig. 7 Cumulative distribution function (*CDF*) of corn grain yield under the wheat-corn-millet (*WCM*) cropping system, comparing simulated yield for the 15 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

cropping mode to simulate the crop rotation/sequencing effects on crop production. The simulated yield was significantly higher in NT than CT (DMRT at 95% confidence intervals). With increasing CO_2 from 300 to 380 ppm which is assumed to be the variation over the 96 years, grain yield also increased close to as much as the tillage practice difference. Differences in soil water at maturity and in transpiration between the cultural practices generally corresponded to the yield difference. Khakbazan et al. (2009) reported reducing

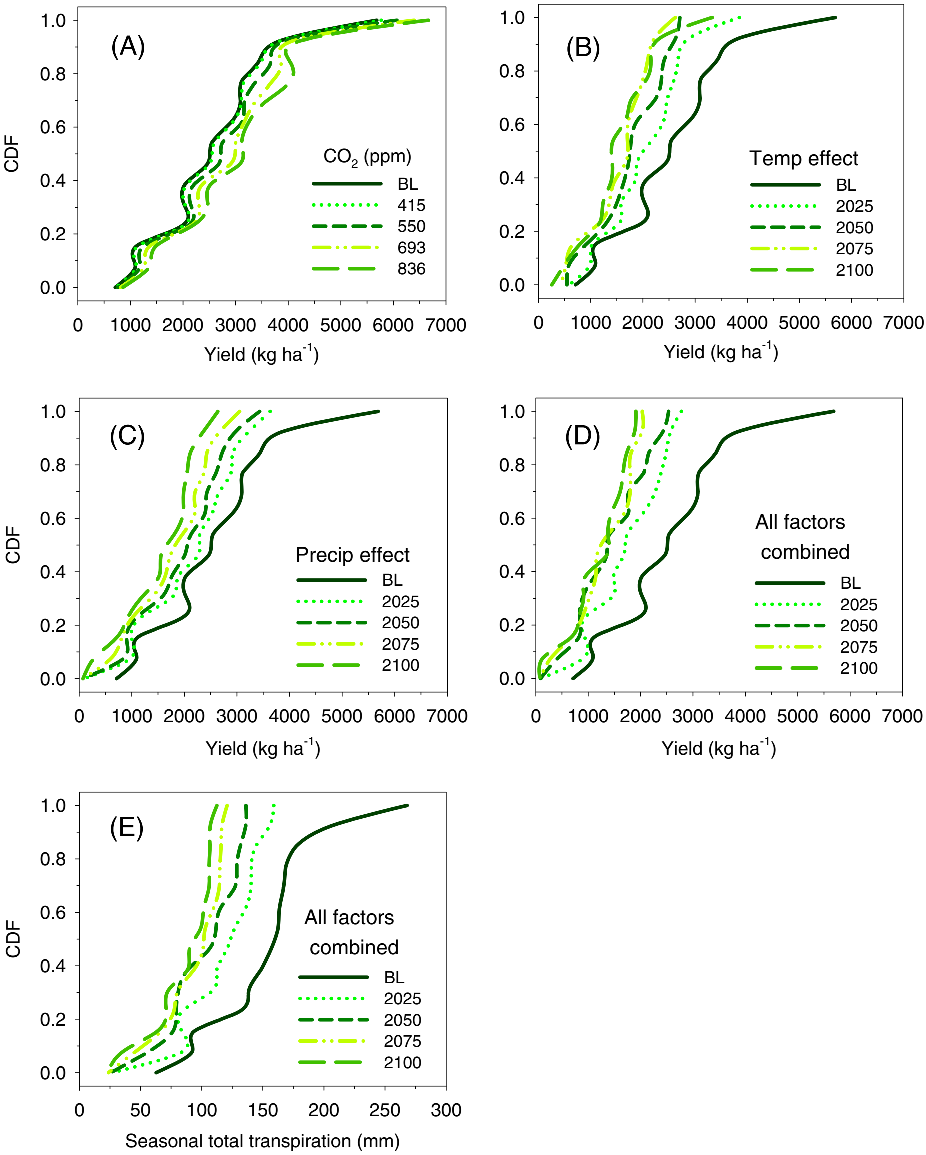

Fig. 8 Cumulative distribution function (*CDF*) of millet grain yield under the wheat-corn-millet (*WCM*) cropping system, comparing simulated yield for the 15 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined for the years 2025, 2050, 2075, and 2100; and **e** CDF of seasonal total transpiration for the projected years corresponding to **d**

tillage intensity in rainfed agriculture as a potential management practice for better production by conserving soil and water in canola. At Akron, Colorado, the soil water, grain yield, biomass, and ET was also reported to be higher in NT than in CT in simulations of the system using RZWQM2 (Saseendran et al. 2010). The current simulation results corresponded well with these findings.

Table 5 Statistical analysis for the simulation data (Fig. 8) of the future climate change impacts on millet yield (A) and on transpiration (B) under the wheat-corn-millet (WCM) cropping system

		K-S test	Yield[#]		
			CDF average	Higher CDF	Lower CDF
(A)		*p*		kg ha^{-1}	
CO_2 (ppm) effect	Baseline	-	2575[a]	3517[a]	1632[a]
	415	0.998	2609[a]	3559[a]	1658[a]
	550	0.904	2745[a]	3728[a]	1761[a]
	693	0.904	2910[a]	3938[a]	1882[a]
	836	0.617	3060[a]	4126[a]	1995[a]
Temperature effect	Baseline	-	2575[a]	3517[a]	1632[a]
	2025	0.333	2040[ab]	2722[b]	1358[ab]
	2050	0.152	1732[b]	2288[b]	1176[ab]
	2075	0.060	1539[b]	2109[b]	1042[ab]
	2100	0.060	1539[b]	2035[b]	968[b]
Precipitation effect	Baseline	-	2575[a]	3517[a]	1632[a]
	2025	0.904	2096[ab]	2876[b]	1315[a]
	2050	0.617	1926[ab]	2666[bc]	1186[a]
	2075	0.152	1727[b]	2412[bc]	1043[a]
	2100	0.060	1516[b]	2133[c]	900[a]
All factors combined[##]	Baseline	-	2575[a]	3517[a]	1632[a]
	2025	0.152	1701[b]	2325[b]	1076[b]
	2050	0.060	1405[b]	2016[bc]	795[b]
	2075	0.006	1273[b]	1791[bc]	754[b]
	2100	0.004	1183[b]	1660[c]	707[b]
(B)		*p*		mm	
All factors combined[##]	Baseline	-	152.6[a]	187.5[a]	117.7[a]
	2025	0.060	116.0[b]	143.2[b]	88.8[ab]
	2050	0.001	100.0[bc]	126.7[bc]	73.3[b]
	2075	<0.001	91.7[bc]	113.6[c]	69.8[b]
	2100	<0.001	84.5[c]	105.6[c]	63.4[b]

[#] Yield and transpiration data were analyzed with both Kolmogorov-Smirnov (K-S) test and Duncan's Multiple Rage Test (DMRT). The data were divided into the averages of all CDF data (CDF 0–1), upper CDF (data higher than CDF 0.5), and lower CDF (data lower than CDF 0.5)

[##] Combination of CO_2, temperature, and precipitation projections

[a,b,c] The values with the same superscript letters are not significantly different (DMRT at 95% confidence intervals)

Wheat yields were also simulated to vary under the different crop rotations of wheat-fallow (WF), wheat-corn-fallow (WCF), and wheat-corn millet (WCM) (Fig. 9a). The simulated yields on 380 ppm CO_2 level varied more in WCF (354–5,712 kg ha^{-1}) and WCM (0–4,515 kg ha^{-1}) than WF (1,599–3,977 kg ha^{-1}) (Fig. 9b). This difference is attributable to differences in the available soil water, fertilizer, and plant residue conditions in the soil profile. The yields were significantly higher in WF and WCF than WCM according to DMRT at 95% confidence intervals (Table 5). Average grain yields of the crop

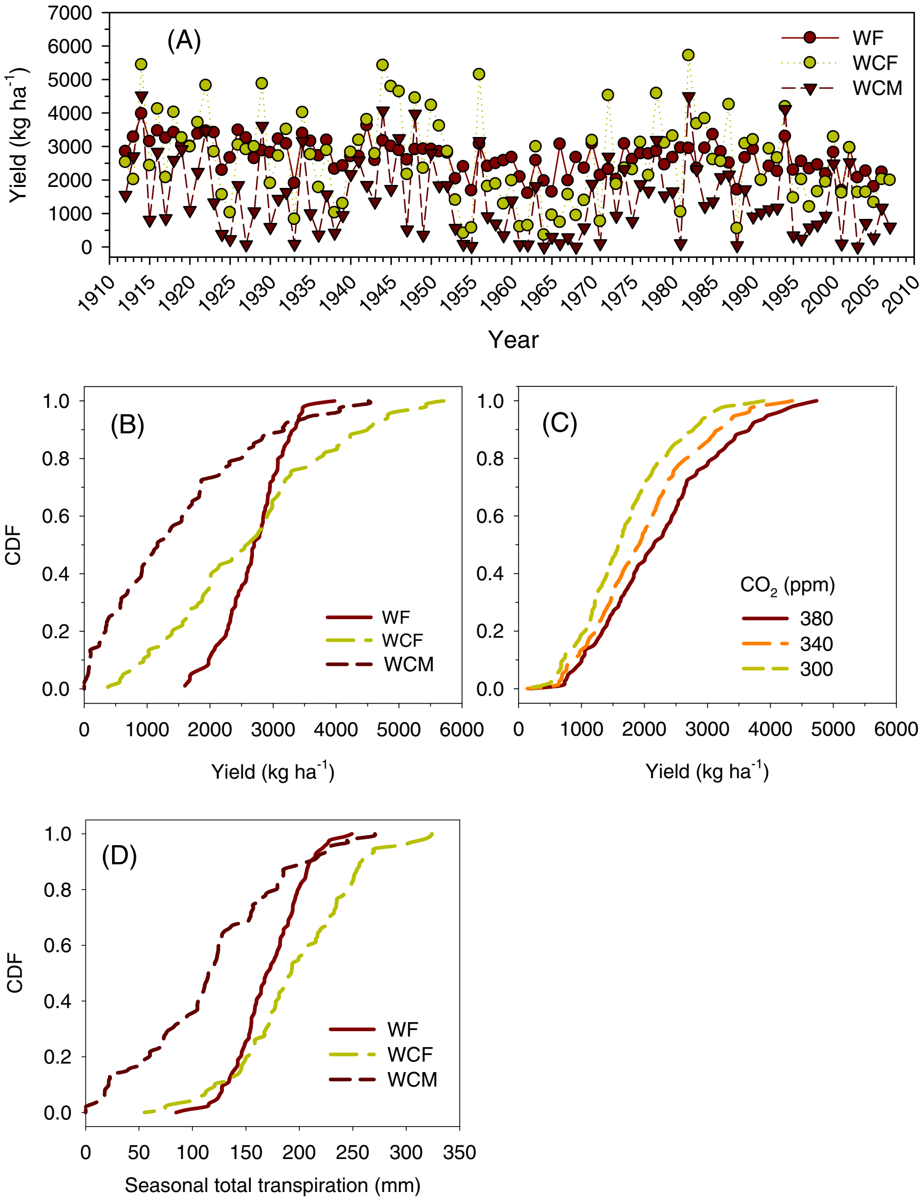

Fig. 9 **a** Simulated wheat grain yields under wheat-fallow (*WF*), wheat-corn-fallow (*WCF*), and wheat-corn-millet (*WCM*) cropping systems during the past 96 years from 1912 to 2007 at 380 ppm CO_2 level, **b** cumulative distribution function (*CDF*) of the yields for the different cropping systems at 380 ppm CO_2 level, **c** combined CDF of WF, WCF, and WCM for the different CO_2 concentrations during the period, and **d** CDF of seasonal total transpiration for the different cropping systems corresponding to CDF in **b**

rotations increased with the increasing CO_2 concentrations from 300 to 380 ppm (Fig. 9c). The yield differences between the crop rotations were generally higher than those between the CO_2 concentrations during the 96 years. General trend of differences in transpiration between the crop rotations corresponded to differences in grain yield (Fig. 9d).

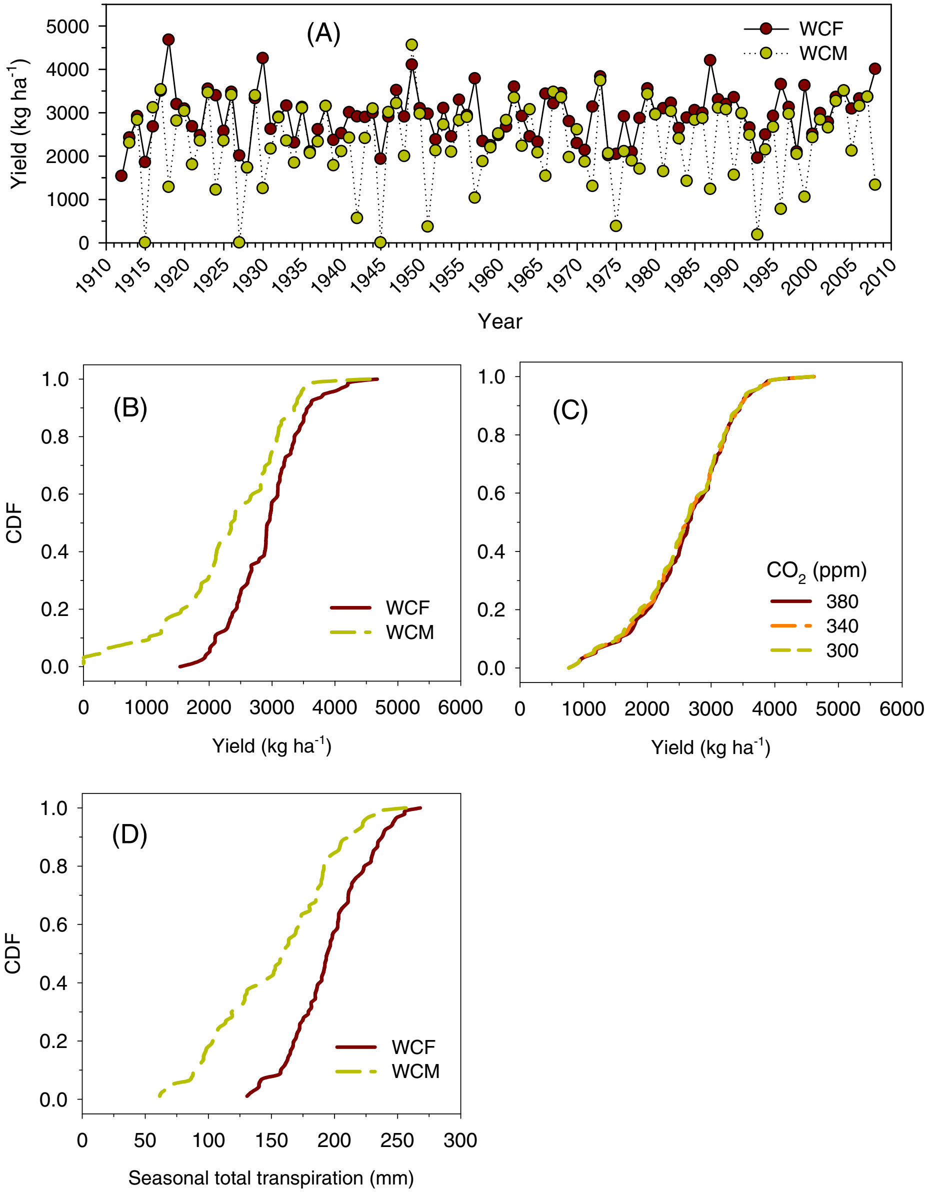

Fig. 10 **a** Simulated corn grain yields under wheat-corn-fallow (*WCF*) and wheat-corn-millet (*WCM*) cropping systems during the past 96 years from 1912 to 2007 at 380 ppm CO_2 level, **b** cumulative distribution function (*CDF*) of the yields for the different cropping systems at 380 ppm CO_2 level, **c** combined CDF of WCF and WCM for the different CO_2 concentrations during the period, and (D) CDF of seasonal total transpiration for the different cropping systems corresponding to CDF in **b**

Simulated corn yields varied from 1,534 to 4,673 kg ha^{-1} in WCF and from 0 to 4,557 kg ha^{-1} in WCM (Fig. 10a). Significant difference (DMRT at 95% confidence intervals) was found between the corn yields in WCF and WCM (Fig. 10b and Table 6). This yield variation numerically and statistically matched with transpiration variation (Fig. 10d). However, yield did not change with increasing CO_2 concentrations (Fig. 10c). This corresponds to the insignificant C_4 crop response to the CO_2 concentrations reported by Long et al. (2006).

Lobell and Field (2007) reported that the effects of CO_2 and temperature trends on the yields of crops in the global scale have likely largely cancelled each other over the past two decades, with a small net effect on yields. According to these authors' analysis, potential impacts of temperature increases may have also been countered by adaptation measures taken by farmers (i.e., changes in planting dates or use of different cultivars). The present study showed that cultural practices such as crop rotations and tillage practices could dominate over the fertilization effects of CO_2 on crop production.

3.5 Adaptation strategies to mitigate climate change impacts

Dhungana et al. (2006) claimed that future crop production can be adapted to climate change by implementing alternative management practices and developing new genotypes that are adapted to future climate conditions. We hypothesized that in the semi-arid climate of Akron, Colorado, early planting of the crops may help the plants complete their life cycles before the higher temperatures during the summer set in. Thus, we simulated the WF, WCF and WCM systems under the above 'combined effects of temperature, precipitation and CO_2' CC scenario to identify optimum planting windows for the crop that ameliorate the negative simulated impacts of CC on these crops. We repeated all the above simulations with the crops planted at 30, 20 and 10 days before their actual planting dates to see if these simulated plantings date would increase crop yields compensating for the negative impacts of temperature increases in the CC scenarios under investigation.

Our simulation results showed that early planting did not result in significant changes in corn, millet, and wheat yields in the agroclimate of the location in all the crop rotations and CC projection years of 2025, 2050, 2075 and 2100 (Fig. 11—year 2100 scenario only shown). Appropriate cultivar selection to adapt to warming conditions would only be feasible if there is sufficient plasticity in photoperiod and vernalization requirements of crop plants (Masle et al. 1989). However, the crop models used in the simulations do not take into account such adaptabilities. Improvement in better simulations of such processes can improve the simulation results presented. On the other hand, better water conservation will be a good adaptation strategy. The results for no tillage (NT) versus the conventional tillage (CT) showed that the NT maintained higher yields in WF rotation than the CT to year 2075.

4 Summary, conclusions, and further discussion

Climate change impacts on wheat-fallow (WF), wheat-corn-fallow (WCF), and wheat-corn-millet (WCM) cropping systems in the Central Great Plains were simulated using the CERES crop modules in RZWQM2. Crop yield differences between the crop rotations were higher than the yield differences with the elevated CO_2 concentrations over the past 96 years. The results of this investigation indicated that in the event of a climate change projected to year 2100 (the scenario adopted for analysis), the negative effects of enhanced temperatures would dominate over the positive impacts of atmospheric CO_2 increases on crops in the dryland cropping systems. Consequently, wheat yields were projected to decrease to some extent in all of the cropping systems analyzed (WF, WCF and WCM). However, corn and millet yields in all the crop rotations analyzed were found to decrease

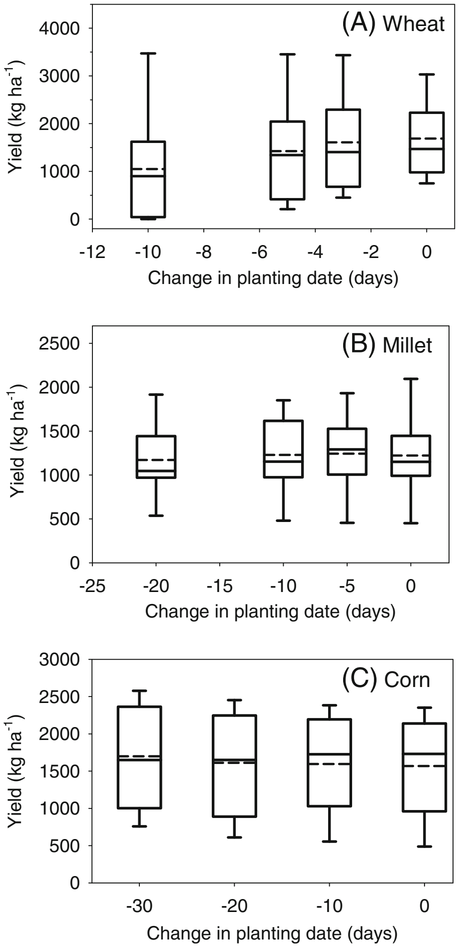

Fig. 11 Grain yields of wheat **a**, millet **b**, and corn **c** as a function of early planting, i.e., early planting vs. the planting date (0) for the projected year 2100. Error bars and a box represent the 10th, 25th, 75th, and 90th percentiles of the yield data, showing the median (*solid line*) and mean (*broken line*) in the box

more significantly (within 95% confidence intervals). As an adaptation strategy to ameliorate the yield reduction under the climate scenario investigated, simulations using early planting dates up to 30 days from the historical dates did not show any promising results. The results for no tillage (NT) versus the conventional tillage (CT) showed that the NT maintained higher yields in WF rotation than the CT to year 2075. Thus, NT is a good adaptation strategy consistent with the recommended practice under current climate.

Long et al. (2006) made the case that the crop models may overestimate the effects of CO_2 fertilization. The fertilization factors used in earlier models, derived from the past enclosure environmental chamber studies, were twice those of the free-air concentration enhancement (FACE) studies in the field. The newer models now use the field fertilization factors. The RZWQM2 model used here was calibrated and validated with the FACE wheat data from Maricopa, AZ for CO_2 enrichment effects, as well as different water and N levels (Ko et al. 2010). This model also included the effect of CO_2 on increasing stomatal resistance and reducing potential transpiration demand. The decrease in potential demand decreases the actual transpiration as well. However, both the fertilization factors and the effects on actual transpiration could be improved by using the more detailed, fully energy balance and biochemical process based, models of photosynthesis and transpiration. The models also do not include the gradual development of natural adaptations within the plants.

This study is an example of using a process based agricultural systems model (RZWQM2), which was previously calibrated and evaluated against a rich set of experimental data (15 to 17 years), for evaluating potential climate change effects on cropping systems, including realistic crop rotations. The application is specific to dryland crops (winter wheat, corn, and proso millet) in the semi-arid continental climate of the Central Great Plains. However, the simulation methods, use of synthesized climate projections (Ray et al. 2008), and statistical analysis of CDF's over many years provides a repeatable methodology for assessment of projected CC effects on any cropping system.

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