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Responses of crop yield and water use efficiency to climate change in the North China Plain

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ABSTRACT

Based on future climate change projections offered by IPCC, the responses of yields and water use efficiencies of wheat and maize to climate change scenarios are explored over the North China Plain. The climate change projections of 21st century under A2A, B2A and A1B are from HadCM3 global climate model.

A climate generator (CLIGEN) is applied to generate daily weather data of selected stations and then the data is used to drive CERES-Wheat and Maize models. The impacts of increased temperature and CO_2 on wheat and maize yields are inconsistent. Under the same scenario, wheat yield ascended due to climatic warming, but the maize yield descended. As a more probable scenario, climate change under B2A is moderate relative to A2A and A1B. Under B2A in 2090s, average wheat yield and maize yield will respectively increase 9.8% and 3.2% without CO_2 fertilization in this region. High temperature not only affects crop yields, but also has positive effect on water use efficiencies, mainly ascribing to the evapotranspiration intensification. There is a positive effect of CO_2 enrichment on yield and water use efficiency. If atmospheric CO_2 concentration reaches nearly 600 ppm, wheat and maize yields will increase 38% and 12% and water use efficiencies will improve 40% and 25% respectively, in comparison to those without CO_2 fertilization. However, the uncertainty of crop yield is considerable under future climate change scenarios and whether the CO_2 fertilization may be realized is still needed further research.

1. Introduction

Climate change may have important impacts on agriculture. Based on the simulation of GCMS, future changes of global average temperature are expected to be between 2 °C and 4.5 °C in this century (IPCC, 2001), and some regional areas would be even warmer than the global average (Giorgi and Bi, 2005). So, both for policymakers and scientists, impacts of global warming on agriculture and water resources are referred to as an important issue (Gregory and Ingram, 2000; Sanchez, 2000; Fuhrer, 2003).

Under climate warming, and CO_2 concentration increasing as well, the crop production could be affected in several ways. The environment changes including soil conditions (mainly changes of soil moisture) and air conditions could strongly affect the physiological processes such as photosynthesis, respiration and partitioning of photosynthesis production (Chartzoulakis and Psarras, 2005; Yang and Zhang, 2006). Along with the mean temperature increasing, the occurring frequency of extreme temperature may increase, that may abruptly affect the crop activity (Körner et al., 2002; Wu et al., 2006). Effects of higher temperature, elevated CO_2 concentration and changed precipitation are complicated (Dhungana et al., 2006; Walker and Schulze, 2008). However, CO_2 fertilization will alleviate the effects of temperature and precipitation on crop yield (Brown et al., 2000; Krishnan et al., 2007; Ludwig and Asseng, 2006). Increment of atmospheric CO_2 had an obvious positive effect on photosynthetic rates, leading to enhancement of total biomass and yield of C3 crops (Dhakhwa et al., 1997; Wolf et al., 2002; de Costa et al., 2006). With the physiological process's changes, the management practices could be affected through changes of water use (irrigation) and agricultural inputs such as herbicides, insecticides and fertilizers.

The impact of future climate change on crop production has been widely studied by using crop models and climate change scenarios (Challinor et al., 2005; Hussain and Mudasser, 2007; Challinor and Wheeler, 2008; Tao et al., 2008). Future climate scenarios may be beneficial for wheat in some regions, but could reduce productivity in zones where optimal temperatures already

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exist (Ortiz et al., 2008). The tendency of wheat yield in American Northern Plains will increase 25% in 2030 and 36% in 2095 (Izaurralde et al., 2003). Furthermore, winter wheat production in southern Sweden had the same tendency, being predicted to increase by 10–20% in 2050 (Eckersten et al., 2001). However, wheat yield in southern Australia will decrease about from 13.5% to 32% under most climate change scenarios (Luo et al., 2005).

Rainfed maize yield is vulnerable to climate change, especially in dry regions (Mati, 2000; Jones and Thornton, 2003; Abraha and Savage, 2006). Maize yield in American Corn Belt will increase about 17% in 2095, but that in Northern Plains and Southern Plains will decrease about 9% and 6% (Izaurralde et al., 2003). However, the increment of maize yield on Loess Plateau of China was obviously higher than other regions, which are 57% for A2A and 54% for B2A during 2070–2099 with conventional tillage (Zhang and Liu, 2005).

The potential impact of climate change on agriculture is impressible in semi-humid and semi-arid region (Thomson et al., 2006; Tao et al., 2003). The North China Plain (NCP) locates in the semi-humid region and is vulnerable to climate change (Lin, 1996). The North China Plain as the main food supply area contributes approximately 41% of the total wheat yield and more than 30% of the total maize yield in China. In future, evapotranspiration and water use efficiency of crop will alter with climate change (Thomas, 2008; Mo et al., 2007). To adapt crop systems to the changing climate, it is important to know how climate change affects agricultural production and water use efficiency.

The aim of this paper is to explore the responses of winter wheat and summer maize yields and water use efficiencies to climate change with the DSSAT CERES model. Climate change projections of A2A, B2A and A1B are from HadCM3 model. The Climate Generator (CLIGEN) is used to create daily weather series with monthly projection data. The uncertainties of crop yield responses are also explored.

2. Methods and materials

2.1. Study region

The North China Plain locates in the north of China (31°24′N to 42°42′N, and 110°18′E to 122°42′E) (Fig. 1), with a warm and semi-humid continental monsoon climate. The mean annual temperature of the plain is 8–15 °C. Winter is cold and dry, whereas summer is hot and wet. The mean annual precipitation is 600–800 mm. The main agricultural system is winter wheat and summer maize rotation cropping. Planting areas of wheat and maize in the North China Plain occupy about 45% and 33% of total planting area in China. Average yields of wheat and maize are 4500 kg ha^{-1} and 5300 kg ha^{-1} in this region, respectively. Growth period of winter wheat is from October to next June and that of summer maize is from June to September. The growth period length of wheat and maize are about 250 days and 100 days, respectively. Agricultural soil is mainly calcareous and alluvial soil in most regions, but partly yellow and brown soil. Nice soil texture supplies advantaged condition for high crop production. The water demand of winter wheat is far beyond the precipitation during wheat growing, so it is necessary to irrigate. During maize growing, there is no irrigation, because the need of evapotranspiration can be satisfied by rainfall. Seven sites (Beijing, Shijiazhuang, Anyang, Jinan, Zhengzhou, Xinyang, Xuzhou) were selected to reflect spatial variability in this study.

2.2. Materials introduction

The DSSAT CERES crop model and the Climate Generator model (CLIGEN) are chosen in this paper. The former is mainly used to simulate the crop growth process and water balance and the later is used to generate the weather data to drive the crop model. In a CERES model, the soil data, weather data under baseline and under climate change projections, crop genetic parameters and crop management data are needed as the input data. By running CERES-Wheat and CERES-Maize model, the yield, biomass and evapotranspiration of wheat and maize will be obtained.

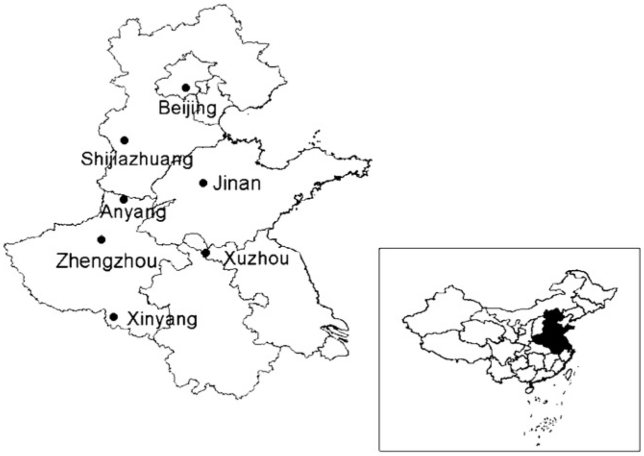

Fig. 1. The locations of the seven selected sites over the North China Plain.

CLIGEN model as the stochastic weather generator researches the general characters of weather and climate and simulates daily weather data based on the statistics of historical climate. Based on the probability of dry and wet, range of temperature change and solar radiation of history climate data, CLIGEN takes monthly weather data as input, and then generates precipitation, daily maximum temperature, minimum temperature and solar radiation.

2.3. DSSAT CERES model description

DSSAT CERES4.0 (Crop Estimation through Resource and Environment Synthesis) is a model based on the crop growth module in which crop growth and development are controlled by phenological development processes. The DSSAT model contains the soil water, soil dynamic, soil temperature, soil nitrogen and carbon, individual plant growth module (including CERES-Maize and CERES-Wheat models) and crop management module (including planting, harvesting, irrigation, fertilizer and residue modules). This model is not only used to simulate the crop yield, but also be used to explore the effect of climate change on agriculture productivity and irrigated water (Alexandrov and Hoogenboom, 2001). For example, by setting a certain management method, the responses of yield to temperature and CO_2 concentration can be studied (Tubiello and Fischer, 2007).

2.4. Data processing

The soil data are obtained from the soil database of China (http://www.soil.csdb.cn), which includes the soil physical characteristics in different layers, containing bulk density, organic carbon concentration and fractions of sand, silt and clay. Climatic

Table 1
CO_2 concentrations under future climate projections in three periods (ppm).

	A2A	B2A	A1B
2030s	488	445	479
2060s	632	521	588
2090s	775	597	697

Table 2
Precipitation, maximum and minimum temperature under baseline and A2A.

Station	Baseline			2030s			2060s			2090s		
	Precipitation (mm)	T_{max} (°C)	T_{min} (°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)
Shijiazhuang (SJ)	515	19.2	8.4	0.4%	1.9	2.1	19.8%	3.3	3.8	44.6%	5.3	6.0
Anyang (AY)	542	19.7	9.1	−9.0%	2.2	1.8	14.3%	3.5	3.5	36.7%	5.4	5.6
Beijing (BJ)	580	17.8	7.1	27.8%	1.7	2.4	55.7%	3.0	4.2	72.6%	4.7	6.4
Jinan (JN)	664	19.5	10.5	1.4%	2.1	2.0	44.0%	3.1	3.7	79.9%	4.7	5.8
Zhengzhou (ZZ)	631	20.1	9.25	−11.4%	2.2	1.2	−2.8%	3.9	3.1	16.0%	5.5	5.1
Xinyang (XY)	1087	20.2	11.4	−5.5%	1.9	0.8	0.2%	3.9	2.8	10.2%	5.4	4.7
Xuzhou (XZ)	826	19.7	10.0	12.1%	2.3	1.7	21.2%	3.9	3.4	45.5%	5.3	5.3

Table 3
Change of precipitation, maximum and minimum temperature under B2A compared to baseline.

Station	2030s			2060s			2090s		
	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)
SJ	61.0%	0.5	2.4	76.0%	1.2	3.3	82.6%	2.3	4.2
AY	44.5%	1.0	2.2	62.9%	1.6	3.1	74.1%	2.7	4.0
BJ	53.1%	0.0	2.4	58.9%	0.7	3.1	75.7%	1.6	3.9
JN	5.4%	0.3	0.5	17.5%	1.0	2.6	34.0%	2.1	3.4
ZZ	9.8%	0.7	1.1	24.5%	1.6	2.1	29.3%	2.6	2.8
XY	11.0%	1.1	0.9	16.4%	2.1	1.9	29.9%	2.6	2.7
XZ	27.7%	0.8	1.4	33.6%	1.7	2.6	51.8%	2.5	3.3

data for the baseline period (1970–1999) are from China Meteorological Administration. Three scenarios of A2A, B2A and A1B are chosen as climate change projections, from the output of HadCM3 model. The monthly precipitation, maximum temperature and minimum temperature for projections of 2000–2100 were downloaded from http://ftp.badc.rl.ac.uk.

The climate change data in three periods are obtained by computing monthly mean maximum and minimum temperature during 2030–2039 (as 2030s), 2060–2069 (as 2060s) and 2090–2099 (as 2090s). We analyze the variations of temperature and precipitation in the three periods by comparing with those in 1990–1999 (1990s). The monthly temperatures and precipitations under climate change scenarios can be obtained by the temperature under baseline (1990s) adding the increments and multiplying increments in percent for precipitation, respectively. Some key parameters in a stochastic weather generator (CLIGEN) are adjusted by using weather data of every station in the last 40 years to get the probability of the dry and wet climate, the range of

Table 4
Change of precipitation, maximum and minimum temperature under A1B compared to baseline.

Station	2030s			2060s			2090s		
	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)	Precipitation (Δ%)	T_{max} (Δ°C)	T_{min} (Δ°C)
SJ	21.4%	1.2	1.7	33.9%	3.0	3.5	40.4%	3.4	4.3
AY	51.5%	0.9	1.5	60.4%	2.7	3.3	70.4%	3.1	4.1
BJ	32.7%	1.1	1.8	65.3%	2.6	3.6	70.8%	3.0	4.4
JN	48.6%	0.1	1.5	67.2%	1.8	3.4	70.2%	1.9	4.0
ZZ	46.0%	0.6	1.3	33.4%	2.4	3.0	55.8%	2.8	3.8
XY	−1.1%	1.2	1.1	8.3%	3.3	3.0	25.7%	3.6	3.8
XZ	31.5%	0.4	1.5	20.3%	2.3	3.2	48.1%	2.5	4.0

Table 5
Genotype parameters of wheat and maize in CERES model.

Genotypes	Parameters	Meaning	Value
Wheat of Lumai8	P1V	Days required to complete vernalization	40
	P1D	Percentage reduction in development rate in a photoperiod	80
	P5	Grain filling phase duration (°C d)	600
	G1	Kernel number per unit canopy weight at anthesis (#/g)	22
	G2	Standard kernel size under optimum conditions (mg)	28
	G3	Standard, non-stressed dry weight of a single tiller at maturity (g)	1.7
	PHINT	Interval between successive leaf tip appearances (°C d)	90
Maize of Yedan4	P1	Thermal time from seedling emergence to the end of the juvenile phase	250
	P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod	0.52
	P5	Thermal time from silking to physiological maturity	600
	G2	Maximum possible number of kernels per plant.	900
	G3	Kernel filling rate during the linear grain filling stage (mg/day).	15.5
	PHINT	Phylochron interval; the interval in thermal time (°C d)	55

temperature and solar radiation variation. Then the monthly weather data in 2030s, 2060s and 2090s under the three climate projections are input to the CLIGEN model. In each decade, 100 time series are randomly generated at daily scale in a year, which is intended to assess the weather variability on crop model predictions.

CLIGEN can simulate temperature well, but there are a bit biases in precipitation. Because the precipitation simulated is related with the rainy days and the probability, it is affected by the amount of rainfall. The greatest difference between simulated and observed values occurred in September under A2A. The precipitation in this month under A2A is obviously less than that under A1B and B2A, in which the error is about 15%. Except for some specific conditions, the average differences of precipitation are small, ranged from −0.1% to 6.8%. The errors of temperature between simulated and observed value are near zero.

According to IPCC SRES (Special Report on Emissions Scenarios), CO_2 concentrations will increase at the inconsistent rates under three scenarios (see Table 1). It is predicted that climate change scenario over China is similar to B2A projection. Variations of precipitation, maximum and minimum temperatures under A2A, B2A and A1B in comparison to baseline are given in Tables 2–4.

2.5. Model running

The effects of climate change on crops will be reflected by comparing the crop yield and water use efficiency under future climate projects and under baseline. So, we separately use the weather data under baseline and future to drive the CERES model.

In order to investigate the impacts of CO_2 and temperature on crops, we use the CERES model to simulate separately the crop yield and water use efficiencies with and without CO_2 fertilizer effect. The effect of climate warming on crops will be studied by simulating crop growth in different periods, because the temperature obviously ascends with time.

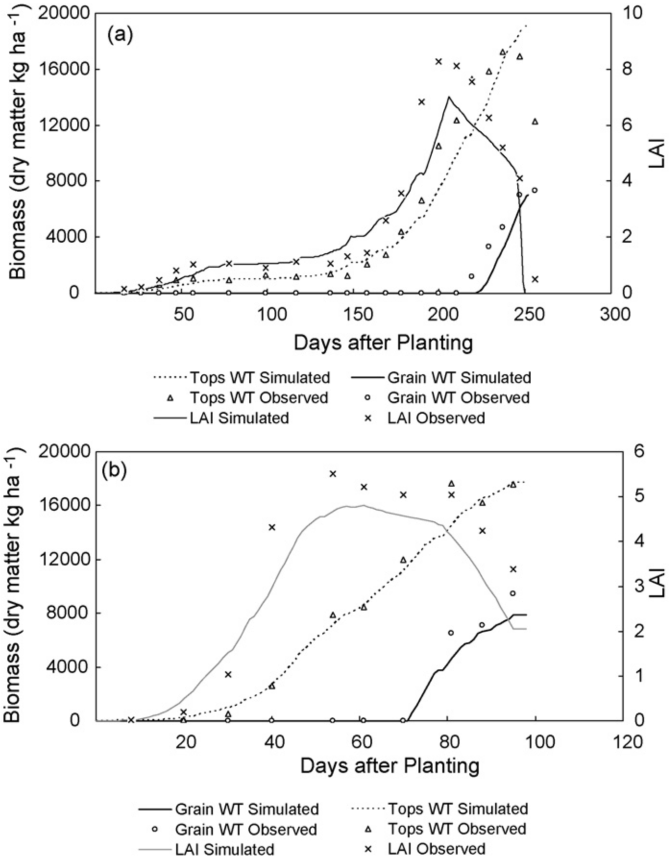

Fig. 2. Comparisons of LAI, grain weight and tops weight of wheat (a) and maize (b) between simulated and observed.

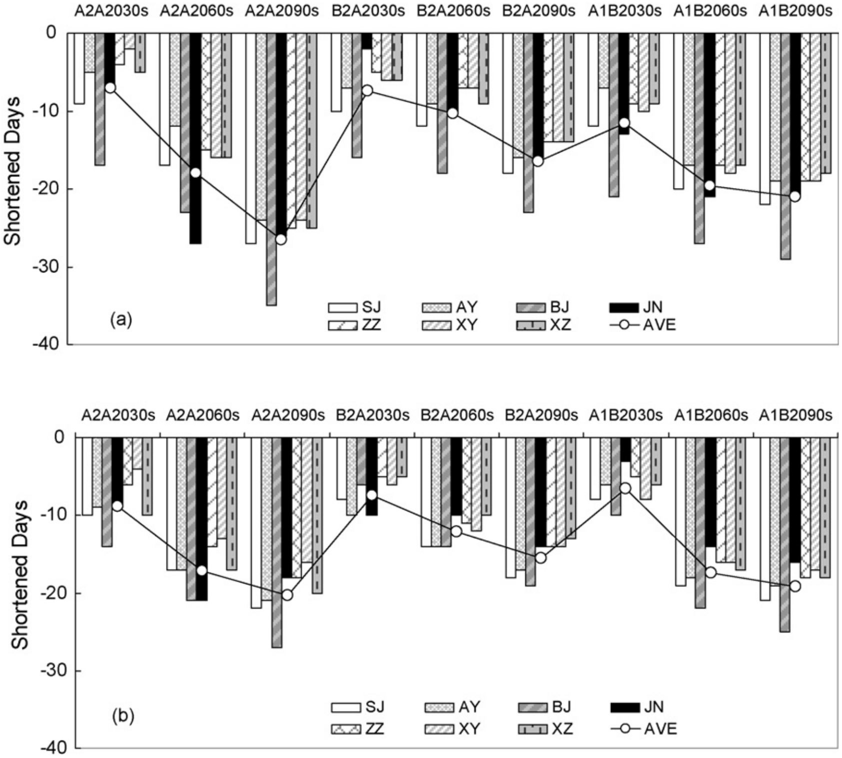

Fig. 3. Changes of crop growing period under future climate scenarios relative to baseline (a: winter wheat, b: summer maize).

3. Results and discussions

3.1. CERES model validation

According to the actual crop bred in the North China Plain, a specific parameter set for the genotype is selected (Table 5). The grain yield and leaf area index (LAI) in wheat and maize double cropping is used to validate the model prediction. The measurements were conducted in Yucheng Agroecosystem Station (116°34′N, 36°56′E) for 1991–1992. The cultivars of wheat and maize are Lumai8 and Yedan4, respectively.

The trends of wheat LAI simulated and observed are consistent (Fig. 2a). It can be found that the mean of LAI observed is about 3.1, a bit higher than simulated LAI of 2.6. However, the average top biomass (tops) weight (standing for the dry matter weight above the ground) simulated (5015 kg ha^{-1}) is less than that observed (5659 kg ha^{-1}). The simulated grain weight is about 95% of the observed.

As given in Fig. 2b, maize maximum LAI simulated and observed are separately 4.80 and 5.52, both appearing in the 61st day after maize planting. Mean LAI during the whole growing process simulated is less than that of observed, as 2.84 and 3.4 respectively. The top biomass simulated is in agreement with the observed. The grain yield simulated is 83% of the observed.

3.2. Change of growing period under climate scenarios

Higher temperature directly shortens the growing period in comparison to that under baseline. Also, higher temperature may accelerate crop growth and development process and make the crop mature early. Affected by higher temperature, growing period decreases significantly. The regional average shortened days of growing period length are shown in Fig. 3 (a and b). It can be found that the impact of temperature on maize growth period is not as evident as that on wheat.

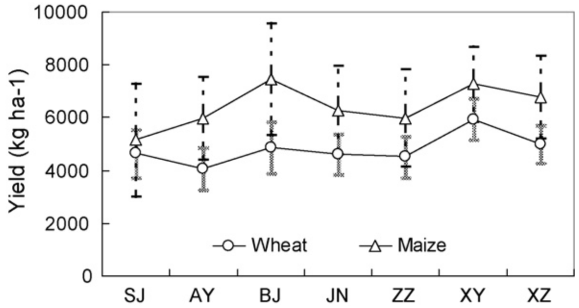

Fig. 4. Mean and amplitude of wheat and maize yields under baseline in seven locations.

The changes of growing period in different stations impacted by temperature are inconsistent (Fig. 3a and b) and show obvious spatial differences. For wheat, the maximum difference among seven stations of shortened days reaches 15 days. The least difference appeared under B2A scenario in 2090s, being 9 days. For maize, the maximum difference happens under A2A in 2090s, being 11 days. Under B2A, the difference is still the least in 2060s.

3.3. Changes of crop production

3.3.1. Crop yield change without CO_2 fertilization

The CO_2 fertilization is not considered in simulating crop yields under baseline. Under this condition, the winter wheat

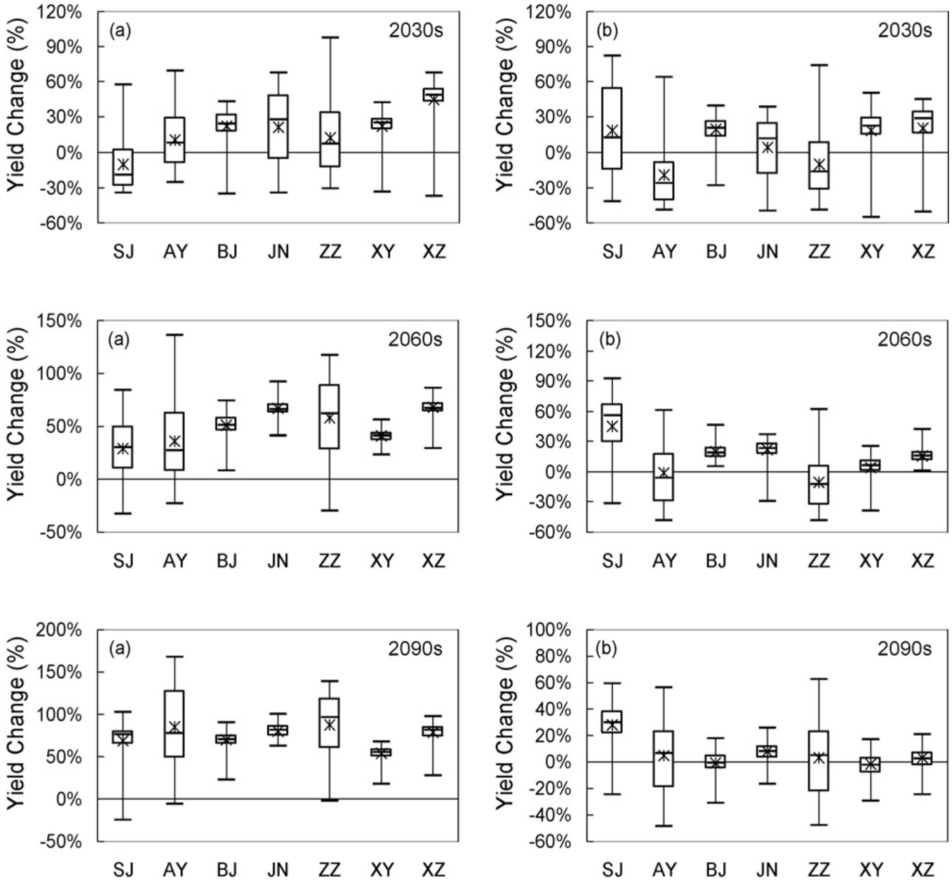

Fig. 5. Change of crop yield with CO_2 fertilization in 2030s, 2060s and 2090s under A2A (a: winter wheat, b: summer maize; star is mean value and the range of confidence from 25% to 75%).

yields of seven stations range from 4054 to 5953 (kg ha^{-1}). We use the standard deviation of crop yield to reflect the fluctuation and find the fluctuation of wheat yield is not very obvious (σ = 820 kg ha^{-1}). During wheat growing, irrigation alleviates the water stress and keeps wheat yield steady. Also, the maize yield is simulated under this condition with yields ranging from 5152 to 7453 (kg ha^{-1}) (Fig. 4). The variation of maize yield is evident (σ = 1762 kg ha^{-1}), mainly caused by the strong variability of precipitation.

Taking the simulation value of 1970–1999 as the reference, the responses are analyzed. If we do not consider the CO_2 fertilization, the average yield of winter wheat for this region will change about (−3.4% ± 10.0%), (−0.12% ± 8.9%) and (4.0% ± 12.2%) under A2A, B2A and A1B in 2030s.

For individual stations, the changes of winter wheat yield are different, increasing in some stations or decreasing in others. Averaged yield will increase 1.6–18.9% under A2A and 2.9–13.9% under B2A in 2090s relative to that in 2030s. Under A1B, there are slight decreases in Shijiazhuang (−0.1%) and Anyang (−3.6%). In Xuzhou, variation range of wheat yield even reaches 20% in most conditions. For other stations, there existed obvious differences among the nine conditions.

For maize, the effect of temperature increasing on yield is markedly negative. Averaged maize yield will decrease in most conditions about −19.5% to 29.0%, but it will increase 14.1%, 5.0%, 3.2% under B2A in the three periods and 29.0% under A1B in 2030s respectively. Furthermore, maize yield presents a declining trend with time. Compared with maize yield in 2030s, the averaged yields in 2090s will decrease 14.1% under A2A, 11.0% under B2A and 38.2% under A1B, respectively.

3.3.2. Comparison of crop yields with/without CO_2 fertilization

Taking crop yield without CO_2 fertilization as reference, crop yield will ascend evidently when CO_2 fertilization is considered. We take Jinan site as an example. Under the baseline, wheat and maize yields will increase linearly with CO_2 concentration at the rates of 12% and 9%/100 ppm CO_2 up to 775 ppm. The result is consensus with the study of Van Ittersum et al. (2003) who reports wheat yield rising is 10–16%/100 ppm CO_2.

The responses of crop to air warming and CO_2 enriching are complex and interactive. Also, the effect of CO_2 fertilization is far more than that of temperature increasing. Compared with that without CO_2 fertilization, regional wheat yield will increase 21.0% in 2030s, 46.9% in 2060s and 68.8% in 2090s under A2A (Fig. 5a). The increase of CO_2 concentration under B2A is the least among the three scenarios, so the change of wheat yield is significantly lower than that under A2A, being 14.8% in 2030s, 29.5% in 2060s and 39.2% in 2090s (Fig. 6a). Changes of wheat yield are 22.8%, 40.1% and 59.9% in the three periods under A1B (Fig. 7a). In comparison to variations of wheat yield in different periods, it can be seen that increased temperature and CO_2 concentration make wheat yield increase 32.0–78.5% under A2A, 17.2–59.5% under B2A and 27.7–54.8% under A1B in 2090s relative to that in 2030s. These results are greater than that obtained by other researches. Bender et al. (1999) showed that wheat grain yield will increase with a rate of 35% under doubling ambient atmospheric CO_2. Ewert et al. (2002) measured the response of spring wheat to elevated CO_2 (700 ppm CO_2) and presented that the increment of wheat yield was about 30% to 65% in south Spain. However, Anwar et al. (2007) demonstrated that in future climate scenarios rainfed wheat yield will decrease by about 29% in south-eastern Australia and the effect of elevated CO_2 is small, only 4%.

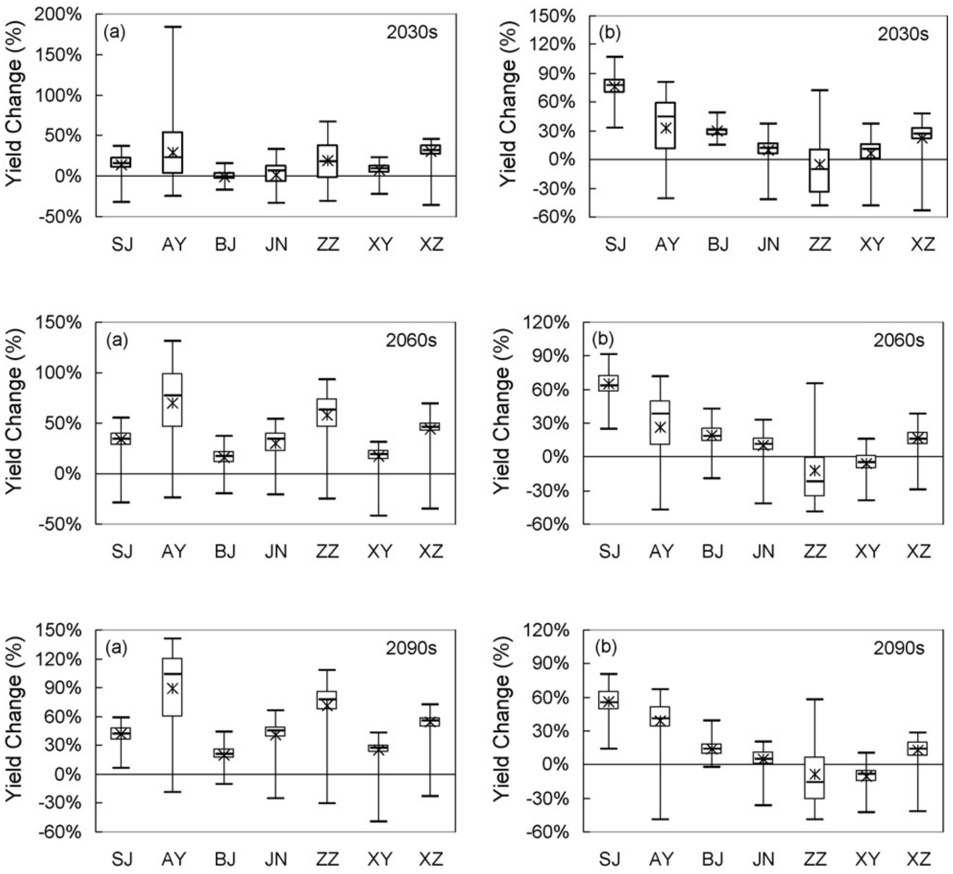

Fig. 6. Change of crop yield with CO_2 fertilization in 2030s, 2060s and 2090s under B2A (a: winter wheat, b: summer maize).

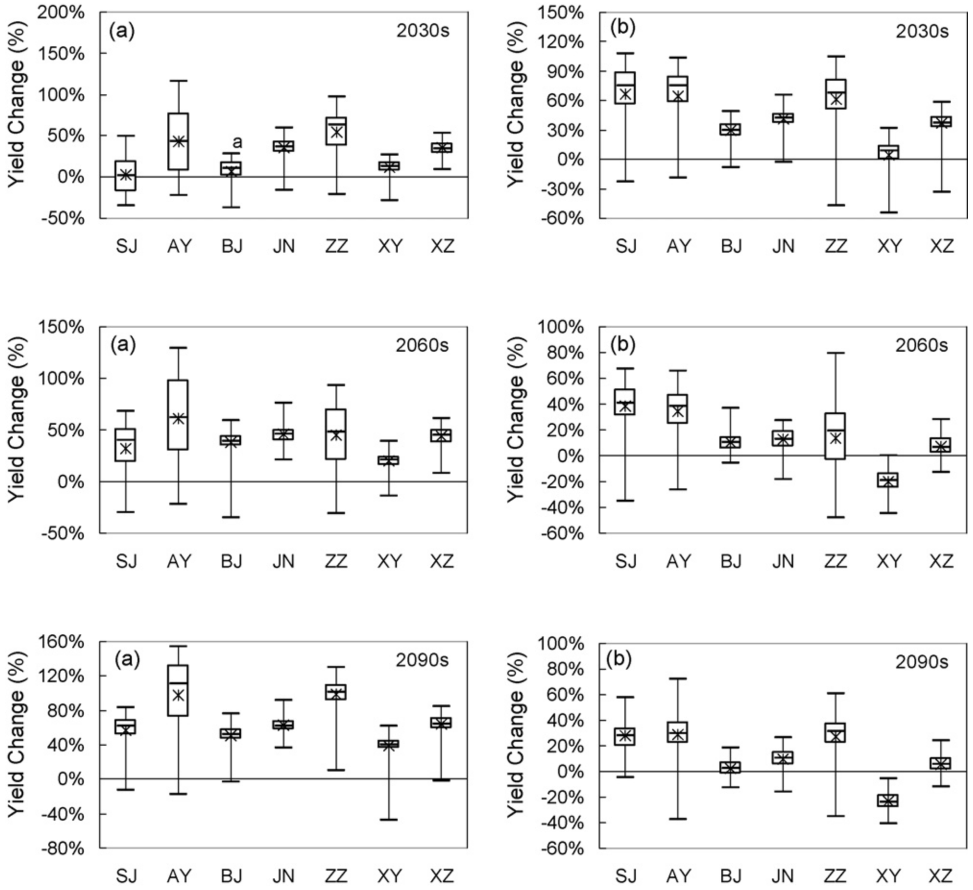

Fig. 7. Change of crop yield with CO_2 fertilization in 2030s, 2060s and 2090s under A1B (a: winter wheat, b: summer maize).

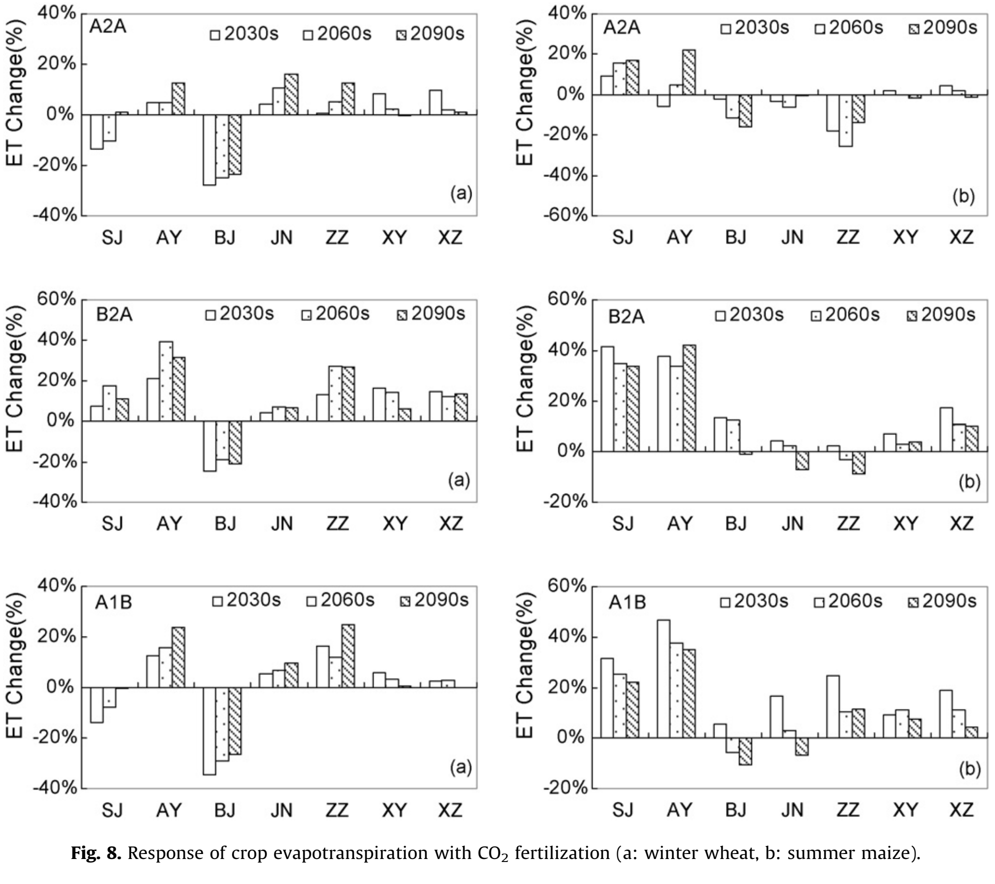

Fig. 8. Response of crop evapotranspiration with CO_2 fertilization (a: winter wheat, b: summer maize).

The model prediction shows that CO_2 rising causes wheat yield to improve considerably, but the wheat yields in most years fluctuate around the median value (Fig. 9a). The average change values in 2030s, 2060s and 2090s are separately 17.3%, 49.2% and 76.6% under A2A, 14.5%, 41.5% and 53.1% under B2A and 28.9%, 43.1% and 70.5% under A1B. The variations of yield in Anyang and Zhengzhou are higher than that in other stations. Although the maximum variations of seven stations happen in different scenarios, they both appear in 2030s. In addition, the variability of wheat yield will decrease with temperature increasing.

Elevated CO_2 concentration also has positive effects on maize yield. CO_2 directly alleviates the decrease range of maize yield (Figs. 5b, 6b and 7b). The increase of maize yield in this region is less than that of wheat caused by CO_2 fertilization, ranging from 6.2% to 43.6%. Maize yield reduces linearly with temperature increasing in different periods under the B2A and A1B climate change scenarios in this region (Fig. 9b). Spatial variability is different probably due to heterogeneity in growing conditions in different situations. Walker and Schulze (2006) find that temperature increasing will reduce maize yield, but CO_2 elevating enhance maize yield about 30%.

Combined the effects of temperature increasing and CO_2 elevating, wheat yield will enhance more than that only one of the factors is considered, due to air warming shortens the growth dormant period. This implicitly indicates crop yield increase greatly although the growing period is reduced.

3.4. Response of evapotranspiration to climate change

As a whole, averaged evapotranspiration of wheat in this region will increase about 3–19% under future climate change projections. It is shown that the warming has positive effect on evapotranspiration in most sites compensating for the shortened growth period, except Beijing and Shijiazhuang sites. Increments of maize evapotranspiration of this region range from 6.2% (in 2030s under A2A) to 32.9% (in 2090s under A1B).

When CO_2 fertilization is included, evapotranspiration will decrease compared with that without CO_2 (Fig. 8), and the fluctuation amplitude is also alleviated. The change of wheat evapotranspiration ranges from −2.0% to 14.0% and that of maize evapotranspiration is −3.0–21.8%, a bit higher than wheat (Fig. 9c).

Evapotranspiration decrease should attribute to the increase of both temperature and CO_2. Air warming will shorten the crop growth period. The elevated CO_2 concentration will cause stomatal closure and reduce plant evaporation (Unsworth and Hogsett, 1996). Increase of vapor pressure deficit caused by leaf temperature increase can also impact the ET. In order to identify the effects of temperature and CO_2 on evapotranspiration of wheat and maize, the changes of crop ET under A2A are analyzed. By comparing ET in 2030s with ET in 2090s, it can be found that ET of wheat and maize will separately increase 8.3% and 21% if temperature increase 3.5 °C, but ET will decrease 3.8% and 3.0% while the concentration of CO_2 increases 287 ppm. However, when the effects of temperature and CO_2 are considered at the same time, the ET of wheat and maize only increases 4.8% and 2.8%.

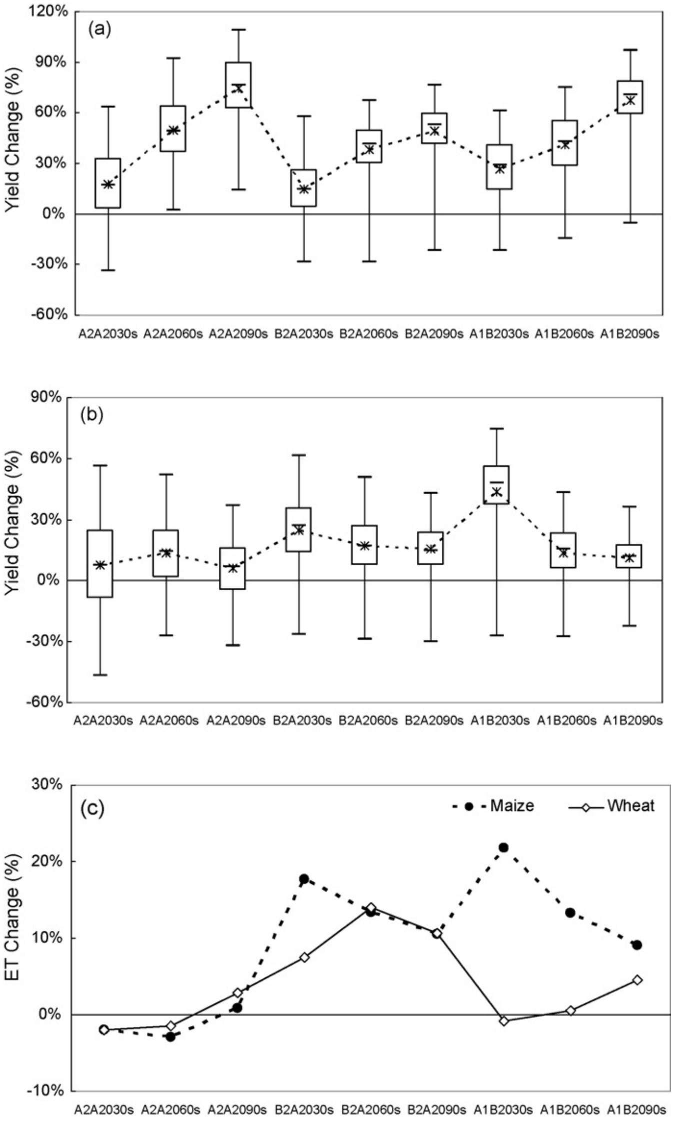

Fig. 9. Changes of regional average crop yield and ET with CO_2 fertilization effect under three scenarios (a: winter wheat, b: summer maize).

3.5. Impact of climate change on water use efficiency (WUE)

The maximum WUE under baseline is 12.5 kg ha^{-1} mm^{-1} occurred in Anyang, and the minimum found in Beijing is only 8.8 kg ha^{-1} mm^{-1} (Fig. 10). The high evapotranspiration makes WUE of wheat and maize in Beijing becoming the lowest. Compared with WUE under baseline, mean trends of crop WUE of most locations under future climate change without CO_2 effect will decrease in the three periods. The changes of wheat and maize WUE in this region are −8.1 to 4.3% and −36.1 to −2.0% respectively. In most conditions except A1B in 2030s, the WUE of wheat and maize are decreasing. Analyzing the wheat WUE of every site, there are obvious decreasing trends in most sites except Beijing. WUE of wheat in Beijing will increase 11.5–48.4% without CO_2 effect.

Without CO_2 effect, the trends of WUE of wheat and maize show different change characteristics. The WUE of wheat in 2030s and 2090s are −4.8% and −3.2% under A2A, −8.1% and −5.4% under

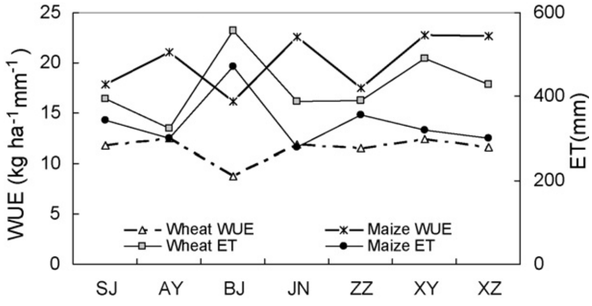

Fig. 10. Evapotranspirations and water use efficiencies of wheat and maize of seven stations under baseline.

B2A, and 4.3% and −1.1% under A1B. However, there is an obvious decreasing trend of the maize WUE during the three periods. The WUE values of maize in 2030s and 2090s under A2A, B2A and A1B are separately −11.0% and −36.1%, −8.7% and −20.6%, −2.0% and −31.3%. When we consider the impact of CO_2 increasing, the averaged WUE of this region will increase under all scenarios in our case.

When CO_2 fertilization effect is considered, the results show that WUE of wheat improves about 28.1% in 2030s, 55.8% in 2060s and 78.1% in 2090s under A2A in comparison with that without CO_2 fertilization. The increase under A1B is the least, only being 26.8% in 2030s, 45.7% in 2060s and 65.0% in 2090s.

The complex effects of CO_2 and temperature are considered by comparing the differences of WUE between 2090s and 2030s. At first, we consider the effect of the single factor of the temperature. That temperature ascending 3.5 °C under A2A, 1.8 °C under B2A and 2.3 °C under A1B will make wheat water use efficiency change 1.6%, 2.8% and −5.4%, respectively. Under the same condition, the maize water use efficiency will have an obvious decrease by −25.1%, −11.9% and −29.3%. Then, the effects of CO_2 and the temperature are considered at the same time. The water use efficiency of wheat will increase by 51.6%, 25.8% and 32.8% in turn. That of maize will decrease by −3.1%, −0.9% and −14.9%. These results indicate that elevated CO_2 can improve the water use efficiencies of crops in a certain degree.

4. Conclusions

By combining a CERES model and climate change projections, the responses of crop yield and water use efficiencies are studied. Different periods under the same climate scenarios can reflect the effect of temperature rising. After adding CO_2 fertilizer effect in the CERES model, the integrative impacts of temperature and CO_2 are investigated. It is found that wheat yield will ascend with temperature increase and maize yield will descend in most conditions. Water use efficiencies of wheat and maize will decline affected by temperature increasing. This study proves the importance of CO_2 fertilization on crop yield and evapotranspiration. Under future climate change scenarios, CO_2 enriching can effectively alleviate the impact of temperature increasing on crop yield.

Our results show that wheat yield will change −2.0–11.3% and maize yield change −19.5–29.0% without CO_2 fertilization under future climate change. There is an ascending trend of wheat yield under each scenario, whereas maize yield will decline. If we only considered the effect of temperature increasing, the higher temperature in 2090s is benefit to the irrigated winter wheat. However, high temperature may decrease the rainfed summer maize yield. The impact of CO_2 fertilization on crops is far more than that of temperature. The increase of wheat and maize yields are 15.0–60.5% and 10.6–25.7% in comparison with that without CO_2 fertilization, respectively.

After CO_2 fertilization is included, climate change has a positive effect on water use efficiency. Under irrigation, increased temperature and elevated CO_2 will improve water use efficiency with 9.2–74.9% in wheat and 0.8–17.7% in maize relative to that under baseline. Only increased temperature is considered, water use efficiency will decline about −8.1% to and −36.1% to −2.0% for maize.

The interactions of temperature and CO_2 are complicated. When we analyze the effect of climate change, it is necessary to combine many other factors, such as solar radiation, extreme weather, pest and insect disease etc. The effect of climate change on wheat and maize yield and water use efficiency still need further research.

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