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Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain

Xingguo Mo *, Suxia Liu, Zhonghui Lin, Ruiping Guo

Key Laboratory of Water Cycle and Its Related Land Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

The North China Plain (NCP) is one of the most important regions for food production in China, with its agricultural system being significantly affected by the undergoing climate change and vulnerable with water stress. In this study, the Vegetation Interface Processes (VIP) model is used to evaluate crop yield, water consumption (ET), and water use efficiency (WUE) of a winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.) double cropping system in the NCP from 1951 to 2006. Their responses to future climate scenarios of 21st century projected by the GCM (HadCM3) with Intergovernmental Panel on Climate Change Special Report on Emission Scenario (IPCC SRES) A2 and B1 emissions are investigated. The results show a rapid enhancement of crop yield in the past 56 years, accompanying with slight increment of ET and noticeable improvement of WUE. There exist spatial patterns of crop yield stemmed mainly from soil quality and irrigation facilities. For climate change impacts, it is found that winter wheat yield will significantly increase with the maximum increment in A2 occurring in 2070s with a value of 19%, whereas the maximum in B1 being 13% in 2060s. Its ET is slightly intensified, which is less than 6%, under both A2 and B1 scenarios, giving rise to the improvement of WUE by 10% and 7% under A2 and B1 scenarios, respectively. Comparatively, summer maize yield will gently decline by 15% for A2 and 12% for B1 scenario, respectively. Its ET is obviously increasing since 2050s with over 10% relative change, leading to a lower WUE with more than 25% relative change under both scenarios in 2090s. Therefore, possible adaptation countermeasures should be developed to mitigate the negative effects of climate change for the sustainable development of agro-ecosystems in the NCP.

1. Introduction

Greenhouse gases emission from fossil combustion, cement production and land use/cover changes have propelled the global climate changing, which appears as a widespread rising of surface air temperatures, alteration of precipitation patterns and global hydrologic cycle, and increased frequency of severe weather events, such as drought spells and flooding. In many regions, agricultural crops are sensitive to climate change (Izaurralde et al., 2003; Lobell and Field, 2008). Usually, air warming will accelerate the crop development, alter the phenological period, and enhance the maintenance respiration; on the other hand, atmospheric CO_2 enrichment will increase the leaf photosynthetic rate and reduce transpiration simultaneously, adding additional carbon to the ecosystems, and hence leading to changes in the cycling of water, nutrients and energy balance (Polley, 2002; Fuhrer, 2003). Due to complex interactions between the climatic and other environmental factors, the impacts of climate change on agricultural ecosystems may be interacted under diversified agronomical practices. For example, the responses of wheat yield to global warming are different between rain-fed and irrigated conditions, and between well and less fertilized conditions (Tubiello et al., 2000).

The physically process-based models, designed for crop ecosystem simulation, in which the environmental and management factors and their interactions are integrated, are broadly applied to project the responses of crops to future climate change scenarios (Brown and Rosenberg, 1997; Mearns et al., 2001; van Ittersum et al., 2003; Trnka et al., 2004; Zhang and Liu, 2005; Thomson et al., 2006; Walker and Schulze, 2006). With the crop models, a lot of researches on the responses of wheat and maize to global change were conducted. For example, Southworth et al. (2002) predicted the wheat responses in the Midwestern United States for 2050–2059 with atmospheric CO_2 concentration of 555 ppm, elucidating that wheat yields would increase 60–100% above current yields across the central and northern areas, but both small increases and decreases were found in the southern areas. Trnka et al. (2004) reported that winter wheat would

* Corresponding author.
E-mail address: moxg@igsnrr.ac.cn (X. Mo).

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enhance its productivity under both Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 and B1 scenarios. Under the three emission scenarios (A2a, B2a, and GGa1), Zhang and Liu (2005) predicted with EPIC model that the productivities and evapotranspiration of wheat and maize would noticeably increase over the Loess Plateau. Generally, it is projected that winter wheat as a C3 crop will increase its productivity and water use efficiency in most cases due to the atmospheric CO_2 fertilization, but the annual variability and vulnerability of crop yield are also exaggerated. Maize as a C4 crop has low growth response to elevated CO_2 concentration and then benefits less from its enrichment, due to their CO_2 concentrating mechanism in the photosynthetic path (Kim et al., 2007). The increased air temperature and changed precipitation pattern will significantly affect crop phenological process and stomatal conductance, which lead to alteration of yield and water use efficiency (Kattge and Knorr, 2007). However, the results from Free Air Carbon Enrichment (FACE) experiments show that the stimulation of grain yield by CO_2 enrichment is lower than expected (Kimball et al., 2002; Long et al., 2006). This discrepancy is possibly related to a fact that the crop models usually predict with non-limited supply of water and nutrition and near optimum temperature for crop growth. Usually, assessment of climate change impact is intended to seek the adaptation measures that may be the choices to mitigate the negative feedbacks to agro-ecosystems, to maintain and even increase the crop yields under future scenarios. These measures include selection of the most favorable crops, guidance for new cultivars breeding, and application of dynamic cropping (Hanson et al., 2007).

The North China Plain (NCP) is the country's most productive region of agriculture, accounting for about 69% of wheat (*Triticum aestivum* L.) and 35% of maize (*Zea mays* L.) grain yields of the whole country (Liu et al., in press). In the recent two decades, the intensive agricultural systems are mainly composed of wheat–maize double cropping, which is strongly dependent on the available irrigation from aquifer pumping, reservoir and river withdrawing. However, as stressed by the climatic variability and economic development, the water resources in this region are vulnerable. In order to meet the irrigation requirement of the intensified agriculture, groundwater has been pumped in excess of recharge, giving rise to continuously dropping of groundwater table during the last several decades and forming the so-called "groundwater funnel" in some areas. Consequently, the overuse of water resources has deteriorated the agricultural sustainability and caused serious environmental hazards. As an aspect of water deficit mitigation, the responses of agricultural system in the NCP to climate change have been highly concerned.

So far, there are several reports on the response of crop yield of the NCP to climate change. For example, Thomson et al. (2006) reported that under A2 and B2 scenarios wheat yield and soil carbon sequestration would significantly increase in the NCP. Liu et al. (in press) chose two typical counties each in the south and north of the plain respectively to explore the response of crop yield to climate change with the Vegetation Interface Processes (VIP) model under different scenarios.

However, there have not been many researches on the regional responses of crop yield, water consumption (ET) and water use efficiency (WUE) to climate change in wheat–maize double cropping system over the plain. Because water is the critical limited factor in the NCP, it is better to study the three variables of crop yield, ET and WUE together than just to study each of them alone. Except some statistic yield data at county and provincial scales, the observed data of ET and WUE over a region are usually not available. The yield data sometimes contain uncertainty because of some unavoidable factors (Mo et al., 2005). Using a physically process-based crop model to simulate crop yield, ET and WUE is an effective way for the analysis. As in situ measurements are always at point scale, models can be used to upscale information from point to large area. The successful simulation of crop productions in the past several decades will improve the reliability of projection on the future climate change responses.

The purpose of this study is to explore the regional crop response to climate change. For this, firstly the spatial variability and evolution of crop yield, ET and WUE with a process-based crop model in the NCP is explored. The contribution of climate change to their enhancement in the past 56 years is then identified. Further, the impacts of future climate changes under A2 and B1 scenarios on the wheat–maize double cropping system are assessed. Finally discussions and conclusions are given.

2. Methods and data

2.1. Model description

The VIP model (Mo and Liu, 2001; Mo et al., 2005) is a physically process-based ecosystem dynamic model with the simulation of land surface energy balance, water cycle as well as carbon cycle at each cell of the land surface coverage (Fig. 1).

Water cycle deals with precipitation, infiltration, runoff, drainage and evapotranspiration (including soil evaporation, canopy transpiration, and evaporation from intercepted water by canopy). Moisture transfer in the soil, which is divided into six layers, is described with the Darcy's law.

Energy balance includes radiation, latent heat, sensible heat, and ground heat flux. The radiation transfer and absorption in the crop canopy layer with 20 sub-layers are simulated separately with visible and near infrared radiation wavebands, and with direct and diffuse fractions (Mo and Liu, 2001). Energy balance equations of canopy and soil surface are solved simultaneously with the Newton–Raphson method (see Acs, 1994).

Carbon cycle module includes assimilation via photosynthesis, crop growth and soil organic matter decomposition schemes. The photosynthetic production is input into the crop growth module for biomass and leaf area estimation. In the crop growth module, crop phenological stages are expressed with air temperature degree–day which determines the fractions of assimilation partitioned to crop components (leaf, stem, root and grain), and leaf area is estimated by leaf biomass with specific leaf area. A scheme similar to Century and RothC models (Parton et al., 1993; Coleman et al., 1997) is designed to describe soil organic decomposition.

The VIP model has not yet dealt with nitrogen cycle mechanically in this study. As nitrogen is the key factor to determine the photosynthesis capacity, a correction factor is introduced to account for the influence of nitrogen to the yield improvement. Detail is shown in the following Section 3.2.

As a whole, water cycle, energy transfer and carbon cycle are interacted via evapotranspiration, stomatal conductance and photosynthesis in the VIP model. Soil water transfer is coupled with soil thermal transfer (Mo et al., 2006). The canopy photosynthesis estimation is based on a biochemical model (Farquhar et al., 1980; Collatz et al., 1992). Since photosynthesis of canopy leaves responses to irradiance in a nonlinear way, photosynthesis in sunflecks is often light saturated, whereas photosynthesis of shaded leaves is still increasing with irradiance. It is reasonable and effective to simplify the canopy leaves into two classes, namely sunlit and shaded for photosynthesis estimation at canopy scale (De Pury and Farquhar, 1997; Wang and Leuning, 1998). To account for the light extinction profile in canopy, a multi-layer scheme for both groups is used to upscale the leaf photosynthesis to canopy (Mo and Beven, 2004).

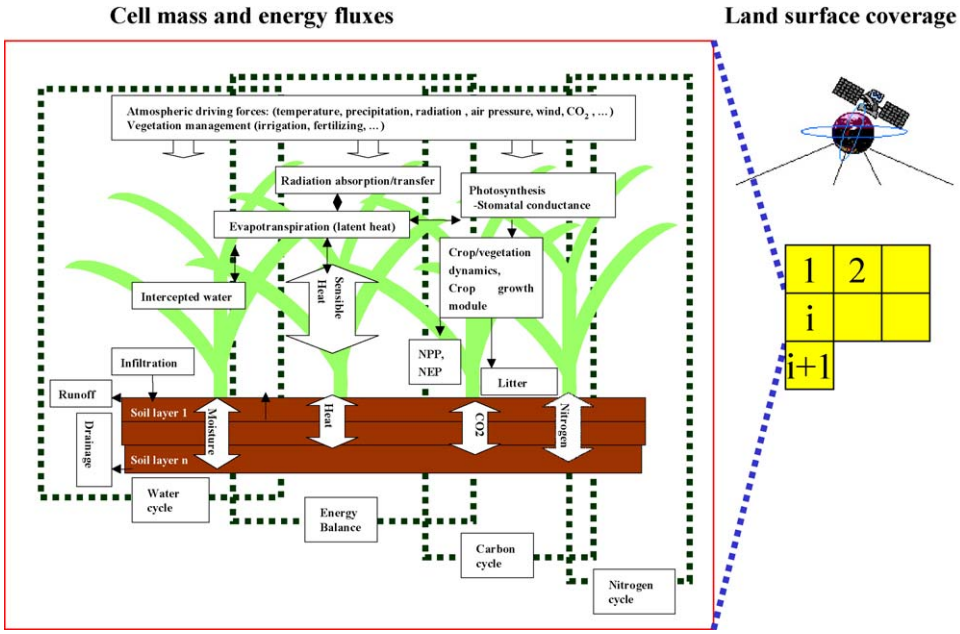

Fig. 1. The framework of the VIP model.

Leaf assimilation rate is limited by the efficiency of photosynthetic enzyme system. The CO_2 assimilation rates, A_n, for C3 and C4 leaves are expressed as

$$A_n = \min(A_c, A_e) - R_d \quad (1)$$

A_c and A_e (both with the units μmol C m^{-2} s^{-1}) are the gross rates of photosynthesis limited by ribulose bisphosphate carboxylase-oxygenase (Rubisco) activity and the rate of ribulose bisphosphate (RuBP) regeneration through electron transport, respectively. R_d is the daytime respiration (μmol C m^{-2} s^{-1}). A_c can be expressed as,

$$A_c = \frac{V_{cmax}(c_i - \Gamma)}{c_i + k_c(1 + o_i/k_o)} \quad \text{, for C3} \quad (2)$$

$$A_c = V_{cmax} \quad \text{, for C4} \quad (3)$$

where V_{cmax} is the maximum carboxylation rate when photosynthesis is limited by Rubisco activity (μmol CO_2 m^{-2} s^{-1}); c_i and o_i are the intercellular CO_2 and O_2 concentrations (Pa); Γ is the CO_2 compensation point (Pa); k_c and k_o are the Michaelis–Menten constants for CO_2 and O_2 (Pa), respectively.

2.2. Study region

The NCP is one of the country's granaries, extending from latitude 32°00′N to 40°24′N and longitude 112°48′E to 122°45′E (Fig. 2). It locates in the eastern part of China with an area of 33×10^4 km^2, which is an alluvial plain developed by the intermittent flooding of the Huang (yellow), Huai and Hai rivers. The plain administratively covers seven provinces (mega cities), including Hebei, Shandong, Henan, Anhui, Jiangsu, Beijing and Tianjin. The warm temperate climate varies gradually from sub-humid in the southern to semi-arid in the northern part. The annual precipitation is about 500–1000 mm, which distributes irregularly among seasons. More than 70% of precipitation falls in summer. Besides soybean/millet/sorghum, the double cropping system of winter wheat–summer maize prevails in the plain, in which maize is the most common autumn harvest crop. Due to insufficient precipitation in the growing season, the spring crops (such as wheat) usually need supplemental irrigation to obtain favorite production, which is about 80% of the climate-adjusted genetic yield potential ceiling (Tilman et al., 2002).

2.3. Data

About three types of data are used in this study, i.e. GIS data, climate and agricultural data. GIS data are used as basic land surface information for simulating regional yield, ET and WUE. Climate data are used as atmospheric forces to drive the VIP model to do the simulation under the historic and future climate conditions. Agricultural data are used for model validation and crop parameter determination.

2.3.1. GIS data

The GIS datasets include: (1) land use/cover digital data and land use map; (2) Digital Elevation Model (DEM); (3) yield level map; and (4) soil texture map. All are re-sampled to a 8×8 km^2 grid cell resolution and the data source for each is as follows. The spatial resolution of 8 km is determined by following the resolution of long-term data of National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer

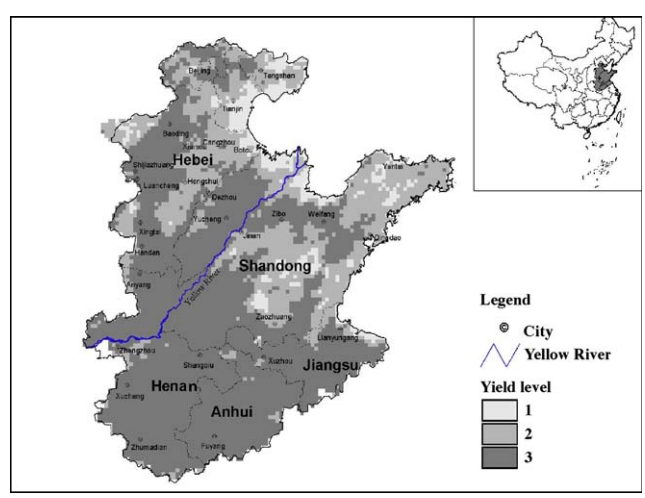

Fig. 2. Geographical and land quality map of the NCP (dotted line is the provincial boundary. Yield levels 1–3 refer heavy alkalized, medium alkalized soil, and all other soil types, respectively).

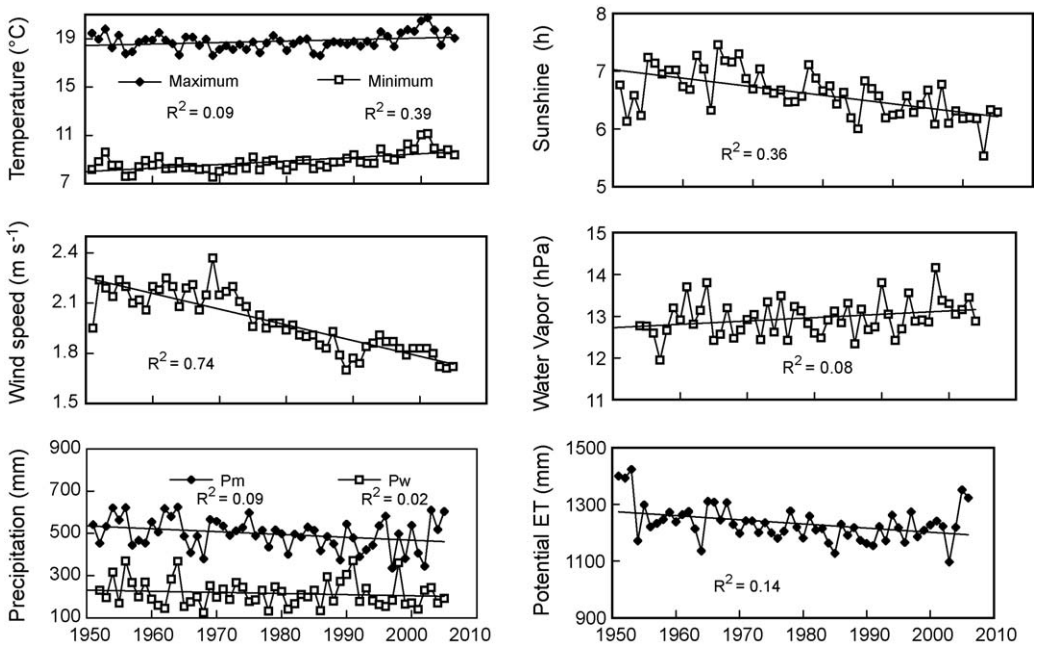

Fig. 3. Annual variation of the climatic variables over the NCP during 1951–2006 (potential evapotranspiration is calculated by Penman–Monteith formula. *P*w and *P*m are precipitation during the growth season for wheat and maize).

(NOAA-AVHARR) in our previous work to get the vegetation information.

The land use/cover digital data are derived from Landsat Thematic Mapper (TM) images for identifying arable land. In our simulation, only winter wheat and summer maize are considered. The topographical elevation above sea level is derived from elevation contour at a scale of 1:250,000, most of which is below 300 m.

In addition to land use and digital elevation data, classified saline-alkaline land maps and maps of soil physical texture are also used as the geographical background. The study area is divided into three kinds of land according to the yield levels (Fig. 2), which are based on land quality in the NCP. The land quality classification is digitized via ARCINFO based on "Map of Soil Types Related to Low Crop Yield in Huang-Huai-Hai Plain" at the scale of 1:1,000,000 printed in 1984 by the Institute of Soil Science, Chinese Academy of Sciences. Here Huang-Huai-Hai Plain is another name of the NCP, although their covering areas have a little bit difference. On the map, the soil is divided into three types: alkali-saline soil, sandy soil and sajong black soil. For the alkali-saline soil, it is again divided into light, medium and heavy alkali-saline soil. The classification, which is not in quantity but in quality, is based on the information virtually retrieved from the resources satellite images in the spring season from 1978 to 1981 of the plain, with further reference from the tape data information of the satellite images for other seasons at some typical sites and the professional information including sub-regional soil type map in the NCP. After digitizing the land quality information, three yield levels are defined. Yield level 1 refers to heavy alkali-saline soil, level 2 refers to medium alkali-saline soil, and level 3 refers to all other soil types. The fractions of the area with yield levels 1–3 to the whole study area are 6.7%, 28.6% and 64.7%, respectively. Soil texture data are digitized from a 1:14,000,000 scale map (Institute of Soil Science, 1986).

2.3.2. Climate data

Climatic data at 101 observatory stations are collected in and around the study domain. Daily atmospheric pressure, air temperatures (maximum, minimum and mean), water vapor pressure, wind speed, precipitation and sunshine duration are used to drive the model. Along with global warming, the climate over the NCP is changing (Fig. 3). However, the changing trends for each of the atmospheric variables are different. Annually both maximum and minimum air temperatures increase remarkably over the NCP from 1950s to 2000s with a rapid increase in 1990s. The mean anomalies in 1997–2006 are 0.9 and 1.2 °C for the maximum and minimum temperatures, respectively, and the increments in winter are slightly higher than summer (not shown). The mean daily sunshine duration and wind speed are in declining tendency. The decrease of sunshine is possibly related with more cloudy days and heavy aerosol conditions. The anomalies of sunshine duration and wind speed are about −0.4 h and −0.2 m s^{-1}, respectively in the latest 10 years. It is also worthily noted that there are not significant trends in both annual precipitation and water vapor pressure, but the potential evaporation is declining during this period, which is mainly resulted from the attenuated global radiation and air movement.

The climate change projections from the runs of the GCM HadCM3, archived by the British Atmospheric Data Center (http://badc.nerc.ac.uk/home/index.html), for A2 and B1 scenarios developed for the Third Assessment Report (Nakicenovic and Swart, 2000) of IPCC SRES are used to simulate the responses of crop yield, ET and WUE to climate changes in the 21st century for the NCP. The A2 scenario describes a very heterogeneous world of high population growth, slow economic development and strong regional cultural identities. B1 is a rather optimistic scenario assuming "convergent world" and putting an emphasis on global solutions to economic, social and environmental sustainability. The B1 scenario also assumes high economic growth but with substantial shift to nuclear energy. The data for A2 scenario include monthly values of maximum, minimum and mean temperatures, precipitation, relative humidity, wind speed and short wave radiation. So do the data for B1 scenario but maximum and minimum temperatures are missing. According to the projections, for example, in 2090s, atmospheric CO_2 concentration, precipitation and daily mean air temperature will respectively increase 280 ppm, 16% and 2.8 °C for B1 and 470 ppm, 48% and 4.5 °C for A2.

Table 1
Phenological parameter values for crops (C_0, C_1 and C_2 are the degree–day values from sowing to seeding, seeding to flowering and flowering day to maturity, respectively).

	Winter wheat			Summer maize		
	C_0	C_1	C_2	C_0	C_1	C_2
Degree–day	110	950	1100	100	1300	1200

Table 2
The value of photosynthetic capacities V_{cmax} (μmol C m^{-2} s^{-1}) for the three yield-level-lands over the North China Plain of the current cultivars.

	Winter wheat			Summer maize		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
V_{cmax}	90	60	30	40	30	20

2.3.3. Agricultural data

The statistic data of grain yields of wheat and maize and fertilizer at county scale are collected from China Agricultural Yearbook and provincial agricultural annals. The grain yields are used to validate the simulation at regional scale. Planted areas are also collected from the annals to trace the variation of crop yield.

Based on the knowledge of planting system from the local areas, for winter wheat, it is sown when the daily temperature keeps lower than 18 °C for 3 days continuously. For maize, it is sown 3 days after the harvesting of winter wheat. Phenological parameters for crops such as the degree–day values from sowing to seeding, seeding to flowering and flowering day to maturity are shown in Table 1.

As the pattern of irrigated fields is not available, it is thus assumed that there is not at all irrigation on yield level 1 land. On yield levels 2 and 3 lands, irrigation is applied to the fields when soil moisture in root zone is depleted to 70% of its field capacity.

2.4. Numerical modeling

The model is run with 8 km grid and 30 min time step and the meteorological variables are interpolated to each grid with the inverse square distance method. The history (1951–2006) and future (2010–2099) under A2 and B1 scenarios are analyzed.

There are 20 grids in the GCM output over the NCP with the spatial resolution of 3.75° longitude × 2.5° latitude. A simple downscaling method is used for crop yield response scenario analysis to climate change by the VIP model. Climatic data series of 1990s is treated as the baseline. The atmospheric driving forces every decade in the future for the scenario analysis are the baseline added with the decadal average of annual relative change of precipitation and the absolute changes of temperature of A2 and B1 within that decade. In detail, the projected annual temperatures and precipitations are averaged over every decade from 1990s to 2090s, and then the increments between 1990s and 21st century decades are calculated, in which the precipitation changes are expressed as relative changes over the GCM grids. At a climatic station, the daily series of air temperature from 1990 to 1999 are added with the annual increment in the GCM grid where the station is located. Due to the possible large values of the increments, the daily series of precipitation is multiplied with its relative change.

The relative difference, RD, of a variable (yield, or ET, or WUE) is defined for the response analysis as:

$$\mathrm{RD} = \frac{Y_{21\mathrm{stdec}} - Y_{1990\mathrm{s}}}{Y_{1990\mathrm{s}}} \tag{4}$$

where $Y_{21\mathrm{stdec}}$ and $Y_{1990\mathrm{s}}$ represent the variables corresponding to the relative decade in the 21st century and 1990s, respectively. WUE is defined as grain yield in dry matter divided by evapotranspiration.

One of the most important parameters in the model is the crop potential carbohydrate rate, denoted as V_{cmax}, representing the leaf maximum photosynthesis capacity. The values of V_{cmax} for individual yield levels are defined based on the data at the counties of Botou, Xianxian and Luancheng corresponding to yield levels 1–3, all located in the Hebei province. The observed biomass data at the Luancheng Agro-ecological Station are used to calibrate V_{cmax} value representing yield level 3. The V_{cmax} values for other yield levels are adjusted according to the yield levels and the recent years' statistic grain yields at the corresponding counties, with a reference to its value at yield level 3. The calibrated V_{cmax} values are listed in Table 2.

From the historical records in the past 56 years, the agricultural conditions in the NCP have been improved considerably. For example, much more irrigation facilities and chemical fertilizers are available, and a large number of drainage tunnels are built to ameliorate the saline-alkaline soils. At the same time, new crop cultivars with specific agronomical, morphological and physiological traits are bred and planted extensively, which may increase the crop potential yield regionally (Wang et al., 2001; Liu et al., 2003). Essentially, all of these agricultural management factors should be considered during the crop yield modeling, as they will contribute to crop production. Unfortunately, spatial pattern data of agricultural management are not available, so we have to use a simple way to make the consideration of this in the simulations.

It is assumed that the enhancement of production is mainly due to the increment of the crop photosynthetic capacity stimulated by fertilizer input, irrigation and new varieties. Hence, in order to better simulate the historical production trajectory, a correction factor of V_{cmax} is introduced to account for the influences of fertilizer input, genetic characteristics, and irrigation guarantee on leaf photosynthetic capacity. At present only the data record of fertilizer application is available to quantify the correction factor. As the records shown, the statistic yield in the NCP has increased three to five times since 1950s to 1990s, with a rapid increment occurred in 1970s to mid of 1990s. It approaches a plateau since late 1990s. This trend coincides with the time series of chemical fertilizers applied in the plain (Fig. 4). It is obvious that since late 1960s intensified input of chemical fertilizers has been the dominant driving of crop yield enhancement in this region. However, as the yield gap between the potential and field production due to soil nutrition stress is much more mitigated

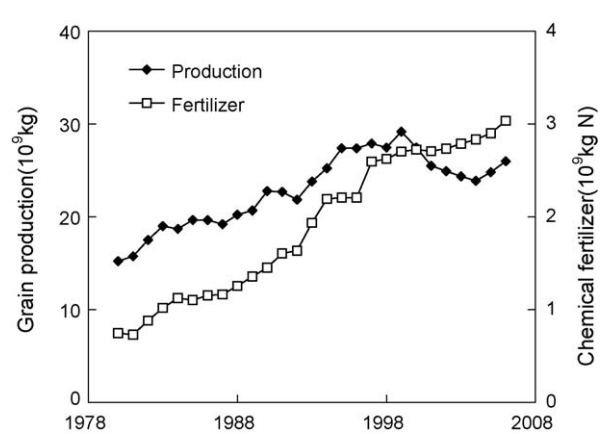

Fig. 4. Annual statistic grain yield and fertilizer application in Hebei Province part of the NCP from 1978 to 2006.

in the current stage than the early decades, further more fertilizer input will be less efficient. Historical dataset of crop yields and chemical fertilizers in the NCP also shows that yield enhancements are tightly related with fertilizer input when there is obvious gap between potential and actual yields (Xu et al., 2005; Zhang et al., 2005). Based on this trend-match between crop yield and fertilizer application, a correction factor is introduced and set as 0.25 before 1969, and then increases linearly to 1 from 1969 to 1997. It was kept as 1 after 1997 as the utilities of chemical fertilizers have been constrained since the late of 1990s to avoid of the possible adverse effect of over-application of chemical fertilizers on the water environment in this region.

3. Results

3.1. Model validation

Fig. 5 presents the comparison between the simulated and the statistic yield data of Hebei Province, which covers more than 100 counties with all the three yield-level-lands included. The predicted grain production values of wheat and maize are in reasonable agreement with the statistical values with the relative errors of 18% and 17%, respectively. Generally, differences between the simulated and the statistic grain yield may result from both the model prediction and the statistical data. Since the statistic yield data are obtained by multiplying the yields in reference fields with their planted sizes in every county, this kind of data could contain errors from both measurements and artificial interferences (Mo et al., 2005). In addition to model structure and parameter uncertainties, pest and weather disasters may also significantly reduce the crop yields at the final stage, which has not been taken into account in the simulations yet.

3.2. Spatial patterns of simulated yield, ET and WUE

With the agreement between the simulated and observed yield in the Hebei province, it is able to get the spatial pattern of yield over the whole plain via the simulation. Fig. 6a and b present the spatial patterns of simulated grain yield of wheat and maize with 10 years average (1997–2006) over the NCP. The patterns are corresponding to land quality classification as expected. As soil and groundwater are heavily salinized, no favorable water for irrigation purpose is available in the eastern coast zone (yield level 1 land) aside of the Bohai Sea. The yield amounts of this area are quite low, about 2396 ± 327 and 3855 ± 290 kg ha^{-1} for wheat and maize, respectively. In the areas of yield level 2, such as those around Hengshui and Jinan cities, the fields are secondary salinized due to shallow groundwater level and flooding irrigation in the last several decades, the yield amounts are about 4816 ± 261 and 5413 ± 149 kg ha^{-1} for wheat and maize, respectively. In the western part of the plain (yield level 3), since the fields are free from soil salinity and irrigation facilities are available, the yield amounts of wheat and maize are about 5770 ± 419 and 5797 ± 247 kg ha^{-1}, respectively. The simulated variation of yield among grids within the same yield level is resulted from local climate and soil texture variability. The simulated crop yield is relatively homogeneous within each yield-level-land, implicating that the soil quality is the dominant factor of yield variability at regional scale, and much more significant than climatic factors. As it is assumed no irrigation on land of yield level 1 but being irrigated on yield levels 2 and 3, irrigation status is also a significant factor to dominate the spatial pattern of crop yield. As for the climate variability, it is the major stimulus of inter-annual yield variations via regulating the crop phenological processes and photosynthetic environments, which will be shown in the following section.

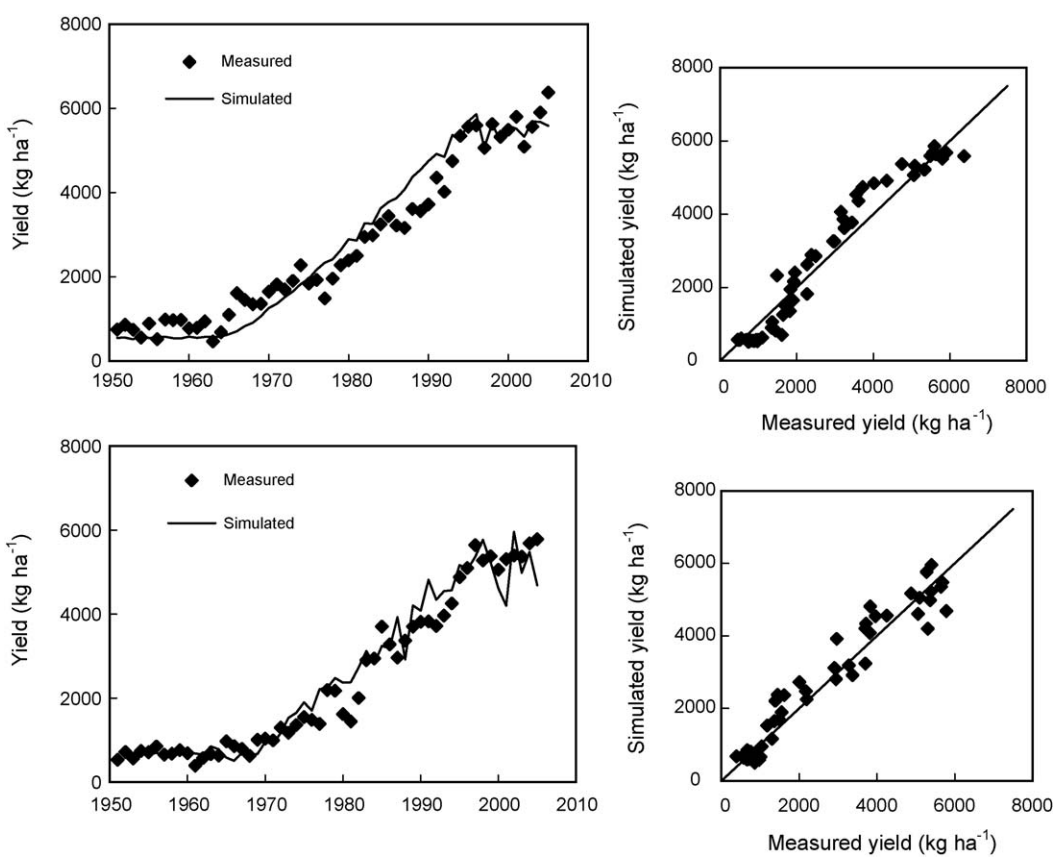

Fig. 5. Comparison of averaged statistic and simulated yield over the Hebei province part of the NCP for wheat (upper panel) and maize (lower panel).

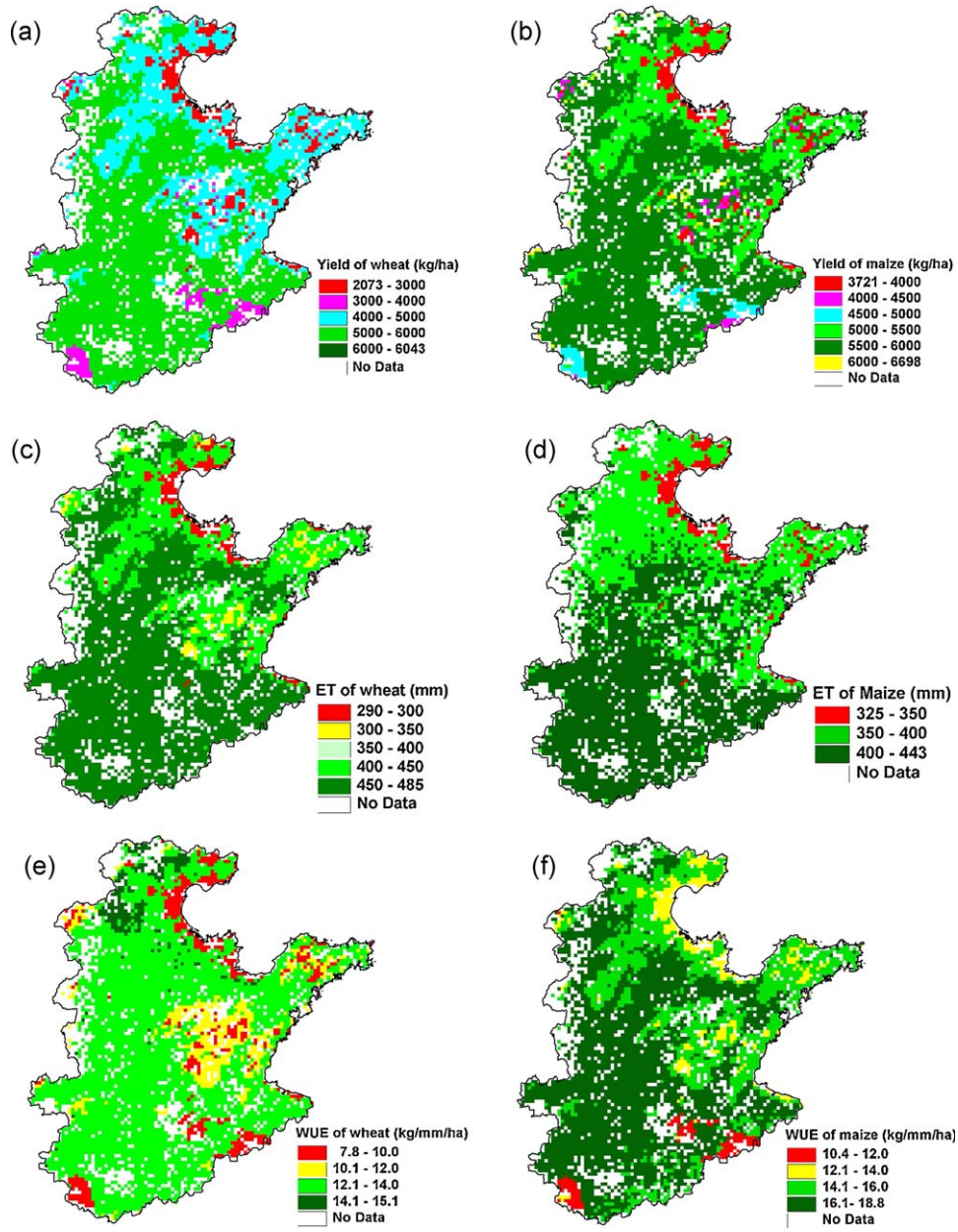

Fig. 6. Spatial patterns of yield, evapotranspiration (ET), water use efficiency (WUE) for wheat and maize averaged over 1997–2006 in the NCP.

Fig. 6c and d present the spatial patterns of total ET in wheat and maize growing periods respectively. It is seen that the cumulative ET amounts for wheat and maize in the growth season have clear decreasing trends from southern to northern areas. The total ET amounts of wheat and maize on yield level 3 land are quite different, being 472 ± 6 and 403 ± 7 mm, respectively, which are comparable with the data measured by the large scale lysimeters in Luancheng (37°53′N, 115°41′E) (Hebei Province) and Yucheng (36°57′N, 116°38′E) (Shandong Province) agro-ecosystem experimental stations located in the central part of NCP (Liu et al., 2002; Yang et al., 2000). ET amounts on the lands of yield levels 1 and 2 are respectively 302 ± 2 and 445 ± 5 mm for wheat and 346 ± 7 and 395 ± 5 mm for maize.

Fig. 6e and f present the WUE of wheat and maize in the plain. It is seen that the spatial pattern of wheat WUE, ranging from 7.8 to 15.1 kg mm^{-1} ha^{-1}, is apparently corresponding to that of the yield levels. WUE values for maize are a bit lower, ranging from 10.4 to 18.8 kg mm^{-1} ha^{-1}. Averagely, WUE on the land of yield level 3 is higher than that on the land of yield levels 2 and 1 for both wheat and maize. Compared with other well-managed regions in the world (Mo et al., 2005), WUE in the NCP is still low.

3.3. Temporal variations of simulated crop yield, ET and WUE from 1951 to 2006

Over the region, the evolutions of simulated yield, ET and WUE over the NCP have experienced three stages in the study period, namely the low level stage in 1950s, the rapid improving stage afterwards, and the relative high level stage since 1990s. However the slopes of individual variables are quite different (Fig. 7).

The grain yields of wheat and maize show similar trend, but maize yield is a bit higher than wheat on average. Correspondingly, before 1965, the yield amounts are about 800 kg ha^{-1} for wheat and 600 kg ha^{-1} for maize. They then reach 6000 kg ha^{-1} for wheat and 6300 kg ha^{-1} for maize in 1990s (Fig. 7a), about eight times of those before 1965.

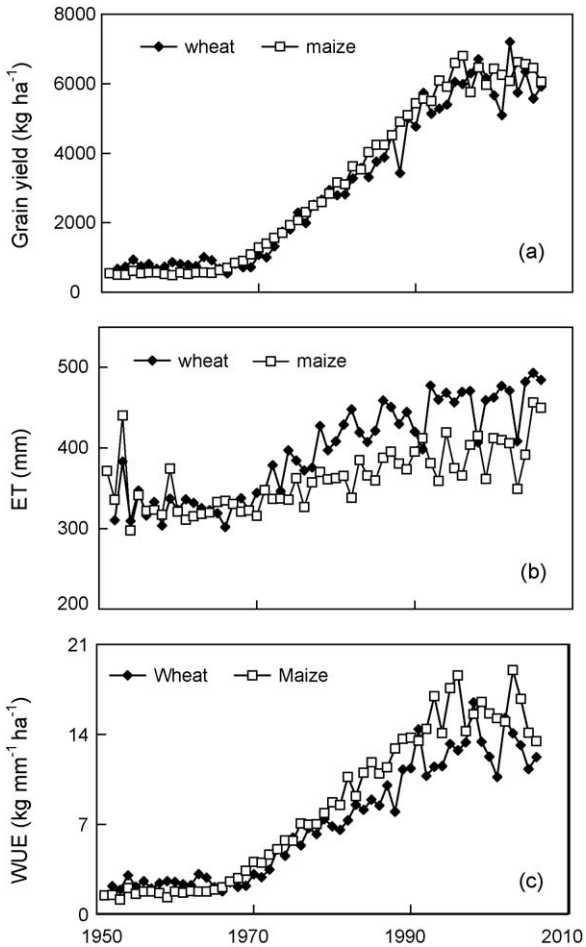

Fig. 7. Trends of yields, ET over the growing period and water use efficiency (WUE) for wheat and maize in the NCP from 1951 to 2006.

Since more production usually consumes more water, there are clear increments of ET in both wheat and maize growing seasons when their productions have rapidly increased from 1960s to 1990s (Fig. 7b). The increments of ET are about 130 mm for wheat and 90 mm for maize.

As the relative change of ET is much less than that of grain yield, the WUE is thus greatly improved from 2 to 14 kg mm^{-1} ha^{-1} for wheat and from 2 to 17 kg mm^{-1} ha^{-1} for maize (Fig. 7c). The field experiments at Luancheng Station reported that grain yield amounts have increased 50% with some enhancement of ET from 1982 to 2002, resulting in a significant improvement of WUE being 15 kg mm^{-1} ha^{-1} (wheat) and 20 kg mm^{-1} ha^{-1} (maize) (Zhang et al., 2005).

Keeping in mind that in the simulation V_{cmax} is set increasing, the above results show that the improvement of the cultivar's photosynthetic capacity not only improves yield, but also raises WUE.

3.4. The responses of crop yield and ET to climate variability

As crop yield is simulated with a gradually varied V_{cmax}, the simulated crop yield from 1951 to 2006 shows not only the effect of climate variability but also the effect of agricultural management, such as fertilizer input and others.

To assess the response of crop yield and ET only to climate variability (the change of precipitation, temperature) and CO_2 enrichment, the model is run from 1951 to 2006 with a fixed photosynthetic capacity rates corresponding to the prevailing cultivars.

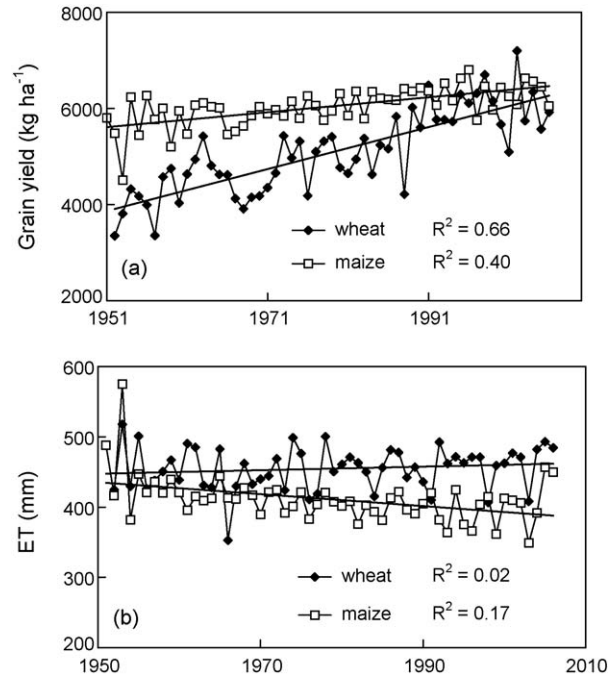

Fig. 8. Simulated yields, ET over the growing period with a fixed photosynthesis capacity rate for wheat and maize in the NCP.

The results show that there are still significant increases of net primary production (NPP) and grain yield of winter wheat, whereas production increments of summer maize are relatively stable (Fig. 8a), implicating that the climate over the past 56 years in the NCP turns to be favorable to crops. The coefficient of variation (CV), which is the ratio of standard deviation to the mean, of grain yield attributed to annual climate variability is 13.7% for winter wheat and 5.0% for summer maize, respectively. Hence, it can be deduced that winter wheat production is more sensitive to climatic variability than summer maize.

There is not evident intensification of ET in wheat growth period from 1951 to 2006 (Fig. 8b), whereas the ET of maize is obviously declined with a reduction about 30 mm from 1950s to 2000s. This can be interpreted in that wheat as a C3 crop is sensitive to the CO_2 fertilizing effects on leaf stomatal conductance, which may compensate for the warming effects on ET, whereas maize as a C4 crop is not so sensitive to CO_2 fertilizing effects. The CV of ET is 6.9% with mean annual ET of 464 mm for wheat, and 5.9% with of 425 mm for maize in this period.

3.5. The response of crop yield, ET and WUE under SRES A2 and B1 scenarios

By fixing V_{cmax} to the value for the current cultivars, the crop yield, ET and WUE under SRES A2 and B1 scenarios are predicted. Compared with the yield of 1990s, it is found that the predicted yield of winter wheat is enhanced under both A2 and B1 scenarios. However, mostly the increment is higher than B1 (Fig. 9a). The maximum increment is 19% under A2 occurring in 2070s and 13% under B1 in 2060s, the former is noticeably larger than the later. The results show that as winter wheat is a C3 crop, it will benefit more from CO_2 enrichment. However, the grain enhancement is also affected by both precipitation and temperature patterns, which make the increments fluctuate in different decades.

Different from the variation of yield, cumulative ET in the growing stage of winter wheat seems to be affected only slightly by climate change, as shown in Fig. 9c. The cumulative ET amounts gently increase for both A2 and B1 scenarios, which is less than 6%.

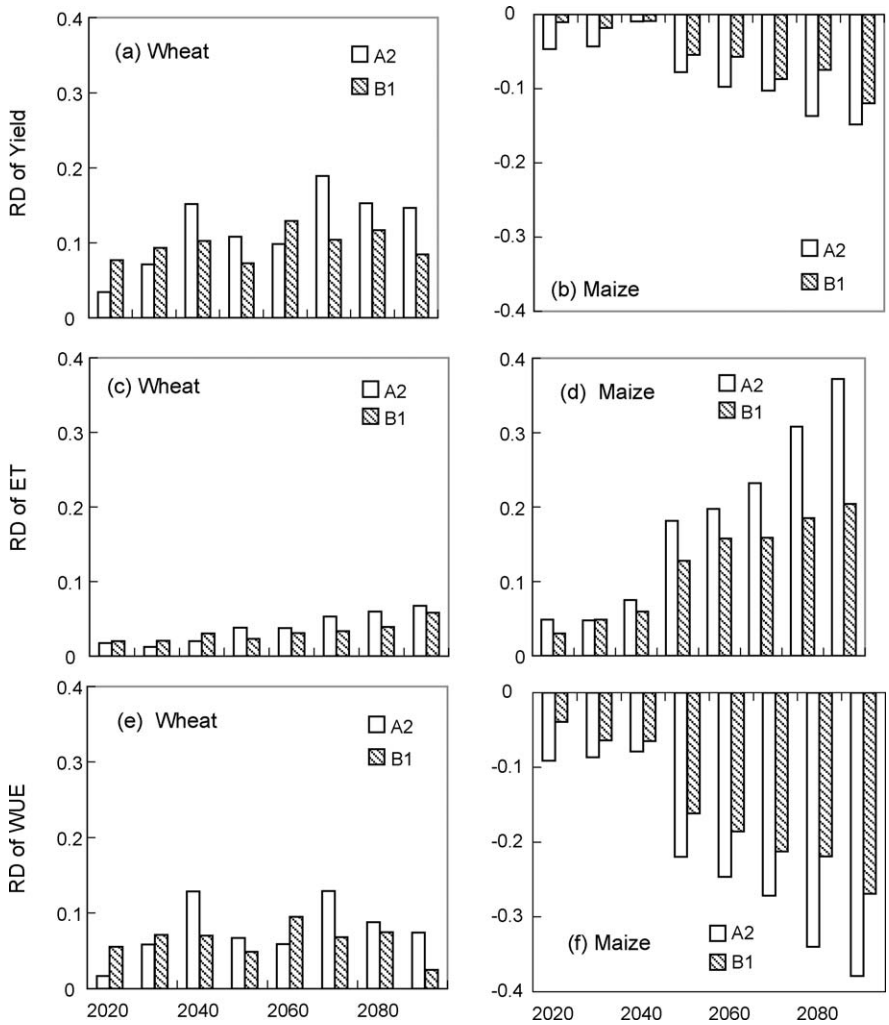

Fig. 9. Responses, noted as RD defined in the text, of yield, ET over the growing season and WUE to A2 and B1 scenarios from 2020s to 2090s for wheat and maize in the NCP.

As it is known, the air warming will intensify evapotranspiration, whereas both lower stomatal conductance resulted from higher CO_2 concentration and growing period shortened by warming will mitigate the rising of total ET amount. As a consequence, the change of ET is not remarkable.

For summer maize, the yield is reduced gradually with air warming under both A2 and B1 scenarios (Fig. 9b) from 2020s to 2090s. In 2090s, yield will fall by 15% for A2 and 12% for B1 scenario respectively. The effect of CO_2 enrichment on C4 maize is weak, which is predicted nearly 10% by the model with double air CO_2 concentration under current climate condition. The thermal warming effect on grain yield is significantly larger than that of CO_2 fertilization in maize, leading to a net reduction of grain yield under both scenarios. By sensitivity analysis, it is found that the yield reduction is mainly caused by shortened growing period and higher maintenance respiration.

Different from the ET in winter wheat, cumulative ET in maize growing period (Fig. 9d) is significantly increased over 10% since 2050s. At the end of 21st century, the cumulative ET amounts under A2 and B1 scenarios will respectively be 37% and 20% higher than the current values over the maize growing period.

Because the percentage of wheat yield enhancement is larger than that of ET decrease, the WUE is slightly improved by 10% and 7% under A2 and B1 scenarios, respectively (Fig. 9e). The WUE values for maize (Fig. 9f) are reduced more than 25% under both A2 and B1 scenarios in 2090s, resulted from decreased yield and noticeably increased ET. The negative response of maize to climate change implies that new maize cultivars should be bred with higher heat tolerance and larger growing degree–days to mitigate the warming effects.

There are at least three reasons to be able to explain why maize yield will decrease under climate change condition (Fig. 9) even though rainfall will increase 16–48% and CO_2 increase from 280 and 450 ppm across the two emission scenarios considered in 2090.

Firstly, for summer maize as a C4 crop, because of its inner structure, it is mostly sensitive to temperature about 2.8–4.5 °C. Therefore, summer maize gets yield loss with the increase of temperature. The effect of CO_2 enrichment on C4 maize is small and weak. The thermal warming effect on grain yield is significantly larger than that of CO_2 fertilization in maize, leading to net reduction of grain yield under both scenarios.

Secondly, the growth season of summer maize is matched with the wet season in the area. Precipitation in the normal year can almost satisfy the water demand of maize. Therefore even though there is an expected increase of precipitation, the maize yield responds a little.

Thirdly, the variation of variables like temperature, precipitation, CO_2 concentration as shown in the study is not a gradual change. It is possible that our conclusion is just true only for the amount of the change we assigned. More study should focus on the continuous response with the driving variables changing gradually.

For winter wheat, as it is a C3 crop, it is very sensitive to the CO_2 concentration. Besides, even in normal years, precipitation cannot satisfy winter wheat's water needs. The increase of precipitation will help the yield production. In this way, under the climate change scenarios of A2 and B1, wheat gets yield gain.

4. Discussions

4.1. Uncertainty of the modeling

Using a process-based model to assess climate change impact on crop production and explore its related mechanism is an effective way to provide some useful decision-making suggestions for food safety in the future. However, as agro-ecosystem is greatly affected by anthropogenic activities, environmental and biological factors, crop production prediction based on process-based models at regional scale and its response to climate change are still under exploration (Ines et al., 2002; Liu, 2009).

Firstly, due to the uncertainty of future climate change scenario, it is quite uncertain for crop production response prediction. The neglect of crop acclimation may also overestimate the climatic change effect. The variation of precipitation, a key variable of climate change, in frequency and intensity will exert strong influence on rain-fed conditions where water limitation is the critical factor for crop production. Relative to rain-fed crops, irrigated crops are less affected by climate change (Liu et al., in press). Being lack of detail irrigation/rain-fed pattern in the NCP, it may bring uncertainties.

Also, without considering changes in solar radiation and humidity may prevent from thorough appreciation of the future projections, although their changes are small. It was proposed that the increase in diffuse radiation caused by the injected stratospheric sulfate aerosols could have enhanced terrestrial photosynthesis (Roderick et al., 2001; Gu et al., 2003; Steiner and Chameides, 2005; Knohl and Baldocchi, 2008). Plant canopies may use diffuse radiation more efficiently than they use direct beam radiation in photosynthesis. The observations show that from a variety of plant canopies diffuse radiation leads to radiation use efficiencies (RUE) two or more times higher than direct beam radiation. In practice, greater canopy photosynthesis can be produced under a moderately turbid sky, even though global solar radiation is reduced compared with clear sky conditions, because of the shift in RUE (Gu et al., 2003). So far a lot of such studies are carried out for forest, whereas there are only a few cases for crops (Greenwald et al., 2006).

The relationship between diffuse radiation and photosynthesis is complex. Using a 6-year data set from temperate mountain grassland in Austria, Wohlfahrt et al. (2008) showed that differences between ecosystems may be reconciled based on their green area index (GAI)—the sensitivity to diffuse radiation increasing with GAI. Canopy-level measurements of photosynthesis under diffuse light show increased productivity attributed to more uniform distribution of light within a forest canopy. Brodersen et al. (2008) show that leaf-level and canopy-level photosynthetic processes react differently to the directionality of light, and increases in canopy-level photosynthesis occur even though leaf-level photosynthesis decreases under diffuse light. It is important to study regional haze in China on climate and crop production. Although there are some ground-based broadband and spectral radiation data (Xia et al., 2007), sufficient observed data have not been available to further explore the relationship in China.

Secondly, uncertainty in model structure and parameters will also contribute to model prediction bias. The productivities of crops are affected by spatial and temporal interlinking environmental factors [availability of water (precipitation and soil water holding capacity), temperature, disease and weed stress], new cultivars and agronomical managements. Documents show that genetic gain in yield is 64.63 kg ha^{-1} $year^{-1}$ or 1.20% per year for typical winter wheat cultivars planted prevailingly in the NCP during the past 30 years (Zhou et al., 2007). Being lack of such factors in the prediction it may under- or over-estimate the crop responses to climate change.

Even though the VIP model fully considers the geo-physical processes for the crop simulation, it is still hard to catch all the influential factor of crop yield. In the version of the VIP model this study used, pest hazard is neglected and extreme climatic effect is not considered, which is possible to reduce the reliability of the model estimation in some years. The fully process-based modeling and conceptual simplification as the correction factor of V_{cmax} introduced to consider the fertilizer effects may be an efficient way to treat such complexity of crop modeling.

Thirdly, as a fixed fraction of irrigation grids has to be set in the simulation, this will inevitably introduce uncertainty. Besides, food production can be affected by irrigation availability under climate change. The study assumes that the irrigation is supplied when the soil moisture in root zone is depleted to 70% of its field capacity. Therefore the predictions of yield, ET and WUE are a kind of optimal results. Actually water resources in the NCP are not sufficient to agriculture demand after the water is assigned to domestic user, ecological system and such high water demanding industries as printing, iron and steel, petrochemical, metallurgy, electrical power, pulp and paper industry. The documents (e.g., Lin et al., 2000) show that the rate of water deficit in the NCP is 18%, reaching 36% during the key growth stage (heading, anthesis and milking) for wheat in the normal years.

Fourthly, the limitation of knowledge to judge the positive and negative effect of climate change to crop yield may introduce uncertainty. It is still insufficient on the understanding of yield formation and adaptation to climate change. Raising temperature extends the growing season in temperate regions, but it also accelerates the crop development and shortens the crop life expectation. In addition, the hotter summer may reduce the milking time and then the photosynthetic matter accumulation. On the other hand, the warming alone will reduce the crop production due to less captured radiation and higher maintenance respiration cost. Low temperature, drought, as well as hot and dry wind are the main factors reducing yield in wheat, whereas both drought and lasting cloudiness conditions are unfavorable to summer maize yield forming. Agro-meteorological records show that the growing periods of winter wheat and maize have been shortened significantly from 1981 to 2005 over the North China (Tao et al., 2006; Xiao et al., 2008). Our simulation results also show that the growing days of winter wheat and summer maize will decline as much as 20–30 days at the end of 21st century, with the specific genetic characteristics of current cultivars, which will be very unfavorable to grain yield formation in the plain. However, the CO_2 fertilization effects on C3 crops usually compensate for the assimilation reduction due to temperature rising. Field experiments show that acclimation to elevated CO_2 concentration will reduce the carboxylation efficiency and the activities of enzymes when prolonged exposure to higher CO_2 concentration (Kim et al., 2007). As a result, the C3 crop yields enhancement will be mitigated under temperature warming and CO_2 enriching condition. So far it is not yet obvious how crops will respond to increase in both CO_2 concentration and temperature. However the chamber results (Reddy et al., 1995; Hamilton et al., 2008; Bannayan et al., 2009) are very helpful to explore the mechanism about the interactive impact of elevated CO_2 concentration and warming climate on plants including crops.

Fifthly, data limitation may also bring uncertainty. At regional scale, there are quite different soil chemical properties. For example, soil salinization is happened over many fields in the

northeast part of the NCP. It is known that the cumulative salt in root zone deteriorate soil condition and considerably reduces crop production. Ideally, a high resolution map of soil quality and quantitative description of the relationship between saline concentration and crop growth will greatly benefit the accurate description of crop production patterns over the plain.

4.2. Implication of the results

With the distributed simulation by the VIP model we get the whole picture of yield, ET and WUE in the NCP. The picture shows the spatial patterns of crop yields at a relatively high resolution, which can provide a more comprehensive view for decision makers than the raw yield data county by county do. Besides very often collection of the yield data at county and sub-county scales year by year is a hard work. In addition, there are no observed data for ET and WUE in the plain, the simulated spatial pattern of yield, ET, and WUE makes it possible for the crop systems to be better integrated and managed.

The results are meaningful for China's capacity to produce sufficient food in the 21st century. One of the most prominent meanings of our results is to show that yield response is in multiple-folds, an isolated deduction from single aspect is not sufficient. For example, it is found from Figs. 7 and 8, no matter if the agricultural factors, such as fertilizer, are considered, over the past 56 years, the regional yield level of maize is higher than that of wheat and the water consumption of maize is lower. From Fig. 7, it is seen that for the period from 1950s to 1960s, the yields for both wheat and maize are quite low. However, with higher agricultural management levels indexed with higher V_{cmax}, the response of maize yield is larger than the response of wheat yield (Figs. 7 and 8), implicating that maize is more efficient to agricultural management. From this point it seems that maize is a more efficient crop in the NCP than wheat at present. However, considering the negative response of maize yield and higher increase of ET to climate change than the increase of ET for wheat, it can be figured out that wheat will be more efficient in the future (Liu et al., in press). Further more it also needs to be bearing in mind that wheat itself relies on irrigation much more than maize does. In the NCP, in wheat growing period (spring), the multi-year averaged precipitation is only about 200 mm (Fig. 3), water deficit being near 200 mm. The multi-year averaged precipitation in maize growing period is about 500 mm, thus, except drought year, precipitation usually meets the water demand of maize and high production may be acquired without irrigation.

Therefore the multiple-fold adaptation countermeasures are needed. Among them increasing WUE is the main factor in the climate change adaptation. WUE can be raised potentially through ameliorating the poor soil quality and adopting water techniques in the NCP. Specifically, in water shortage areas, carefully managed deficit irrigation techniques should be considered to be the most effective way for conserving water resources (Anapalli et al., 2008). For the purposes of production improvement and environmental protection, the present prevailing gravity irrigation way that is not efficient on water use should be replaced by other more efficient techniques. The outbreak of pest and/or heat waves, etc., may considerably raise the risk of final grain yield disruption. Furthermore, in order to adapt to climate warming, new cultivars should be bred to endure higher temperature and to fix carbon more efficient, which may alleviate the unfavorable impact of climate change and keep the agro-ecosystem sustainable.

5. Conclusions

The VIP model is used to explore the response of regional crop yield, water consumption and water use efficiency to climate change over the NCP. The yield predictions of winter wheat and summer maize over the NCP are validated with statistic yields, illustrating the model's ability to simulate the grain yields reasonably well.

This study shows that the crop production has increased rapidly in the past 56 years over the NCP. Accompanying production improvement, crop ET has also risen and WUE has been improved significantly. There exist spatial patterns of crop yield stemmed mainly from soil quality and irrigation facilities. Under IPCC SRES A2 and B1 scenarios, production of winter wheat will increase with slightly intensified ET, resulting in improved WUE; By contrast, summer maize production will slightly decline with significant increase of ET, resulting in noticeable decline of WUE.

The simulated spatial pattern of crop yield, ET and WUE in relative high resolution gives a whole picture of the crop production in the plain. The simulation results show that maize is more efficient to agricultural management than wheat, in that wheat relies more on irrigation than maize does, yield level of maize is higher than that of wheat, the water consumption of maize is lower, and the response of maize yield is larger than that of wheat yield to agricultural management. However, the simulation also suggests that wheat is more resilient to climate change than maize. Thus to say if wheat or maize is more favorable in the plain depends on the conditions in the future. Nonetheless our results provide scientific basis and references for governments' decision-making from the view of regional climate change response.

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