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Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain

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Abstract This paper explores changes in climatic variables, including solar radiation, rainfall, fraction of diffuse radiation (FDR) and temperature, during wheat season (October to May) and maize season (June to September) from 1961 to 2003 at four sites in the North China Plain (NCP), and evaluates the effects of these changes on crop growth processes, productivity and water demand by using the Agricultural Production Systems Simulator. A significant decline in radiation and rainfall was detected during the 43 years, while both temperature and FDR exhibit an increasing trend in both wheat and maize seasons. The average trend of each climatic variable for each crop season from the four sites is that radiation decreased by 13.2 and 6.2 MJ m^{-2} a^{-1}, precipitation decreased by 0.1 and 1.8 mm a^{-1}, minimum temperature increased by 0.05 and 0.02°C a^{-1}, maximum temperature increased by 0.03 and 0.01°C a^{-1}, FDR increased by 0.21 and 0.38% a^{-1} during wheat and maize season, respectively. Simulated crop water demand and potential yield was significantly decreased because of the declining trend in solar radiation. On average, crop water demand was decreased by 2.3 mm a^{-1} for wheat and 1.8 mm a^{-1} for maize if changes in crop variety were not considered. Simulated potential crop yields under fully irrigated condition declined about 45.3 kg ha^{-1} a^{-1} for wheat and 51.4 kg ha^{-1} a^{-1} for maize at the northern sites, Beijing and Tianjin. They had no significant changes in the southern sites, Jinan and Zhengzhou. Irrigation, fertilization development and crop variety improvement are main factors to

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contribute to the increase in actual crop yield for the wheat–maize double cropping system, contrasted to the decline in the potential crop yield. Further research on how the improvement in crop varieties and management practices can counteract the impact of climatic change may provide insight into the future sustainability of wheat–maize double crop rotations in the NCP.

1 Introduction

The North China Plain (NCP) is one of the largest agricultural production areas in China. It covers a total area of 320,000 km^2, of which 180,000 km^2 is used for agricultural production (Fig. 1). In the last four decades, notable changes in climate have been observed. A significant decrease in global solar radiation was found since 1961 due to increased aerosol in the atmosphere as a result of increased industrial activities (Che et al. 2005; Shi et al. 2008), which has led to an increase in the fraction of diffuse radiation (FDR) (Che et al. 2005, 2007). Air temperature has been rising, especially since the 1980s (Shen and Varis 2001; Tao et al. 2003; Ren et al. 2008), while annual precipitation showed a decreasing trend in the NCP (Varis and Vakkilainen 2001; Qian and Lin 2005; Liu et al. 2005). A detailed understanding of how such changes in climate has impacted on the processes governing crop production and water use, and how agricultural management has evolved in the changing climate can provide useful insights for the development of sustainable agricultural systems in the face of future climate change.

Several studies have investigated the impact of past climate change on crop growth and water demand in China including the NCP. A study on potential evapotranspiration (PET) over China from 1954 to 1993 based on the Penman–Monteith equation showed a decreasing trend in PET in most parts of China, with a decreasing trend in the NCP (Thomas 2000a). A combined analysis of the influences of precipitation

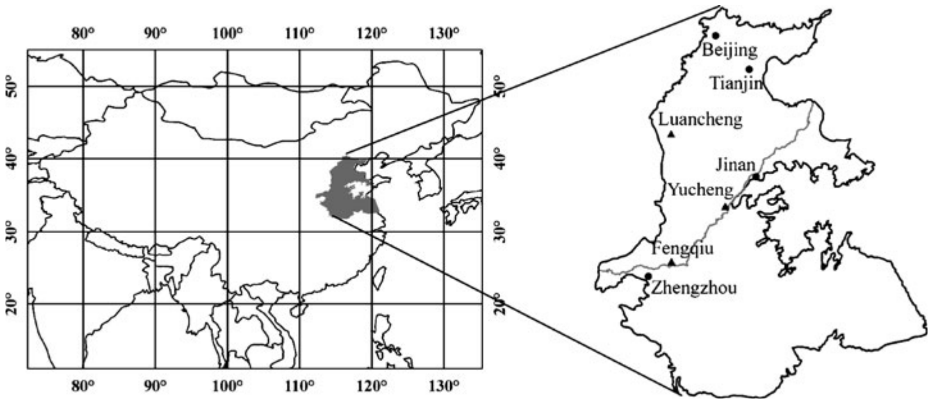


Fig. 1 The North China Plain and the locations of Beijing, Tianjin, Jinan, Zhengzhou sites and Luancheng Agro-ecosystem station, Yucheng Comprehensive Experimental Station and Fengqiu Agro-ecological Experimental Station

and PET changes (from 1954 to 1993) indicated improved soil moisture conditions and increased yield index in most parts of China (Thomas 2000b). Thomas (2006) simulated the effects of climate change on potential yield for rainfed cropping systems during the period 1951–1990 with gridded (0.25° × 0.25°) climate dataset and digital soil data. The results showed that potential crop yields displayed a tremendous variation both in temporal and spatial respects during study period. Tao et al. (2003) studied the changing trends in agricultural water demand and soil moisture on croplands over China during the last half-century with a soil–water balance model and found a decreasing trend in agricultural water demand and improved soil moisture conditions in Southwest China, but an opposite trend in the NCP. Tao et al. (2006) analysed the effects of temperature change from 1981 to 2000 on crop phenology and yields in China. Their results in Zhengzhou showed accelerated phenological development of wheat, but delayed phenology for maize. They also found that the temperature and rainfall change tended to reduce grain yield for both wheat and maize, but the reduction in wheat yield was not statistically significant.

The above studies have not related climatic change with crop growth processes. Further, the analysis based on observed data on crop phenology and yield could not separate the compounding effects of changes in climate and changes in crop varieties and management practices. This study aims to conduct a comprehensive analyse on how the past climatic change has impacted crop growth processes of the double cropping system in relation to water demand and supply conditions and the implications of such changes to the future sustainability of the wheat–maize system. The objectives are to: (1) analyse the changes in climatic variables during the wheat and maize growing seasons in the last 43 years (1961–2003) at four selected sites in the NCP, (2) study how the past climate change has impacted the crop growth processes, productivity and water demand of the wheat and maize crops using a modelling approach that enables the assessment of climate change impact by using fixed crop varieties and management practices and (3) investigate how the climate and management factors have influenced crop yield and water demand.

2 Materials and methods

2.1 Study sites

Four study sites, Beijing (39.30°, 116.28°), Tianjin (39.1°, 117.17°), Jinan (36.68°, 116.98°), Zhengzhou (34.72°, 113.65°), were selected (Fig. 1) due to their complete daily climate records from 1961 to 2003, including daily maximum and minimum temperature, precipitation, global solar radiation and diffuse radiation. Daily climate data from the four stations were obtained from China Meteorological Administration. A major consideration for the site selection is the data availability of solar radiation. Zhengzhou and Jinan are located in the mid- and lower reaches of the Yellow River respectively, while Tianjin and Beijing are in the further north of the NCP.

The winter wheat plus maize rotation system has been practiced to these four sites. The growing period for winter wheat is from October to May, and that for maize is from June to September.

2.2 The agricultural system model

The Agricultural Production Systems Simulator (APSIM) (McCown et al. 1996; Keating et al. 2003) was developed by Agricultural Production Systems Research Unit in Australia. APSIM is a component-based simulation framework with modules for simulating crop growth and development, soil water and nitrogen dynamics. It allows flexible specification of management options such as rotation type, fertilization and irrigation and simulations of their interactions. It runs at a daily time-step using daily meteorological data, including maximum and minimum temperatures, rainfall and total solar radiation. This study used the APSIM model version 5.3 to simulate the phenological development, biomass growth, grain yield and water balance of wheat and maize crops in the double cropping system. We used the following main built-in modules: wheat crop (WHEAT), maize crop (MAIZE), soil water (SOILWAT2), soil nitrogen (SOILN2), crop residue (RESIDUE) and management specification (MANAGER).

In APSIM, the crop processes are simulated with a generic crop module template (Wang et al. 2003). Crop phenology is divided into phases; the duration of each phase is determined by a cultivar-specific thermal time target. Daily thermal time is calculated using three cardinal temperatures (base, optimum and maximum) for each crop (modified by vernalisation and photoperiod in periods when crop is sensitive to vernalisation and photoperiod). Leaf area growth is simulated using leaf initiation rate, leaf appearance rate and relationship between plant leaf area and temperature. Potential daily biomass production is calculated based on light interception and radiation use efficiency (RUE), and it can be reduced by sub-optimal temperatures, water or N-deficit. Grain yield is a function of grain number, grain filling rate and assimilate re-translocation. PET was calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972). Evaporation from the soil surface is calculated based on the concept of first and second stage evaporation (Ritchie 1972). Potential water demand is estimated based on a transpiration efficiency (TE, biomass produced per unit water transpired) concept proposed by Tanner and Sinclair (1983). Daily radiation, maximum and minimum temperatures are required for evapotranspiration (ET) calculation. Simulated actual water uptake is a function of crop water demand and soil water supply from the rooted soil layers. Detailed descriptions of APSIM structure, its crop and soil modules can be found in Keating et al. (2003) or at the APSIM website: http://www.apsim.info/apsim/.

APSIM has been widely tested in Australia and elsewhere such as the Netherlands, the United States, Philippines, West Asia and North Africa under a wide range of conditions (Asseng et al. 1998, 2000; Nelson et al. 1998; Lyon et al. 2003; Heng et al. 2007). It has also been tested and used in China for simulating growth and yield of different crops. Chen et al. (2004) evaluated the performance of APSIM in simulating crop growth and soil water for different cropping systems in the Gansu Loess Plateau, China. Sun and Feng (2005) assessed the effects of drought risk to wheat production using APSIM-Wheat in Beijing, China. Wang et al. (2007) evaluated the applicability of APSIM in simulating the production and water use of wheat–maize double cropping system in the NCP. These applications of the APSIM model indicate that model simulation can explain at least 60% of the variation in biomass, yield and water use in these tested areas.

2.3 Experimental data and model testing

Observed data on crop phenological stages, leaf area index (LAI), biomass, grain yield, crop water use and soil water dynamics in wheat–maize rotations from three experimental stations in the NCP were used to calibrate and test the APSIM. These data include three years of data (1998–2001) from the Luancheng Agro-ecosystem station (37.85°N, 114.67°E) located in the north part of NCP southwest from Beijing and Tianjin, seven years of data (1997–2001, 2002–2005) from the Yucheng Comprehensive Experimental Station (36.11°N, 116.00°E) located in the centre of the NCP southeast from Jinan and two years of data (2004–2006) from Fengqiu Agro-ecological Experimental Station (35.01°N, 114.33°E) located roughly in the west edge of the southern part of the NCP (north to the Yellow River near Zhengzhou) (Fig. 1).

Solar radiation, maximum and minimum temperature and rainfall at each of the three experimental sites were recorded with an automatic meteorological station. Dry matter and LAI for both wheat and maize were measured at 5- or 7-day intervals. Each time, ten plants of wheat and five of maize were randomly selected from the sampling area for measuring green-leaf area and dry matter was determined after the harvested samples were oven-dried for 8–10 h (Zhang et al. 2004). Soil water content data were measured every 5 days with neutron probes at Luancheng and Yu Cheng. The measurement at Luancheng was from the depth of 20 to 160 cm with 20 cm measurement intervals, and that at Yucheng was from 10 to 150 cm depth with 10 cm intervals. Actual ET was measured daily with large-scale weighing lysimeters with a 0.02 mm precision at Luancheng and Fengqiu and a 0.04 mm precision at Yucheng (Yang et al. 2000; Zhang et al. 2002).

The crop genetic parameters used for the simulation of phenological development of the wheat and maize crop were derived on the basis of observed flowering and maturity dates. The crop parameters affecting crop yield formation (grain number and grain-filling rate) were selected on the basis of measured biomass production and grain yield. All other crop parameters were kept unchanged as in the original APSIM version 5.3, except the modification in radiation use efficiency (RUE) as described below. Values for the drained upper limit (DUL), i.e. field capacity of soil, and the lower limit (LL15), i.e. permanent wilting point (water content at 15 bars), were used to define plant-available water holding capacity (DUL–LL15), which were either obtained directly from the site measurements, or derived from published soil water profile data at the experimental stations. In the simulation for model testing, the model was initialised so that the first measurements of soil moistures could be matched. Nitrogen was applied based on crop demand so that no nitrogen stress impact was simulated.

2.4 Adjustment of crop RUE in the simulation modelling

In APSIM model, the crop RUE was assumed to be a constant or stage-dependent, and does not change with radiation environment. In reality, RUE increases with fraction of diffuse radiation (FDR) (de Wit 1965; Sinclair et al. 1992; Healey et al. 1998). While the decline in total solar radiation in the NCP may lead to crop yield reduction, the increasing trend in FDR could compensate the reduction to some extent. To account for the impact of FDR on RUE, a simple approach was developed to modify RUE used in APSIM-wheat and -maize modules.

Several studies showed that RUE increased linearly with FDR (Roechette et al. 1996; Choudhury 2000; Rodriguez and Sadras 2007). The results of Choudhury (2000) and Rodriguez and Sadras (2007) showed that the value of RUE for wheat (RUE_{wheat}) was doubled when FDR increased from 0 to 1.0. For the same range of FDR, Roechette et al. (1996) reported the value of RUE for maize (RUE_{maize}) was multiplied 1.9 times. Based on these results, we assumed that RUE_{wheat} was linearly increased by 100% and RUE_{maize} was linearly increased by 90% when FDR changed from 0 to 1.0.

For both wheat and maize crops, we assume that RUE = a•FDR + b, where a and b are constants. Based on the above assumptions, for wheat $a + b = 2b$ or $a = b$ (RUE doubles when FDR increases from 0 to 1.0), while for maize, $a + b = 1.9b$ or $a = 0.9b$ (RUE increases by 90% when FDR increase from 0 to 1.0). In the model calibration, we firstly adjusted the RUE for wheat and maize to simulate the experimental data in 2003 at Yucheng. The default RUE = 1.24 g MJ^{-1} for wheat and RUE = 1.6 g MJ^{-1} for maize were used in the simulations. These two RUE values, together with the seasonal average FDR (=0.58 for wheat and 0.61 for maize from the four simulation sites) were used to derive the a and b constants for wheat and maize crop RUE to get the following equations:

$$RUE_{wheat} = 0.78\ FDR + 0.78 \quad (1)$$

$$RUE_{maize} = 0.93\ FDR + 1.03 \quad (2)$$

In the simulation, the model was run once at the beginning just for calculating the seasonal average FDR from the observed daily total and diffuse radiation during each wheat season (October to May) and maize season (June to September) from 1961 to 2003. The seasonal average FDR for wheat and maize each year was then used to modify the RUE of both wheat and maize crops for subsequent simulations.

2.5 Modelling the impact of past climate change on productivity and water balance of the wheat-double cropping system from 1961 to 2003

The calibrated APSIM model at the Yucheng experimental station was used to simulate the crop growth, grain yield and water balance of a wheat–maize double cropping system using the historical climate data from 1961 to 2003. In the simulations, the same winter wheat variety (Zhixuan No.1) and maize variety (Yedan No.22) were used for all the years and at all four sites. These varieties are the same as the ones in the field experiment at Yucheng. The use of a fixed variety for each crop during simulations allows the analysis of the impact of climate change only on crop growth and water demand.

In the simulations, winter wheat was planted on October 5th, 5th, 10th and 15th at Beijing, Tianjin, Jinan and Zhengzhou, respectively, and harvested at physiological maturity. Maize was planted on June 12th in Beijing and Tianjin and June 15th in Jinan and Zhengzhou, which were several days before wheat harvest. Maize was intercropped into the wheat to mimic local practice and was harvested 1 day before sowing winter wheat. Because no detailed soil information is available at the four climatic sites, soil type at each site was assumed to be the same as that at its nearest experimental station.

Two sets of simulations were conducted. The first set simulated crop yield and water demand under the full irrigation condition, using the automatic irrigation facility in APSIM. Soil water content was increased to field capacity by applying irrigation water anytime when soil water content dropped below field capacity The second set simulated dryland crop yield without irrigation applications when impacts of other stress factors such as nutrient, disease and pests were not considered.

2.6 District wheat and maize yield and observed growing period

Wheat and maize yields in Beijing and Tianjin, obtained from the Beijing Statistical Bureau (1999), Department of Rural Socio-economic Investigation of National Bureau of Statistics of China (2000) and Editing Committee of China Agriculture Yearbook (2001–2003), were taken as a reference to compare with the crop yields simulated under fully irrigated conditions. The length of the observed crop growth periods for wheat and maize obtained from two nearby locations, Tangshan and Tai'an (unpublished), close to Tianjin and Jinan respectively, were compared with the simulated growth period durations of wheat and maize.

2.7 Quantification of model performance and data analysis

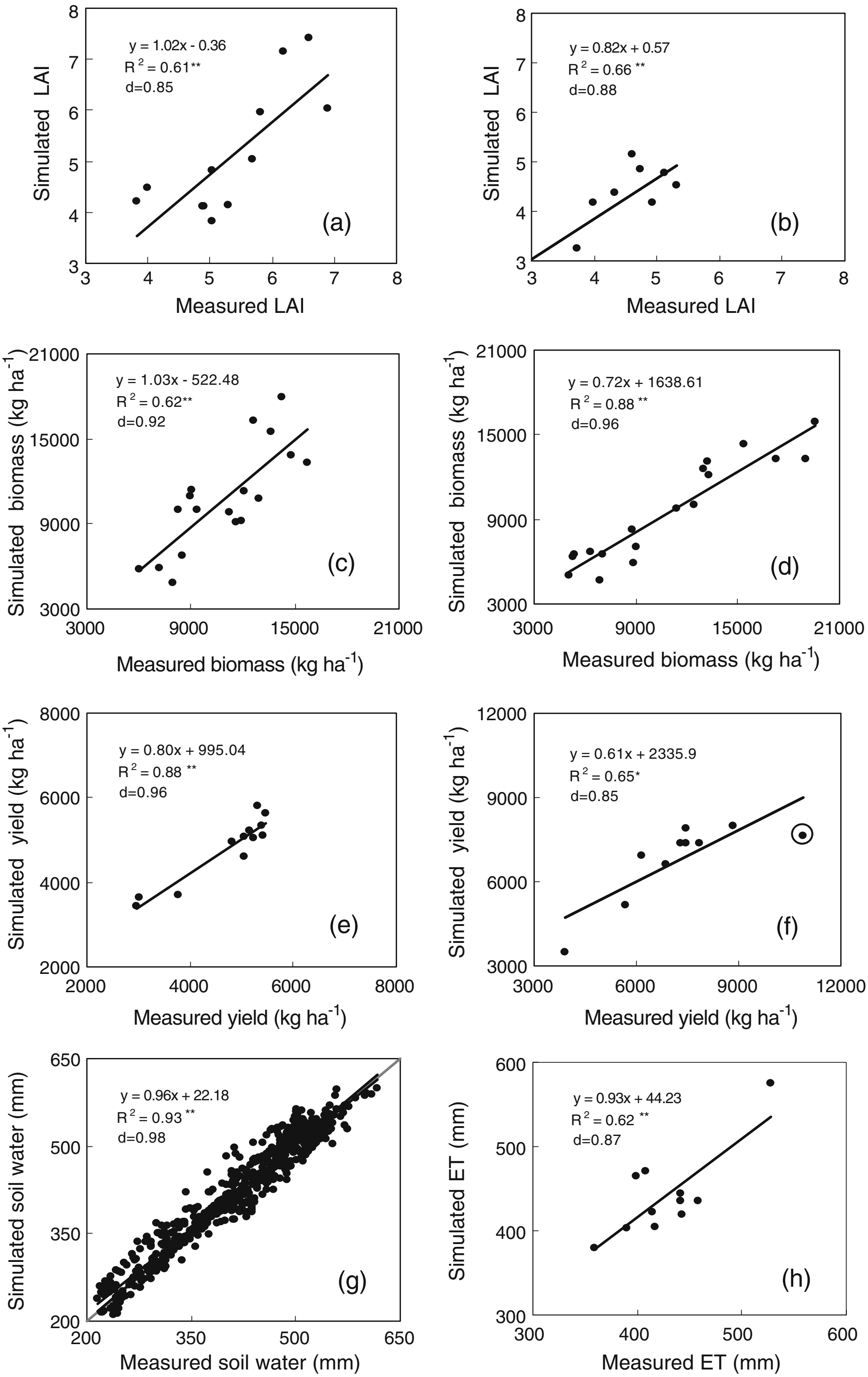
The model performance was evaluated using the slope, the coefficient of determination (r^2) of the regression lines and an index of agreement (d) (Willmott 1981, 1982; Willmott and Wicks 1980) between simulated and observed values.

Regression and Kendall-tau statistic (Lobell and Asner 2003; Chmielewski et al. 2004) were used for the linear trend analysis on global radiation, FDR, mean temperature and total precipitation for the maize and wheat season, respectively. The same statistical analysis was done for simulated durations of crop growth seasons, crop yield, water demand and irrigation water requirement (calculated as the difference in evapotranspiration in the wheat and maize seasons from the simulations with fully irrigation and no irrigation).

3 Results

3.1 Performance of the APSIM model

LAI, total biomass, grain yield, soil water content and crop water use simulated from the APSIM model were compared with the corresponding experimental data at the three stations, Luancheng, Yucheng and Fengqiu (Fig. 2). APSIM generally captured the variations in maximum leaf area, biomass and grain yield at the 95% significance level (Fig. 2a–f). For wheat, the slopes of the regression lines in Fig. 2a, c and e were close to 1.0 and the intercepts were relatively small, indicating no significant systematic over- or under-estimations. The index d values were larger than 0.85. For maize, the comparisons between the simulated crop leaf area, biomass and yield and the measured values indicated the slopes of the regression lines ranging from 0.61 for


y = 1.02x - 0.36
R 2 = 0.61**
d=0.85
(a)
Simulated LAI
Measured LAI
y = 0.82x + 0.57
R 2 = 0.66 **
d=0.88
(b)
Simulated LAI
Measured LAI
y = 1.03x - 522.48
R 2 = 0.62**
d=0.92
(c)
Simulated biomass (kg ha-1)
Measured biomass (kg ha-1)
y = 0.72x + 1638.61
R 2 = 0.88 **
d=0.96
(d)
Simulated biomass (kg ha-1)
Measured biomass (kg ha-1)
y = 0.80x + 995.04
R 2 = 0.88 **
d=0.96
(e)
Simulated yield (kg ha-1)
Measured yield (kg ha-1)
y = 0.61x + 2335.9
R 2 = 0.65*
d=0.85
(f)
Simulated yield (kg ha-1)
Measured yield (kg ha-1)
y = 0.96x + 22.18
R 2 = 0.93 **
d=0.98
(g)
Simulated soil water (mm)
Measured soil water (mm)
y = 0.93x + 44.23
R 2 = 0.62 **
d=0.87
(h)
Simulated ET (mm)
Measured ET (mm)

◀ **Fig. 2** Observed vs. simulated values of maximum LAI, total biomass and yield for wheat (**a**, **c** and **e**) and maize (**b**, **d** and **f**) at Luancheng, Yucheng and Fengqiu stations, and observed vs. simulated soil water content (**g**) and cumulative ET (**h**) during wheat and maize growing season at Luancheng and Yucheng. The *circled point* in **f** indicates the high maize yield in 1999 at Yucheng, which the model underestimated. **Significant at $p < 0.01$; *significant at $p < 0.05$

yield to 0.82 for LAI; the model explained 88% of the variation in biomass and 66% of the variation in yield, and the index d values were also larger than 0.85 (Fig. 2b, d, f). The model underestimated the high maize yield observed at Yucheng in 1999 by about 3200 kg ha^{-1}.The model explained 82% of the variation in maize yield in the other years.

Figure 2g shows the comparison between simulated and observed soil water contents at Luancheng (160 cm depth) and at Yucheng (150 cm depth). Figure 2h exhibits the comparison between simulated and measured crop seasonal ET at the three sites. The model explained 72% of the variation in soil water content and 62% in ET, with the index d values of 0.98 for soil water and 0.87 for ET, indicating its good performance.

The measured data lacked accurate irrigation and fertilisation records and measured crop yields were inconsitent with nearby crop yields, especially the high maize yield in 1999 at Yucheng (data not shown). All these may have contributed to the scattering of the simulated data as compared with measurements. Thus, it is possible that the model can give better simulation results for the wheat–maize rotation crop system if better quality experimental data are available.

3.2 Observed climate trend in the NCP during the period 1961–2003

All four sites (Beijing, Tianjing, Jinan and Zhengzhou) showed a significant ($p < 0.01$ or $p < 0.05$) decreasing trend in global solar radiation during the growth seasons of wheat and maize from 1961 to 2003 (Table 1). In the past 43 years, the decrease during the wheat season ranged between 3.6 MJ m^{-2} a^{-1} at Zhengzhou (south) and 17.7 MJ m^{-2} a^{-1} at Tianjin (north). Over the maize season, solar radiation decreased by between 1.8 MJ m^{-2} a^{-1} in Zhengzhou (south) and 13.1 MJ m^{-2} a^{-1} at Beijing (north). Annual total solar radiation decreased significantly ($p < 0.01$ or $p < 0.05$) by 29.1 MJ m^{-2} a^{-1} at Beijing, 22.8 MJ m^{-2} a^{-1} at Tianjin, 20.9 MJ m^{-2} a^{-1} at Jinan and 5.7 MJ m^{-2} a^{-1} at Zhengzhou. On a regional basis, the decreasing rate at the northern sites is higher than that at the southern sites. The mean decreasing trend in annual total solar radiation from these four sites was about 19.6 MJ m^{-2} a^{-1}. It must be acknowledged that solar radiation in agricultural areas may not be changing at the same rate as in the urban areas where the meteorological stations are located. Unfortunately, solar radiation data from agricultural areas are not as readily available as from urban areas.

Opposite to solar radiation, the mean seasonal FDR showed an increasing trend at all the four sites during both wheat and maize seasons. Over the past 43 years, during the wheat season, FDR increased significantly ($p < 0.01$) by around 0.24% a^{-1} at Zhengzhou and by 0.43% a^{-1} at Jinan, but not significantly at Beijing and Tianjin. During the maize season, it was increased significantly ($p < 0.01$ or

$p < 0.05$) at all the four sites, by 0.32, 0.30, 0.54 and 0.41% a^{-1} at Beijing, Tianjin, Jinan and Zhengzhou (Table 1), respectively. The four sites all showed the significant ($p < 0.01$ or $p < 0.05$) increasing trends in the annual mean FDR. In general, the increasing trend was larger at the southern sites than northern sites. The averaged increasing trend in the annual average FDR from the four sites was about 0.26% a^{-1}.

Both minimum temperature and maximum temperature during the wheat and maize seasons increased at all the four sties since 1961 (Table 1). The increases in minimum and maximum temperatures during the wheat season were both statistically significant ($p < 0.01$ or $p < 0.05$) at all four sites. For the maize season, minimum temperature increased significantly at Beijing and Tianjin, but not at the other two sites, and maximum temperature showed an increasing trend, but below the 95% significance level. In general, both minimum temperature and maximum temperature increased more during wheat season than during maize season. The average temperature increased significantly during both wheat season and maize season at all four sites.

Precipitation showed decreasing trends at all four sites during both wheat and maize seasons over the past 43 years, with the exception of Beijing during wheat season (Table 1). For wheat season, the decrease in precipitation was significant only at Tianjin. During the maize growing seasons, precipitation showed significant decreasing trends at all locations Annual total precipitation showed decreasing trends, but the trends were not significant at any of the four sites.

3.3 The impact of climate change on crop phenology and grain yield

The simulation results showed that the warming in the past 43 years would have shortened the length of crop growth period if no variety change is considered (Fig. 3). The simulated reduction in the duration of wheat growth period is statistically significant ($p < 0.01$) at all the four sites. The reduction in wheat growing season length ranged from 0.2 days a^{-1} at Tianjin to 0.3 days a^{-1} at Beijing. The simulated length of growth duration of maize tended to decrease as well, but not significant ($p > 0.05$) except at Beijing (about 0.2 days a^{-1}).

The climate change evidently influences the simulated intercropping period between wheat and maize (Fig. 4). The time interval between maize sowing and wheat harvest (or wheat sowing and maize harvest) showed a decreasing trend from 1961 to 2003. For example at Beijing, maize was sown before wheat harvest (intercropping) for almost every year before 1980s, and maize had to be forced to harvest in many years until early 1980s. The results of the intercropping between wheat harvest and maize sowing and maize harvest before maturing means that if the current crop varieties were used 40 year ago, the crop would not be able to mature before the sowing time of the next crop in the rotation, which would affect crop yield. The decrease in simulated overlap period also implies that climate warming will result in fewer season overlap problems (planting before the previous crop is fully mature and harvested).

Simulated grain yield of both wheat and maize under fully irrigated conditions decreased significantly ($p < 0.01$) in the past 43 years at Beijing and Tianjin, while that in Jinan and Zhengzhou changed little (Fig. 5). From 1961 to 2003, simulated wheat yield was decreased by 48.3 and 42.2 kg ha^{-1} a^{-1} at Beijing and Tianjin,

Table 1 Trends in total solar radiation (St), fraction of diffuse radiation (FDR), minimum temperature (Tmin), maximum temperature (Tmax) and precipitation (P) in the wheat season, maize season and whole year at four sites across the North China Plain during the period 1961–2003

Site	Period	St		FDR		Tmin		Tmax		P	
		Trend (MJ m^{-2} a^{-1})	R^2	Trend (% a^{-1})	R^2	Trend (°C a^{-1})	R^2	Trend (°C a^{-1})	R^2	Trend (mm a^{-1})	R^2
Beijing	Wheat season	−16.1**	0.63	0.02	0.01	0.08**	0.68	0.03**	0.23	0.8	0.03
	Maize season	−13.1**	0.63	0.32**	0.55	0.05**	0.59	0.01	0.04	−2.4*	0.04
	Annual	−29.1**	0.72	0.08**	0.17	0.07**	0.64	0.02*	0.12	−1.5	0.01
Tianjin	Wheat season	−17.7**	0.46	0.21	0.06	0.03**	0.21	0.04**	0.31	−0.1	0.002
	Maize season	−4.3*	0.10	0.30*	0.15	0.01**	0.02	0.02*	0.10	−2.0**	0.03
	Annual	−22.8**	0.37	0.22**	0.16	0.02*	0.11	0.03**	0.22	−3.6	0.06
Jinan	Wheat season	−15.1**	0.48	0.43**	0.68	0.04**	0.46	0.03**	0.21	−0.6	0.02
	Maize season	−5.6*	0.16	0.54**	0.64	0.01**	0.07	0.01	0.01	−1.8*	0.02
	Annual	−20.9**	0.50	0.46**	0.76	0.03**	0.35	0.01	0.09	−2.4	0.02
Zhengzhou	Wheat season	−3.6	0.04	0.24**	0.27	0.04**	0.34	0.03*	0.12	−0.3	0.001
	Maize season	−1.8	0.02	0.41**	0.64	0.01**	0.09	0.003	0.002	−1.1**	0.06
	Annual	−5.7	0.02	0.26**	0.53	0.03**	0.26	0.01	0.01	−0.3	0.001

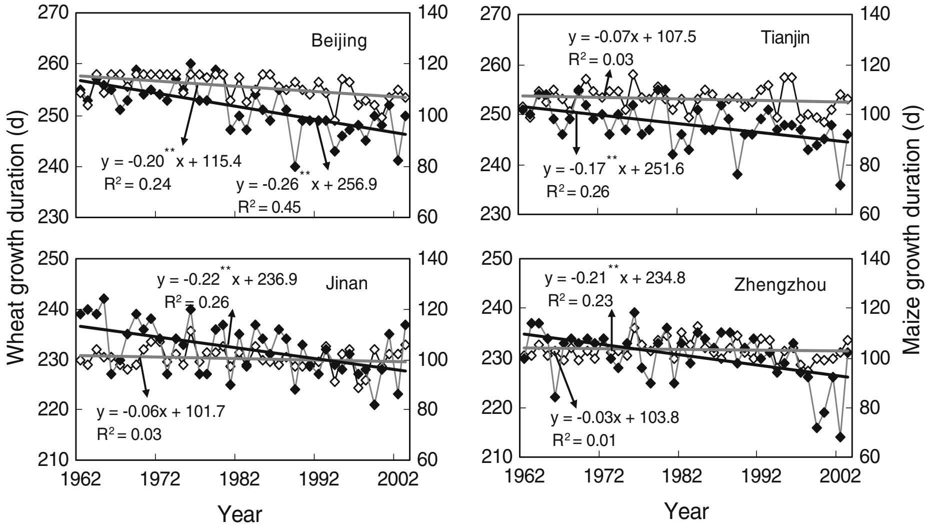
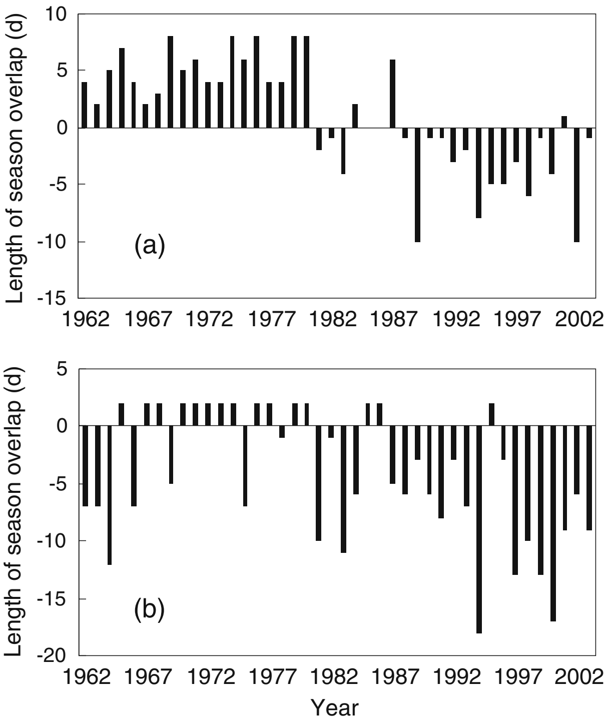


Fig. 3 The simulated length of growth duration of wheat (*filled symbols*) and maize (*open symbols*) from 1961–2003 at four sites in the NCP. *Straight lines* show the linear trends. **Significant at $p < 0.01$

Fig. 4 The length of overlap period from maize sowing date to wheat harvest date (**a**) (positive values represent the days that maize was sown before wheat harvest, and the negative values represent the days that maize was sown after wheat harvest); the length of overlap period from wheat sowing date to maize harvest date (**b**) (positive values represent the days that wheat is sown when maize was forced to be harvested before maturity, and the negative values represent the days that wheat was sown after maize harvest) from 1961–2003 at Beijing



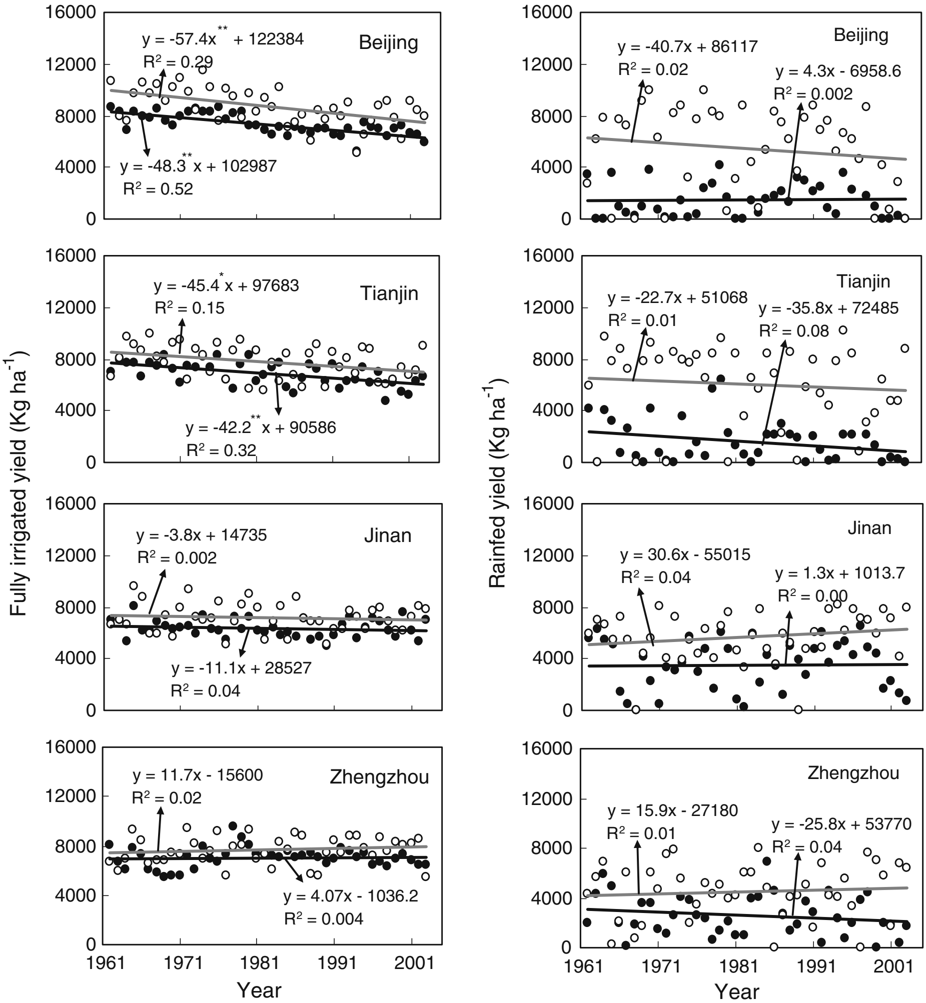


Fig. 5 The yield of wheat (*filled symbols*) and maize (*open symbols*) under potential (*left panels*) and rainfed (*right panels*) conditions from 1961–2003 at four sites in NCP. Straight lines show the linear trends. **Significant at $p < 0.01$; * Significant at $p < 0.05$

while the simulated maize yield under full irrigation was decreased by 57.4 and 45.4 kg ha^{-1} a^{-1} at the two sites respectively.

Simulated rainfed wheat yield had decreasing trends at all the four sites (Fig. 5), due to the effects of the reduction in annual precipitation (except Beijing) together with temperature increase and radiation decrease. However, the reduction in rainfed wheat yield was not significant ($p > 0.05$) at all four sites. Simulated rainfed maize yield decreased (not significantly) at Beijing and Tianjin and increased slightly at Jinan and Zhengzhou. The large variations in rainfed yield due to the inter-annual variation of precipitation makes the trend in rainfed yield less prominent.

3.4 The impact of climate change on crop water demand and irrigation water requirement

The simulations showed that the past climate change would have reduced the water demand (ET under full irrigation) of both wheat and maize if no variety change is considered (Fig. 6). The simulated water demand reduction for wheat was significant ($p < 0.01$ or $p < 0.05$) at all four sites and ranged from about 1.0 mm a^{-1} at Zhengzhou to about 3.1 mm a^{-1} at Beijing. Water demand for maize was also decreased at the four sites. The reduction was significant ($p < 0.01$ or $p < 0.05$) at Beijing, Tianjin and Jinan, ranging from 1.6 mm a^{-1} at Jinan to 3.0 mm a^{-1} at Beijing.

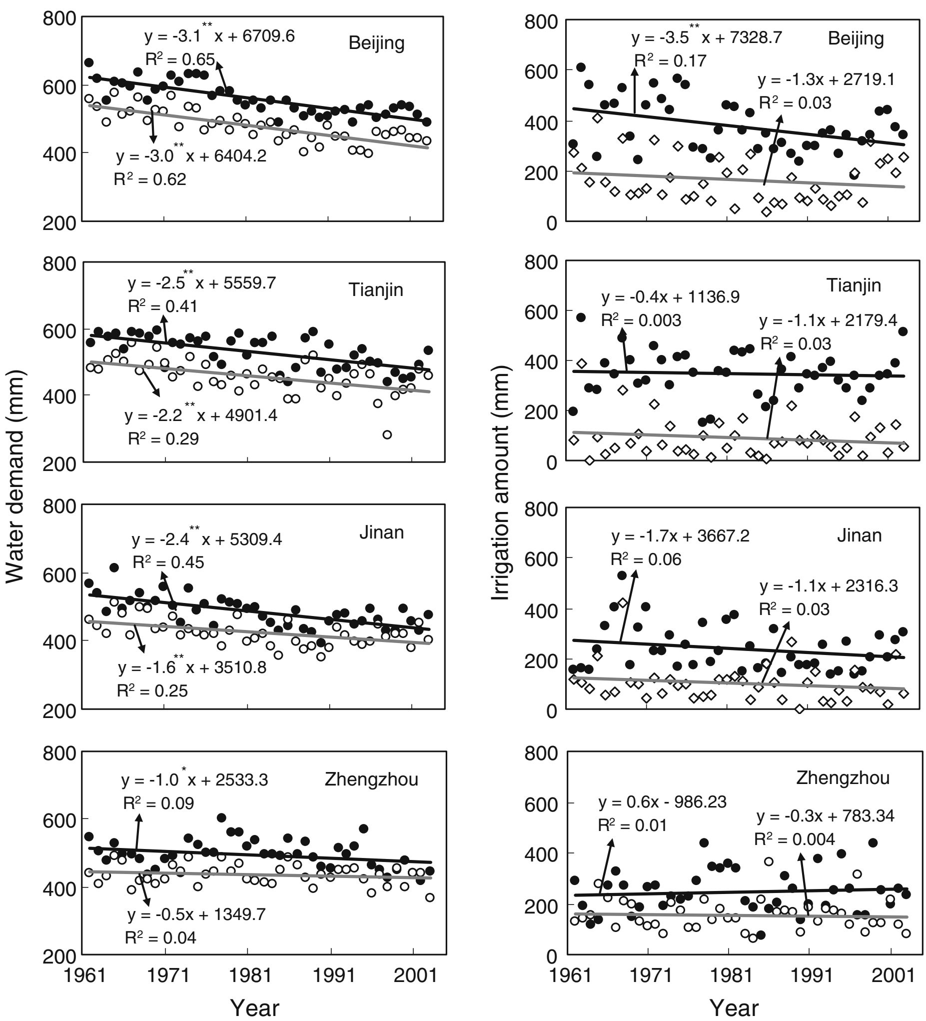


Fig. 6 Water demand and irrigation water required of wheat (*filled symbols*) and maize (*open symbols*) from 1961 to 2003 at four sites in NCP. Straight lines show the linear trends. **Significant at $p < 0.01$; *Significant at $p < 0.05$

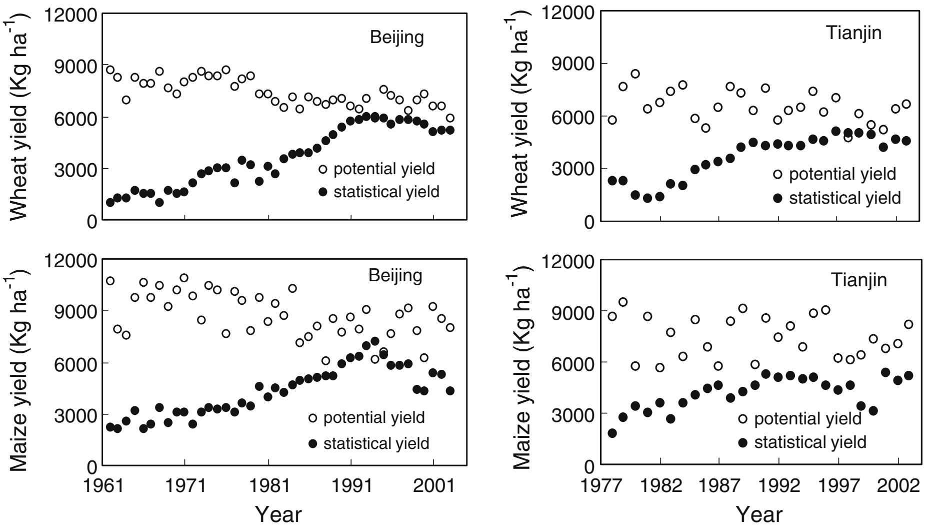


Fig. 7 Simulated yield under full irrigation (*open symbols*) and statistical (*filled symbols*) yield of wheat and maize at Beijing from 1962–2003 and at Tianjin from 1978–2003

The simulated irrigation water requirement (Fig. 6) for wheat showed a decreasing trend at Beijing, Tianjin and Jinan, and an increasing trend at Zhengzhou (Fig. 6). But only the decrease at Beijing (3.5 mm a^{-1}) was significant ($p < 0.01$). Irrigation water requirement for maize also showed a decreasing trend at all four sites, but not significant at the 95% significance level. The reduction in irrigation water requirement was a combined result of changes in crop water demand, rainfall and the length of growing period of each crop.

3.5 Comparison with the average district crop yield

The average district wheat and maize yields from Beijing and Tianjin were compared with the simulated yields under fully irrigated conditions (potential yield) as shown in Fig. 7. In spite of the simulated decline in potential yield, district wheat and maize yield showed a steady increase between the 1962 and 1990 (between 1978 and 1990 at Tianjin), most likely as a result of the use of irrigation and fertilizer, crop variety improvements and other management practice improvements (Chameides et al. 1999; Mellouli et al. 2000; Zhu and Chen 2002; Evenson and Gollin 2003; Qaim and Zilberman 2003; Zhang et al. 2005). In recent years (since 1991), district wheat and maize yields showed a decreasing trend in Beijing, while stabilised in Tianjin. Both in Beijing and Tianjin, the simulated yield trend under fully irrigated conditions roughly followed the trend in district yield since 1991.

4 Discussion

A significant warming trend was observed from 1961 to 2003 at all the four study sites in the NCP, which corresponds well to the global warming trend from 1956 to

2005 (IPCC 2007). During both wheat and maize growth seasons, the magnitude of minimum temperature increase was generally larger than that of maximum temperature. All four sites showed declining trends in solar radiation during both wheat and maize seasons, a result of increased aerosol loadings caused by anthropogenic activities (Che et al. 2005; Liang and Xia 2005). It is noted that the reduction in solar radiation at northern Beijing was far larger (a multiple of 4.5 for the wheat season and 7.1 for the maize season) than that at southern Zhengzhou. This is because air pollution caused by the burning of fossil fuel due to industrial development at Beijing is more serious than that at Zhengzhou. It is more interesting that solar radiation decreased slightly at Zhengzhou, but FDR increased significantly. A possible reason is that the aerosol particle vertical distribution in the troposphere moves up (Qiu and Yang 2000). Although the climate data used were obtained from the weather stations in four capital cities, the current observations of decreased radiation, increased FDR, increase in temperature and decline in rainfall are consistent with the regional study results, such as radiation trends by Che et al. (2005, 2007), rainfall trends by Liu et al. (2005) and temperature trends by Shen and Varis (2001) and Tao et al. (2003). Thus, the climatic trends in this study are reasonable and the simulation results based on the observation data are presentative in the NCP.

In spite of the increased productivity of the wheat–maize rotation cropping system since the 1960s in the NCP (Wu et al. 2006, 2008), the climate change in the last more than four decades was simulated to have negative impacts on crop potential yield for both wheat and maize, especially in the northern locations of the NCP. The negative impacts were mainly caused by reduced radiation together with shortened crop growth period (due to temperature increase).The decline in precipitation, especially in maize season, also reduced crop yield, which was indicated by the trends in the simulated rainfed yield. The declines in both simulated and district crop yield since 1991 in Beijing seem to indicate the negative impacts of changed radiation and temperature environment, though human activities, such as crop improvement, irrigation and fertilizer applications have maintained or improved district crop yield.

The current simulated crop yield results should be interpreted cautiously. The simulations conducted did not consider varietal changes in the last 43 year, nor did they include the impacts of extreme temperatures (e.g. hot dry wind impact on wheat grain filling) and other biotic stresses like pests and diseases. Improved crop varieties and improved irrigation and fertilisation may have contributed to a major part of crop yield increase as shown in the district crop yield in Fig. 7. Considering these factors, the trends in simulated crop yield do not contradict those of the observed average district yield. It is certain that the decline in solar radiation would have reduced growth rate and the changes in the simulated overlap of growth periods of wheat and maize indicate that the increase in temperature may have lessened the problem of accommodating two crops in 1 year.

Decline in global radiation in the last more than four decades has led to a reduction in crop water demand and irrigation water requirement, especially in the northern locations of the NCP. This is consistent with the findings of Thomas (2000a) and Wang et al. (2008). The decline in crop water demand and irrigation water requirement seems to imply that less water would have been applied for irrigation than would be required if no climate change occurred. In that sense, the past climate change may have contributed to reduced exploitation of surface and groundwater resources for irrigation, but this would be accompanied with production potential reduction.

Irrigation applications by exploiting groundwater and/or surface water have ensured a steady increase in crop yield (Fig. 7) considering that crop yield simulated under rainfed conditions showed large interannual fluctuations (Fig. 5). The success and increased yield of the wheat–maize double cropping system in the NCP are at least partially attributable to the irrigation applications, especially in the early half of the last four decades (Jin and Young 2001). Improved crop varieties may have contributed to other part of the yield increase. The small gap between simulated yield potential and district yield since 1991 indicates that irrigation has largely met crop water demand. It has to be emphasized that the wheat–maize double cropping system supported by exploiting groundwater has led to significant depletion of groundwater resources in large areas of the NCP (Liu et al. 2001). The changes in climate in the last 43 years may be partly driven by global warming, and to a large extent, by rapid regional industrial development. There are many uncertainties regarding future climate change. One scenario would be the reduced aerosols in the atmosphere due to improved environmental conditions in the future. This could lead to a bounce-back of radiation (Wild et al. 2005). This, together with the projected hotter and drier environment, would lead to increased crop water stress, and a worsened water shortage situation in the NCP. These hypotheses of the changes in crop water status are supported by Tao et al. (2003) and Thomas (2008). Their results show that agricultural water demand is expected to increase and soil-moisture deficit would increase, based on the combination of observed climate data and General Circulation Models (GCM). More studies should be conducted for future climate change and sustainability of the wheat-maize double cropping system.

This study also demonstrates the effectiveness of using agricultural system modelling to understand cropping systems–climate interactions. The comparison of simulated yield with that at experimental sites and from the district indicates the model's ability to simulate the response of crops to past climate.

5 Conclusions

Significant decline in radiation and rainfall, increase in minimum and maximum temperatures and FDR was identified for both wheat and maize seasons at four locations in NCP. The decline in total radiation was simulated to reduce water demand by 2.3 mm a^{-1} for wheat and 1.8 mm a^{-1} for maize in the 43 years from 1961 to 2003. The climate change lessened water deficit, reduced potential yield by 45.3 kg ha^{-1} a^{-1} for wheat and 51.4 kg ha^{-1} a^{-1} for maize at the northern locations if no crop variety change occurred. The increase in FDR compensated somewhat the reduced growth for both wheat and maize. The increase in temperature contributed to the easy accommodation of the two crops in one rotation year.

The depletion of groundwater resources for irrigation may be further deteriorated in the future because of the projected global warming, drying and bounce-back of solar radiation. More studies should be focused on the sustainable use of irrigated groundwater for sustaining the wheat–maize double cropping system under changing climate.

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