Climate change impacts on dryland cropping systems in the Central Great Plains, USA

Jonghan Ko · Lajpat R. Ahuja · S. A. Saseendran · Timothy R. Green · Liwang Ma · David C. Nielsen · Charles L. Walthall

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

J. Ko · L. R. Ahuja (✉) · S. A. Saseendran · T. R. Green · L. Ma
USDA-ARS Agricultural Systems Research Unit, 2150 Centre Avenue, Bldg D., Ft. Collins, CO 80526, USA
e-mail: Laj.ahuja@ars.usda.gov

D. C. Nielsen
USDA-ARS Central Great Plains Research Station, 40335 County Road GD, Akron, CO 80720, USA

C. L. Walthall
USDA-ARS, Office of National Programs, 5601 Sunnyside Ave., Beltsville, MD 20705, USA

Present Address:
J. Ko
Chonnam National University, 300 Youngbong-dong, Buk-gu, Gwangju 500-757, Republic of Korea

Ⓓ Springer

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

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° 09' N, 103° 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

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:

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

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

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 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%	$+\Delta P_w$

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

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

		K-S test	Yield[#]		
			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.
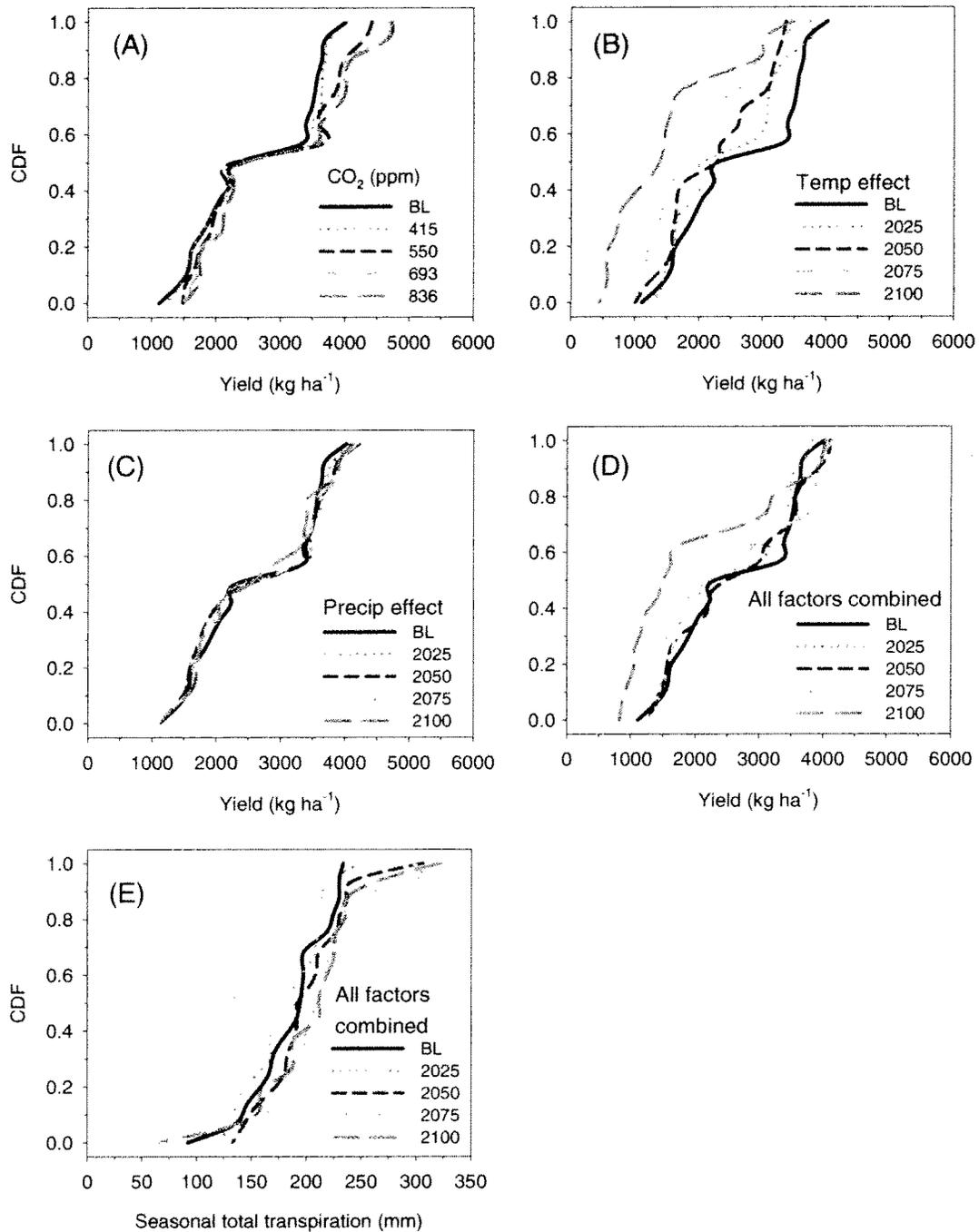
Fig. 3 Cumulative distribution function (*CDF*) of wheat grain yield in no tillage (*NT*) under the wheat-fallow (*WF*) cropping system, comparing simulated yield for the 17 baseline years (1992–2007) with the projections of yield caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all 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

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)

| | | K-S test | Yield[#] | | |
			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

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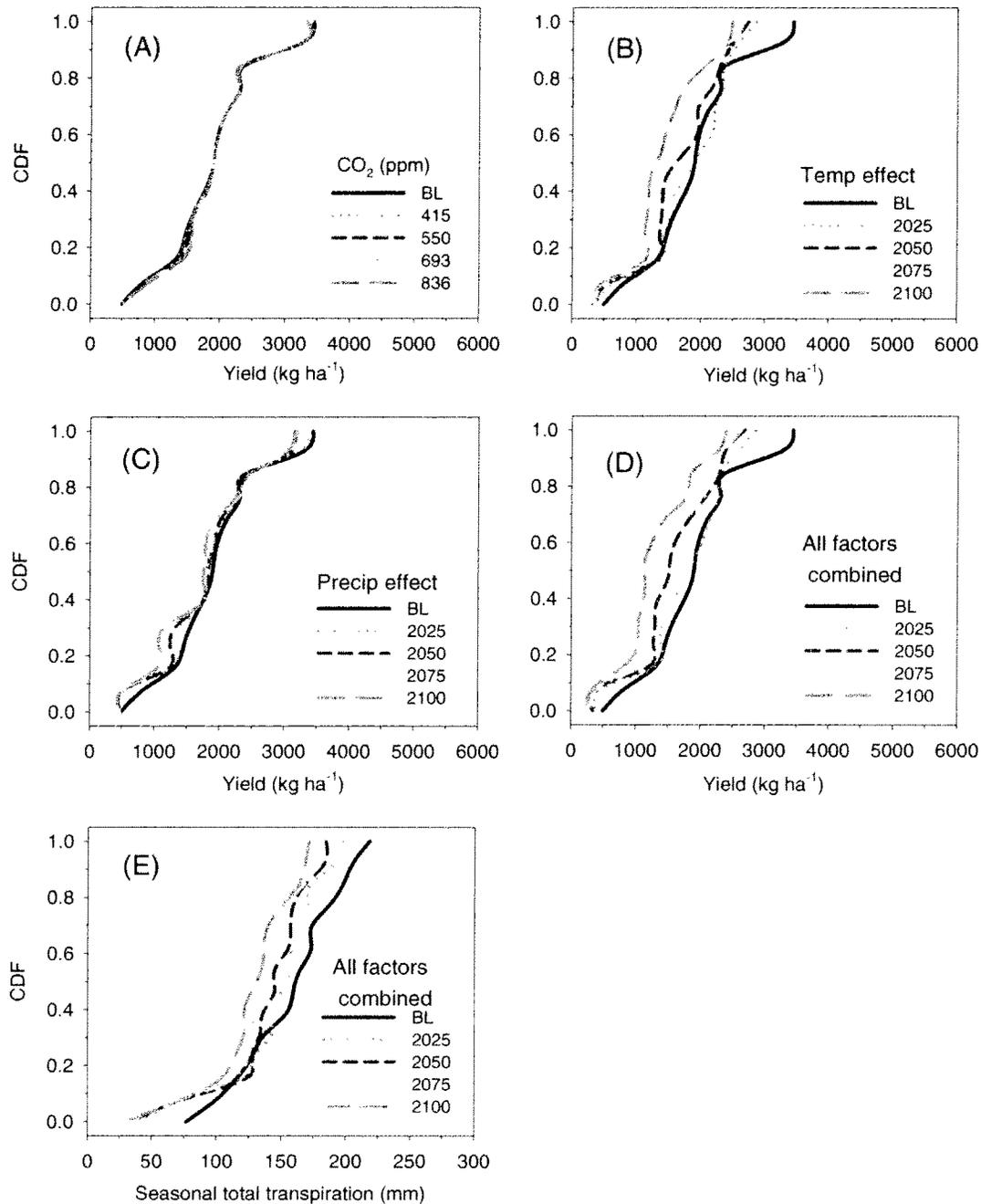
Fig. 7 Cumulative distribution function (*CDF*) of corn grain yield under the wheat-corn-millet (*WCM*) cropping system, comparing simulated yield for the 15 baseline years (1992–2007) with the projections of yields caused by **a** CO_2; **b** temperature; **c** precipitation; **d** all three factors-combined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

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
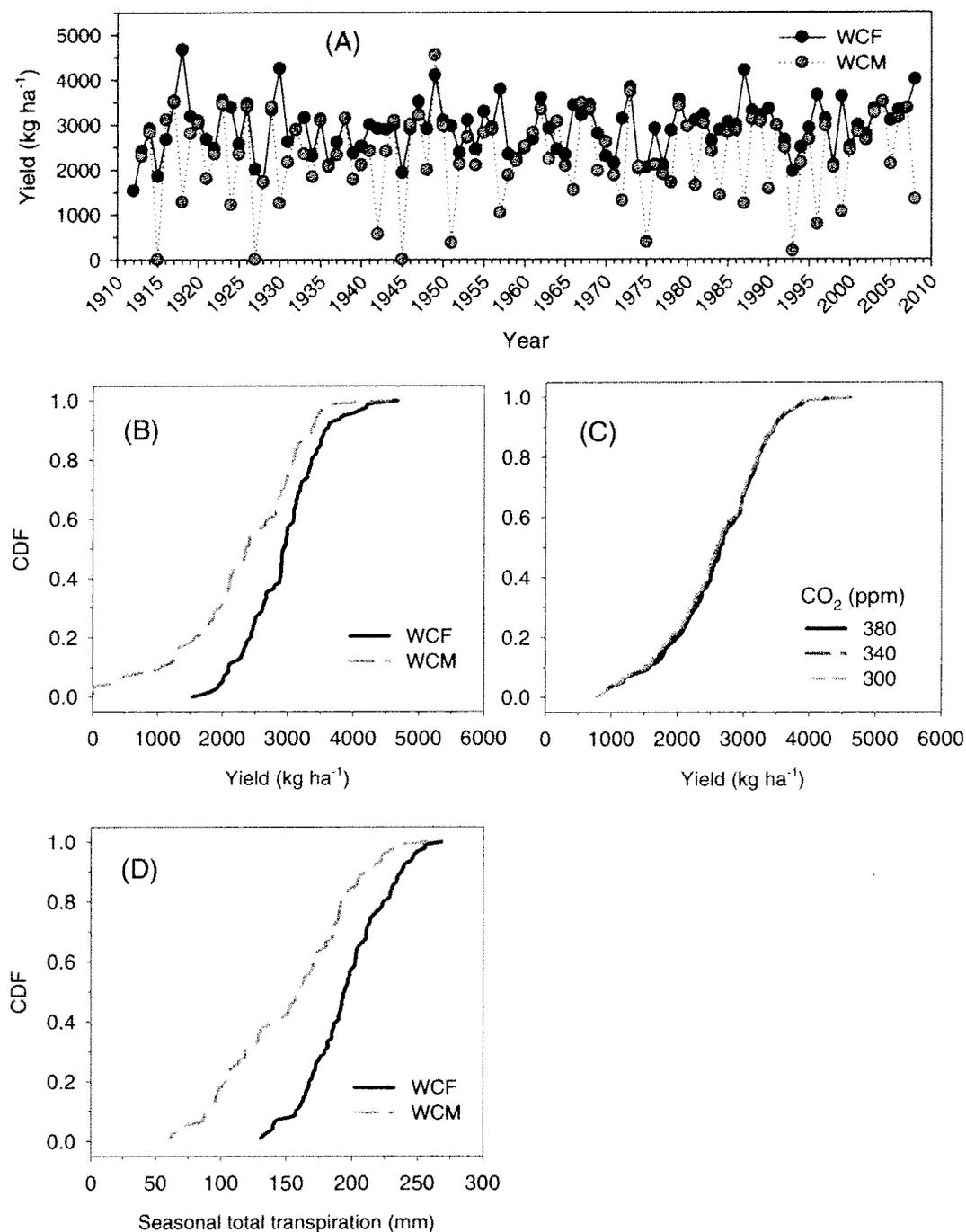
Fig. 10 a Simulated corn grain yields under wheat-corn-fallow (*WCF*) and wheat-corn-millet (*WCM*) cropping systems during the past 96 years from 1912 to 2007 at 380 ppm CO_2 level, **b** cumulative distribution function (*CDF*) of the yields for the different cropping systems at 380 ppm CO_2 level, **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
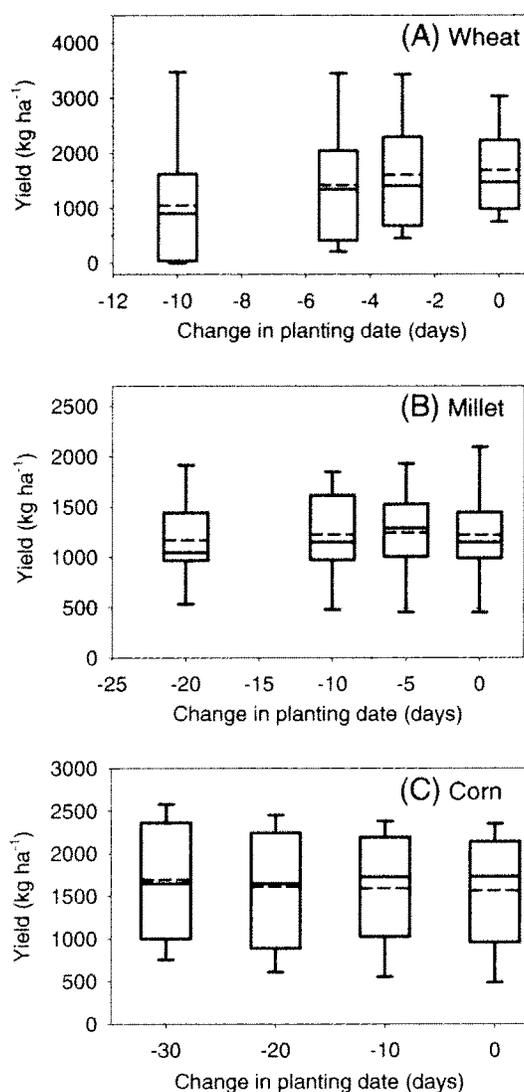
Fig. 11 Grain yields of wheat a, millet b, and corn c as a function of early planting, i.e., early planting vs. the planting date (0) for the projected year 2100. Error bars and a box represent the 10th, 25th, 75th, and 90th percentiles of the yield data, showing the median (*solid line*) and mean (*broken 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

Favis-Mortlock DT, Evans R, Boardman J, Harris TM (1991) Climate change, winter-wheat yield and soil-erosion on the English south downs. Agr Syst 37:415–433

Grossman-Clarke S, Pinter PJ Jr, Kartchall T, Kimball BA, Hunsaker DJ, Wall GW, Garcia RL, LaMorte RL (2001) Modeling a spring wheat crop under elevated CO_2 and drought. New Phytol 150:315–335

Hatfield J, Boote K, Fay P, Hahn L, Izaurralde C, Kimball BA, Mader T, Morgan J, Ort D, Polley W, Thomson A, Wolfe D (2008) Agriculture. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity. A report by the U.S. climate change science program and the subcommittee on global change research, Washington, p 362

Hu C, Saseendran SA, Green TR, Ma L, Li X, Ahuja LR (2006) Evaluating N and water management in a double cropping system using RZWQM. Vadoze Zone J 5:493–505

IPCC (2007) Summary for policymakers. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Review, Cambridge

Jamieson PD, Berntsen J, Ewert F, Kimball BA, Olesen JE, Pinter PJ Jr, Porter JR, Semenov MA (2000) Modeling CO_2 effects on wheat with varying nitrogen supplies. Agr Ecosys Environ 82:27–37

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) The DSSAT cropping system model. Europ J Agron 18:235–265

Khakbazan M, Mohr RM, Derksen DA, Monreal MA, Grant CA, Zentner AP, Moulin AP, McLaren DL, Irvine RB, Nagy CN (2009) Effects of alternative management practices on the economics, energy and GCG emissions of a wheat-pea cropping systems in the Canadian prairies. Soil and Tillage Research 104:30–38

Kimball BA (1983) Carbon dioxide and agricultural yield: An assemblage and analysis of 770 prior observations. Water Conservation Laboratory, Report No. 14. USDA/ARS, Phoenix, AZ

Kimball BA, Kobayashi K, Bindi M (2002) Responses of agricultural crops to free-air CO_2 enrichment. Adv Agron 77:293–368

Ko J, Ahuja LR, Kimball B, Saseendran SA, Ma L, Green TR, Ruane AC, Wall GW, Pinter P, Bader DA (2010) Simulation of free air CO_2 enriched wheat growth and interactions with water, nitrogen, and temperature. Agr Forest Meteorol 150:1331–1346

Leaky ADB, Uribelarrea M, Ainsworth EA, Naidu SL, Rogers A, Ort DR, Long SP (2006) Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. Plant Physiol 140:779–790

Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impact of recent warming Environ Res Lett 2: 014002 (7 pp). doi:10.1088/1748-9326/2/1/014002

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319:607–610

Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR (2006) Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science 312:1918–1921

Ma L, Hoogenboom G, Ahuja LR, Nielsen DC, Ascough JC II (2005) Evaluation of the RZWQM-CROPGRO hybrid model for soybean production. Agron J 97:1172–1182

Ma L, Hoogenboom G, Ahuja LR, Ascough JC II, Saseendran SA (2006) Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. Agr Syst 87:274–295

Ma L, Malone RW, Jaynes DB, Thorp K, Ahuja LR (2008) Simulated effects of nitrogen management and soil microbes on soil N balance and crop production. Soil Sci Soc Am J 72:1594–1603

Ma L, Hoogenboom G, Saseendran SA, Bartling PNS, Ahuja LR, Green TR (2009) Effect of estimating soil hydraulic properties and root growth factors on soil water balance and crop production. Agron J 101: doi:10.2134/agronj2008.0206x

Masle J, Doussinault G, Sun B (1989) Responses of wheat genotypes to temperature and photoperiod in natural conditions. Crop Sci 29:712–721

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models: Part I. A discussion of principles. J Hydrol 10(3):282–290

Nonhebel S (1996) Effects of temperature rise and increase in CO_2 concentration on simulated wheat yields in Europe. Clim Change 34:73–90

Ottman MJ, Kimball BA, Pinter PJ, Wall GW, Vanderlip RL, Leavitt SW, LaMorte RL, Matthias AD, Brooks TJ (2001) Elevated CO_2 increases sorghum biomass under drought conditions. New Physiologist 150:261–273

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production user SRES emissions and socio-economic scenarios. Global Environ Change 14:53–67

Peart RM, Jones RB, Curry K, Boote KJ, Allen LH (1989) Impacts of climate change on crop yield in the Southern U.S.A. In: Smith JB, Tirpak DA (eds) The potential effects of global climate change on the United States, Report to Congress, U.S. Environmental Protection Agency, EPA-230-05-89-050, Washington D.C., Appendix C