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Crop yield responses to climate change in the Huang-Huai-Hai Plain of China

Suxia Liu[a,*], Xingguo Mo[a], Zhonghui Lin[a], Yueqing Xu[b], Jinjun Ji[c], Gang Wen[c,d], Jeff Richey[e]

[a] *Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences (CAS), Beijing 100101, China*
[b] *Institute of Resources and Environment, China Agricultural University, Beijing 100091, China*
[c] *Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, CAS, Beijing 100029, China*
[d] *China Clean Development Mechanism Fund, Ministry of Financial, Beijing 100045, China*
[e] *School of Oceanography, University of Washington, Seattle, WA 98195, USA*

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ABSTRACT

Global climate change may impact grain production as atmospheric conditions and water supply change, particularly intensive cropping, such as double wheat–maize systems. The effects of climate change on grain production of a winter wheat–summer maize cropping system were investigated, corresponding to the temperature rising 2 and 5 °C, precipitation increasing and decreasing by 15% and 30%, and atmospheric CO_2 enriching to 500 and 700 ppmv. The study focused on two typical counties in the Huang-Huai-Hai (3H) Plain (covering most of the North China Plain), Botou in the north and Huaiyuan in the south, considering irrigated and rain-fed conditions, respectively. Climate change scenarios, derived from available ensemble outputs from general circulation models and the historical trend from 1996 to 2004, were used as atmospheric forcing to a bio-geo-physically process-based dynamic crop model, Vegetation Interface Processes (VIP). VIP simulates full coupling between photosynthesis and stomatal conductance, and other energy and water transfer processes. The projected crop yields are significantly different from the baseline yield, with the minimum, mean (±standardized deviation, SD) and maximum changes being −46%, −10.3 ± 20.3%, and 49%, respectively. The overall yield reduction of −18.5 ± 22.8% for a 5 °C increase is significantly greater than −2.3 ± 13.2% for a 2 °C increase. The negative effect of temperature rise on crop yield is partially mitigated by CO_2 fertilization. The response of a C3 crop (wheat) to the temperature rise is significantly more sensitive to CO_2 fertilization and less negative than the response of C4 (maize), implying a challenge to the present double wheat–maize systems. Increased precipitation significantly mitigated the loss and increased the projected gain of crop yield. Conversely, decreased precipitation significantly exacerbated the loss and reduced the projected gain of crop yield. Irrigation helps to mitigate the decreased crop yield, but CO_2 enrichment blurs the role of irrigation. The crops in the wetter southern 3H Plain (Huaiyuan) are significantly more sensitive to climate change than crops in the drier north (Botou). Thus CO_2 fertilization effects might be greater under drier conditions. The study provides suggestions for climate change adaptation and sound water resources management in the 3H Plain.

1. Introduction

Throughout the last 150 years, atmospheric CO_2 concentration has increased from ~280 ppmv to ~385 ppmv in 2008 (http://www.esrl.noaa.gov/gmd/ccgg/trends/) due to widespread human activities such as fossil fuel burning, cement production, and modified land-use patterns (IPCC, 1996; Fan et al., 2007). At the current rate of increase the concentration of atmospheric CO_2 will double before 2100, which will likely have dramatic effects on global and regional-scale climate. Globally, many climatic variables are already changing. For example, since 1950 the Huang-Huai-Hai (3H) Plain in China, which comprises most of the North China Plain (Fig. 1), has experienced a reduction in precipitation at an average rate of 2.92 mm year^{-1}, and a temperature increase at an average rate of 0.20 °C decade^{-1} with minimum temperature increasing more rapidly than maximum temperature (Mo et al., 2006; Tian, 2006). Tao et al. (2006) showed that at Zhengzhou, a typical station in the 3H Plain, maximum and minimum temperatures in winter, spring and summer increased by 0.39–0.95 °C decade^{-1} since 1980. Although change in climate is represented by changes in several climatic variables (i.e., air pressure, humidity, solar irradiance, atmospheric CO_2 concentration, ozone, and air quality, among others mentioned in Brown and Rosenberg, 1997; Mera et al., 2006; Robock and Li, 2006), the changes in precipitation, temperature, and atmospheric CO_2 concentration have been the main focus to date. Other climate variables previously assumed to be station-

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* Corresponding author.
E-mail address: liusx@igsnrr.ac.cn (S. Liu).

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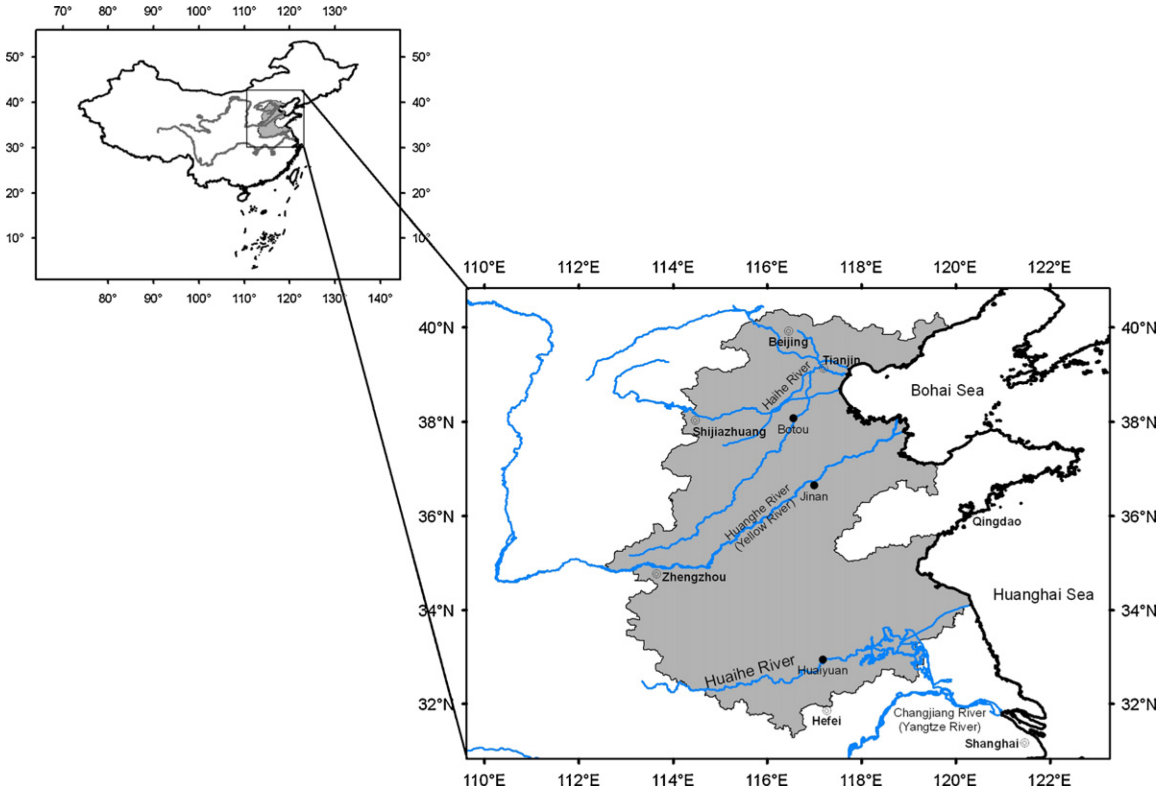

Fig. 1. The location of the two typical counties in the 3H Plain (Shaded area) within China (The Haihe, Huanghe and Huaihe Rivers are on the China map from north to south, from which the Huang-Huai-Hai Plain was formed).

ary (no trend) are now being investigated. For example, Roderick et al. (2007) and McVicar et al. (2008) found negative trends in near-surface terrestrial wind-speeds, which will influence both the actual and potential evapotranspiration estimation.

Observations on the 3H Plain show that crops are significantly affected by climate variation. The increase in temperature shortens the phenological phases, reducing the time for light/water uptake and carbon assimilation, while changes in rainfall affect water availability. In addition, accelerated crop development and a shortened grain filling period reduce grain yield. Although it is difficult to assess the role of technological advances in farming practices on yield, Tao et al. (2006) reported a strong negative correlation between maize yield and increasing summer temperatures on the 3H Plain. There is also a correlation between climate variation and the planting, anthesis, and maturity dates for maize throughout the last two decades.

How crop yield responds to climate change will affect food security of a nation. For example, if we can understand the role of climate forcing on yield in the past, present, and projected future changes, it will be helpful for establishing a warning system so that adaptations can be made at an early stage. This knowledge is especially critical to the 3H Plain, which is a very important agricultural region, accounting for about 69.2% of wheat and 35.3% of maize yield in China based on the yield data (http://www.stats.gov.cn/tjsj/ndsj/2005/indexch.htm) averaged over 1996–2007. The 3H Plain is particularly sensitive because it is situated on the transition between semi-humid and semi-arid zones, where rainfall distribution is irregular during a year with more than 70% falling in summer. Intensive double-cropping systems may also be particularly vulnerable to climate change as it affects water availability and crop water use. The spring crops (such as wheat) commonly need supplemental irrigation to obtain favorable production. In this way, farmers can mitigate the response caused by one driving factor with the response caused by another factor. For example, less precipitation in winter may reduce grain yield, and the reduced yield may be mitigated by adding irrigation. Of course the two effects may be not able to be exactly offset to zero. This same explanation will be used below when we use the word “offset”. As surface water cannot meet the intensive demand for industrial and agricultural development, the water resources supply in this region is vulnerable (Liu and Wei, 1989; McVicar et al., 2002). To meet the irrigation requirement, groundwater has been over-pumped (Xu et al., 2005). As a consequence, the water table has continuously fallen over the last several decades, creating the so-called “groundwater funnel” in some northern parts which has considerably deteriorated the agricultural sustainability and environmental conditions.

With rising concerns over food security and water resources limitations, the responses of agricultural systems to climate change of the 3H Plain have garnered much attention by domestic and international research scientists as well as managers, stakeholders and farmers over the last decades. Using the regional climate change and crop models, Lin et al. (2005) demonstrated that future climate change without CO_2 fertilization could reduce the crop yields in China. Tao et al. (2006) synthesized crop and climate data from representative stations across China during 1981–2000 and showed that temperature was negatively correlated with crop yield at all stations except Harbin in northeastern China. Some studies (Thomson et al., 2006) showed that winter wheat yields in 3H would increase on average due to warmer nighttime temperatures and higher precipitation. Zhang and Liu (2005) documented at the Loess Plateau, where wheat yield increased 7–58% and maize yield increased 32–64% under three Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). They explained that the overall increase in yield for the three scenarios was attributed to the considerable increase in precipitation, which is the important limiting factor for agricultural production in that region. Generally, if moisture demand is met, productivity will be enhanced due to increased atmospheric CO_2 and photosynthetic efficiency. Temperature increase, especially warmer nighttime temperature (Hatfield, 2009) will reduce crop yield while the simulated increase in precipitation and CO_2 concentration will enhance crop yield, so the processes may offset each other (Barry and Cai, 1996). As parts of China include almost every climate zone, it will be interesting to see more case studies of crop yield response to climate change.

Reviewing studies of the 3H Plain, other localities in China, and elsewhere, e.g., Australia (Anwar et al., 2007), Africa (Fischer et al., 2005; Huntingford et al., 2005), India (Challinor et al., 2007), Spain (Iglesias et al., 2000), US (Izaurralde et al., 2003) and globally (Parry et al., 2004; Tan and Shibasaki, 2003; Tubiello and Fischer, 2007), there are three ways to explore the response of crop yield to climate change.

First, seek evidence of crop response to climate change within historical data of both crop yield and climate (Tao et al., 2006; Egli, 2008; Malone et al., 2009). The results can be a basis for making a prediction for the future or used directly to derive climatic scenarios as in Thomas (2008). Second, use a weather generator such as ClimGen (Stockle et al., 1997; Zhang and Liu, 2005; Kou et al., 2007; Tao et al., 2008) to generate daily weather data to be used to drive a crop model, examining crop yield change for different climate inputs. The third and most popular method is to use the output of GCMs to drive a crop model. This method may be subdivided as follows: (1) directly use the output of (regional) transient simulations of a GCM or ensemble of GCM projections as the input of the crop model (Trnka et al., 2004; Lin et al., 2005); or (2) use GCM output from double CO_2 equilibrium scenarios, for example, which do not provide information about the timing of the projected climate change, but represent conditions likely to be realized before the end of the century (IPCC, 1996; Tubiello et al., 2000). Green et al. (2007) combined GCM output and historical data in a daily weather generator to simulate water regimes in grass and forest ecosystems in Australia. Even though GCM models have been improved to output not only monthly mean values but also daily values (Trnka et al., 2004; Lin et al., 2005; Huntingford et al., 2005), it is still difficult to obtain consistent input for a crop model, as different GCM models produce different outputs (Trnka et al., 2004; Huntingford et al., 2005). No matter which GCM technique is used, the GCM outputs show significant variation in the estimates of rainfall characteristics (Izaurralde et al., 2003; Huntingford et al., 2005). It is sometimes more practical to consider the outputs of many GCMs and the observed baseline of climate to generate a climate scenario, as this study will do. In this case, the study of the response of crop yield to climate change is a sensitivity analysis.

Elevated levels of anthropogenic CO_2 may be beneficial to plants in a process described as CO_2 fertilization (Hendrey and Kimball, 1994). This is confirmed by the free-air carbon enrichment experiments (FACE), where enrichment under field conditions and CO_2 concentration elevated to 550 ppmv consistently increased biomass and yields 5–15% (Ainsworth and Long, 2005). As reviewed by Tubiello and Ewert (2002), about half of the crop-yield climate-change studies explicitly analyzed the effects of elevated CO_2 on crop growth and yield so far. Two kinds of conclusions can be drawn with and without considering CO_2. As commonly observed with CO_2 fertilization, the yield loss due to warm weather may be mitigated (Anwar et al., 2007) or reversed. However, the potential benefit of elevated CO_2 on crop growth is still unclear (Parry et al., 2005). Current estimates are based upon field experiments that have assumed near optimal applications of fertilizer, pesticide and water, and it is possible that the actual 'fertilizing' effect of higher levels of CO_2 is less than what is expected. In dry environments with nutrient limitations, the effect has been considered small (Anwar et al., 2007). In these cases the CO_2 fertilization effect cannot compensate for stresses imparted by other environmental factors. To date, the equations used in most crop models (e.g., APSIM, CropSyst, CERES-wheat, DSSAT, EPIC, CERES, WOFOST) are based on the concept of radiation-use efficiency (RUE) and transpiration efficiency (Brown and Rosenberg, 1997; Izaurralde et al., 2003). Because of its simplicity it is sometimes very hard to provide reliable predictions of yield. Further understanding of the mechanistic feedbacks between photosynthetic rates and leaf stomatal conductance should better constrain the effect of elevated CO_2 on yield, which can be resolved by using smaller computing time-steps (Connor and Fereres, 1999; Grant et al., 1999; Anwar et al., 2007) with a bio-geo-physically process-based model.

C3 (wheat) and C4 (maize) plants are the main crops of the 3H Plain. A widely held view is that the relative response of C4 plants to elevated CO_2 is usually smaller than that for C3 species, as C4 appears to be CO_2 saturated at ambient CO_2 level and shows very low responsiveness to higher CO_2 concentration (Adriana et al., 1998; Parry et al., 2004; Mera et al., 2006). However, from the meta-analysis and long-term effect analysis, this is not always true for some wild C4 species, and the differences in CO_2 response between C3 and C4 grass species are not as large as the current perception (Wand et al., 1999; Stock et al., 2005). It is only absolutely true for growth under non-stressful environmental conditions (Ghannoum et al., 2000; Kim et al., 2007). In some results (Lin et al., 2005; Xiong et al., 2007), maize in China shows a greater benefit from elevated CO_2 than rice under both A2 (medium-high) and B2 (medium-low) greenhouse gas emission climate change scenarios. It will be interesting to examine how C3 and C4 plants respond to climate change with more study cases across the world.

In most studies of the response of crop yield to climate change in the world, simulations focus on one crop. If several crops are considered, the model is run separately for each crop (Brown and Rosenberg, 1997), or the water balances are calculated separately for each crop, as shown in Thomas (2008). It will be interesting to review the results of running the model continuously for multiple crop-rotation system, so that the soil water depletion by the first crop can be considered when modeling the water balance of the second crop. Such an approach is useful because, for any given climate, cropping systems, not a single crop, constitute the fundamental units controlling the movement of nutrients and the patterns of water use upon which crop productivity depends (Tubiello et al., 2000).

The objective of this paper is to compare the responses of crop productivity to climate change with and without CO_2 fertilization effects and between C3 and C4 crops based on a crop model. The model can be run over the entire 3H region to give the spatial pattern of the response of agricultural systems to climate change as reported elsewhere (Mo et al., 2005, 2009). In this paper, in order to indicate the response under the above conditions in detail, we concentrate on the responses at two typical counties of the 3H Plain, Botou and Huaiyuan, similar to Tubiello et al. (2000). Yield responses are analyzed across the north–south gradient spanned by these two sites with the focus on the local cropping systems. Because of the great concern for water shortage on the 3H Plain, irrigation practices are widely used, especially for northern counties. Irrigated and rain-fed conditions are known to influence crop yield differently (e.g., Mo et al., 2005), and both are considered in the present study.

2. Materials and methods

The response of crop yield to climate change is analyzed at Botou and Huaiyuan, with generated climate as atmospheric forcing. The climate scenario is generated from the combined results of GCMs and the historical trend. The model used is Vegetation Interface Processes (VIP), a bio-geo-physically process-based dynamic crop

Table 1
Climate resources for agriculture development in the south and north region of the 3H Plain (Potential evapotranspiration is calculated based on Penman-Monteith Equation. The data are from National Meteorological Administration of China. The time period of data collection is from 1956 to 2000 and the ranges are spatial variability within each region).

Item	Huang-Huai Plain (South)	Huang-Hai Plain (North)
Annual sunshine duration (h a^{-1})	2100–2500	2500–2900
Annual total solar radiation (MJ m^{-2} a^{-1})	4770–5250	5250–5570
Photosynthetic Active Radiation in above 0 °C days (MJ m^{-2} a^{-1})	1840–2000	2000–2130
Annual averaged temperature (°C a^{-1})	15.4–13.5	13.5–11.0
Annual accumulative temperature in ≥0 °C days (°C day a^{-1})	5500–5100	5100–4200
Annual accumulative temperature in ≥10 °C days (°C day a^{-1})	4900–4500	4500–3800
Non-frost day (day a^{-1})	225–210	210–185
Annual precipitation (mm a^{-1})	1050–650	650–480
Potential evapotranspiration (mm a^{-1})	1113–1136	1084–1174

Table 2
Human resources and land resources of the two typical counties in 2005.

County	Land area (km^2)	Total population (in thousands)	Farmland area 10^5 ha	Planting area 10^5 ha	Multi-cropping index	Effective irrigation area 10^5 ha	Farmland irrigation rate %
Huaiyuan	2396	1277	1.227	2.444	1.99	0.875	71.3
Botou	1007	552	0.545	0.787	1.44	0.485	89.0

Note: Data from provincial statistic year books in 2006.

model (Mo and Liu, 2001; Mo et al., 2005). By calculating photosynthesis with high temporal resolution (as short as a 30 minute-time step) from detailed biophysical processes rather than simply RUE, the model outputs can be used to resolve variability caused by the CO_2 fertilization effect and differences between C3 and C4 crops.

2.1. *Study region*

The 3H Plain is one of China's principle agricultural centers, extending between 31°14′–40°25′N and 112°33′–120°17′E. It makes up part of eastern China, with an area of 33,104 km^2 (Fig. 1), which is an alluvial Plain developed by the intermittent flooding of the Huanghe (Huang means Yellow and he means river in Chinese), Huaihe and Haihe rivers. Seven provinces/mega-cities are situated on the Plain (Beijing, Tianjin, Hebei, part of Shangdong, Henan, Anhui and Jiangsu). As shown in Table 1 there is pronounced spatial variability in climate between the south and north for crop development in the 3H Plain. The warm temperate climate varies gradually from semi-humid in the south to semi-arid in the north, with mean annual precipitation from 1956 to 2000 ranging between 480 and 1050 mm. The human resources, land resources, and the utilization of water resources for the two representative sites are shown in Tables 2 and 3.

Botou sits on an alluvial Plain, in the Hebei province. It has a land area of 1007 km^2, a total population of 552,000 and 54,500 ha of farmland. It is cold in winter, with mean temperature from 1956 to 2000 below freezing in January and February (−3.4 °C and −0.8 °C, respectively). July is the hottest month; with an average temperature of 26.7 °C. The mean annual temperature is 12.6 °C. The mean annual precipitation is 610 mm, with most rainfall falling between June and August. Botou receives plenty of sunlight for growing, but water resources are in short supply. The surface runoff mostly comes from flooding water, which is difficult to control due to the low, flat topography. Groundwater distribution has a multi-layered structure, with brackish water in the shallow and medium layers. Therefore, deep groundwater, which is almost the only freshwater available, is the main resource of water supply. Heavy exploitation of deep groundwater began in the mid 1970s, and currently is the main source of irrigation water (Wu and Huang, 2001). The long-term excessive use of groundwater has led to a gradual and continuous drop of the groundwater level, forming the well documented "Cangzhou funnels", and a set of geological environmental problems, such as ground subsidence.

Huaiyuan sits in the Anhui Province, alongside the middle reach of Huaihe River, in the warm temperate semi-humid monsoon climatic zone. Its main soil types are black soil, paddy soil, alluvial soil and brown soil, roughly corresponding to sandy clay loam, silt clay, loamy sand and silt clay based on USDA soil taxonomy (Zhang et al., 2004). The mean annual air temperature, sunshine duration, and non-frost days are 15.4 °C, 2207 h, and 220 days, respectively from 1956 to 2000. The mean annual precipitation is 900 mm, with half of the rainfall concentrated between June and August. Characterized by a monsoonal climate, there is sufficient sunlight, a long period without frost, and a short and severe cold period. Such a climate, with abundant and well-distributed light, heat and water resources, is favorable for growing multiple crops.

2.2. *Climate change scenarios*

As summarized by Qin et al. (2005), Chinese scientists used about 40 climate models including DKRZ/Germany, HADLEY/UK, GFDL/US, CCC/Canada, CSIO/Australia, CCSR/Japan, NCAR/US and NCC_IAPT63/China to predict the temperature and precipitation of China for the 21st century under the scenarios of greenhouse gas emission only, greenhouse gases plus aerosols, and the SRES A2 and B2 scenarios. From the study based on the version in 1990s of one of these models (National Climate Change Coordination Committee, 2007), the simulated annual averaged air temperature over Asia area (70°–140°E, 15°–60°N) is about 0.5–9.6 °C lower than the observed temperature, and the simulated annual total

Table 3
Water utilization in the two typical counties.

Typical counties	Exploration rate (%)	Available resources per hectare (m^3 ha^{-1})	Well irrigation area (%)	Agricultural water use (%)
Botou	106.7	1155	83.8	87.3
Huaiyuan	11.9	5370	13.2	90.2

Note: Data from provincial statistic year books in 1993.

precipitation is 3–784 mm higher than the observed precipitation. The correlation coefficient between the simulated annual averaged temperature and the observed is about 0.64–0.94 and that for precipitation is 0.42–0.70. This is comparable with the recent international study (Johnson and Sharma, 2009).

Even with the effort to update the models within the last decade, there is still bias between the simulation results of GCM models over the 3H Plain and the observations at yearly and monthly scales (Fu et al., 2009). A number of systematic biases are presented across the set of climate models (Koutsoyiannis et al., 2008) from eight stations from around the globe. There have been no publications to compare these model efficiencies at a daily scale yet.

From many perspectives, an average over the set of models clearly provides climate simulation superior to any individual model, thus justifying the multi-model approach in many recent attribution and climate projection studies (Qin et al., 2005; Bader et al., 2008). Based on this situation, averaging the simulation results is one of the choices, which needs the output of climate prediction from these models, as in our case.

Table 4 shows the projection of averaged temperature and precipitation change in the 3H Plain for each 30 years of the 21st century (Qin et al., 2005). It shows that the regional warming will be stronger in the 3H Plain, with an average temperature increase of 1.4 °C for A2 scenario by 2020 and 1.5 °C for the B2 scenario. By 2100, temperature will increase about 6.1 °C for the A2 scenario and 4.2 °C for the B2 scenario. Precipitation is extraordinarily complicated, with greater fluctuations accompanying temperature rise. In the long run, precipitation increases over the whole of the 3H region, but declines before the 2020s.

Observed national standard meteorological data were collected at Cangzou (38.18°N, 116.52°E; 1954–1995) to represent Botou in a distance of about 33 km, and at Bengbu (32.56°N, 117.21°E; 1952–2000) to represent Huaiyuan in a distance of about 18 km. The historical interannual variation of air temper-

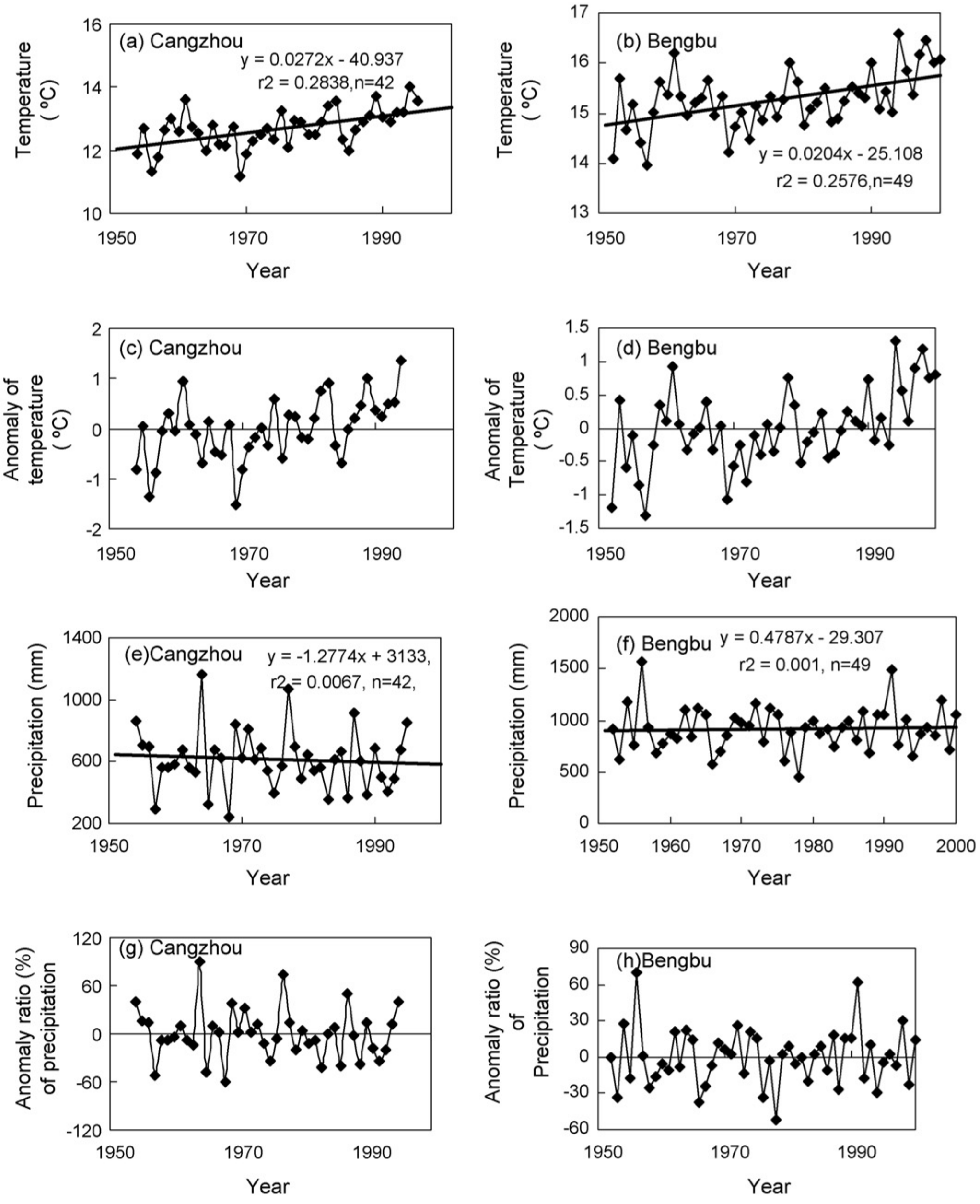

Fig. 2. Yearly variation of (a) air temperature (c) its anomaly calculated from the long-term average temperature, (e) precipitation (g) its anomaly ratio (%) for wheat and maize in Cangzhou representing Botou. Those for Bengbu representing Huaiyuan are shown in (b), (d), (f), and (h).

Table 4
Projection of average change of temperature and precipitation in the 3H Plain for each 30 years of the 21st century by 40 global climate models. The value in the parentheses is the minimum and maximum change from the models, extracted from Qin et al. (2005). A2 (medium-high) and B2 (medium-low greenhouse gas emission) are climate change scenarios.

Decades	Temperature (°C)	Precipitation (%)
A2		
2020	1.4 (1.1 to 2)	−1 (−4 to 2)
2050	2.9 (2.2 to 4.2)	1 (−8 to 12)
2070	4.8 (3.6 to 6.9)	5 (−7 to 21)
2100	6.1 (4.2 to 8.8)	15 (−4 to 45)
B2		
2020	1.5 (1 to 2.1)	2 (−7 to 8)
2050	2.7 (1.7 to 4.6)	4 (−2 to 16)
2070	3.9 (3 to 6)	7 (−3 to 27)
2100	4.2 (2.9 to 6.7)	12 (−2 to 24)

ature and precipitation at the two sites (Fig. 2) is apparent. The mean annual temperature at Botou is increasing slightly at the rate of 0.27 °C decade^{-1}, with a total increase of 1.13 °C during 1954–1995. Throughout the 42-year record, the annual air temperature anomaly was positive for 20 years and negative for 22 years, having quite equal fluctuations. However, positive anomalies mainly occurred after the 1980s (six times in the 1980s and ten times in 1990s). Annual precipitation has been stable with a slight decline. As to the precipitation anomaly curve, there are 19 positive years and 23 negative years. Most of the fluctuation falls within 15–30% of the mean.

In Huaiyuan, the mean annual air temperature has increased by 0.20 °C decade^{-1}, with a total increase of 0.98 °C in the past 49 years. The air temperature anomaly was positive for 24 years and negative for 25 years, with quite equal fluctuations. As in Botou, most of the positive anomalies occur after the 1980s and negative anomalies in the 1960s and 1970s. Annual precipitation has been quite stable throughout the record, with 26 positively anomalous years and 23 negatively anomalous years, both with equal deviations. Again, most of the fluctuation in precipitation falls between 15 and 30% of the mean. The meteorological data at both sites indicate a warming trend, especially since the 1980s.

Based on the averaged change of temperature and precipitation from the 40 climate models and the historical trends, we set the climate scenarios with temperature increases of 2 and 5 °C and precipitation fluctuations of ±15% and ±30%, based on the total variance of a decade (1996–2004) of daily climate data as a baseline for the two stations.

This method of climate generation applies the identical variance in the historical data (1994–2004) to future climate, including air pressure, air temperature, maximum and minimum temperature, humidity, sunshine duration, wind speed, and precipitation. The principle behind the method of Anwar et al. (2007) is somewhat similar to our method.

Although we mainly focus on the change of precipitation and temperature, it is worth noting that over the decades many other meteorological elements are not actually constant. For example, recently wind speed has been reported to be decreasing at many mid-latitude terrestrial sites over the last 30 years (Roderick et al., 2007; McVicar et al., 2008). Also the historical data from 1981 to 2000 (Mo et al., 2006; Liu et al., 2009) in the 3H Plain show that wind speed tended to decrease at the rate of 0.016 m s^{-1} year^{-1}. In addition, the rate of increase of the minimum temperature is 0.067 °C year^{-1}, which is higher than that of maximum temperature, being 0.047 °C year^{-1}, possibly causing a decrease of water vapor and partially causing a reduction in atmospheric demand. These tendencies are also found for the whole of China (National Climate Change Coordination Committee, 2007). Paying attention to these complex interactions may provide more accurate predictions. However, with the limitation of the research tool, the change in precipitation, temperature, and atmospheric CO$_2$ concentration has to be the main focus of climate change for this study.

2.3. The VIP model

The VIP (Vegetation Interface Processes) model is a bio-geophysically process-based model, designed to simulate land surface energy partitioning and hydrological cycling, crop growth, and soil organic matter decomposition. In the model, soil is divided into six layers and soil moisture transfer is described with Richards' equation. Crop canopy radiation transfer and absorption are simulated separately, with visible and near infrared radiation (NIR) wave bands, direct and diffuse fractions. Canopy leaf area index is separated into sunlit and shaded fractions and solar radiation absorption and photosynthesis are calculated for sunlit and shaded components using Farquhar's methodology for photosynthesis estimation (Farquhar et al., 1980). Energy balances in the canopy and soil surface are solved simultaneously with the stomatal conductance–photosynthesis empirical relationship (Mo and Liu, 2001). Crop phenological evolution is determined by thermal time (degree-days, i.e., the cumulative air temperature above a base temperature of 0 °C). A soil organic decomposition scheme simulates the carbon sequestration, which uses the conceptual pools of Century (Parton et al., 1993). The model has been applied to crop evapotranspiration and yield prediction over the 3H Plain (e.g., Mo and Liu, 2001; Mo et al., 2005; Mo et al., 2009). Because fertilizer application is very popular everywhere in the 3H Plain to enhance crop productivity, during the simulation it is assumed that nutrients are not limiting factors.

2.4. Cropping system

Generally, the main crops in the 3H Plain are winter wheat, summer maize and rice. We consider the wheat–maize cropping system for the comparison between the two sites. The reasons are as follows: (1) Chinese Statistics Yearbook (2001) shows that the cropping area of wheat and maize in 3H occupies 59 and 36% of that in all of China (Table 5). The cropping areas of wheat and maize occupy 44.2 and 23.3% of all the grain crops in the 3H plain. (2) The average ratio of planting area of wheat to the total grain planting area is 0.4–0.45 in Botou and 0.41–0.43 in Huaiyuan from 1996 to 2006. This makes wheat the first choice. (3) The ratio of planting area of maize in Huaiyuan to the total grain planting area (about 0.1–0.14) is relatively small compared with that in Botou, which is 0.4–0.5. However the ratio of planting area of rice in Botou to the total grain planting area (about 0.02) is much lower compared with that in Huaiyuan, which is 0.41–0.45. Thus, we chose wheat and maize for the study, instead of choosing wheat and rice. (4) Maize planting is increasing in Huaiyuan although its planting area is small relative to other grain crops. The increase of planting area for maize (372%) is the highest among other crops through

Table 5
The cropping area and structure of grain crops in the 3H region in 2000.

Region	Grain	Rice	Wheat	Maize	Soybeans	Potato
Cropping area (10^5 ha)						
A	1085	300	267	231	127	105
B	355	53	157	83	30	21
C	33	18	59	36	24	20
Cropping structure (%)						
A	100.0	27.6	24.6	21.3	11.7	9.7
B	100.0	14.9	44.2	23.3	8.4	6.0

Data source: China Statistics Yearbook 2001, published by Statistic Publishing House of China, September 2001.
A: China, B: the 3H region, C: A/B (%).

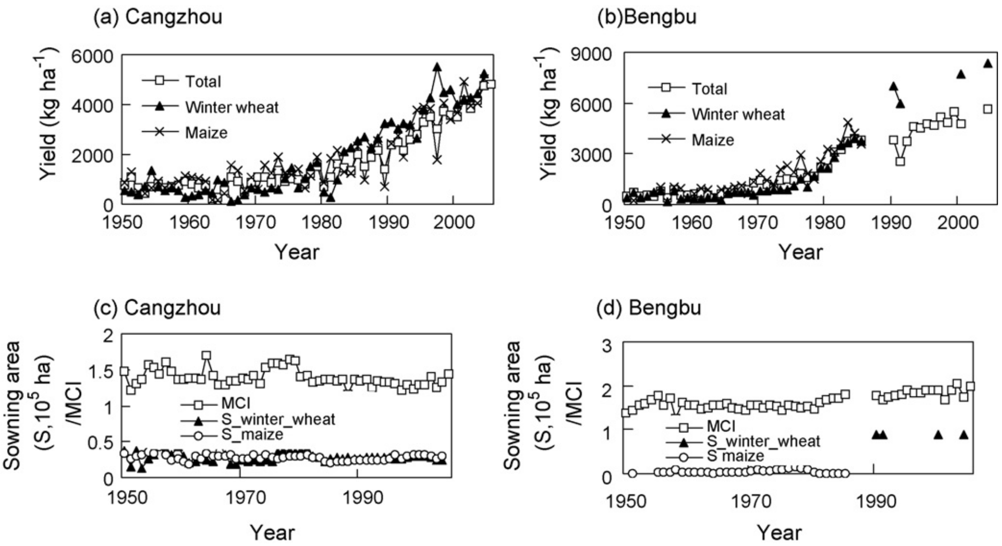

Fig. 3. Yearly variation of (a) total yield, yield for winter wheat and yield for maize in kg per ha and (c) multiple cropping index (MCI) and sowing area for wheat and maize in Cangzhou representing Botou. Those for Bengbu representing Huaiyuan are shown in (b) and (d).

1980–1990, compared with 128, 78, and 235% for wheat, rice and potatoes, respectively (Chinese Statistics Yearbook, 2001). From 1996 to 2006, the planting area of wheat decreased, but the planting area of maize increased from 22,908 to 26,774 ha. The tendency of increasing planting area of maize in Huaiyuan has been observed. Whether it is good to keep this increasing tendency in the future is an important issue for local government. Our work of predicting the response of maize's yield will be helpful to answer this question.

In Botou, grain yield per unit area has been increasing (Fig. 3a). Yield reached 4784 kg ha^{-1} in 2005, an 843% increase from 1949. Multiple cropping index (MCI, the ratio of the area from which farmers can get harvest within a year to the total area of the cultivated land), which indicates the extent of the cultivated land's utility, varied significantly since 1949, reaching a maximum of 1.7 in 1964 and a minimum of 1.2 in 1988 (Fig. 3c). A value of 1.4 was reported for 2005, and most other years, corresponding to almost three harvests every two years. The MCI has not changed much in the past 20 years. Since 1949, the area of summer maize in Botou has slightly increased with obvious fluctuations before the 1980s, and been relatively steady since then. A similar temporal pattern was observed for winter wheat.

In Huaiyuan, a similar trend of grain yield is observed as in Botou (Fig. 3b). Although in the beginning of the 1990s Huaiyuan experienced a reduction in growth, its grain production has increased over the last 20 years, with a 1.26% increase to 5685 kg ha^{-1} in 2004 since 1991. The MCI increased from 1.5 in 1980 to 2.0 in 2005, as crop management changed from three harvests every two years to two harvests per year (Fig. 3d). The planting area of grains experienced a slight decline since the 1990s.

2.5. Strategies for comparison

The model was first evaluated using yield data with baseline atmospheric forcing data from 1996 to 2004, and then run with the projected climate scenarios forced with projected meteorological data. By considering two sites, two crops, with and without CO_2 fertilization, irrigated and rain-fed conditions, temperature increases of 2 and 5 °C, and precipitation variabilities of ±15% and ±30%, the model was run for 96 cases (Table 6). Cases 1–48 are those without CO_2 enrichment. Cases 49–96 are those with CO_2 enrichment. Cases 1–24 and 49–72 are for the Botou site. Cases 25–48 and 73–96 are for the Huaiyuan site.

The cases without CO_2 enrichment used CO_2 concentrations measured at Mauna Loa, Hawaii from 1996 to 2004. The cases with CO_2 enrichment used 500 ppmv as the CO_2 concentration for the 2 °C temperature rise and 700 ppmv for the 5 °C warming. We have

Table 6
Case numbers of the 96 VIP model runs (M: maize; W: wheat) under temperature increases of 2 and 5 °C, precipitation variability of ±15% and ±30%, without CO_2 enrichment using CO_2 concentrations measured at Mauna Loa, Hawaii from 1996 to 2004 and with CO_2 enrichment using 500 and 700 ppmv for the 2 and 5 °C temperature rise, respectively.

Climate change scenario		Irrigated		Rainfed		Irrigated		Rainfed	
		M	W	M	W	M	W	M	W
		Botou (54618)				Huaiyuan (58221)			
0; +5 °C	Without considering CO_2 enrichment	1	2	3	4	25	26	27	28
+30%; +5 °C		5	6	7	8	29	30	31	32
−30%; +5 °C		9	10	11	12	33	34	35	36
0; +2 °C		13	14	15	16	37	38	39	40
+15%; +2 °C		17	18	19	20	41	42	43	44
−15%; +2 °C		21	22	23	24	45	46	47	48
0; +5 °C	Considering CO_2 enrichment	49	50	51	52	73	74	75	76
+30%; +5 °C		53	54	55	56	77	78	79	80
−30%; +5 °C		57	58	59	60	81	82	83	84
0; +2 °C		61	62	63	64	85	86	87	88
+15%; +2 °C		65	66	67	68	89	90	91	92
−15%; +2 °C		69	70	71	72	93	94	95	96

to admit that to set a constant change in air temperature (namely, 2 °C and 5 °C) to atmospheric CO_2 concentrations of 500 ppmv and 700 ppmv is a bit prescriptive. Using a fixed ratio of temperature to CO_2 concentration is a simplification as these two factors are concomitant (Morison and Lawlor, 1999). On all plots of atmospheric CO_2 concentration and corresponding air temperature increases there is usually error analysis or a swath of potential responses that may occur (e.g., Bader et al., 2008, page 89). However at present this is a way for us to consider CO_2 effects. More detailed consideration of complex temperature–CO_2 concentration response will be our further work.

During the simulation, irrigation was applied when soil moisture was lower than 65% of field capacity. This implies that water is always available when needed. In this paper we compare rainfed and irrigated conditions separately. For the rain-fed conditions, crops may incur water-stress during long droughts. For the irrigated conditions, we assume water is always available when irrigation is needed for crop growth. This is a somewhat man-made assumption. However it can at least direct us to know if the water requirement of crops is fully satisfied and how crops will be affected by climate change.

Assuming Y_{case} represents the yield simulated by the model under each of 96 cases, Y_{base} represents the yield simulated by the model forced with current climate, (i.e., the historical climate data from 1996 to 2004). The relative yield change (%), *RYC*, is calculated as

$$RYC = \frac{Y_{case} - Y_{base}}{Y_{base}} \times 100\% \tag{1}$$

Besides the direct comparison of *RYC*, statistical tests were also used to show the significance. The One-Sample *T*-Test was used to test for significance of the change of yield under climate change for all 96 cases with the null hypothesis $H_0 : \overline{RYC}_0 = 0$. For a data sample *RYC*, the standardized random variable

$$T = \frac{\overline{RYC} - \overline{RYC}_0}{s/\sqrt{n}} \tag{2}$$

is *t* distributed, where $\overline{RYC}$ is the mean of *RYC* from the data sample, $\overline{RYC}_0$ is the mean of *RYC* for the population, *n* is the count number of the data sample, and *s* is the standard deviation of the data sample calculated from:

$$s^2 = \frac{\sum_i^n (RYC_i - \overline{RYC})}{n-1} \tag{3}$$

Giving a significance level α, with the information of degrees of freedom, which is equal to $(n-1)$, we can get the first of the *T*-values, denoted as T_1, from the look-up table of *t*-distribution. The upper (with plus) and lower (with minus) corresponding values of a $100(1-\alpha)$ interval estimate of the mean of *RYC* relative to zero (null hypothesis), denoted as *LCV* and *UCV*, respectively, are calculated by

$$[LCV, UCV] = \left[\overline{RYC}_0 - T_1\frac{s}{\sqrt{n}}, \quad \overline{RYC}_0 + T_1\frac{s}{\sqrt{n}}\right] \tag{4}$$

By denoting the mean of *RYC* calculated from the data sample as *DS_CV*, we can calculate the second of *T*-values corresponding to *DS_CV* relative to $\overline{RYC}_0$, denoted as T_2. From T_2, by looking up the *t* distribution table, we can get a *p*-value. If $p < \alpha$, H_0 will be rejected at the significance level of α. If $p \geq \alpha$, we do not have enough evidence to reject H_0 at this significance level. The condition to reject H_0 can be also that the value of *DS_CV* is outside the interval of *LCV* and *UCV*.

For the two-sided *T*-test, we need to consider (usually with a given value) the probability of rejecting H_0 when the null hypothesis is true (Type I error, i.e., the significance level α). On the other hand, we also need to consider the probability of not rejecting H_0 when the null hypothesis is not true (i.e., the Type II error, denoted as β). Statistical power, which is equal to $1-\beta$, is used for this deliberation. The higher the power is, the higher the probability of rejecting null hypothesis when the null hypothesis is not true (Park, 2008). It is easy to calculate statistical power by calculating the third of *T*-values corresponding to *LCV* or *UCV* relative to *DS-CV* (alternative hypothesis), denoted as T_3. From T_3, by looking up the t distribution table, we get β and then the power.

Before doing the *T*-test, the assumption of normality was checked statistically by using the skewness, kurtosis and ominibus tests and virtual test by the normal probability plot and box plot. The assumption of randomization was checked by the method outlined by Edgington (1987). For data that do not follow normality, a natural-logarithm transformation of the original data with a constant added to keep the data all positive is used. Usually a constant, which is a little larger than the absolute value of the minimum value of the data sample, can work. If the data still do not follow normality, a larger constant may work finally.

The *T*-tests start with a small significance level (α) of 0.001. If the test result is "not to reject the null hypothesis", a larger significance level of 0.01, or 0.05 is tried. In this way significant differences can be identified over a range of levels, rather than arbitrarily selecting one significance level. A smaller significance level corresponds to a higher confidence level.

The significance levels of the changes of yield under climate change in each of the pair cases were also tested, such as between: 2 and 5 °C temperature increases, with and without CO_2 fertilization, increased and decreased precipitation, irrigated and rainfed land, maize and wheat, and Botou and Huaiyuan. To test the significance of difference between two samples, we used the Paired *T*-Test, which tests for equality of the means of the two samples, or if the difference in means between the two samples is equal to zero. In this way, all the theory of the One-Sample *T*-Test can be used in the Paired *T*-Test.

3. Results

3.1. Baseline historical simulations

The VIP model has been widely evaluated on the 3H Plain with statistical, field, and remote sensing data at both plot (Mo and Liu, 2001) and regional (Mo et al., 2005) scales. Here "statistical data" means the county yield statistics derived by estimating yields under different productivity levels and their relevant planting sizes (McVicar et al., 2002). These data, to some extent, represent a regional ground truth, and offer a validation of the prediction (Mo et al., 2005). Fig. 4 shows one example of the VIP model performance, where modeled net ecosystem produc-

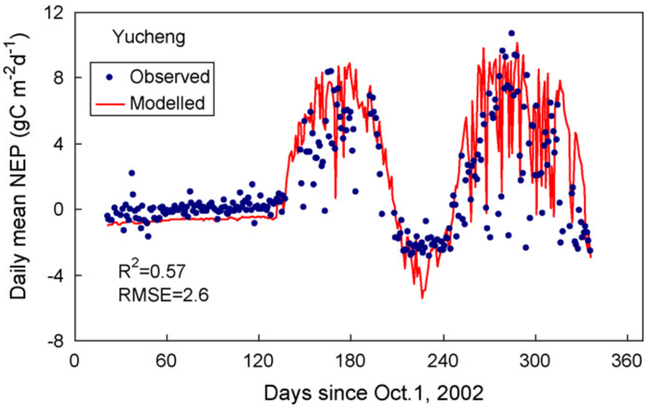

Fig. 4. VIP simulated and measured daily mean net ecosystem productivity (NEP, g C m^{-2} d^{-1}) at the Yucheng Station, near Botou (the unit of RMSE is the same as NEP).

Table 7
Relative Yield Change (RYC, %, see Equation 1) for all 96 cases (M: maize; W: wheat) under temperature increases of 2 and 5 °C, precipitation variability of ±15% and ±30%, without CO_2 enrichment using CO_2 concentrations measured at Mauna Loa, Hawaii from 1996 to 2004 and with CO_2 enrichment using 500 and 700 ppmv for the 2 and 5 °C temperature rise, respectively.

Climate change scenario		Irrigation		Rainfed		Irrigation		Rainfed	
		M	W	M	W	M	W	M	W
		Botou (54618)				Huaiyuan (58221)			
0; +5 °C	Without considering CO_2 enrichment	−26.7	−18.5	−31.0	−24.6	−34.1	−36.2	−38.2	−36.5
+30%; +5 °C		−25.7	−17.9	−24.5	−18.0	−32.5	−34.3	−32.6	−30.3
−30%; +5 °C		−28.2	−19.3	−38.2	−34.1	−36.0	−38.3	−45.1	−46.0
0; +2 °C		−9.6	−3.5	−11.5	-6.5	−16.9	−2.2	−19.0	−1.8
+15%; +2 °C		−8.7	−3.1	−8.1	−2.0	−16.7	−0.6	−14.5	2.3
−15%; +2 °C		−10.3	−4.2	−15.0	−11.8	−17.8	−3.8	−21.8	−7.8
0; +5 °C	Considering CO_2 enrichment	−19.6	31.9	−22.0	38.8	−28.3	−8.1	−30.6	−5.8
+30%; +5 °C		−17.8	32.9	−15.1	49.1	−26.5	−6.2	−23.8	1.5
−30% ;+5 °C		−20.5	31.6	−29.5	24.2	−29.1	−10.4	−37.6	−17.7
0; +2 °C		−5.7	19.7	−6.4	20.7	−12.5	16.4	−13.7	18.1
+15%; +2 °C		−4.9	19.9	−2.8	26.1	−12.1	17.5	−8.1	22.9
−15%; +2 °C		−6.3	19.0	−9.8	14.3	−14.0	14.8	−16.1	11.6

tivity (NEP) closely compares to measurements from the Yucheng agro-ecosystem station near Botou. These results encourage us to use the model to simulate the response of crop yield to climate change.

3.2. General pattern of yield response to climate change

Generally, the climate change affects crop yield, with the mean of 96 values of *RYC* being −10.33% and standard deviation being 20.27%, and the lowest and highest *RYC* values being −46% and 49%, respectively, as shown in Table 7. As −10.33% is outside of the interval estimate of the mean of *RYC* relative to null hypothesis of zero, [−5.44%, 5.44%], and the *p*-value is less than 0.001, the null hypothesis is rejected at the significance level of $\alpha = 0.001$ (Table 8). That is, over all the 96 cases the yield under climate change is significantly different from baseline yield at the significance level $\alpha = 0.001$.

The reduction of yield with a 5 °C increase in temperature is larger than that with a 2 °C increase. The average value of *RYC* is about −18.5 ± 22.8% for a 5 °C rise and −2.3 ± 13.2% for a 2 °C rise. The difference of *RYC* between temperature increases of 2 and 5 °C are statistically significant at $\alpha = 0.001$. Details of the statistical test results are shown in Table 8. For convenience, the power is only reported in the text when it is significantly less than 0.999, and the reader is referred to Table 8 for other statistics such as the *LCV* and *UCV*.

3.3. Crop yield response to climate change without considering CO_2 fertilization

In all cases without a CO_2 fertilization effect, crop yield is reduced up to 46% with an increase in temperature, as shown in the upper panel of Table 7. On average there is a negative correlation between a change in temperature and yield. The likely reason is that there is a shorter growth period (same thermal time, but less calendar time) under higher air temperatures. *RYC* over the 24 cases with temperature being 2 °C higher is less negative (−9.0 ± 6.7%) than that with the temperature being 5 °C higher (−31.1 ± 8.0%). The difference is significant at $\alpha = 0.001$. The most negative *RYC* (−46.0%) occurred at Huaiyuan in rain-fed wheat when temperature was raised 5 °C and precipitation was decreased 30% (case 36, Table 6). Xiong et al. (2007) found that for the three crops (rice, wheat and maize) averaged across China, mean harvest yields per unit area generally decreased under both A2 and B2 scenarios in the periods of 2020s, 2050s, and 2080s, up to 18–37% in the next 20–80 years if CO_2 fertilization was not taken into account.

There is only one exception at Huaiyuan rain-fed land where wheat yield shows a positive response with *RYC* being 2.3% (case 44) under the 15% increase of precipitation with the 2 °C increase of temperature. It is interesting that this positive yield response does not occur at the same place under higher increase of precipitation (30%) with the 5 °C temperature increase. Generally, warmer weather will reduce yield and higher precipitation will increase yield, the two effects roughly offsetting each other. Our results show that without considering CO_2 enrichment, the negative effect of a 5 °C temperature increase on yield cannot be offset by increased precipitation, even at the +30% level. However, the effect of a 2 °C temperature increase is indeed compensated for by only a 15% increase of precipitation. This indicates that without CO_2 enrichment, the effect of global warming on crop yield would be serious, and a rise in precipitation may not change its negative effect on crop yield.

3.4. Crop yield response to climate change considering CO_2 fertilization

More simulations produce a positive change in *RYC* when CO_2 fertilization is included. There are positive and negative responses corresponding to temperature rises of 2 and 5 °C, as shown in the lower panel of Table 7. On average, with CO_2 fertilization, *RYC* over the 24 cases with a temperature rise of 2 °C is positive (4.46 ± 14.83%), and that with a temperature rise of 5 °C is negative, plus with a larger variance (−5.78 ± 25.82%). From the statistical test, it is shown that with CO_2 fertilization the difference is only significant at $\alpha = 0.01$ with the power of rejecting the null hypothesis being 0.316.

By comparing the cases with and without CO_2 fertilization, it is seen that an increase in CO_2 concentration will be beneficial to crop growth. With CO_2 enrichment, the negative responses to warming are mitigated or can become positive. Positive response cases become even stronger when CO_2 fertilization is accounted for. The difference of *RYC* between the cases with CO_2 fertilization and the cases without CO_2 fertilization is statistically significant at $\alpha = 0.001$.

In Tubiello et al. (2000), at two Italian locations under the double CO_2 scenario, the negative effect of a simulated ~4 °C temperature increase in the changed climate were stronger than the positive effects of elevated CO_2, with precipitation increases of 10–30%. Specifically, warmer air temperatures accelerated plant phenology, reducing dry matter accumulation and yields of maize and wheat by 5–50%. Their very negative results may be due to a larger temperature and precipitation variability in their study. In addition, it is possible that the equations used in their model to predict the effects of elevated CO_2 on crop yield, which are based on the concept of RUE and performed in daily time steps, produce differ-

Table 8

Paired *T*-Test results of the difference of the mean of Relative Yield Change (*RYC*), denoted as *DS_CV*, for each pair cases (C_1 and C_2) defined in the text at the significance level (α) with the null hypothesis H_0: $C_1–C_2 = 0$. The definition of the symbols are defined in the text. Those "transformed" rows are the results based on transformed data, which are natural logarithm of original data with a constant added to keep the data all positive, due to the original data which do not follow normality. Case 27 is for One-Sample *T*-Test result. Power is only calculated when the null hypothesis is rejected.

Case no	Case description	α	n	T_1	s (%)	*LCV* (%)	*UCV* (%)	*DS_CV* (%)	T_2	p-value	Reject H_0?	T_3	Beta	Power (0.001)	Power (0.01)	Power (0.05)	Power (0.1)
1	Temp. 2 & 5 °C higher	0.001	48	3.5099	13.58	–6.8794	6.8794	16.2	8.2653	<0.001	Yes	–4.7554	<0.001	>0.999	>0.999	>0.999	>0.999
	(Transformed)	0.001	48	3.5099	0.35	–0.1755	0.1755	0.42	8.4000	<0.001	Yes	–4.8901	<0.001	>0.999	>0.999	>0.999	>0.999
2	With & without CO_2 fertilization	0.001	48	3.5099	17.11	–8.6695	8.6695	19.37	7.8421	<0.001	Yes	–4.3322	<0.001	>0.999	>0.999	>0.999	>0.999
	(Transformed)	0.001	48	3.5099	0.28	–0.1404	0.1404	0.39	9.7500	<0.001	Yes	–6.2401	<0.001	>0.999	>0.999	>0.999	>0.999
3	With CO_2, Temp. 2 & 5 °C higher	0.01	24	2.8073	15.58	–8.9273	8.9273	10.24	3.2201	0.004	Yes	–0.4128	0.684	–	0.316	0.739	0.854
4	Without CO_2, Temp. 2 & 5 °C higher	0.001	24	3.7676	7.74	–5.9529	5.9529	22.17	14.0316	<0.001	Yes	–10.2640	<0.001	>0.999	>0.999	>0.999	>0.999
5	Maize & wheat	0.001	48	3.5099	16.97	–8.5993	8.5993	–20.03	–8.1755	<0.001	Yes	11.6854	<0.001	>0.999	>0.999	>0.999	>0.999
6	Maize, Temp. 2 & 5 °C higher	0.001	24	3.7676	2.84	–2.1852	2.1852	17.06	29.4138	<0.001	Yes	–25.6462	<0.001	>0.999	>0.999	>0.999	>0.999
7	Wheat, Temp. 2 & 5 °C higher	0.001	24	3.7676	19.16	–14.73	14.73	15.35	3.9258	0.001	Yes	–0.1582	0.876	0.124	0.725	0.924	0.963
8	Maize, with CO_2, Temp.2 & 5 °C higher	0.001	12	4.4369	2.49	–3.19	3.19	15.55	21.5972	<0.001	Yes	–17.1603	<0.001	>0.999	>0.999	>0.999	>0.999
9	Maize, without CO_2 Temp.2 & 5 °C higher	0.001	12	4.4369	2.42	–3.11	3.11	18.58	26.5429	<0.001	Yes	–22.1060	<0.001	>0.999	>0.999	>0.999	>0.999
10	Wheat, with CO_2, Temp.2 & 5 °C higher	0.1	12	1.7959	20.92	–10.847	10.847	4.94	0.8179	0.4308	No	0.9780	0.349	–	–	–	–
	(transformed)	0.1	12	1.7959	0.97	–0.50	0.50	0.49	1.7500	0.108	No	0.0459	0.964	–	–	–	–
11	Wheat, without CO_2 Temp.2 & 5 °C higher	0.001	12	4.4369	9.53	–12.20	12.20	25.75	9.3636	<0.001	Yes	–4.9268	<0.001	>0.999	>0.999	>0.999	>0.999
12	Maize, with & without CO_2	0.001	24	3.7676	1.81	–1.39	1.39	6.17	16.6757	<0.001	Yes	–12.9080	<0.001	>0.999	>0.999	>0.999	>0.999
13	Wheat, with & without CO_2	0.001	24	3.7676	15.19	–11.68	11.68	32.57	10.5065	<0.001	Yes	–6.7388	<0.001	>0.999	>0.999	>0.999	>0.999
14	Precip. up & down	0.001	32	3.6335	6.34	–4.07	4.07	7.46	6.6607	<0.001	Yes	–3.0272	0.005	0.995	>0.999	>0.999	>0.999
15	Precip. up, Temp. 2 & 5 °C higher	0.01	16	2.9467	14.20	–10.46	10.46	14.26	4.0169	0.001	Yes	–1.0702	0.301	–	0.699	0.921	0.961
16	Precip. down, Temp. 2 & 5 °C higher	0.001	16	4.0728	13.36	–13.60	13.60	18.40	5.5090	<0.001	Yes	–1.4362	0.171	0.829	0.978	0.996	0.998
17	Irrigated & Rainfed	0.1	48	1.6779	5.47	–1.33	1.33	1.38	1.7468	0.087	Yes	–0.0689	0.945	–	–	–	0.055
18	Without CO_2, Irrigated & Rainfed	0.01	24	2.8073	4.56	–2.61	2.61	2.97	3.1935	0.004	Yes	–0.3862	0.703	–	0.297	0.728	0.847
19	With CO_2, Irrigated & Rainfed	0.1	24	1.7139	5.88	–2.06	2.06	–0.21	–0.1750	0.863	No	1.8889	0.072	–	–	–	–
20	Irrigated, Temp. 2 & 5 °C higher	0.001	24	3.7676	12.64	–9.72	9.72	15.25	5.9109	<0.001	Yes	–2.1432	0.043	0.957	0.995	0.999	>0.999
21	Rainfed, Temp. 2 & 5 °C higher	0.001	24	3.7676	14.65	–11.27	11.27	16.89	5.6488	<0.001	Yes	–1.8812	0.073	0.927	0.991	0.998	0.999
22	Botou-Huaiyuan	0.001	48	3.5099	13.03	–6.60	6.60	10.97	5.8351	<0.001	Yes	–2.3252	0.024	0.976	0.997	>0.999	>0.999
	(Transformed)	0.001	48	3.5099	0.35	–0.18	0.18	0.34	6.8000	<0.001	Yes	–3.2901	0.002	0.998	>0.999	>0.999	>0.999
23	Botou, Temp. 2 & 5 °C higher	0.01	24	2.8073	14.35	–8.23	8.23	8.85	3.0205	0.006	Yes	–0.2131	0.833	–	0.167	0.649	0.796
24	Huayuan, Temp. 2 & 5 °C higher	0.001	24	3.7676	7.54	–5.80	5.80	23.56	15.2987	<0.001	Yes	–11.5311	<0.001	>0.999	>0.999	>0.999	>0.999
25	Without CO_2, Botou & Huaiyuan	0.001	24	3.7676	6.66	–5.12	5.12	6.65	4.8897	<0.001	Yes	–1.1221	0.273	0.727	0.951	0.990	0.996
26	With CO_2, Botou & Huaiyuan	0.001	24	3.7676	16.26	–12.51	12.51	15.29	4.6054	<0.001	Yes	–0.8378	0.411	0.589	0.915	0.982	0.992
27*	One-sample-test	0.001	96	3.3580	20.27	–5.44	5.44	–10.33	–4.9938	<0.001	Yes	7.62237	<0.001	>0.999	>0.999	>0.999	>0.999

Table 9

Yield (Unit: g C m^{-2}) for all 96 cases (Control cases: at current CO_2 level; M: maize; W: wheat) under temperature increases of 2 and 5 °C, precipitation variability of ±15% and ±30%, without CO_2 enrichment using CO_2 concentrations measured at Mauna Loa, Hawaii from 1996 to 2004 and with CO_2 enrichment using 500 and 700 ppmv for the 2 and 5 °C temperature rise, respectively.

Climate change scenario		Irrigation		Rainfed		Irrigation		Rainfed	
		M	W	M	W	M	W	M	W
		Botou (54618)				Huaiyuan (58221)			
0; +5 °C	Without considering CO_2 enrichment	240.61	217.21	177.81	121.02	195.74	207.67	166.41	183.17
+30%, +5 °C		244.02	218.82	194.60	131.50	200.24	213.70	181.35	201.04
−30%; +5 °C		235.57	215.11	159.29	105.72	189.92	200.88	147.84	155.81
0; +2 °C		296.61	257.41	228.06	149.92	246.66	318.20	218.16	283.25
+15%; +2 °C		299.78	258.28	236.83	157.28	247.40	323.49	230.08	295.12
−15%; +2 °C		294.50	255.55	218.94	141.44	244.15	312.92	210.57	265.80
Control		328.26	266.62	257.70	160.41	296.95	325.31	269.17	288.41
0;+5 °C	Considering CO_2 enrichment	263.88	351.60	201.03	222.66	212.79	298.92	186.70	271.78
+30%, +5 °C		269.84	354.33	218.77	239.12	218.25	305.31	205.02	292.81
−30%; +5 °C		260.87	350.78	181.57	199.14	210.43	291.52	168.11	237.28
0; +2 °C		309.42	319.03	241.29	193.61	259.87	378.71	232.37	340.71
+15%; +2 °C		312.04	319.77	250.59	202.27	261.14	382.22	244.95	354.54
−15%; +2 °C		307.66	317.13	232.55	183.33	255.44	373.60	223.41	321.92
Control		328.26	266.62	257.70	160.41	296.95	325.31	269.17	288.41

ent yield estimation results from a physically process-based model, such as VIP.

3.5. General responses of C3 and C4 crops to climate change

The differences of *RYC* due to different degrees of warming are crop-dependent. For maize, the difference is significant at $\alpha = 0.001$. For wheat the difference is also significant at $\alpha = 0.001$, but the power of rejecting null hypothesis is 0.124. The power of rejecting the null hypothesis reaches 0.963 at the significance level of $\alpha = 0.1$. The difference of *RYC* between maize and wheat is statistically significant at $\alpha = 0.001$.

The different behaviors of C3 (wheat) and C4 (maize) crops to CO_2 enrichment further complicate the temperature interpretation. For maize as a C4 crop, with or without CO_2 enrichment the yield responses are all negative. The absolute values of the negative *RYC* for maize in the cases without CO_2 enrichment are larger than those in the cases with CO_2 enrichment. The elevated concentration of CO_2 mitigates the *RYC*. With and without CO_2 enrichment, the most negative response is −37.6% (−45.1%), the least negative one is −2.8% (−8.1%) and the mean of the response is −17.3 ± 9.6% (−23.5 ± 10.8%). The difference of *RYC* of maize between with and without CO_2 enrichment is statistically significant at $\alpha = 0.001$.

For winter wheat as a C3 crop, the negative simulated response for the cases without CO_2 fertilization becomes less negative or positive with CO_2 enrichment. With and without CO_2 enrichment, respectively, the most negative responses were −17.7% and −46.0%, the most positive responses were 49.1% and 2.3%, and the mean responses were 16.0 ± 16.5% and −16.2 ± 14.9%. The elevated concentration of CO_2 mitigates the negative changes in *RYC* for winter wheat, reverses some of the negative responses, and makes the positive responses stronger. The difference of *RYC* of wheat between with and without CO_2 enrichment is also statistically significant at $\alpha = 0.001$.

Our results show that maize still suffers loss and wheat may gain with CO_2 enrichment. Lin et al. (2005) and Xiong et al. (2007) found that including CO_2 fertilization effects, the three crops of rice, wheat and maize all increased yield under both A2 and B2 scenarios in most periods. The difference between our results and theirs may be due to two aspects. Unlike their simulations on each crop separately, our study considered the farming system, in which multiple crops are grown in rotations. Also, the model we used is a biophysical process-based model, quite different from other crop models (such as CERES, EPIC) which use RUE to model photosynthesis.

It is interesting to compare the absolute value of yield for maize and wheat as shown in Table 9 in all the cases with and without CO_2 enrichment. In control cases at current CO_2 levels, and for almost all climate change scenarios, the maize yield is slightly lower than the wheat yield in both Huaiyuan and Botou County. Only for some climate change scenarios is maize yield slightly higher than wheat yield in Botou County. However we do not recommend such a comparison based only on the yield itself for decision-making. The reason is that a direct comparison of absolute values of production in kg ha^{-1} or g C m^{-2} between different grains is not appropriate. Other aspects such as net economic returns must be considered, but that involves more analyses and some assumptions. Based on both absolute yield and *RYC* comparisons, winter wheat may be a more successful crop than maize, in light of future climate change scenarios.

3.6. Crop yield response to precipitation changes

Predicting changes in precipitation for the 3H Plain is a complex and difficult exercise (Qin et al., 2005). Our results indicate that more precipitation will certainly be beneficial to agricultural production. Comparing the values of *RYC* for precipitation unchanged (0), increased (+15% or +30%) and decreased (−15% or −30%), the results (Table 7) show that for cases where the *RYC* is negative, increasing precipitation mitigates the negative change of yield with increasing temperatures. Of the cases where the *RYC* is positive, those cases with increased precipitation are the most positive. And, conversely, as expected, decreasing precipitation makes a negative *RYC* value more negative, or will reduce the benefit gained from the combination of other climatic variables.

With decreased precipitation the difference of *RYC* between temperature increases of 2 and 5 °C is significant at $\alpha = 0.001$ with power being 0.998. With increased precipitation, the difference of *RYC* between 2 and 5 °C temperature increases is significant at $\alpha = 0.01$ with power being 0.669. The differences of *RYC* between increased and decreased precipitation are statistically significant at $\alpha = 0.001$.

It is interesting to see that with and without CO_2 enrichment, the most negative and positive changes of *RYC* all occur for rain-fed crops rather than irrigated crops. Without CO_2 enrichment, the most negative *RYC* (−46.0%) occurs for rain-fed land when temperature is raised 5 °C at Huaiyuan and precipitation is decreased 30% (case 36 in Table 6). The most positive *RYC* (2.3%) occurs also for rain-fed land at Huaiyuan under the 15% increase of precipitation with the 2 °C increase of temperature (case 44). With CO_2 enrichment, the most negative *RYC* (−37.6%) occurs for rain-fed land when temperature is raised 5 °C at Huaiyuan and precipitation is decreased 30% (case 83 in Table 6). The most positive *RYC* (49.1%) occurs also for rain-fed land when temperature is raised 5 °C at Botou and precipitation is increased 30% (case 56).

Zhang and Liu (2005) found that precipitation is the major limiting factor of agricultural production on the Loess Plateau. There, it receives annual average precipitation of 200–608 mm from 1970 to 2000, with potential evapotranspiration calculated using Penman's equation being 1100 mm. There, significant simulated increases in predicted wheat and maize yields were the result of increased simulated precipitation and CO_2 concentration, which combined to outweigh the negative effect of temperature rise. With a 23–37% increase in annual precipitation and a 2–5 °C rise in temperature, there are yield gains for both wheat and maize.

3.7. *The role of irrigation in crop yield response to climate change*

Table 7 shows the marginal effect of irrigation on the yield, in response to simulated climate change. For both irrigated and rain-fed lands, the difference of *RYC* under 2 and 5 °C temperature increases is significant at $\alpha = 0.001$. The difference of *RYC* between irrigated and rainfed lands is statistically significant at $\alpha = 0.001$ with power being only 0.055.

On average, without CO_2 enrichment, the mean of *RYC* for irrigated land is less negative (−18.5 ± 12.6%) than that for rain-fed land (−21.5 ± 14.2%). The difference is significant at $\alpha = 0.01$, and the power is 0.297. On average, with CO_2 enrichment, the mean of *RYC* for irrigated land is −0.8 ± 20.1%, and that for rain-fed land is −0.6 ± 23.2%. The difference is not significant even at the significance level of $\alpha = 0.1$. These results show that CO_2 enrichment blurs the role of irrigation.

There is an obvious difference of yield between the irrigated and rain-fed land, as shown in Table 9. Whether under the control case or climate change scenarios, the yields from irrigated land are all higher than the yields from rain-fed land, indicating that some level of irrigation on the 3H Plain is always beneficial to production, which is expected given a water-limited landscape with precipitation being less than potential evapotranspiration (Table 1). The results of Thomas (2008) further support this observation, which showed an increasing demand for irrigation in China's future using climate-change scenarios based on data collected during 1951–1990. However, as shown by Tubiello et al. (2000) at Modena, Italy, 60–90% more irrigation water was required to maintain yield under climate-change scenarios. This implies that adaptation to climate change may be limited for irrigated crops, and will depend on site-specific water availability.

3.8. *Variability of crop yield response to climate change for Botou and Huaiyuan*

Taking into account the interactions between all the variables used to drive the crop-yield simulations (i.e., variation in precipitation, CO_2 enrichment effects, irrigation, and crop type), agricultural production loss tends to accompany climate change in both Botou and Huaiyuan. This can be shown from Table 7 that the mean response for Botou over 48 cases is −4.9 ± 21.2% and that for Huaiyuan is −15.8 ± 17.9%. In all cases, Botou incurs a less negative response than Huaiyuan. The difference of *RYC* between Botou and Huaiyuan are statistically significant at $\alpha = 0.001$ with power being 0.976.

As shown in Table 7, on average, without CO_2 enrichment, the mean of *RYC* for Botou is −16.7 ± 10.5%, and that for Huaiyuan is −23.4 ± 15.2%. The differences of *RYC* between Botou and Huaiyuan are significant at $\alpha = 0.001$ with power being 0.727. With CO_2 enrichment, the mean of *RYC* for Botou is −7.0 ± 22.7% and that for Huaiyuan is −8.3 ± 17.5%. The differences of *RYC* between Botou and Huaiyuan are significant at $\alpha = 0.001$ with power being 0.589. This shows that although CO_2 enrichment mitigates the yield loss response under simulated climate change for the two sites, the response pattern that Botou incurs a less negative response than Huaiyuan is true for both situations with and without CO_2 fertilization.

Because Botou and Huaiyuan are representative of the north and south of the 3H Plain, respectively, the results infer that the southern region will be more sensitive to projected climate change than the north. This result may surprise some, because the current water resources are more abundant in the south. Of course this conclusion is only relevant to the projections used in this study.

The differences of *RYC* due to different degrees of warming are different for south and north counties. For the south county, Huaiyuan, the difference of *RYC* between under 2 and 5 °C temperature higher is significant at $\alpha = 0.001$. For the north county, Botou, the difference is only significant at $\alpha = 0.01$ and the power is 0.167.

It is interesting to further compare the response differences between 2 and 5 °C temperature rise cases, with and without CO_2 fertilization taken into account, for the two crops at the two sites. First by checking the situation averaging over the two sites, we found that all of the response patterns to warming for the two crops are logical. As shown in Table 10, for maize and wheat averaged over the two sites, the pattern of different responses between 2 and 5 °C temperature rise cases with CO_2 enrichment is similar to the scenarios without CO_2 enrichment, i.e., less negative and/or more positive. With CO_2 enrichment, *RYC* for maize over the 12 cases with a temperature rise of 2 °C, is less negative on average (−9.4 ± 4.3%) than that with a temperature rise of 5 °C (−25.1 ± 6.4%). Without CO_2 enrichment, *RYC* for maize over the 12 cases with a temperature rise of 2 °C is also less negative on average (−14.2 ± 4.5%) than that with a temperature rise of 5 °C (−32.7 ± 6.1%). Without CO_2 enrichment, the average *RYC* for wheat over the 12 cases with a temperature rise of 2 °C is less negative (−3.7 ± 3.7%) than that

Table 10
The mean and standard deviation of *RYC* (%) for Botou, Huaiyuan and both sites without and with CO_2 enrichment for the two crops (M: Maize. W: Wheat) under 2 and 5 °C temperature rise.

		For both sites			For Botou			For Huaiyuan		
		+5 °C		+2 °C	+5 °C		+2 °C	+5 °C		+2 °C
Without	M	−32.7 ± 6.1	<	−14.2 ± 4.5	−29.1 ± 5	<	−10.5 ± 2.5	−36.7 ± 4.4	<	−17.8 ± 2.4
	W	−29.5 ± 9.5	<	−3.7 ± 3.7	−22.1 ± 6.4	<	−5.2 ± 3.6	−36.5 ± 4.9	<	−3.7 ± 4.8
	M&W	−31.1 ± 8	<	−9 ± 6.7	−25.6 ± 6.6	<	−7.9 ± 4.1	−36.7 ± 4.8	<	−10 ± 8.6
With	M	−25.1 ± 6.4	<	−9.4 ± 4.3	−20.8 ± 4.9	<	−6 ± 2.3	−29.3 ± 4.7	<	−12.7 ± 2.7
	W	13.5 ± 23.3	<	18.4 ± 3.9	***34.7* ± *8.4***	**>**	***19.9* ± *3.7***	−7.8 ± 6.3	<	16.9 ± 3.7
	M&W	−5.9 ± 25.8	<	4.5 ± 14.8	7 ± 29.7	~	7 ± 13.9	−18.6 ± 12.4	<	2.1 ± 15.8

with a temperature rise of 5 °C (−29.5 ± 9.5%). With CO_2 enrichment, *RYC* for wheat over the 12 cases with a temperature rise of 2 °C, is more positive (18.4 ± 3.9%) than that with a temperature rise of 5 °C (13.5 ± 23.3%). The first three results are all statistically less negative at $\alpha = 0.001$ and the fourth is statistically more positive at the significance level of $\alpha = 0.1$ with power being 0.518.

However, looking at the two sites, respectively, the situation is different. As shown in Table 10 in Huaiyuan, without CO_2 enrichment, the average *RYC* for wheat with a temperature rise of 2 °C is less negative (−3.7 ± 4.8%) than that with a temperature rise of 5 °C (−36.5 ± 4.9%). With CO_2 enrichment, *RYC* with a temperature rise of 2 °C becomes positive (16.9 ± 3.8%) and that with a temperature rise of 5 °C is still negative (−7.8 ± 6.3%). In Huaiyuan, without CO_2 enrichment, the average *RYC* for maize with a temperature rise of 2 °C is less negative (−17.8 ± 2.4%) than that with a temperature rise of 5 °C (−36.7 ± 4.4%). With CO_2 enrichment, *RYC* with a temperature rise of 2 °C is less negative (−12.7 ± 2.7%) than that with a temperature rise of 5 °C (−29.3 ± 4.7%).

In Botou, without CO_2 enrichment, the average *RYC* for maize with a temperature rise of 2 °C is less negative (−10.5 ± 2.5%) than that with a temperature rise of 5 °C (−29.1 ± 5.0%). With CO_2 enrichment, *RYC* with a temperature rise of 2 °C is less negative (−6.0 ± 2.3%) than that with a temperature rise of 5 °C (−20.8 ± 4.9%). Without CO_2 enrichment, the average *RYC* for wheat with a temperature rise of 2 °C is less negative (−5.2 ± 3.6%) than that with a temperature rise of 5 °C (−22.1 ± 6.4%). Very spectacularly, with CO_2 enrichment, *RYC* with a temperature rise of 2 °C becomes positive (19.9 ± 3.8%) and that with a temperature rise of 5 °C is even more positive (34.7 ± 8.4%).

For wheat in Botou, CO_2 fertilization can offset the negative effects caused by warming. This supports the view that the north of the 3H Plain may be more capable to face the challenge of climate change. This implies that the CO_2 fertilization effect might be greater under relatively dry conditions than in wetter soils, because photosynthesis would occur more readily in a more CO_2 responsive mode (Andre and DuCloux, 1993; Samarakoon and Gifford, 1995; Xiong et al., 2007). This also confirms that winter wheat as a C3 crop is much more sensitive to CO_2 concentration change than maize as a C4 crop.

4. Discussion and conclusions

This study provides an impact analysis of climate change on crop yield by using the VIP ecosystem model for sites on the 3H Plain in China. Two typical counties, Botou and Huaiyuan, represent the north and south plain, respectively. Six climate change scenarios with temperature increases of 2 °C and 5 °C, and precipitation amounts of ±15% and ±30% were used for the impact analysis. Also included were irrigated versus rain-fed conditions as well as C3 (wheat) and C4 (maize) plant types.

Overall, the study shows that there is an impact of higher temperatures on crop yield in all 96 cases. The negative relationship between temperature and yield is attributed to the decreased length of the optimal growth period. As the crop yield is only simulated for two temperature change scenarios, we cannot say with certainty that all temperature rises will be harmful for agriculture. For example, a small amount of warming may be beneficial, as documented by Liu et al. (2004) using a different methodology. Identifying a potential temperature threshold for the yield response requires a continuous simulation in time to verify.

Although temperature rises of 2 °C and 5 °C will generally reduce the grain yields, the increase in temperature has variable effects for different situations:

First, the negative effect of temperature rise on crop yield may be mitigated by CO_2 fertilization. *RYC* with CO_2 enrichment is statistically significantly different from *RYC* without CO_2 enrichment at $\alpha = 0.001$. The response of yield to warmer weather becomes complicated when taking CO_2 fertilization into account. Without considering CO_2 fertilization, *RYC* with a 2 °C increase in temperature is significantly different at $\alpha = 0.001$ from *RYC* with a 5 °C increase in temperature. By considering CO_2 fertilization, differences of *RYC* with temperature 2 and 5 °C higher are blurred. For all simulations, CO_2 enrichment has a positive effect on crop yield.

Second, C3 (wheat) and C4 (maize) crops respond differently to temperature rise. *RYC* for maize is statistically significantly different from *RYC* for wheat at $\alpha = 0.001$. For both crops, elevated CO_2 mitigates a negative change in *RYC*, and enhances positive changes in all climate-change scenarios. For maize, *RYC* with CO_2 enrichment is statistically different from *RYC* without CO_2 enrichment at $\alpha = 0.001$. For wheat, *RYC* with CO_2 enrichment is also statistically different from *RYC* without CO_2 enrichment at $\alpha = 0.001$. However, under the same conditions, maize always has a more negative response. Winter wheat may be a more successful crop than maize, in light of projected climate change scenarios. This interesting result causes us to think about whether we need to change the double (maize–wheat) cropping in 3H. However, because it is difficult to remove maize as a traditional plant in the 3H Plain since ancient times, and because more aspects need to be considered comprehensively, it may be too early to recommend another rotation based only on this result.

Third, temperature has different effects for an increase or decrease in precipitation. With the decrease of precipitation the difference of *RYC* between 2 and 5 °C temperature increases is significant at $\alpha = 0.001$. With the increase of precipitation, the difference of *RYC* between 2 and 5 °C temperature increases is significant at $\alpha = 0.01$. The differences of *RYC* between the increase of precipitation and the decrease of precipitation are statistically significant at $\alpha = 0.001$. An increase in precipitation will mitigate the loss and increase the projected gain of crop yield, and conversely, a precipitation decrease will exacerbate the loss and reduce the projected gain of crop yield. This result agrees with the common knowledge that agriculture on the 3H Plain largely relies on water from precipitation (Xu et al., 2005).

Fourth, temperature has different effects on irrigated and rain-fed lands. Generally, as expected, crop yield is higher from irrigated land than rain-fed land in the 3H Plain. This is true not only for the baseline but also for the climatic change situation. However the difference of *RYC* between irrigated and rain-fed lands are only statistically significant at $\alpha = 0.1$ with power being 0.055. The mean of *RYC* is marginally less negative in irrigated land than that for the rain-fed case, showing that irrigation helps to mitigate the negative response of crop yield, and some level of irrigation in the 3H Plain is beneficial to agriculture. CO_2 enrichment blurs the role of irrigation.

Fifth, crops in the southern 3H Plain, which is wetter, are more sensitive to climate change than crops in the drier north. The difference of *RYC* between Botou and Huaiyuan are statistically significant at $\alpha = 0.001$. The differences of *RYC* due to different degrees of warming are different for south and north counties. For the south county of Huaiyuan, the difference is significant at $\alpha = 0.001$. For the north county of Botou, the difference is only significant at $\alpha = 0.01$. Generally, considering the interactions among all climate variables simulated, both Botou and Huaiyuan are likely to incur agricultural production losses in response to warming. The responses of crop yields to climate change in Botou and Huaiyuan are diverse. In all cases, Botou incurs less negative responses than in Huaiyuan and this pattern is true with and without CO_2 fertilization, suggesting that the northern part of the 3H Plain will be less sensitive to projected climate change than the south. Although the current water resources in the southern 3H Plain are more abundant than in the north, there is no guarantee that the south is more robust than the north. For the two counties and for the two crops studied here, *RYC* with a temperature rise of 2 °C generally is less negative or more positive than that with a temperature rise of 5 °C, with and without CO_2 enrichment. However, for wheat in Botou with CO_2 enrichment, higher temperature resulted in a higher yield gain. This again indicates that CO_2 fertilization may offset warming, especially for the northern county. The CO_2 fertilization effect might be greater under drier conditions than in wetter soils, and wheat is more sensitive to CO_2 fertilization than maize.

An important constraint not incorporated into this research is how farmers adapt to climate change. Though irrigation was taken into consideration, fertilizer management and crop variety choices are among other factors that may mitigate losses in yield. Data are not available to characterize such adaptations, so the model assumes these factors do not change. Consequently, we are not able to measure the importance of these factors in the model simulations. The interaction between hydrology, ecology, and adaptation is an important area of future research.

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