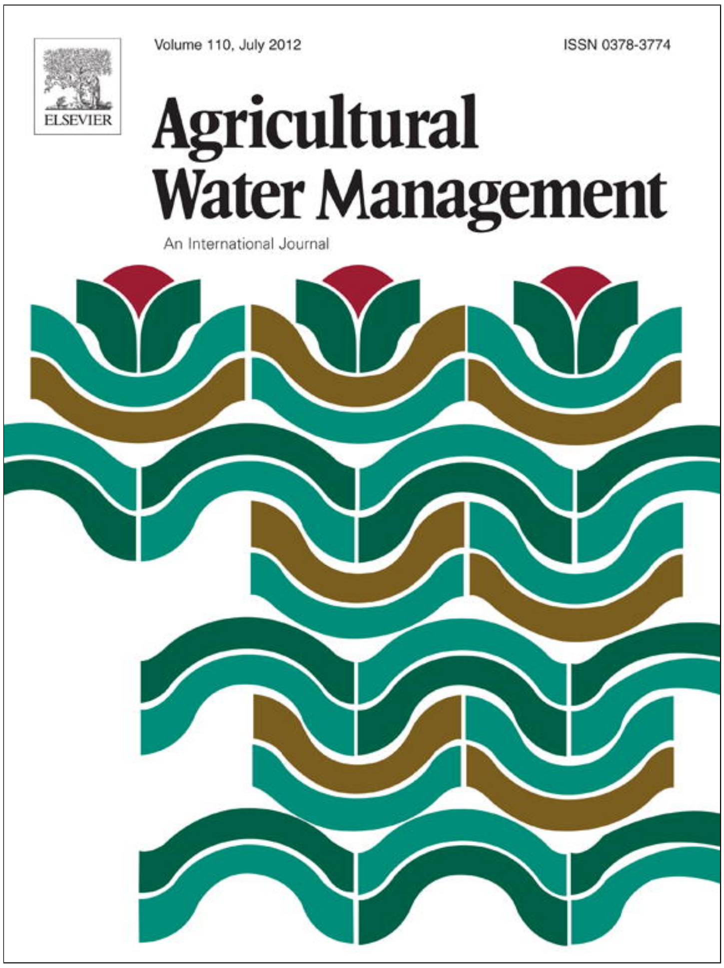
Volume 110, July 2012
ISSN 0378-3774
ELSEVIER
Agricultural
Water Management
An International Journal

Agricultural Water Management 110 (2012) 94–108

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Modeling the impacts of climate change on irrigated corn production in the Central Great Plains

Adlul Islam[a,1], Lajpat R. Ahuja[a,*], Luis A. Garcia[b], Liwang Ma[a], Anapalli S. Saseendran[a,c], Thomas J. Trout[d]

[a] USDA-ARS Agricultural Systems Research Unit, 2150 Centre Avenue, Bldg D., Fort Collins, CO 80526, United States
[b] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, United States
[c] Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, United States
[d] USDA-ARS, Water Management Research Unit, Fort Collins, CO, United States

ARTICLE INFO

Article history:
Received 21 February 2012
Accepted 3 April 2012
Available online 27 April 2012

Keywords:
Climate change
Corn yield
Evapotranspiration
Water use efficiency
Climate change
Multi-model scenarios

ABSTRACT

The changes in temperature and precipitation patterns along with increasing levels of atmospheric carbon dioxide (CO_2) may change evapotranspiration (ET) demand, and affect water availability and crop production. An assessment of the potential impact of climate change and elevated CO_2 on irrigated corn (*Zea mays* L.) in the Central Great Plains of Colorado was conducted using the Root Zone Water Quality Model (RZWQM2) model. One hundred and twelve bias corrected and spatially disaggregated (BCSD) climate projections were used to generate four different multi-model ensemble scenarios of climate change: three of the ensembles represented the A1B, A2, and B1 emission scenarios and the fourth comprised of all 112 BCSD projections. Three different levels of irrigation, based on meeting 100, 75, and 50% of the crop ET demand, were used to study the climate change effects on corn yield and water use efficiency (WUE) under full and deficit irrigation. Predicted increases in mean monthly temperature during the crop growing period varied from 1.4 to 1.9, 2.1 to 3.4, and 2.7 to 5.4 °C during the 2020s, 2050s, and 2080s, respectively, for the different climate change scenarios. During the same periods, the projected changes in mean monthly precipitation varied in the range of −4.5 to 1.7, −6.6 to 4.0 and −11.5 to 10.2%, respectively. Simulation results showed a decrease in corn yield, because the negative effects of increase in temperature dominated over the positive effects of increasing CO_2 levels. The mean overall decrease in yield for the four different climate change scenarios, with full irrigation, ranged from 11.3 to 14.0, 17.1 to 21.0, and 20.7 to 27.7% during the 2020s, 2050s, and 2080s, respectively, even though the CO_2 alone increased yield by 3.5 to 12.8% for the scenario representing ensembles of 112 projections (S1). The yield decrease was linearly related to the shortening of the growing period caused by increased temperature. Under deficit irrigation, the yield decreases were smaller due to increased WUE with elevated CO_2. Because of the shortened crop growing period and the CO_2 effect of decreasing the ET demand, there was a decrease in the required irrigation. Longer duration cultivars tolerant to higher temperatures may be one of the possible adaptation strategies. The amount of irrigation water needed to maintain the current yield for a longer duration corn cultivar, having the same WUE as the current cultivar, is projected to change in the range of −1.7 to 6.4% from the current baseline, under the four different scenarios of climate change evaluated in this research.

Published by Elsevier B.V.

1. Introduction

Global climate change induced by increasing concentrations of greenhouse gasses (GHG) in the atmosphere is likely to increase temperatures, change precipitation patterns and increase the frequency of extreme events. Agricultural crop production might be significantly affected by changes in climate and rising CO_2 levels. Changes in temperature and precipitation may either benefit or harm agricultural systems depending on the location in the world (Peiris et al., 1996; Rosenzweig and Hillel, 1998). The increased CO_2 levels enhance photosynthesis rates (i.e., CO_2 enrichment effect), yields in some crops (Kimball et al., 2002; Parry et al., 2004; Tubiello and Ewert, 2002) and water use efficiency (WUE) under water stress conditions (Chaudhuri et al., 1990; Kimball et al., 1995). Therefore, the overall effect of increased CO_2 levels and climate change on crop yields will depend on local climatic conditions as well as cropping systems and management practices.

* Corresponding author. Tel.: +1 970 492 7315; fax: +1 970 492 7310.
E-mail address: Laj.Ahuja@ars.usda.gov (L.R. Ahuja).
[1] Now at: ICAR Research Complex for Eastern Region, PO Bihar Veterinary College, Patna 800 014, India.

0378-3774/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.agwat.2012.04.004

Irrigated crop production in the arid and semi-arid regions of the world is critical to sustaining the increasing human population. According to the recent report of the Inter-Governmental Panel on Climate Change (IPCC, 2007), there will be decreasing water availability in many semi-arid and arid areas due to climate change. This is expected to lead to decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semi-arid tropics. The cereal productivity will tend to decrease in spite of some beneficial effects of increased CO_2 levels. Hence, the effects of future climate change in these regions are a serious concern. Lobell et al. (2011) estimated that the yields of cereal crops (maize, rice, and wheat) has already declined in the last three decades between 2.5 and 3.8% globally due to climate change, much of it in the arid and semi-arid regions.

Numerous studies have been conducted using crop models to project the effects of climate change on the production of various crops in different regions of the world, with inputs of future climate projections obtained from several Global Circulation Models (GCMs). These studies are contained in the IPCC report (IPCC, 2007) and described in a number of publications (Anderson et al., 2001; Hillel and Rosenzweig, 2011; Izaurralde et al., 2003; Ko et al., 2011; Parry et al., 2004; Phillips et al., 1996; Reilly et al., 2003; Rosenzweig and Parry, 2004; Thompson et al., 2005; Tubiello and Ewert, 2002). The results of different simulation studies showed that the effect of climate change on crop production varied with the GHG emission scenario, time, current climate, cropping systems and management practices from region to region. Accelerated crop growth and maturation under warmer climate will not only reduce corn yield, but would also decrease seasonal evapotranspiration and hence irrigation demands (Guerena et al., 2001; Meza et al., 2008; Tao and Zhang, 2011; Tubiello et al., 2000). However, there are only a few studies of the effects of climate change on irrigated crops in arid/semi-arid regions. None of these studies included the effects of both temperature and increasing CO_2 levels on evapotranspiration and irrigation demands. This study explores the effects of changes in temperature and precipitation and increases in CO_2 concentrations on corn production in relation to potential ET demand and actual ET, and irrigation water use in the semi-arid Central Great Plains of Colorado using the Root Zone Water Quality Model (RZWQM2).

The General Circulation Models are the primary tools that estimate changes in climate due to increased greenhouse gases in a physically consistent manner. There are a number of GCMs developed by different organizations around the world which contributed to the Third Coupled Model Intercomparison Project (CMIP3; Meehl et al., 2007). Based on the likely profile of GHG emissions arising from contrasting patterns of economic development and population growth for the period 2000–2100, IPCC's Special Report on Emission scenarios (SRES) defined a range of future greenhouse gas emission scenarios (IPCC, 2000). The Fourth Assessment Report (AR4) of the IPCC (IPCC, 2007) focused on modeling of four main scenarios (i.e., A1, A2, B1 and B2). A1 scenario is characterized by rapid economic growth, a global population that reaches a peak in mid-century and then gradually declines, the quick spread of new and efficient technologies, and a convergent world. Based on the alternative directions of the technological changes in the energy systems, the A1 scenario family is grouped as A1FI (fossil intensive), non-fossil energy source (A1T) and a balance across all sources (A1B). The A2 family of scenarios is characterized by a world of independently operating, self-reliant nations, continuously increasing population and regionally oriented economic development. The B1 scenarios describe a convergent world with population rising to a peak in mid-century and then declining as in the A1 scenario but with rapid changes toward a service and information economy, reductions in material intensity, introduction of clean and resource efficient technologies, and an emphasis on global solutions to economic, social and environmental stability. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than the A2 scenario, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. Thus, climate projections from several GCMs are available for different emission scenarios.

Selection of the GCM outputs that would most likely represent the region of interest is important in climate change impact assessment studies. One common issue in regional impact assessment studies is that the GCM outputs are generally available at a coarse resolution. Therefore, spatial downscaling to scales more representative of local areas of interest is required (Christensen and Lettenmaier, 2007). Furthermore, as the outputs of different GCMs vary considerably for some regions, selection of the best GCM becomes an issue. In recent years, there has been growing interest in use of multiple GCMs and emission scenarios to account for the uncertainty associated with individual GCM predictions in impact assessment studies. Reifen and Toumi (2009) concluded that the multi-model ensemble mean of all available AR4 models provides the most reasonable basis for obtaining the best projections of future climate change. Raff et al. (2009) selected a subset of 9 GCM projections, from the 112 Coupled Model Intercomparison Project phase 3 (CMIP3) projections, that encapsulates the variability of temperature and precipitation and hence showing the range of risk that may exist. In this study, 112 bias corrected and spatially disaggregated (BCSD) projections from the World Climate Research Program's (WRCP) Coupled Model Intercomparison Project phase 3 (CMIP3) climate projections archive (Maurer et al., 2007) were used to generate four multi-model ensemble climate scenarios. The first scenario comprised all 112 projections, and the other three comprised of 36, 39 and 37 projections representing the B1, A1B and A2 emission paths respectively, which represent low, medium and high emission conditions.

The main objective of this paper was to evaluate the effects of different climatic change scenarios on the production of irrigated corn in relation to ET and water demand in the Central Great Plains of Colorado. The RZWQM2 model combined with four multi-model ensemble climate change scenarios was used for this purpose. In addition, the effect of elevated CO_2 levels on potential ET demand and on growth and yield of corn was also studied for CO_2 levels representing the B1, A1B and A2 emission paths. Simulations were also made using three different irrigation levels (meeting 100, 75 and 50% of ET demand) to study the effect of climate change on water use and corn production under full and deficit irrigation.

2. Material and methods

2.1. The Root Zone Water Quality Model (RZWQM2)

The Root Zone Water Quality Model (RZWQM2, version 2.0) with the Decision Support Systems for Agrotechnology Transfer (DSSAT, version 4.0) crop modules was used in this study. The RZWQM2 is a process-oriented agricultural systems 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 climate conditions (Ahuja et al., 2000). The crop simulation modules (CSM) in the DSSAT 4.0 package 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).

RZWQM2 uses the Green–Ampt equation for infiltration and the Richards' equation for redistribution of water in the soil profile (Ahuja et al., 2000). Potential evapotranspiration is calculated using the extended Shuttleworth–Wallace equation, which is the Penman–Monteith equation modified to include partial crop canopy and the surface crop residue dynamics on aerodynamics and energy fluxes (Farahani and DeCoursey, 2000) such that:

$$\lambda ET = CC(PM_C) + CS(PM_S) + CR(PM_R) \tag{1}$$

where λET is the total flux of the latent heat above the canopy, CC, CS and CR are coefficients based upon the fractions of the area covered by the canopy, bare soil, and residue, respectively, and the corresponding aerodynamic and surface resistances; and PM_C, PM_S and PM_R are the Penman–Monteith equations applied to the canopy, bare soil, and residue, respectively.

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, application of manure and fertilizer at different rates and times by different methods, planting and harvesting operation, and surface crop residue dynamics (Rojas and Ahuja, 2000).

The DSSAT 4.0-CERES (Crop Environment Resource Synthesis) crop plant growth module for corn was used in this study. The DSSAT 4.0-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. Biomass production per day is a product of photosynthetic active radiation intercepted by the canopy and the RUE. The effects of elevated CO_2 on RUE are modeled empirically using curvilinear multipliers (Allen et al., 1987; Peart et al., 1989). A *y*-intercept term in a modified Michaelis–Menten equation was used to fit crop responses to CO_2 concentration as below:

$$RUE = \frac{RUE_m \cdot CO_2}{CO_2 + K_m} + RUE_i \tag{2}$$

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 when $CO_2 = 0$, and K_m is the value of the substrate concentration, i.e., CO_2 at which $(RUE - RUE_i) = 0.5\ RUE_m$; the units of RUE, RUE_m, and RUE_i are g MJ^{-1} and K_m and CO_2 are in ppm. 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 the Shuttleworth–Wallace equation used in RZWQM2-DSSAT package, based on relationships published in the literature (Allen, 1990; Rogers et al., 1983). The decrease in potential transpiration demand, in turn, decreases root water uptake and actual transpiration, and reduces plant water stress.

2.2. Data

Daily weather data on minimum and maximum temperature, wind speed, and solar radiation for the Greeley, Colorado (40.45°N, 104.64°W) for the period 1992–2010 were obtained from the Colorado Agricultural Meteorological Network (CoAgMet) website http://ccc.atmos.colostate.edu/~coagmet/. These data were supplemented by data for minimum and maximum temperature and precipitation from a nearby National Climatic Data Center weather station at the University of Northern Colorado for the period of 1950–1991 to create a 50-year baseline period for studying climatic change impacts. Daily gridded observed data (1/8° resolution) available from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) dataset (Maurer et al., 2007) was also used to fill the gaps in the base data. For future climate projections, bias corrected and spatially disaggregated (BCSD) WCRP's CMIP3 climate projections were used. CMIP3 archive includes projections made from climate models that include coupled atmospheric and ocean general circulation models (Meehl et al., 2007). Each of these models simulates global response to various future greenhouse gas emission paths.

2.3. Model parameterization and calibration

The minimum driving variables for RZWQM2 simulations are maximum and minimum temperature, precipitation, daily solar radiation, 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. An irrigated corn experiment was conducted from 2008 to 2010 in the Greeley, Colorado, to study the effects of deficit irrigation on corn water use efficiency. In the experiment, five levels of irrigation were scheduled based on meeting a certain percentage (100%, 85%, 70%, 55%, and 40%) of the potential crop evapotranspiration demand during the growing season. Soil water content was measured in the field with a portable time domain reflectometry (TDR) moisture meter for the 0–15 cm soil layer and with a neutron attenuation moisture meter between 15 cm and 200 cm below the soil surface at 30 cm intervals. For laboratory measurement, three intact soil profile cores were taken in the experimental area to 182 cm depth. Soil water retention curves (SWRC) and bulk densities were measured for eight different depths in the laboratory using pressure plates at 10, 33, 50, 100, and 1500 kPa suction. The Brooks–Corey equation was fitted to these groups of soil layers to obtain the SWRC (Ma et al., 2012). Field measured water contents after a big storm also allowed estimates of field capacity, assumed equivalent to 0.33 MPa soil water content, and wilting point, assumed 1.5 MPa soil water content, which along with laboratory-measured bulk densities were used to estimate field SWRCs (Ma et al., 2012).

The RZWQM2 model was calibrated for yield, biomass, leaf area index (LAI), and soil moisture under five irrigation treatments in all the 3 years. The model was first manually calibrated for both laboratory-measured and field-estimated SWRCs by matching simulated results with measured soil water, anthesis and maturity dates, maximum LAI, and final biomass and yield. After manual calibration, automated calibration with field-estimated SWRCs was also done to optimize the plant parameters. The step-by-step RZWQM2 model calibration procedure for corn is described in Ma et al. (2012). In this study, the calibrated model (Ma et al., 2012) was used for simulating crop growth and yield under different climate change scenarios.

2.4. Climate change scenario generation

The Delta change or Perturbation factor method (Hay et al., 2000; Ragab and Prudhomme, 2002) is the most commonly used approach for generating future climate scenarios in impact assessment studies. In this method, the differences between (or the ratio of) the control and future climate simulations are applied to historical observations by simply adding (or multiplying) the change factor to daily observed data. This method ignores potential changes in the variance or time series behavior in the future projections. Hamlet et al. (2010) developed a new downscaling technique called the Hybrid Delta Method which utilizes bias corrected and spatially disaggregated precipitation and temperature data downscaled to fine-scale grids (1/8°). The statistical bias

Table 1
General Circulation Models (GCMs) and SRES emission scenarios considered in this study.

	Modeling group, country	WCRP[a] CMIP3 I.D.	SRES[b] A2 runs	SRES A1B runs	SRES B1 runs
1	Bjerknes Centre for Climate Research	BCCR-BCM2.0	1	1	1
2	Canadian Centre for Climate Modeling & Analysis	CGCM3.1 (T47)	1,. . .,5	1,. . .,5	1,. . .,5
3	Meteo-France/Centre National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1
4	CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1
5	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1
6	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	1	1	1
7	NASA/Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1
8	Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1
9	Institute Pierre Simon Laplace, France	IPSL-CM4	1	1	1
10	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	1,. . .,3	1,. . .,3	1,. . .,3
11	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	1,. . .,3	1,. . .,3	1,. . .,3
12	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	1,. . .,3	1,. . .,3	1,. . .,3
13	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1,. . .,5	1,. . .,5	1,. . .,5
14	National Center for Atmospheric Research, USA	CCSM3	1,. . .,4	1,. . .,3, 5,. . .,7	1,. . .,7
15	National Center for Atmospheric Research, USA	PCM	1,. . .,4	1,. . .,4	2,. . .,3
16	Hadley Centre for Climate Prediction and Research/Met Office, UK	UKMO-HadCM3	1	1	1
	Total		36	39	37

[a] WCRP_CMIP3, World Climate Research Programme Coupled Model Inter-comparison Project phase 3.
[b] SRES, Special Report on Emission Scenario.

correction employs a quantile mapping technique (Wood et al., 2002) to remove the systematic bias in the GCM simulations. Quantile mapping is one-to-one mapping between two cumulative distribution functions (CDFs) – one for the GCM simulated data and another for the observed historical data. In the quantile mapping, the probability of non-exceedance for a given temperature (T) or precipitation (P) is first selected from the GCM simulated CDF of T or P and then corresponding to that non-exceedance probability, the T or P value is selected from the observed CDF, which represents the bias corrected GCM value. In the Hybrid Delta Method, BCSD monthly data for the selected location (grid point) are divided into individual calendar months and a probability distribution function for each month is generated. Then quantile mapping is done to re-map the observations onto the bias corrected GCM data to produce a set of transformed observations reflecting the future scenario. Thus, in this method for each month 50 factors are generated (one for each year for the period 1950–1999) as against one factor for each month in the case of delta change method. Thus, this method allows for consideration of inter-annual variability for each month. For creating an ensemble of '*n*' projections, '*n*' number of BCSD projections are considered while constructing a CDF for future and historical time series. In this study, the Hybrid Delta Ensemble method was adopted for generation of different climate change scenarios by varying the number of ensemble members.

One hundred and twelve BCSD projections were obtained from the WRCP archive, which are available at 1/8° spatial resolution, for the period 1950–2099 for the latitude–longitude coordinate of the study area. The 112 BCSD climate projections are comprised of 16 different CMIP3 models simulating three different GHG emission paths of B1 (low), A1B (middle), and A2 (high) (Table 1). The following climate change scenarios were generated for use in this study using the Hybrid Delta Ensemble Method to model their effect on corn production:

1. Ensemble of 112 projections combining all emission scenarios (referred as S1);
2. Ensemble of 37 projections representing lower (B1) emission path (S2);
3. Ensemble of 39 projections representing middle (A1B) emission path (S3); and
4. Ensemble of 36 projections representing higher (A2) emission path (S4).

Approximate CO_2-equivalent concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 for the SRES B1, A1B, and A2 illustrative marker scenarios are about 600, 850, and 1250 ppm, respectively (IPCC, 2007). For studying the effect of increasing CO_2 concentrations on crop yield, CO_2 levels of 600, 850 and 1250 ppm by 2100 were used for the B1, A1B and A2 emission paths, respectively (IPCC, 2007). For the ensemble of 112 projections, an average CO_2 level of the three emission paths (900 ppm) was used.

To simulate the projected climate change impacts on growth and yield of corn, the temperature and precipitation changes corresponding to the climate change scenario (S1–S4) were superimposed on the observed baseline data series. The initial conditions for the soil water and nitrogen levels for the simulations were set equal to an average field measured value. For studying the effect of irrigations under changing climate scenarios, three different levels of irrigation, i.e., 100ET, 75ET and 50ET (irrigation is applied to meet 100, 75 or 50% evapotranspiration demand) were considered. The effects of climate change on crops were evaluated by comparing the crop yield, potential and actual ET, and needed irrigation under future climate and under baseline scenarios, and hence baseline (without change in climate) simulations were also made with three different irrigation levels. Simulation runs were made for three future periods, 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) to estimate the projected changes in corn production. The results in each case were expressed as percentage change with respect to the baseline and as cumulative distribution functions (CDFs). To obtain a CDF, the yearly simulated yields were ordered according to their value from the smallest to the largest. Then, the probability of obtaining a yield is computed as the ratio of its rank to the total number of values in the set. A nonparametric test, the Kolmogorov–Smirnov (K–S) test, was also conducted to determine if the baseline CDF and each of the projection period CDFs differ significantly.

3. Results and discussion

3.1. Temperature and precipitation change

Mean monthly changes in temperature and precipitation under different climate change scenarios during the corn growth period from May to October are presented in Fig. 1. Mean changes in

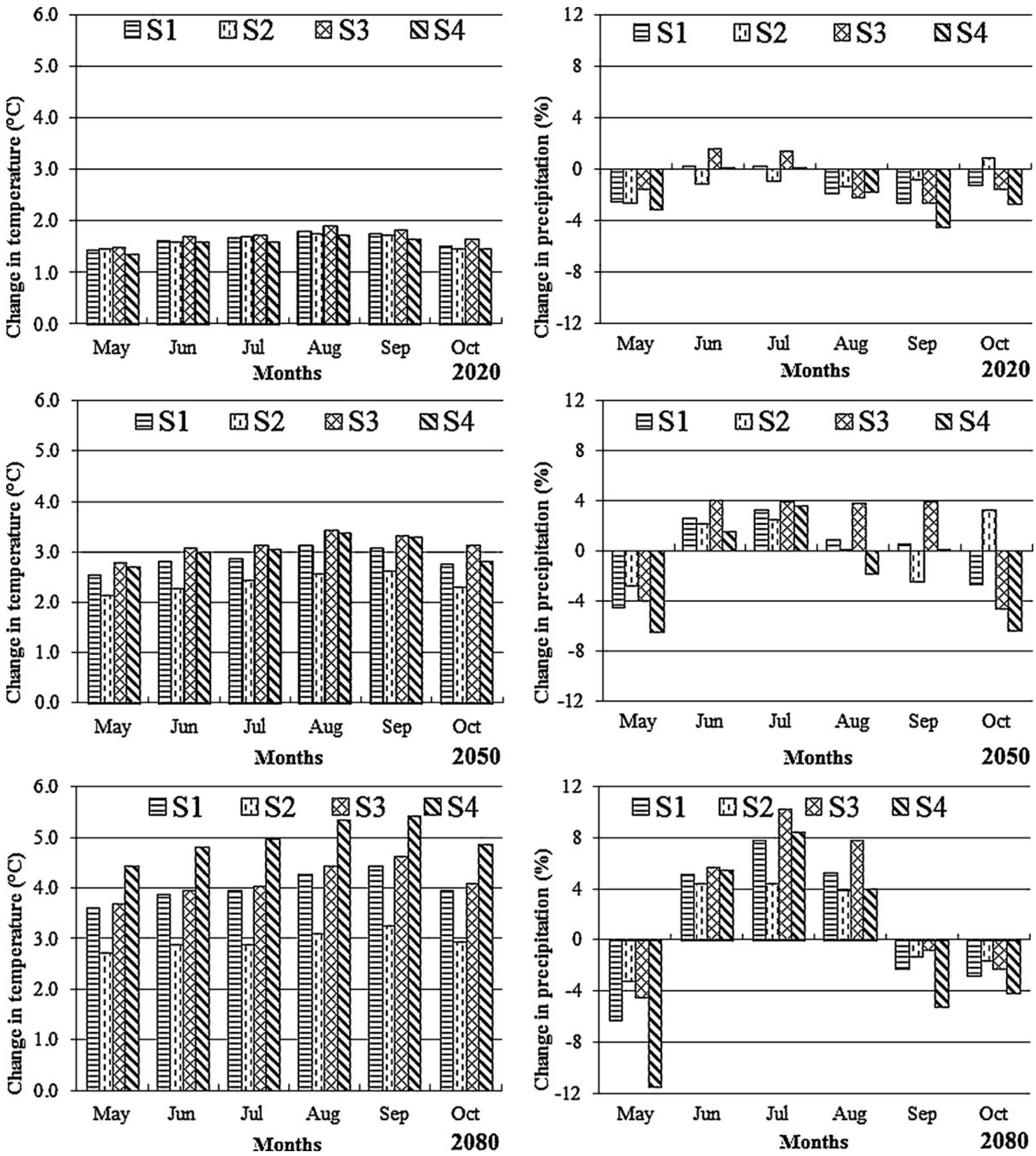

Fig. 1. Mean changes in temperature and precipitation during May–October (corn growing season) under different climate change scenarios (S1–S4).

temperature during the months of May to October varied from 1.4 to 1.9, 2.1 to 3.4, and 2.7 to 5.4 °C during the 2020s, 2050s, and 2080s, respectively. Change in precipitation varied in the range of −4.5 to 1.7, −6.6 to 4.0 and −11.5 to 10.2% during the 2020s, 2050s and 2080s, respectively. As projected by different GCMs, in most of the months precipitation decreased during the 2020s and increased during the 2050s and 2080s. In the month of May the precipitation decreased in all the scenarios during all the three time periods. During June, July and August, the precipitation increased during the 2050s (except S4 scenario in August) and the 2080s, but this increase was only 4.0 and 10.2%, respectively.

3.2. Temperature changes with respect to optimum and base temperatures of corn

Temperature has a significant effect on the growth and development of plants. Each crop species has an optimum temperature range for its development, and deviation from this temperature range can affect its production. The base temperature for vegetative development (at which growth commences) and the optimum temperature (best plant growing conditions) for corn are 8 and 34 °C, respectively (Hatfield et al., 2011; Kiniry and Bonhomme, 1991). Under the S1 scenarios the average number of days with maximum temperature (T_{max}) greater than 34 °C, increased from 17 days (baseline years 1950–1999) to 34, 44, and 50 days during the 2020s, 2050s, and the 2080s, respectively (Table 2); and the number of days with minimum temperature (T_{min}) less than the base temperature (i.e., 8 °C) decreased from 27 (baseline years) to 11, 6 and 4 days during the 2020s, 2050s and 2080s, respectively. As shown in Table 2, during the 2020s the number of days with T_{max} greater than 34 °C almost doubled and varied in the range of 34–35 days under different climate change scenarios. During the 2050s and 2080s, the increase in the number of days with T_{max} greater than 34 °C was higher under the A1B and A2 emission scenarios

Table 2
Average number of days with $T_{max} > 34\,^{\circ}C$ in future years for different scenarios.

Scenarios	Number of days with $T_{max} > 34\,^{\circ}C$			Number of days with $T_{min} < 8\,^{\circ}C$		
	2020s	2050s	2080s	2020s	2050s	2080s
Base	17	17	17	27	27	27
S1	34	44	50	11	6	4
S2	34	40	44	11	8	6
S3	35	46	50	11	6	4
S4	34	46	54	11	6	3

S1, ensemble of 112 projections; S2, ensemble of 37 projections representing B1 emission path; S3, ensembles of 39 projections representing A1B emission path; S4, ensemble of 36 projections representing A2 emission path.

as compared to the B1 emission scenario. Under the A2 emission scenario, during the 2080s the average number of days with temperature greater than 34 °C increased to 54 (218% increase) from 17 days (baseline). This increase in days with maximum temperature exceeding the optimum temperature limit will have a negative effect on crop growth and development. Another effect of the higher temperatures is to speed up the crop development. Several experimental and modeling studies have reported decreases in corn grain yield with increasing temperature due to a shortened life cycle and reproductive phase (Badu-Apraku et al., 1983; Hatfield et al., 2011; Muchow et al., 1990).

3.3. *Climate change impact on yield and water use under fully irrigated condition*

3.3.1. *Change in yield*

Simulation with the S1 scenario (ensemble of 112 projections) resulted in a decrease in yield during the 2020s, 2050s and 2080s with changes in temperature and precipitation (Fig. 2), in agreement with the experimental and modeling studies noted above (e.g., Alexandrov and Hoogenboom, 2000; Parry et al., 2004; Hatfield et al., 2011). As shown in Fig. 2, the changes in temperature (T) resulted in the same probability distribution curve as that of with changes in both temperature and precipitation ($T+P$). Similarly, changes in precipitation (P) resulted in the probability distribution curves similar to that of the baseline (Base-100ET). The changes in precipitation have no effect on yield because with full irrigation (i.e., 100ET) 100% consumptive use demand is met by irrigation. Temperature was the only climate factor that decreased yield of irrigated corn. However, when the effect of elevated CO_2 was considered ($T+P+CO_2$), there was a smaller reduction in yield as compared to the effect of climate change alone (Fig. 2). With climate change, corn yield decreased from 10,339 kg ha^{-1} (baseline yield) to 8702, 7819, and 7056 kg ha^{-1} during the 2020s, 2050s, and 2080s, respectively under the S1 scenario. Taking into account the effect of elevated CO_2 levels with the S1 scenario, the simulated corn yield was 8988, 8451 and 7947 kg ha^{-1} during the 2020s, 2050s, and 2080s, respectively. Overall the decrease in the mean corn yield varied from 15.4 to 16.5, 21.6 to 26.4, and 24.9 to 37.5% during the 2020s, 2050s and 2080s, respectively under the four different climate change scenarios (Fig. 3) when simulation was carried out without considering the effect of elevated CO_2. When the effect of elevated CO_2 was considered, under all four climate change scenarios, the decrease in yield ranged from 11.3 to 14.0, 17.1 to 21.0, and 20.7 to 27.7% during the 2020s, 2050s, and 2080s, respectively. Though the increased CO_2 concentrations increased the corn yield (as compared to yield obtained without the CO_2 effect), it could not fully overcome the negative impact of increasing temperature.

Kolmogorov–Smirnov 2-sample statistics for comparison of the cumulative distribution functions of corn yield between the baseline and climate change scenarios showed that the distribution functions were significantly different with p values less than 0.0001 for all the scenarios and all the three periods (Table 3). The values of the D statistic, maximum absolute difference between the empirical cumulative distribution function for the base and simulated yield under climate change scenarios, for all four climate change scenarios ranged from 0.62 to 0.64, 0.72 to 0.82, and 0.74 to 0.94 during the 2020s, 2050s, and 2080s, respectively. These values of

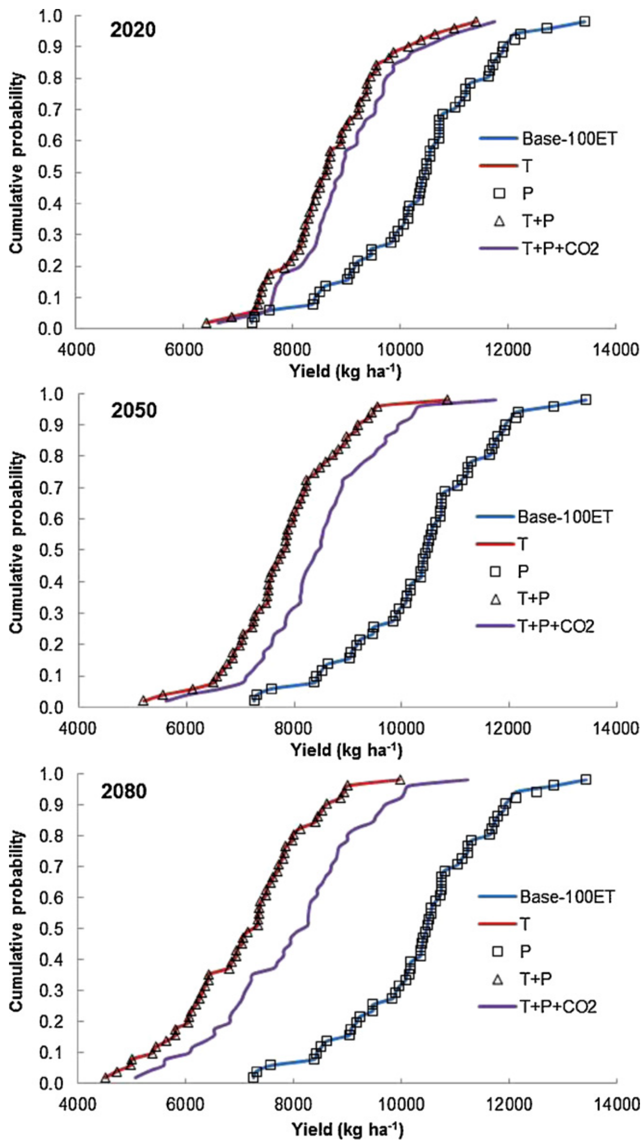

Fig. 2. Cumulative distribution function of mean corn yield in response to changes in temperature, precipitation, and CO_2 levels for the S1 scenario with irrigation to meet full ET demand.

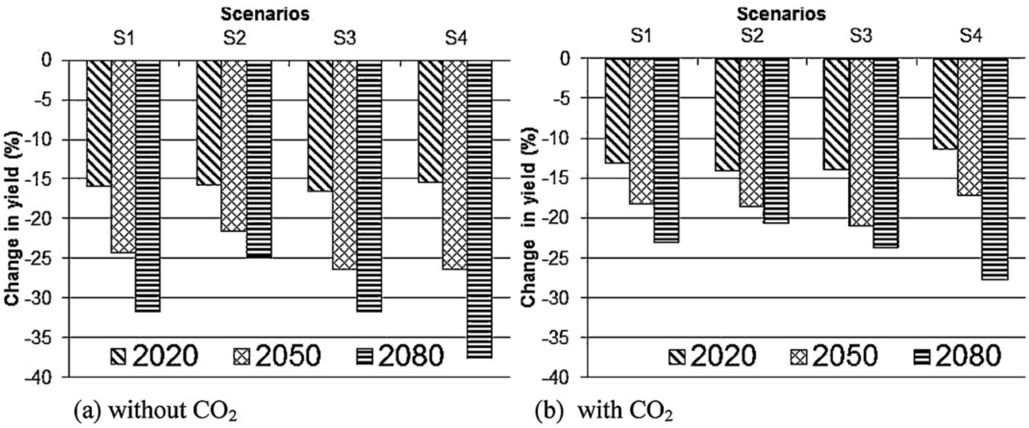

Fig. 3. Relative changes in the mean corn yield under different climate change scenarios (S1–S4) with and without CO_2 effect under full irrigation.

the p (<0.0001) and D statistic indicate that the cumulative distribution functions are significantly different as compared to those of the baseline yield. The differences between the baseline and future simulated yields increased from the 2020s to the 2080s, as indicated by the higher D values. When the effect of elevated CO_2 concentrations was considered, the D values were lower; ranging from 0.52 to 0.62, 0.58 to 0.70, and 0.66 to 0.78 during the 2020s, 2050s, and 2080s, respectively and the p values remained less than 0.0001. These lower values of D, in the case of the elevated CO_2, also indicate that changes in yield are lower as compared to the changes in yield obtained when effect of elevated CO_2 was not considered.

3.3.2. *Change in crop duration, evapotranspiration and water use efficiency*

Increased temperature may accelerate crop growth and development and shorten the crop growing period, as evidenced by the several experimental studies (Badu-Apraku et al., 1983; Muchow et al., 1990). Simulation results showed a substantial decrease in crop maturity time (shortened crop growing period) during the 2020s, 2050s and 2080s under all four climate change scenarios. In the case of the S1 scenario, the crop growing duration changed from 133 (baseline) to 117, 109, and 104 days during the 2020s, 2050s and 2080s, respectively (Table 4 and Fig. 4a). Climate change scenarios representing the higher emission path (A2) resulted in comparatively more decrease in crop duration as compared to the middle (A1B) and low emission (B1) scenarios during the 2080s, whereas during the 2020s the crop duration remained almost the same for all three emission scenarios (Table 4). Further, the mean crop duration decreased linearly with mean increase in temperature for all climate change scenarios (Fig. 4b). Every 1 °C rise in mean temperature resulted in shortening of crop growing duration by about 5 days. The mean grain yield decreased linearly with reduction in the crop growth period (Fig. 4c) because of the reduced seasonal light interception and photosynthesis due to the shorter crop growing period. This result indicates that the shortening of the crop maturity duration caused by increased temperature was an important factor in the yield reduction.

The reduction in the crop growing period due to rise in temperature resulted in a decrease in actual seasonal evapotranspiration as compared to the baseline (Table 4) under all four climate change scenarios. However, the daily evapotranspiration rate increased due to the increase in temperature (Table 4). The change in seasonal crop evapotranspiration remained almost the same for all the four scenarios during the 2020s and 2050s when simulation was made without considering elevated CO_2 levels. There were approximately a 6 and 10% decreases in the actual evapotranspiration demand during the 2020s and 2050s, respectively (Fig. 5a); whereas during the 2080s this decrease ranged from 9.4 to

Table 3
Mean corn yield under different climate change scenarios with full irrigation.

Scenarios	Without CO_2 effect			With CO_2 effect		
	Mean (kg ha^{-1})	SD (kg ha^{-1})	D statistic	Mean (kg ha^{-1})	SD (kg ha^{-1})	D statistic
Base	10339.0	1333.6				
2020s						
S1	8701.5 (−15.8)	1028.1	0.62[a]	8988.4 (−13.1)	1060.6	0.58[a]
S2	8708.4 (−15.8)	1039.9	0.62	8886.8 (−14.1)	1057.9	0.60
S3	8633.2 (−16.5)	991.9	0.64	8896.1 (−14.0)	1023.4	0.58
S4	8744.6 (−15.4)	1074.0	0.62	9167.8 (−11.3)	1130.6	0.52
2050s						
S1	7819.2 (−24.4)	1043.8	0.74	8451.0 (−18.3)	1130.7	0.62
S2	8102.6 (−21.6)	902.4	0.72	8413.1 (−18.6)	936.9	0.68
S3	7609.2 (−26.4)	1017.0	0.76	8164.1 (−21.0)	1092.2	0.68
S4	7607.5 (−26.4)	1042.6	0.74	8568.3 (−17.1)	1176.2	0.58
2080s						
S1	7056.2 (−31.8)	1209.4	0.84	7946.7 (−23.1)	1366.2	0.68
S4	7767.4 (−24.9)	974.5	0.74	8202.5 (−20.7)	1028.0	0.66
S3	7059.8 (−31.7)	1089.4	0.84	7880.7 (−23.8)	1217.4	0.72
S2	6457.6 (−37.5)	1288.2	0.90	7476.1 (−27.7)	1499.2	0.78

S1, ensemble of 112 projections; S2, ensemble of 37 projections representing B1 emission path; S3, ensemble of 39 projections representing A1B emission path; S4, ensemble of 36 projections representing A2 emission path; SD, standard deviation; D stats, Kolmogorov–Smirnov 2-sample statistics; terms in the parenthesis indicates percentage change from baseline period.

[a] p values less than 0.0001 for all the four scenarios and all the three time periods (2020s, 2050s, and 2080s).

Table 4
Change in crop growing period and seasonal water balance components under different climate change scenarios with full irrigation.

Scenarios	Crop duration, days	Act evap (cm)	Act tran (cm)	Pot evap (cm)	Pot tran (cm)	S–W ET (cm)	Act ET (cm)	WUE (kg m^{-3})	Act evap (cm)	Act tran (cm)	Pot evap (cm)	Pot tran (cm)	S–W ET (cm)	Act ET (cm)	WUE (kg m^{-3})
		Without CO_2							With CO_2						
Base	133	23.7	47.2	28.0	47.8	75.8 (5.7)[a]	71.0 (5.3)	1.46	23.7	47.2	28.0	47.8	75.8 (5.7)	71.0 (5.3)	1.46
2020s															
S1	117	21.3	45.4	25.1	45.7	70.7 (6.1)	66.7 (5.7)	1.31	21.9	41.6	25.6	41.9	67.5 (5.8)	63.4 (5.4)	1.42
S2	117	21.3	45.3	25.1	45.7	70.7 (6.1)	66.6 (5.7)	1.31	21.5	43.0	25.4	43.3	68.7 (5.9)	64.5 (5.5)	1.38
S3	116	21.4	45.3	25.0	45.6	70.6 (6.1)	66.6 (5.7)	1.30	21.7	41.8	25.5	42.1	67.6 (5.8)	63.5 (5.5)	1.40
S4	117	21.2	45.4	25.1	45.7	70.9 (6.0)	66.6 (5.7)	1.31	22.1	39.8	26.0	40.1	66.1 (5.6)	61.9 (5.3)	1.48
2050s															
S1	109	20.0	44.3	23.9	44.4	68.3 (6.3)	64.2 (5.9)	1.22	21.2	36.1	25.1	36.2	61.3 (5.6)	57.3 (5.2)	1.48
S2	112	20.4	44.6	24.3	44.8	69.1 (6.2)	65.0 (5.8)	1.25	21.1	40.4	24.9	40.6	65.5 (5.9)	61.4 (5.5)	1.37
S3	108	19.9	44.2	23.6	44.3	67.9 (6.3)	64.1 (5.9)	1.19	21.1	36.7	24.8	36.8	61.6 (5.7)	57.8 (5.4)	1.41
S4	108	20.0	44.2	23.7	44.3	68.0 (6.3)	64.2 (5.9)	1.18	21.7	32.4	25.5	32.5	58.0 (5.4)	54.1 (5.0)	1.58
2080s															
S1	104	19.4	43.7	23.0	43.8	66.8 (6.4)	63.1 (6.1)	1.12	21.1	32.3	24.8	32.3	57.1 (5.5)	53.3 (5.1)	1.49
S2	109	20.0	44.2	23.7	44.4	68.2 (6.3)	64.3 (5.9)	1.21	21.0	38.1	24.7	38.2	63.0 (5.8)	59.2 (5.4)	1.39
S3	104	19.4	43.7	22.9	43.8	66.7 (6.4)	63.1 (6.1)	1.12	20.9	32.9	24.6	33.0	57.5 (5.6)	53.8 (5.2)	1.46
S4	100	18.7	43.4	22.3	43.4	65.7 (6.6)	62.1 (6.2)	1.04	20.6	31.2	24.2	31.2	55.4 (5.5)	51.8 (5.2)	1.44

S1, ensembles of 112 projections; S2, ensembles of 37 projections representing B1 emission path; S3, ensembles of 39 projections representing A1B emission path; S4, ensembles of 36 projections representing A2 emission path; S–W ET, Shuttleworth–Wallace evapotranspiration; WUE, water use efficiency; Act evap, actual evaporation, Pot evap, potential evaporation; Act tran, actual transpiration; Pot trans, potential transpiration.
[a] Terms in the parenthesis indicates average rate of evapotranspiration during crop period in mm/day.

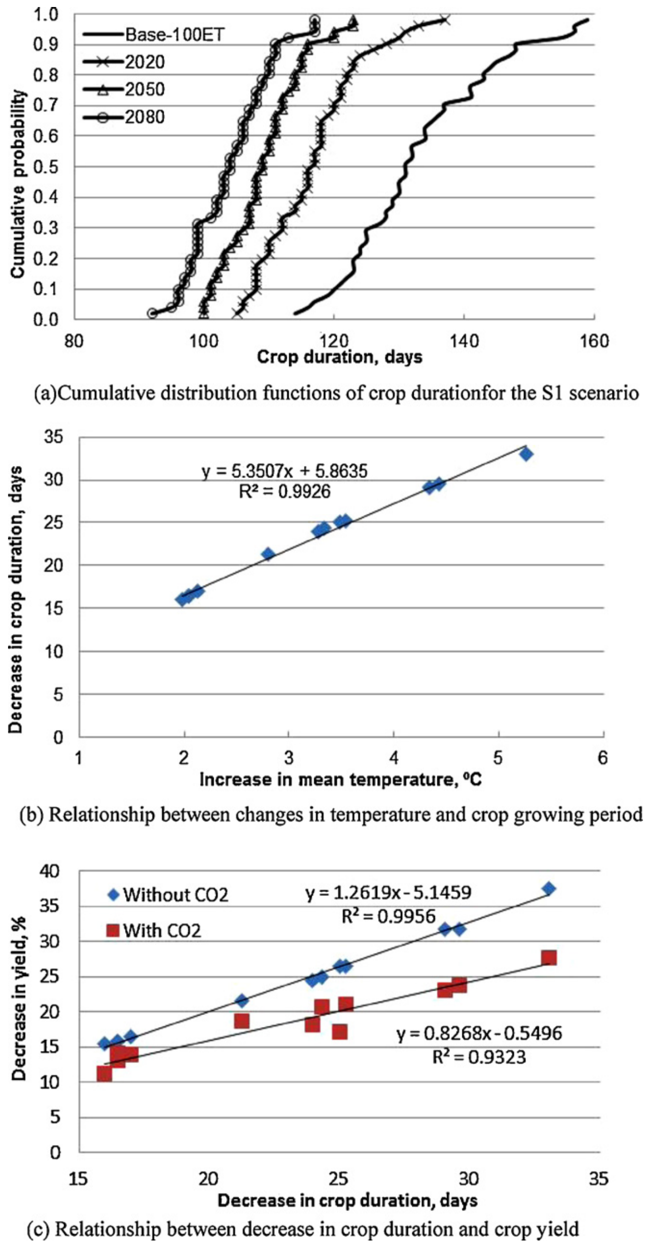

Fig. 4. Effect of climate change on crop growing duration of corn: (a) cumulative distribution functions of crop duration for the S1 scenario; (b) relationship between change in temperature and crop growing period for all scenarios; and (c) relationship between mean decrease in crop duration and mean decrease in yield for all scenarios, under full irrigation.

12.6%. The seasonal potential evapotranspiration decreased by about 7% during the 2020s. During the 2050s and 2080s, the decrease in potential evapotranspiration ranged from 8.9 to 10.4 and 10.1 to 13.3%, respectively. When effect of elevated CO_2 was considered, the decrease in the seasonal crop evapotranspiration was higher, ranging from 9.0 to 12.8, 13.4 to 23.8, and 16.7 to 27.0% during the 2020s, 2050s, and 2080s, respectively, under different climate change scenarios (Fig. 5b).

The water use efficiency (WUE) (yield per unit of actual evapotranspiration) also decreased due to the decrease in yield. With increasing CO_2 concentrations, due to the decrease in stomatal conductance, there was a decrease in transpiration and hence evapotranspiration, along with an increase in grain yield. Thus, the increased CO_2 levels resulted in higher WUE values as compared to the WUE values obtained without considering the effect of elevated

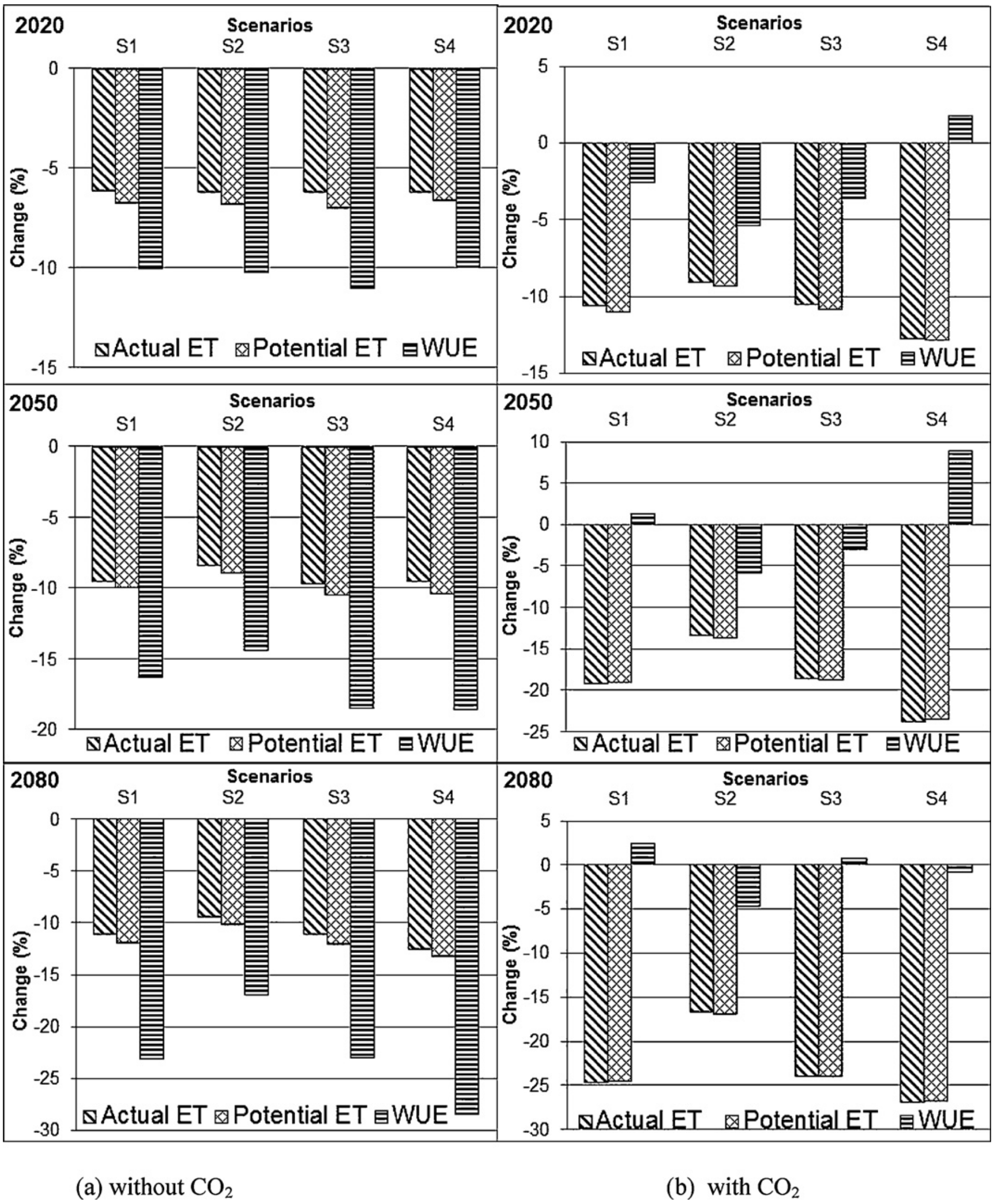

Fig. 5. Change in seasonal actual evapotranspiration, potential evapotranspiration and water use efficiency for the S1–S4 scenarios with and without CO_2 effect under full irrigation.

CO_2. The WUE varied from 1.1 to 1.3 kg m^{-3} in case of the S1 scenario without the considering the effect of elevated CO_2, and 1.4 to 1.5 kg m^{-3} when the effect of elevated CO_2 was considered. These results suggest that with the elevated CO_2 levels, WUE remains closer to the baseline WUE values and partly mitigate the negative effect of increasing temperature.

Fig. 6 depicts the changes in seasonal irrigation water requirements to meet the ET demand under different climate change scenarios. Simulation results showed an increase in seasonal irrigation water use when effect of elevated CO_2 was not considered, but the increase was less than 3%. This increase in irrigation water use is due to a decrease in precipitation and an increase in ET demand during the crop growing period. When the effect of elevated CO_2 was considered, the irrigation water use decreased as compared to the baseline conditions for all the scenarios during the 2020s, 2050s and 2080s respectively. This decrease ranged from 2.0 to 6.8, 5.2 to 16.0 and 8.1 to 15.5% during the 2020s, 2050s and 2080s, respectively. This decrease was primarily due to decrease in actual evapotranspiration demand with increasing CO_2 levels and a shortened crop growing period.

Several studies have suggested longer duration hybrids of corn as one of the possible adaptation strategies to counterbalance the accelerated phenology due to warmer climate (Kapetanaki and Rosenzweig, 1997; Tao and Zhang, 2011; Tubiello et al., 2000). Assuming a longer duration hybrid corn having the same WUE as the current hybrid, the amount of water required to maintain the baseline yield was estimated. When the effect of elevated CO_2 was not considered the estimated increase in irrigation water demand to maintain the baseline yield (100ET) under different climate change scenarios (S1–S4) ranged from 11.0 to 12.4, 16.9 to 23.0 and 20.6 to 40.0% during the 2020s, 2050s and 2080s, respectively. When the effect of elevated CO_2 was considered, these values ranged from −1.7 to 5.8, −8.1 to 6.4 and −2.2 to 5.1% during the 2020s, 2050s and 2080s, respectively. These estimates indicate that

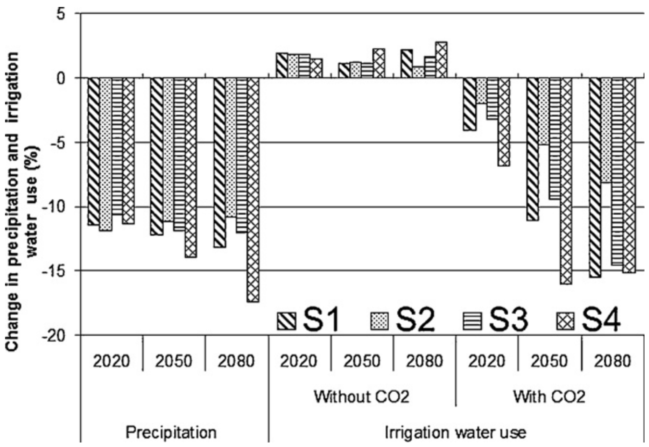

Fig. 6. Changes in seasonal precipitation and irrigation water use from the baseline period under different climate change scenarios (S1–S4) during the 2020s, 2050s and 2080s, with irrigation to meet full ET demand.

with elevated CO_2 levels, total seasonal irrigation water demand may not change significantly under the projected climate change scenarios even when longer duration hybrids are used to maintain yield potential.

3.4. Climate change impact on yield and water use efficiency under deficit irrigation

As a management strategy to meet the challenges of reduced water availability, two deficit irrigations levels (i.e., 75ET, 50ET) were also simulated. Table 5 presents the comparison of the effect of changes in temperature, precipitation, CO_2 on yield under different irrigation levels for S1 scenario. For the baseline period (1950–99), average corn yields for 100ET, 75ET and 50ET simulations were 10,339, 8441 (18.4% decrease) and 4817 (53.4% decrease) kg ha^{-1}, respectively. As expected with only CO_2 increase (without any change in P or T) there was an increase in yield as compared to the corresponding baseline yield for each irrigation level. The gain in yield due to elevated CO_2 was marginal in case of full irrigation (100ET); there was 3. 5, 8.1 and 12.8% increase in yield as compared to the baseline yield for 100ET during 2020s, 2050s, and 2080s, respectively. For deficit irrigation level of 75ET, the gain in yield (as compared to the baseline yield for 75ET) due to the effect of increased CO_2 concentrations was about 7.3, 18.7 and 28.5% during 2020s, 2050s, and 2080s, respectively; whereas for irrigation level of 50ET the increase (as compared to the baseline yield for 50ET) in yield was 10.6, 27.0, and 43.0% during 2020s, 2050s, and 2080s, respectively. Thus, the positive effect of CO_2 was higher under water stress conditions and these results are in agreement with other previous results (Boote et al., 2011; Chun et al., 2011; Leakey, 2009; Ruane et al., 2011; Wechsung et al., 2000; Xiong et al., 2007). However, the simulation with increasing CO_2 concentrations coupled with precipitation and temperature changes, resulted in decrease in corn yield for all the three irrigation levels and for all the three periods (2020s, 2050s, and 2080s). As maize is C4 plant, elevated CO_2 enrichment alone would not benefit maize production significantly, especially for irrigated maize (Alexandrov and Hoogenboom, 2000). Based on the experimental results in the open air and within the Corn Belt using Free-Air Concentration Enrichment (FACE) technology, Leakey et al. (2006) reported that photosynthesis and yield of maize might be unaffected by rising CO_2 in the absence of water stress.

Under deficit irrigation (75ET and 50ET), decreases in yield (relative to the baseline yield for the corresponding irrigation level) due to climate change were lower (Fig. 7) as compared to the decrease in

Table 5
Comparison of climate change effect on corn yield with different irrigation levels under S1 scenario.

Scenario	Crop duration (days)	T_{min} °C	T_{max} °C	Precipitation, cm	100ET			75ET			50ET		
					Irrigation applied, cm	Yield, (kg ha^{-1})	Change in yield (%)	Irrigation applied, cm	Yield, (kg ha^{-1})	Change in yield (%)	Irrigation applied, cm	Yield, (kg ha^{-1})	Change in yield (%)
Base	133	11.35	28.56	17.93	53.33	10339.00	–	35.61	8441.30	–	18.46	4816.88	–
2020													
P	133	11.35	28.56	17.73	53.50	10342.06	0.03	35.78	8417.18	−0.29	18.70	4868.43	1.07
CO_2	133	11.35	28.56	17.93	50.08	10695.74	3.45	33.19	9056.84	7.29	17.07	5328.18	10.61
T	117	13.46	30.56	16.06	54.00	8699.58	−15.86	36.28	7383.70	−12.53	19.04	4263.98	−11.48
$T+P$	117	13.46	30.56	15.89	54.38	8701.48	−15.84	36.53	7392.22	−12.43	19.15	4263.52	−11.49
$T+P+CO_2$	117	13.46	30.56	15.89	51.16	8988.40	−13.06	34.21	7854.14	−6.96	17.93	4682.52	−2.79
2050													
P	133	11.35	28.56	18.00	53.22	10341.58	0.02	35.54	8426.34	−0.18	18.44	4877.06	1.25
CO_2	133	11.35	28.56	17.93	46.10	11180.68	8.14	30.11	10015.84	18.65	15.05	6123.40	27.12
T	109	14.74	31.74	15.69	54.27	7818.42	−24.38	36.57	6674.62	−20.93	19.43	3820.12	−20.69
$T+P$	109	14.74	31.74	15.75	53.92	7819.24	−24.37	36.63	6654.14	−21.17	19.21	3858.56	−19.90
$T+P+CO_2$	109	14.74	31.74	15.75	47.43	8450.98	−18.26	31.63	7705.88	−8.71	16.04	4782.72	−0.71
2080													
P	133	11.35	28.56	18.28	53.01	10349.60	0.10	35.25	8439.66	−0.02	18.13	4887.66	1.47
CO_2	133	11.35	28.56	17.93	42.82	11662.02	12.80	27.69	10850.82	28.54	13.38	6889.56	43.03
T	104	15.81	32.77	15.24	54.38	7056.30	−31.75	37.23	6029.62	−28.57	19.71	3434.82	−28.69
$T+P$	104	15.81	32.77	15.57	54.51	7056.20	−31.75	36.85	6068.14	−28.11	19.43	3480.56	−27.75
$T+P+CO_2$	104	15.81	32.77	15.57	45.08	7946.72	−23.14	30.05	7604.64	−9.91	14.90	4722.76	−1.95

P, scenario with changes in precipitation only; T, scenario with changes in temperature only; CO_2, scenario with changes in CO_2 only; $T+P$, scenario with changes in temperature and precipitation; $T+P+CO_2$, scenario with changes in temperature, precipitation and CO_2; T_{min}, average minimum air temperature during crop growing period (50 years average); T_{max}, average maximum air temperature during crop growing period (50 years average); precipitation, total precipitation during crop growing period (50 years average); irrigation, total irrigation water applied during crop growing period (50 years average).

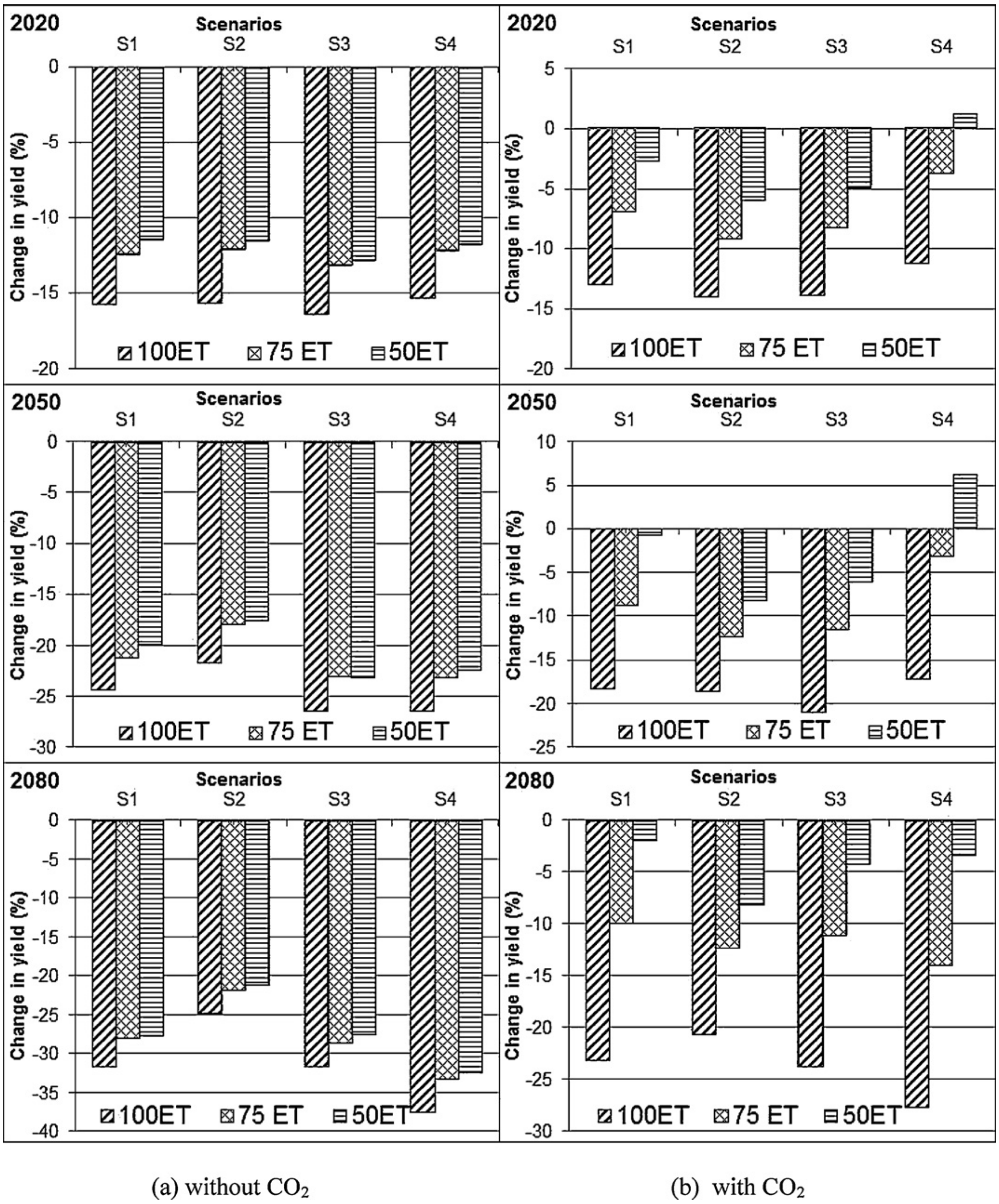

Fig. 7. Comparison of change in yield from the baseline for different levels of irrigation under different climate change scenarios (S1–S4) with and without CO_2 effect.

yield for full irrigation (relative to the baseline yield for the full irrigation). Simulation results for the 75ET deficit irrigation with the S1 scenario and elevated CO_2 levels, showed a decrease of 7.0, 8.7 and 9.9% in yield during the 2020s, 2050s and 2080s, respectively when compared to the baseline yield simulated with 75ET. In the case of 50ET, the decrease in average yield was about 2.8, 0.7 and 1.95%, during the 2020s, 2050s and 2080s, respectively when compared to the baseline yield simulation with 50ET. With increased CO_2 concentrations, the maximum change (increase/decrease) in corn yield for all scenarios (S1–S4) remained below 10 and 15% for the 50ET and 75ET treatments, respectively (Fig. 7). Relatively smaller decreases in yields under deficit irrigations could be explained by the combination of accelerated crop maturity due to higher temperatures combined with more positive effects of higher CO_2 under soil water deficit conditions (Ruane et al., 2011). Under elevated CO_2, reduced stomatal conductance reduces evapotranspiration and crop water use, and thereby ameliorates short-term water stress by conserving soil moisture (Leakey, 2009). The number of days with above-optimum or below-optimum temperatures during crop period was the same for all irrigation levels for any given climate change scenario, and therefore, relative effect of the above – or below-optimum temperatures on growth was the same under all irrigation levels.

The WUE for 75ET remained almost the same as that of 100ET with the elevated CO_2 concentrations (Table 6). The WUE ranged from 1.40 to 1.52 $kg\,m^{-3}$ in the case of the S1 scenario. But with the 50ET there was a decrease in the WUE and it ranged from 1.15 to 1.27 $kg\,m^{-3}$ in the case of the S1 scenario. Comparison of the WUE obtained with and without the elevated CO_2 concentrations, indicated an improved WUE under deficit irrigation when the effect of increased CO_2 concentrations was considered (Fig. 8).

4. Limitations

The crop growth simulation models are frequently used by researchers to understand the complexity of climate–crop

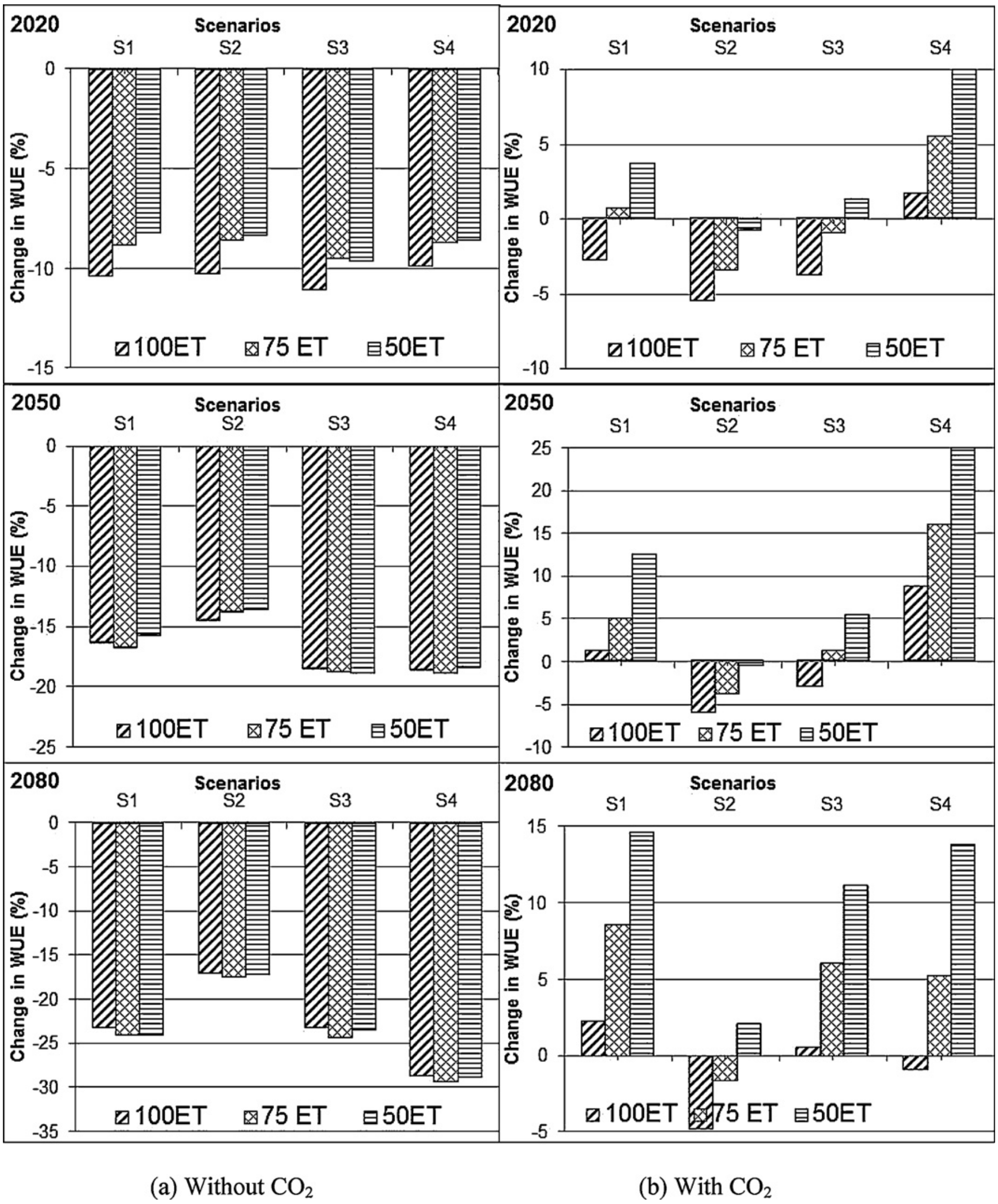

Fig. 8. Changes in water use efficiency with different levels of irrigation under different climate change scenarios (S1–S4) with and without CO_2 effect.

interactions, and probably the only practical approach for assessing climate change impact on agro-ecosystems. Like most studies on climate change impact on crop production using crop simulation models, there are several sources of uncertainty and limitations in this study. Some uncertainties are inherent in the model structure and some are due to model calibration and parameterization. The model has been calibrated using three years of field measured data for different levels of irrigations. The effect of increasing CO_2 concentrations on growth and yield of corn has been simulated using standard relationships/methodology as published in the literature. However, these relationships were derived from a limited number of experiments, often in controlled environments, and were, therefore, not fully tested, particularly for warmer and more variable climate change conditions. Lack of field measured data on the effect of CO_2 on growth and yield of corn under different temperature regimes and different irrigation levels, is one of the major limitations for validation of simulation results in climate change impact assessment studies, including this study. Thus, considerable debate over whether the simulation results obtained using crop models are accurate will remain until more definitive field results are incorporated in the simulation studies. Further, in this simulation study it was assumed that insect pests, diseases, and weeds pose no limitation on crop growth and yield under both current and future climate scenarios. The agronomic practices, e.g., fertilization rates, sowing dates, irrigation applications etc. were assumed to be same in future. Technological development and land use were also assumed to be constant. Thus, the effects of climatic change on crop production under the natural and future field conditions may be different from those obtained using the crop models. However, these simulation studies provide valuable information on possible impact of climate change on crop production, and guideline for adaptation strategies through simulation of different agronomical (changing of planting dates, varieties/cultivars, cropping sequences, irrigation levels etc.) management options.

Table 6
Seasonal evapotranspiration and WUE under deficit irrigation.

Scenario	Crop duration, days	75ET								50ET							
		Without CO_2 effect				With CO_2 effect				Without CO_2 effect				With CO_2 effect			
		Potential ET (cm)	Actual ET (cm)	IW (cm)	WUE (kg m^{-3})	Potential ET (cm)	Actual ET (cm)	IW (cm)	WUE (kg m^{-3})	Potential ET (cm)	Actual ET (cm)	IW (cm)	WUE (kg m^{-3})	Potential ET (cm)	Actual ET (cm)	IW (cm)	WUE (kg m^{-3})
Base	133	75.5	60.2	35.6	1.40		75.8	43.4	18.5	1.11							
2020s																	
S1	117	70.5	57.8	36.5	1.28	67.3	55.6	34.2	1.41	71.1	41.9	19.2	1.02	68.1	40.7	17.9	1.15
S2	117	70.5	57.8	36.5	1.28	68.5	56.6	35.1	1.35	71.1	41.9	19.3	1.02	69.3	41.1	18.4	1.10
S3	116	70.4	57.7	36.2	1.27	67.4	55.6	33.9	1.39	70.9	41.9	19.1	1.00	68.1	40.7	17.8	1.12
S4	117	70.7	57.8	36.3	1.28	65.8	54.8	33.0	1.48	71.3	41.9	19.3	1.01	66.8	39.9	17.2	1.22
2050s																	
S1	109	68.0	57.0	36.6	1.17	61.0	52.3	31.6	1.47	68.6	41.3	19.2	0.93	61.7	38.3	16.0	1.25
S2	112	68.9	57.2	36.2	1.21	65.2	54.9	33.7	1.35	69.4	41.4	19.0	0.96	66.0	40.0	17.4	1.10
S3	108	67.7	57.0	36.6	1.14	61.3	52.6	31.9	1.42	68.2	41.2	19.1	0.90	62.0	38.6	16.2	1.17
S4	108	67.8	57.0	36.9	1.14	57.6	50.2	29.9	1.63	68.3	41.2	19.5	0.91	58.3	36.9	14.8	1.39
2080s																	
S1	104	66.6	56.9	36.9	1.07	56.8	49.9	30.1	1.52	66.9	41.2	19.4	0.84	57.4	37.1	14.9	1.27
S2	109	67.9	56.9	36.3	1.16	62.7	53.6	32.5	1.38	68.4	41.3	19.1	0.92	63.4	39.0	16.7	1.13
S3	104	66.4	56.7	36.8	1.06	57.2	50.4	30.3	1.49	66.8	41.1	19.2	0.85	57.8	37.4	15.0	1.23
S4	100	65.6	56.7	37.9	0.99	55.1	49.1	30.7	1.48	65.9	41.2	20.1	0.79	55.6	36.8	15.3	1.26

S1, ensemble of 112 projections; S2, ensemble of 37 projections representing the B1 emission path; S3, ensembles of 39 projections representing A1B emission path; S4, ensemble of 36 projections representing the A2 emission path; ET, evapotranspiration; IW, irrigation water used; WUE, water use efficiency.

5. Summary and conclusions

Crop production will be significantly affected by changes in climate and rising CO_2 levels. In this study, the impact of climate change on irrigated corn (maize) was simulated using the RZWQM2 model containing the CERES crop module. Four different multi-model ensemble climate change scenarios were generated and used to estimate impact on corn yield and water use. Simulation results indicated that under the projected climate change scenarios, the negative effects of temperature rise would dominate over the positive effects of increasing CO_2 levels resulting in a net decrease in crop yield, even when irrigation to meet full ET demand is provided. When the effect of elevated CO_2 concentrations was considered along with changes in temperature and precipitation, the decrease in yield ranged from 11.3 to 14.0, 17.1 to 21.0, and 20.7 to 27.7% during the 2020s, 2050s, and 2080s, respectively. The yield decreases were attributed to the shortening of the crop maturity date due to the increase in temperature, and the number of days when temperatures were above the optimum limit for the crop. Under deficit irrigation (75ET and 50ET) the relative decrease in yield due to climate change was smaller as compared to the decrease in yield in the case of full irrigation (100ET).

The results of this research also indicate that climate change might not increase the total water demand of the crop, as commonly thought, because of the reduced duration of the crop growing period and the effect of increased CO_2 concentrations of decreasing the potential evapotranspiration demand. Simulation results showed about a 6.0, 10.0 and 12.6% decrease in the actual evapotranspiration during the 2020s, 2050s and 2080s, respectively, with changing climatic conditions. When the effect of elevated CO_2 levels were considered along with climatic changes this decrease in actual evapotranspiration was higher, in the range of 9.0 to 27.0% depending upon the climate change scenarios and decade. The WUE decreased due to decrease in yield under changing climate scenarios when the effect of elevated CO_2 were not considered. However, when the effect of elevated CO_2 were considered and deficit irrigation was assumed (75ET and 50ET) this resulted in improved WUE as compared to the WUE values obtained without considering elevated CO_2 effects.

A shortened crop growing period due to temperature increase is the major cause of the yield decrease. Thus, a potential adaptation strategy is to have longer duration corn cultivars that can also tolerate higher temperatures. Estimation of the irrigation water required to maintain the baseline yield with full irrigation, assuming a longer duration hybrid corn having the same WUE as the current variety, indicated that due to elevated CO_2 concentrations the irrigation water demand may not change significantly. With the elevated CO_2, the changes in irrigation water demand varied in the range of -1.7 to 5.8, -8.1 to 6.4 and -2.2 to 5.1% during the 2020s, 2050s, and 2080s, respectively under different climate change scenarios.

Acknowledgment

The authors would like to thank USDA Foreign Agricultural Service (FAS) for providing the necessary funding under the Global Research Alliance and Norman E. Borlaug International Agricultural Science and Technology Fellowship Program for conducting this research work.

References

Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), 2000. Root Zone Water Quality Model: Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC Highlands Ranch, CO, USA, p. 372.

Alexandrov, V.A., Hoogenboom, G., 2000. Vulnerability and adaptation assessments of agricultural crops under climate change in the Southeastern USA. Theoretical and Applied Climatology 67, 45–63.

Allen, L.H., 1990. Plant response to rising carbon dioxide and potential interaction with air pollutants. Journal of Environment Quality 19, 15–34.

Allen, L.H., Boote, K.J., Jones, J.W., Valle, R.R., Acock, B., Rogers, H.H., Dahlman, R.C., 1987. Response of vegetation to rising carbon dioxide: photosynthesis, biomass, and seed yield of soybean. Global Biogeochemical Cycles 1, 1–14.

Anderson, J.A., Alagarswamy, G., Rotz, C.A., Ritchie, J.T., LeBaron, A.W., 2001. Weather impacts on maize, soybean, and alfalfa production in the Great Lakes region, 1895–1996. Agronomy Journal 93, 1059–1070.

Badu-Apraku, B., Hunter, R.B., Tollenaar, M., 1983. Effect of temperature during grain filling on whole plant and grain yield in maize. Canadian Journal of Plant Science 63, 357–363.

Boote, K.J., Allen, L.H., Vara Prasad, P.V., Jones, J.W., 2011. Testing effects of climate change in crop models. In: Hillel, D., Rosenzweig, C. (Eds.), Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, vol. 1. Imperial College Press, pp. 109–129.

Chaudhuri, U.N., Kirkam, M.B., Kanemasu, E.T., 1990. Root growth of winter wheat under elevated carbon dioxide and drought. Crop Science 30, 853–857.

Christensen, N.S., Lettenmaier, D.P., 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrology and Earth System Sciences 11, 1417–1434.

Chun, J.A., Wang, Q., Timlin, D., Fleisher, D., Reddy, V.R., 2011. Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn. Agricultural and Forest Meteorology 151, 378–384.

Farahani, H.J., DeCoursey, D.G., 2000. Potential evapotranspiration processes in the soil–crop-residue system. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model: Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 51–80.

Guerena, A., Ruiz-Ramos, M., Diaz-Ambrona, C.H., Conde, J.R., Minguez, M.I., 2001. Assessment of climate change and agriculture in Spain using climate models. Agronomy Journal 93, 237–249.

Hamlet, A.F., Salathe, E.P., Carrasco, P., 2010. Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. http://www.hydro.washington.edu/2860/report/ (accessed 18.05.11).

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate impacts on agriculture: implications for crop production. Agronomy Journal 103, 351–370.

Hay, L.E., Wilby, R.L., Leavesley, G.H., 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. Journal of the American Water Resources Association 36 (2), 387–397.

Hillel, D., Rosenzweig, C., 2011. Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, vol. 1. Imperial College Press, 440 pp.

Intergovernmental Panel on Climate Change (IPCC), 2000. IPCC Special Report on Emission Scenarios. A Special Report of IPCC Working Group III. Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK, 570 pp.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, 881 pp.

Izaurralde, R.C., Rosenberg, N.J., Brown, R.A., Thompson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States. Part II. Regional agricultural production in 2030 and 2095. Agricultural and Forest Meteorology 117, 97–122.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. European Journal of Agronomy 18, 235–265.

Kapetanaki, G., Rosenzweig, C., 1997. Impact of climate change on maize yield in central and northern Greece: a simulation study with Ceres-Maize. Mitigation and Adaptation Strategies for Global Change 1 (3), 251–271, http://dx.doi.org/10.1023/B:MITI.0000018044.48957.28.

Kimball, B.A., Pinter Jr., P.J., Garcia, R.L., LaMorte, R.L., Wall, G.W., Hunsaker, D.J., Wechsung, G., Wechsung, F., Kartschall, T., 1995. Productivity and water use of wheat under free-air CO_2 enrichment. Global Change Biology 1, 429–442.

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO_2 enrichment. Advances in Agronomy 77, 293–368.

Kiniry, J.R., Bonhomme, R., 1991. Predicting maize phenology. In: Hodges, T. (Ed.), Predicting Crop Phenology. CRC Press, Boca Raton, pp. 115–131.

Ko, J., Ahuja, L.R., Saseendran, S.A., Green, T.R., Ma, L., Nielsen, D.C., Walthall, C.L., 2011. Climate change impacts on dryland cropping systems in the Central Great Plains, USA. Climatic Change, http://dx.doi.org/10.1007/s10584-011-0175-9(published online, August 09, 2011).

Leakey, A.D.B., 2009. Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and fuel. Proceedings of the Royal Society B: Biological Sciences 276, 2333–2343.

Leakey, A.D.B., Uribelarrea, M., Ainsworth, E.A., Naidu, S.L., Rogers, A., Ort, D.R., Long, S.P., 2006. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. Plant Physiology 140, 779–790.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333 (6042), 616–620, http://dx.doi.org/10.1126/science.1204531.

Ma, L., Hoogenboom, G., Saseendran, S.A., Bartling, P.N.S., Ahuja, L.R., Green, T.R., 2009. Effect of estimating soil hydraulic properties and root growth factors on soil water balance and crop production. Agronomy Journal 101, http://dx.doi.org/10.2134/agronj2008.0206x.

Ma, L., Trout, T.J., Ahuja, L.R., Bausch, W.C., Saseendran, S.A., Malone, R.W., Nielsen, D.C., 2012. Calibrating RZWQM2 model for maize responses to deficit irrigation. Agricultural Water Management 103, 140–149.

Maurer, E.P., Brekke, L., Pruitt, T., Duffy, P.B., 2007. Fine-resolution climate projections enhance regional climate change impact studies. Eos Transactions, American Geophysical Union 88 (47), 504.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., Taylor, K.E., 2007. The WRCP CMIP3 multi-model dataset: a new era in climatic change research. Bulletin of the American Meteorological Society 88, 1383–1394.

Meza, F.J., Silva, D., Vigil, H., 2008. Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. Agricultural Systems 98, 21–30.

Muchow, R.C., Sinclair, T.R., Bennett, J.M., 1990. Temperature and solar radiation effects on potential maize yield across locations. Agronomy Journal 82, 338–343.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14, 53–67, http://dx.doi.org/10.1016/j.gloenvcha.2003.10.008.

Peart, R.M., Jones, R.B., Curry, K., Boote, K.J., Allen, L.H., 1989. Impacts of climate change on crop yield in the Southern U.S.A. In: Smith, J.B., Tirpak, D.A. (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, DC.

Peiris, D.R., Crawford, J.W., Grashoff, C., Jefferies, R.A., Porter, J.R., Marshall, B., 1996. A simulation study of crop growth and development under climate change. Agricultural and Forest Meteorology 79, 271–287.

Phillips, D.L., Lee, J.J., Dodson, R.F., 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: I. corn and soybean yields. Agricultural Systems 52, 481–502.

Raff, D.A., Pruitt, T., Brekke, L.D., 2009. A framework for assessing flood frequency based on climate projection information. Hydrology and Earth System Sciences 13, 2119–2136.

Ragab, R., Prudhomme, C., 2002. Climate change and water resources management in arid and semi-arid regions: prospective and challenges for 21st century. Biosystems Engineering 81 (1), 3–34.

Reifen, C., Toumi, R., 2009. Climate projections: past performance no guarantee of future skill? Geophysical Research Letters 36, L13704, http://dx.doi.org/10.1029/2009GL038082.

Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., Hollinger, S., Izaurralde, C., Jagtap, S., Jones, J., Mearns, L., Ojma, D., Paul, E., Paustian, K., Riha, S., Rosenberg, N., Rosenzweig, C., 2003. US agriculture and climate change: new results. Climatic Change 57 (1–2), 43–67.

Ritchie, J.T., Otter-Nacke, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. USDA-ARS, ARS-38, pp. 159–175.

Rogers, H.H., Bingham, G.E., Cure, J.D., Smith, J.M., Suran, K.A., 1983. Responses of selected plant species to elevated carbon dioxide in the field. Journal of Environmental Quality 12, 569–574.

Rojas, K.W., Ahuja, L.R., 2000. Management practices. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 245–280.

Rosenzweig, C., Hillel, D., 1998. Climate Change and the Global Harvest. Oxford University Press, Oxford, UK, pp. 135–154.

Rosenzweig, C., Parry, M.L., 2004. Potential impact of climate change on world food supply. Nature 367, 133–138.

Ruane, A.C., Cecil, L.D., Horton, R.M., Gordón, R., McCollum, R., Brown, D., Killough, B., Goldberg, R., Greeley, A.P., Rosenzweig, C., 2011. Climate change impact uncertainties for maize in Panama: farm information, climate projections, and yield sensitivities. Agricultural and Forest Meteorology, http://dx.doi.org/10.1016/j.agrformet.2011.10.015.

Shaffer, M.J., Rojas, K.W., DeCoursey, D.G., Hebson, C.S., 2000. Nutrient chemistry process-OMNI. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling. Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, USA, pp. 119–144.

Tao, F., Zhang, Z., 2011. Impacts of climate change as a function of global mean temperature: maize productivity and water use in China. Climatic Change 105, 409–432, http://dx.doi.org/10.1007/s10584-010-9883-9.

Thompson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C., Benson, V., 2005. Climate change impacts for the conterminous USA: an integrated assessment. Part. 3. Dryland production of grain and forage crops. Climatic Change 69, 43–65.

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. European Journal of Agronomy 18, 57–74.

Tubiello, F.N., Donatelli, M.C., Rosenzweig, C., Stockle, C.O., 2000. Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy 13, 179–189.

Wechsung, F., Garcia, R.L., Wall, G.W., Kartschall, T., Kimball, B.A., Michaelis, P., Pinter Jr., P.J., Wechsung, G., Grossman-Clarke, S., Lamorte, R.L., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D., Brooks, T.J., 2000. Photosynthesis and conductance of spring wheat ears: field response to free-air CO_2 enrichment and limitations in water and nitrogen supply. Plant Cell and Environment 23, 917–929.

Wood, A.W., Maurer, E.P., Kumar, A., Lettenmaier, D.P., 2002. Long range experimental hydrologic forecasting for the eastern U.S. Journal of Geophysical Research 107 (D20), 4429.

Xiong, W., Matthews, R., Holman, I., Lin, E., Xu, Y., 2007. Modelling China's potential maize production at regional scale under climate change. Climatic Change 85, 433–451.