Climatic Change (2012) 113:825–840
DOI 10.1007/s10584-011-0385-1

Increased yield potential of wheat-maize cropping system in the North China Plain by climate change adaptation

**Jing Wang · Enli Wang · Xiaoguang Yang ·
Fusuo Zhang · Hong Yin**

Received: 7 July 2010 / Accepted: 6 December 2011 / Published online: 3 January 2012

Abstract In the North China Plain, the grain yield of irrigated wheat-maize cropping system has been steadily increasing in the past decades under a significant warming climate. This paper combined regional and field data with modeling to analyze the changes in the climate in the last 40 years, and to investigate the influence of changes in crop varieties and management options to crop yield. In particular, we examined the impact of a planned adaptation strategy to climate change -"Double-Delay" technology, i.e., delay both the sowing time of wheat and the harvesting time of maize, on both wheat and maize yield. The results show that improved crop varieties and management options not only compensated some negative impact of reduced crop growth period on crop yield due to the increase in temperature, they have contributed significantly to crop yield increase. The increase in temperature before over-wintering stage enabled late sowing of winter wheat and late harvesting of maize, leading to overall 4–6% increase in total grain yield of the wheat-maize system. Increased use of farming machines and minimum tillage technology also shortened the time for field preparation from harvest time of summer maize to sowing time of winter wheat, which facilitated the later harvest of summer maize.

1 Introduction

The North China Plain (NCP) is one of the most important agricultural production regions in China. With a dominant winter wheat-summer maize double cropping system, it provides

J. Wang (✉) · X. Yang (✉) · F. Zhang
College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
e-mail: wangj@cau.edu.cn

X. Yang
e-mail: yangxg@cau.edu.cn

E. Wang (✉)
CSIRO Land and Water, GPO Box 1666, Canberra ACT2601, Australia
e-mail: Enli.Wang@csiro.au

H. Yin
National Climate Center, China Meteorological Administration, Beijing 100081, China

more than 50% of the nation's wheat and about 33% of maize production. Extensive studies showed that China's climate has generally become warmer and drier, especially since late 1970s and across the north part of China (Lin 1996; Smit and Cai 1996; Chen et al. 1998; Tao et al. 2006). Such trends were considered to reduce the length of crop growing periods and potential yield (Chen et al. 2010b). The decline in rainfall at some locations should also have impact on crop yield (Xiong et al. 2007; Tao et al. 2008). However, grain yield of wheat and maize in the NCP has been increasing from 1960s to middle 1990s, which implies autonomous adaptations, because no planned adaptation strategies were officially developed to mitigate the negative impact of climatic change. These adaptations include adopting new crop varieties and management options to achieve high crop yield (Xu and Zhao 2001; Zhang et al. 2005; Sun et al. 2007; Zhou et al. 2007; Liu et al. 2010), which are proved to be also suitable to the conditions with rising temperature.

In recent years since middle 2000s, grain yield of wheat and maize has been further increased, partly due to the application of a so-called "Double-delay" technology in the north part of the NCP (National Bureau of Statistics of China 2008). "Double-Delay" means delayed sowing of wheat crop and delayed harvesting of maize crop (including use of later maturing maize cultivars). It has been promoted to agricultural regions in the NCP by scientists and the government. Therefore, it can be seen as a planned adaption option. However, no studies have systematically analyzed the background and quantified the impacts of the "Double-Delay" technology on wheat-maize cropping system under the warming climate in the NCP.

The effects of climate change and management practices on crop production have been investigated by numerous studies in different parts of the world. Some studies assessed the individual effect of rising temperature (Peng et al. 2004; Tao et al. 2006) and changing crop varieties and sowing dates (Winter and Musick 1993; Egli and Bruening 2000; Kantolic et al. 2007; Zhang et al. 2010). Others analyzed the compound impact of changes in climate, crop varieties and management options (Sadras and Monzon 2006; Monzon et al. 2007; Luo et al. 2009; Tao and Zhang 2010). The general conclusion was that adaptation options, such as the improvement in crop varieties and the change in the sowing date, could alleviate the negative effects of rising temperature and increase crop yield. In addition, the adaptation option differed significantly between crop types and regions due to different climate, crop characteristics, farming practice and other socioeconomic factors (Howden et al. 2007). "Double-Delay" technology in the NCP was developed in addition to the autonomous adaptation strategies. A systematic analysis of its background and its impacts on wheat-maize cropping system under the warming climate in the NCP would shed light for future development of new adaptation strategies.

The objectives of this study are to 1) analyze the climate background for the development of "Double-Delay" technology, including the changes in climate and crop varieties and their impact on crop production, 2) quantify the impact of "Double-Delay" technology on yield potential of wheat-maize double cropping system in different agricultural regions in the NCP.

2 Materials and methods

2.1 Study sites, climate and crop data

Hebei, Shandong and Henan province are the three provinces with highest wheat and maize yields in the North China Plain. Three sites, Luancheng (37.88°N, 114.65°E), Tai'an (36.19°

N, 117.12°E) and Xinxiang (35.31°N, 113.88°E), were selected, each represents a typical agricultural site of Hebei, Shandong and Henan province respectively (Fig. 1). For each site, historic daily weather data from 1961 to 2008 were available from China Meteorological Administration, including daily average, maximum and minimum temperature, rainfall, wind speed, sunshine hours, and relative humidity. Daily global radiation was estimated from sunshine hours based on the Angstrom equation (Wang et al. 2008). Average air temperature at Luancheng, Tai'an and Xinxiang was 14°C, 15°C and 14.7°C, while average annual precipitation was 516 mm, 700 mm and 575 mm, respectively.

Crop phenological stages and varieties used from 1981 to 2005 were recorded at the agro-meteorological experimental stations at Luancheng, Tai'an and Xinxiang. Average grain yield (kg ha^{-1}) of winter wheat and summer maize in Hebei, Henan and Shandong province from 1961 to 2008 were obtained from the internet website of Crop Cultivation Information in China (www.zzys.gov.cn). These crop yield data were used to analyze the trend of change in the length of crop growing period and grain yield.

2.2 "Double-Delay" technology and field experiments

In general, winter wheat is sown in early October, approximately 2 weeks after the harvest of summer maize in late September, to allow time for field preparation. The "Double-Delay" technology practiced in recent years was to delay harvesting of maize crop for about 7 days and delay sowing of wheat crop for about 7 days, depending on climatic regions, compared to traditional planting pattern. It aims to increase maize yield by increasing the growth duration of summer maize.

In order to study the change in crop yield in response to changed sowing time of wheat and harvesting time of maize, a field experiment was conducted by Sun et al. (2007) at the Luancheng Agroecological Experimental Station from 2002 to 2005. The experiment consisted of six treatments (T1 to T6) representing different time of sowing and harvest of winter wheat and summer maize (Table 1). T1 represents the typical sowing and harvest time used by the

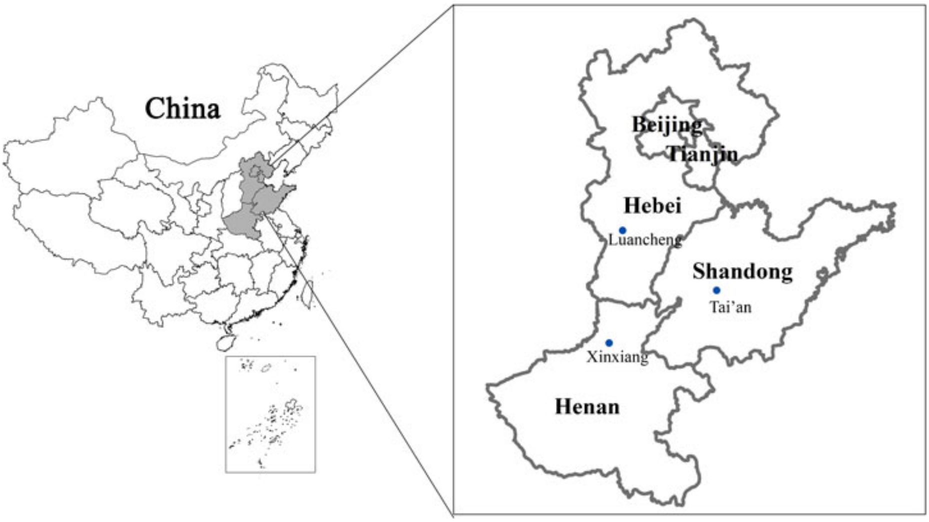


Fig. 1 The North China Plain and the study sites: Luancheng in Hebei province, Tai'an in Shandong province and Xinxiang in Henan province

Table 1 Six treatments of Sun et al. (2007), covering different harvesting dates of summer maize and sowing dates of winter wheat. Plant density of winter wheat was increased with later sowing

Treatments	T1	T2	T3	T4	T5	T6
Harvest time of maize (day/month)	25/09	1/10	5/10	10/10	15/10	20/10
Sowing time of winter wheat (day/month)	5/10	10/10	15/10	20/10	25/10	30/10
Sowing amounts of wheat (kg ha^{-1})	135	142.5	153.75	168.75	183.75	198.75

local farmers. Other treatments were 5–25 days delay in wheat and maize harvesting time. After harvest, the grain yield, thousand-grain weight for wheat and hundred-grain weight for maize were measured. The farming systems model, APSIM (Keating et al. 2003), is used here to simulate the yield change of single crop variety in response to past climate change as described below. These experimental data was used to test APSIM's performance to simulate the wheat yield change with delayed sowing time and maize yield change with delayed harvesting time. Detailed descriptions of the experiments were given by Sun et al. (2007).

2.3 The agricultural system model APSIM and its validation

The Agricultural Production System sIMulator (APSIM, version 5.3) was used to simulate the crop growth and grain yield of the wheat-maize double cropping system in response to different sowing and harvesting dates from 1961 to 2008. Key APSIM modules used included –wheat (Meinke et al. 1998; Keating et al. 2001; Wang et al. 2003), maize (Carberry et al. 1989; Carberry and Abrecht 1991; Keating et al. 1991, 1992), soilwat2 (Probert et al. 1998), soiln2 (Probert et al. 1998), residue2 (Probert et al. 1998), and a manager module that allows conditional application of management rules.

APSIM is well tested, widely used in Australia (Keating et al. 2003), and recently tested and applied in the North China Plain (Wang et al. 2007; Chen et al. 2010a). These studies indicated that APSIM was able to reproduce the observed crop growth, yield and water use in the study areas of the NCP. The model could explain more than 80% of the variation in crop biomass and yield. Here we rely on the previous work on model validation for normal sowing dates of wheat and maize, only carried out additional test of the modeling under delayed sowing time against the data collected by Sun et al. (2007) as described previously.

2.4 Simulation scenarios and APSIM parameterization

To simulate impact of past climate change on grain yield of single wheat and maize variety (i.e. no variety change), one old wheat cultivar “Jinfeng1” and one earlier maturing maize variety “Luyuandan9” were used. Simulations were conducted under normal sowing dates every year from 1961–2008. Trend analysis was performed to investigate the change in simulated length of growing period and grain yield.

To explore the impact of climate change on season overlap problems in the wheat-maize double cropping system, the overlapping period needed for intercropping due to season shortage for the two crops was modeled assuming the current wheat and maize varieties (see below) were planted in the past and no crop varietal changes would have occurred from 1961 to 2008. The trend of change of the simulated length of the overlapping period was analyzed.

Two scenarios of simulations were conducted to study the impact of “Double-Delay” technology on yield potential of irrigated wheat and maize crops at the three sites. Scenarios one (S1) represents traditional sowing and harvesting times of wheat and maize. More recently used wheat varieties “Gaoyou503”, “Keyu13” and “Zhengmai9023” were planted every year on October 4th, 6th, 10th at Luancheng, Tai’an and Xinxiang, respectively and harvested at physiological maturity. Maize varieties “Yedan21”, “Yedan22” and “Zhengdan958” were planted every year on June 5th, 18th, 5th at Luancheng, Tai’an, and Xinxiang respectively, and were forced to harvest on Sept 20th in order to allow about 2 weeks for field preparation before sowing winter wheat, although maize might not reach its physiological maturity stage.

Scenario 2 (S2) represents delayed maize harvest and delayed wheat sowing. The same wheat varieties as that in S1 were sowed on October 11th, 13th, 17th at Luancheng, Tai’an and Xinxiang, respectively and harvested at physiological maturity stage. Maize (simulated using the same varieties as in S1) was harvested at physiological maturity or on Sept 27th, whichever were earlier. This will lead to a maize harvest date on average 7 day later than that in S1.

Tables 2 and 3 showed crop variety parameters for the simulation of phenological development of wheat and maize and crop yield. These parameters were derived by matching the simulated and observed stages of phenology and grain yield of wheat and maize with a trial-and-error method. More detailed descriptions of crop parameters and soil parameters are given by Chen (2008) and Chen et al. (2010b).

For all the simulations, irrigation was applied using the automatic irrigation facility in APSIM to ensure that the crop did not have water stress. When soil water content dropped below field capacity, irrigation water was applied to increase the soil water content to field capacity. Each year, 100 kg N/ha was applied as the base fertilizer and another 100 kg N/ha was added at the jointing stage during the growing season of winter wheat. 80 kg N/ha was applied at sowing and another 100 kg N/ha was added at the stem elongation stage for summer maize to ensure the crops were not nutrient stressed. Because irrigation did not increase soil water content above field capacity, limited drainage as well as N leaching occurred as a result of irrigation.

3 Results

3.1 Climate change since 1960s and pre-winter temperature increase in recent years

The changing trends of climatic variables at Luancheng, Tai’an and Xinxiang from 1961–2008 were shown in Fig. 2. There was a significant increasing trend in annual average and

Table 2 APSIM parameterization for four wheat varieties used in the study

Parameters	Values			
	Gaoyou503	Keyu13	Zhengmai9023	Jinfeng1
vern_sens (sensitivity to vernalisation)	1.7	1.5	1.8	2.7
photop_sens (sensitivity to photoperiod)	2.3	2.0	2.0	3.3
startgf_to_mat (thermal time from beginning of grain-filling to maturity (°C d)	600	420	420	420
Grains_per_gram_stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem))	23.0	24.0	25.0	23.0
potential_grain_filling_rate (potential grain-filling rate (g per kernel per day))	0.0025	0.0023	0.0025	0.0025
Phyllochron (Phyllochron interval (°C d/leaf appearance))	85	85	85	85

Table 3 APSIM parameterization for four maize varieties used in the study

Parameters	Values			
	Yedan21	Yedan22	Zhengdan958	Luyuandan9
Head_grain_no_max (maximum grain numbers per head)	500	560	630	500
Grain_gth_rate (grain-filling rate (mg/grain/day))	9	10	10.5	12
tt_emerg_to_endjuv (thermal time (TT) required from emergence to end of juvenile (°C d))	280	240	240	240
photoperiod_slope (change in TT required to floral initiation per hour photoperiod increase)(°C/hour)	19.0	19.0	19.0	19.0
tt_flower_to_maturity (thermal time required from flowering to maturity (°C d))	900	850	980	700
tt_flower_to_start_grain (thermal time required from flowering to starting grain-filling (°C d))	130	160	160	130

minimum temperatures, while the increase in maximum temperature was significant at 95% level only at Tai'an. The increase in average temperature ranged from 0.4°C per decade at Luancheng to 0.17°C per decade at Tai'an and 0.16°C per decade at Xinxiang, indicating

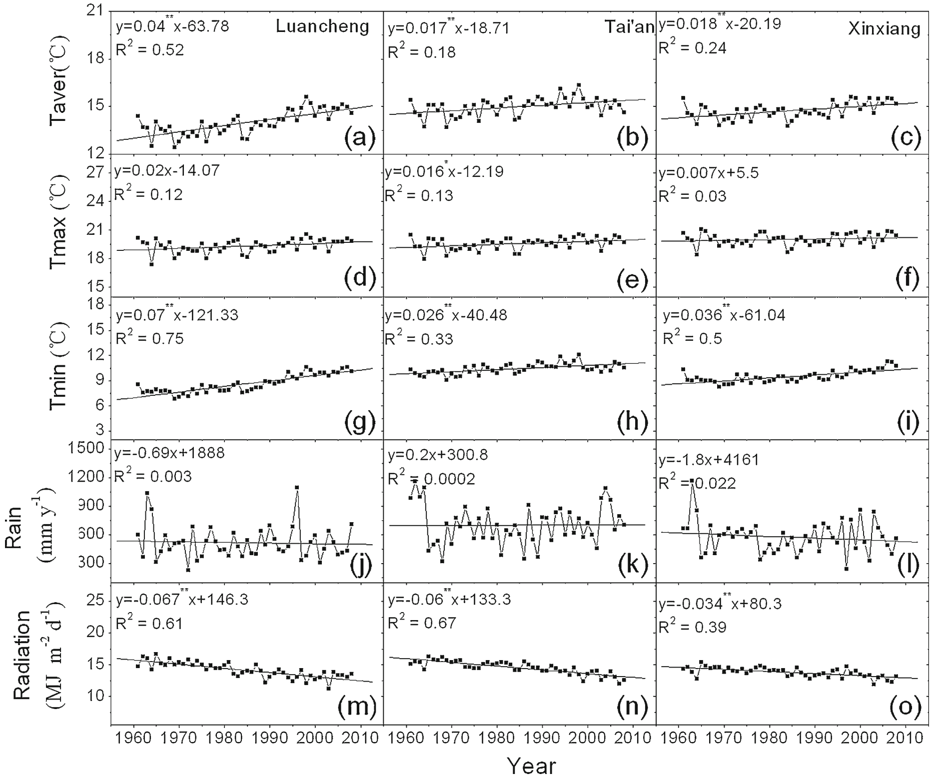


Fig. 2 Trends in annual average (Taver) (**a**–**c**), maximum (Tmax) (**d**–**f**), and minimum (Tmin) (**g**–**i**) temperatures (°C), annual total rainfall (**j**–**l**) (mm) and global radiation (**m**–**o**) (MJ m^{-2} d^{-1}). Straight line is the linear regression line against year. ** Significant at $P<0.01$; * Significant at $P<0.05$

more warming towards north part of the NCP. Global radiation showed a decreasing trend, with a rate of -670 kJ m^{-2} d^{-1} per decade at Luancheng, -600 kJ m^{-2} d^{-1} per decade at Tai'an and -340 kJ m^{-2} d^{-1} per decade at Xinxiang, mainly due to air pollution (Yang et al. 2004; Che et al. 2005). Annual rainfall had no significant trend of change.

Rate of accumulation of temperature above certain base temperature (thermal time) reflects the rate of development of crops. The base temperature for wheat and maize crop development are 0°C and 8°C respectively. Table 4 shows the trends in monthly accumulated temperature above 0°C during the period from October to next May (wheat growing season) and above 8°C during the period from June to September (maize growing season) from 1961 to 2008 at Luancheng, Tai'an, Xinxiang, respectively. There has been a significant increase in accumulated temperature above 0°C in the vegetative growth stage of winter wheat in October, January to April at Luancheng, from February to April at Tai'an and Xinxiang ($P<0.05$). For maize growth season, there was a significant increase in accumulated temperature above 8°C in June-September at Luancheng and in September at Xinxiang ($P<0.05$), while no significant change trend at Tai'an. The increase in temperature accumulation implies accelerated crop development and reduced duration of crop growing period for a given cultivar.

Figure 3 shows accumulated temperature anomalies above 0°C in the two months of October and November before the over-wintering stage of wheat. Although the temperature changes were not uniform at the three study sites, it is noticeable that the anomaly was mainly positive in recent years, showing significant pre-winter warming due to climate variability in the recent past.

3.2 Trend of changes in provincial grain yield of wheat and maize in the NCP since 1960s

Figure 4 shows the changes in average provincial grain yields of wheat and maize in the NCP from 1961 to 2008, which reflects the compound effects of climate, crop varieties, management options and socio-economic factors on grain production. There was a significant increasing trend in grain yields of wheat and maize from 1960s to 2000s. The average yields of wheat and maize were 806 kg ha^{-1} and 1416 kg ha^{-1} in 1960s and reached 4965 kg

Table 4 Trends in monthly accumulated temperature above 0°C during the growing season of wheat (October-May) and that above 8°C during the growing season of maize (June-September) from 1961 to 2008. ** Significant at $P<0.01$; * Significant at $P<0.05$

Site		Luancheng	Tai'an	Xinxiang
Wheat growing season	October	1.29^{**}	0.44	0.55
	November	0.55	0.44	0.45
	December	0.38	0.28	0.17
	January	0.42^{*}	0.27	0.073
	February	1.58^{**}	1.04^{*}	1.28^{**}
	March	1.73^{**}	1.04^{*}	1.18^{*}
	April	1.58^{**}	1.22^{**}	1.3^{**}
	May	0.06	-0.2	0.52
Maize growing season	June	0.63^{*}	-0.067	0.22
	July	0.77^{*}	-0.074	0.44
	August	0.61^{*}	-0.31	0.28
	September	1.36^{**}	0.57	0.66^{*}

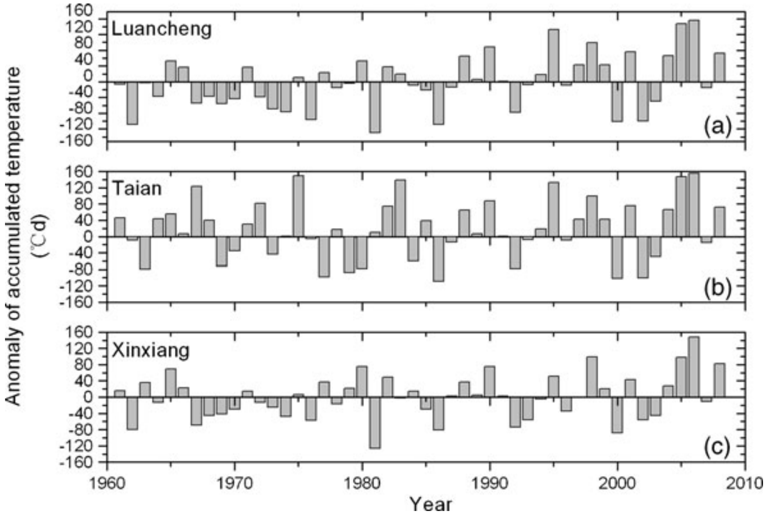


Fig. 3 Anomaly of accumulated temperature (above 0°C) during October and November before the over-wintering stage of winter wheat at Luancheng (**a**), Tai'an (**b**) and Xinxiang (**c**) respectively from 1961 to 2008

ha^{-1} and 5121 kg ha^{-1} in 2000s, respectively. The period from the 1960s to the middle of the 1990s was characterized as a rapid increase period of grain yields due to increased water and fertilizer inputs, improved varieties and management options (Wang et al. 1995; Ellis and Wang 1997; Zhou et al. 2007; Liu et al. 2010). Thereafter, grain yields remained stable because varieties and management options were relatively stabilized and water and fertilizer inputs were able to meet crop demand and even becoming excessive (Ju et al. 2009). The small downwards trend in a short period was caused by farmers's reluctancy to grow grain due to the transitory food surplus and piled storage (Wang et al. 2009a). However, a noticeable further increase in grain yields of wheat and maize can be observed since 2004.

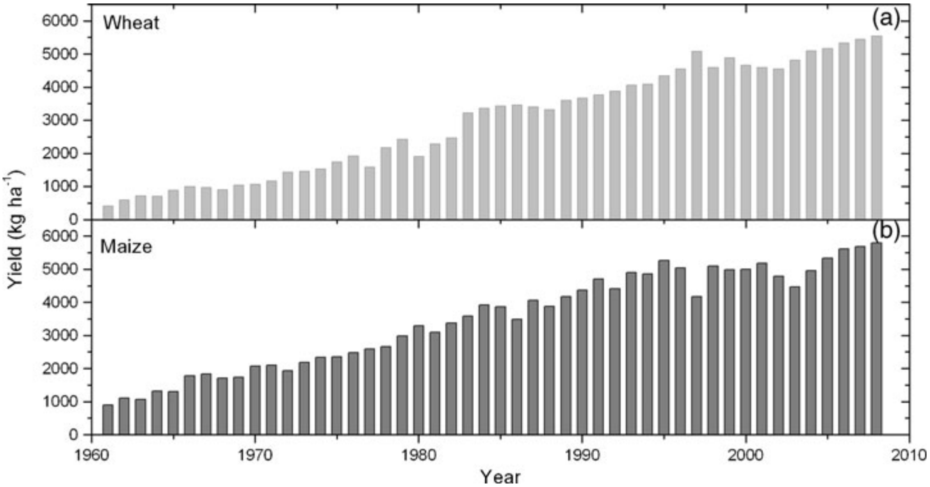


Fig. 4 Changes in average grain yields of wheat (**a**) and maize (**b**) in the North China Plain from 1961 to 2008. The grain yields are average values of crop yields in Hebei, Shandong and Henan Province

3.3 Simulated impact of climate change on phenology and yield of wheat and maize in the NCP

Simulation modeling enables the use of a single cultivar for each crop to grow for many years. By assuming no water and nutrient stresses, the simulation results can be analyzed to disentangle the influence of climatic trend and management options on crop yield. Figure 5 shows the trend of change in simulated length of growing season and yield of winter wheat and summer maize using wheat variety “Jinfeng1” and maize variety “Luyuandan9” at Luancheng, Tai’an and Xinxiang from 1961 to 2008. It shows what would have happened if no crop varietal changes would have occurred in the past. The simulated length of growing season of winter wheat was significantly shortened at all the three sites (about 2 days/decade) due to the increase in average temperature. Consistent with the findings of Liu et al. (2010), the warming mainly occurred in vegetative growth stage, while simulated length of reproductive growth phases was relatively stable. The reduced growing season and biomass growth rate led to a significant reduction in simulated winter wheat yield at all the three sites.

The simulated length of growing season of summer maize had no significant trend of change at Tai’an and Xinxiang. At Luancheng, increased temperature in September reduced the duration of maize growth. There was a declining trend in simulated maize grain yield at all the three sites due to the reduction in solar radiation, which is consistent with the results of Chen et al. (2010b).

Figure 6 shows the change in simulated intercropping period between wheat and maize (using modern wheat variety “Gaoyou503” and maize variety “Yedan21” at Luancheng, wheat variety “Keyu13” and maize variety “Yedan22” at Tai’an and wheat variety “Zhengmai9023” and maize variety “Zhengdan958” at Xinxiang). The intercropping period from

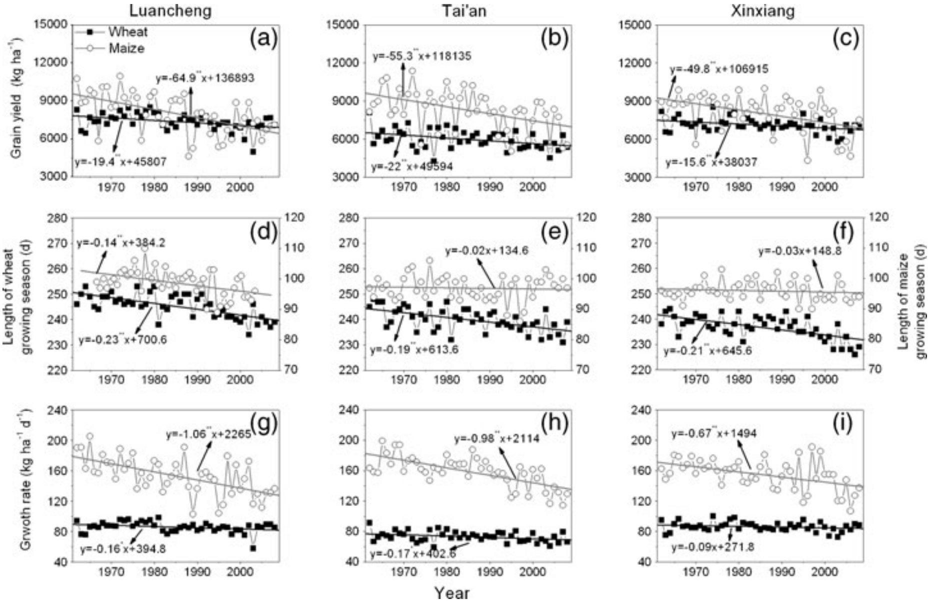


Fig. 5 Simulated grain yield (**a**–**c**), length of growing season (**d**–**f**) and biomass growth rate (biomass/length of growing season) (**g**–**i**) of wheat (cultivar Jinfeng1) and maize (cultivar Luyuandan9) at three study sites (1961–2008). Straight lines show the linear trends against year. ** Significant at $P<0.01$; * significant at $P<0.05$

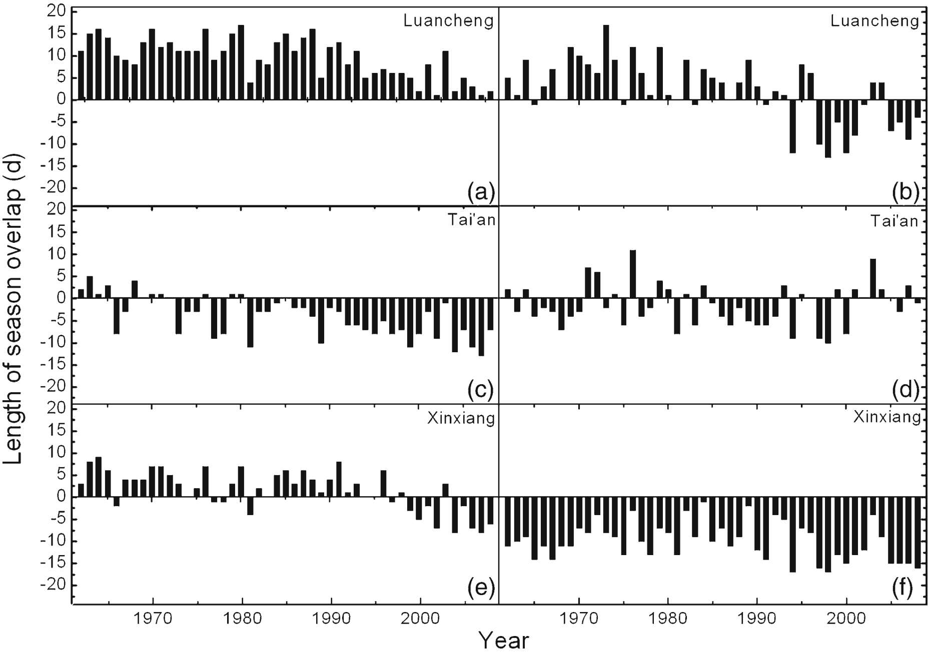


Fig. 6 Simulated length of overlapping period from wheat harvest date to maize sowing date (**a**, **c**, **e**) (positive values represent that maize was sown before wheat harvest and the negative values represent maize was sown after wheat harvest), and of overlap period from maize harvest date to wheat sowing date (**b**, **d**, **f**) (positive values represent that wheat was 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 1961–2008

maize sowing date to wheat harvest date has been decreasing at all the three sites from 1961 to 2008. If the modern wheat variety was planted 40 years ago, maize would have to be planted before wheat maturity in order to get enough season length for maize to mature. The warming also shortened simulated length of season overlap from maize harvest date to wheat sowing date at Luancheng. If the modern maize variety was planted in the past, it would not be able to mature before winter wheat sowing date for almost every year before 1997 at Luancheng. Due to less change in temperature during maize growth season at Tai'an and Xinxiang, there was no significant trend in the change in simulated length of season overlap.

3.4 Impact of adaptation of crop varieties

Figure 7 shows the changes in observed phenological stages of winter wheat and summer maize at the study sites with variety changes from 1980 to 2005. For winter wheat, there was a significant reduction in total growth duration at Tai'an (about 5 days/decade), but not at Luancheng and Xinxiang. The difference between observed and simulated phenological stages at Luancheng and Xinxiang reflect that varietal change had a counter effect to climate change. For summer maize, there was a significant increasing trend in observed total growth season at all three sites, especially at Xingxiang (about 7 days/decade). The observed length of vegetative growth stage was shortened about 1 days/decade at Luancheng but increased slightly at Tai'an and Xinxiang. The observed length of post-flowering period was increased at three sites, significantly at Xinxiang. Longer post-flowering period suggested the potential of increased grain filling period and increased grain yield – a positive adaptation to the warming climate.

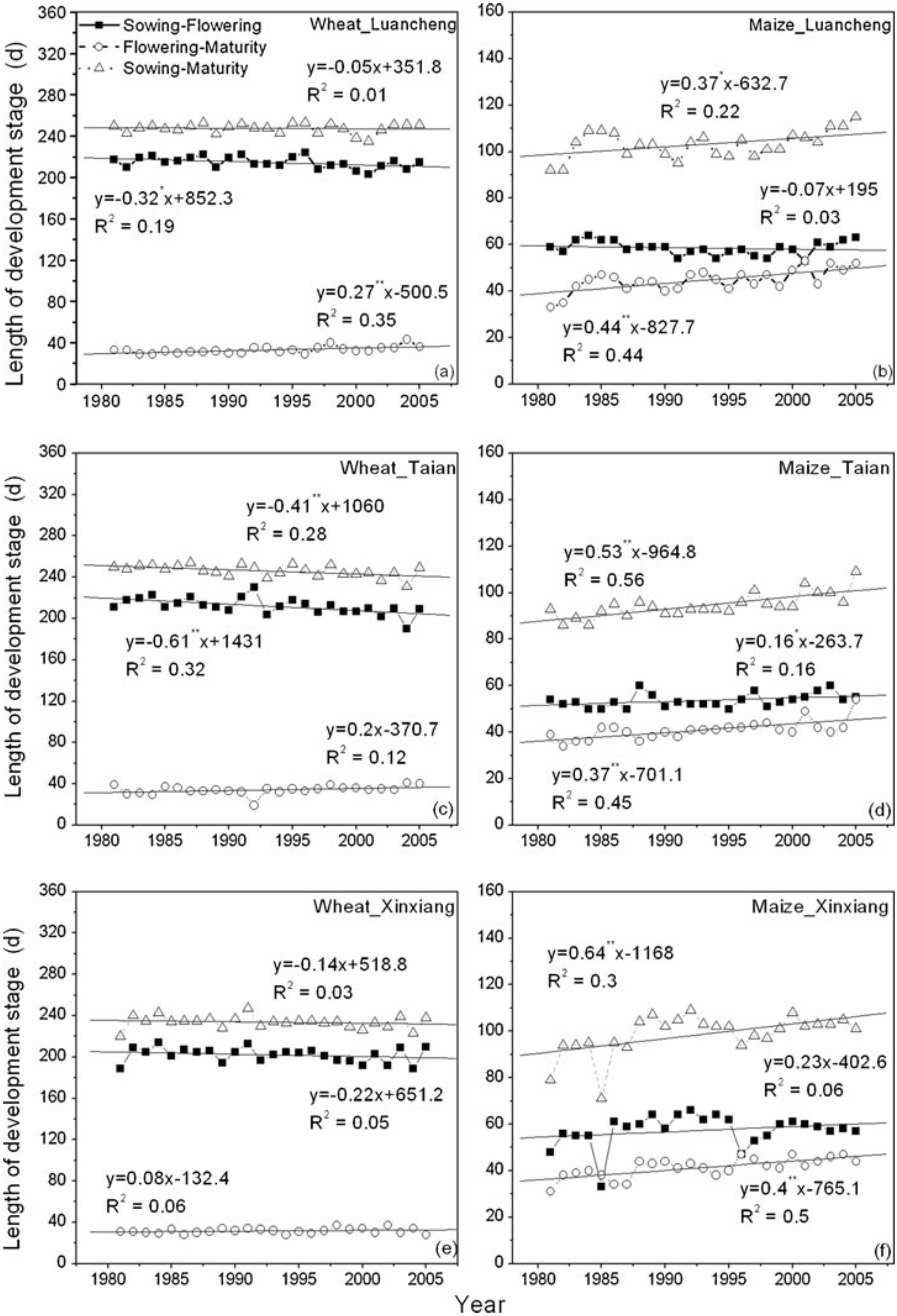


Fig. 7 Trends of change in the durations of observed developmental stages (sowing to maturity, sowing to flowering and flowering to maturity) of winter wheat (10 varieties at Luancheng, 19 varieties at Tai'an and 13 varieties at Xinxiang) and maize (13 varieties at Luancheng, 13 varieties at Tai'an and 15 varieties at Xinxiang) from 1980–2005 at Luancheng (**a**–**b**), Tai'an (**c**–**d**) and Xinxiang (**e**–**f**). Straight lines show the linear trends against year. ** Significant at $P<0.01$; * significant at $P<0.05$

3.5 Impact of adaptation of cultivation management – "Double-Delay"

Field experimental results in Luancheng Agro-ecological Experimental Station from 2003 to 2005 showed that the "Double-Delay" technology resulted in increase in maize yield, but led to reduction in wheat yield (Fig. 8). Average yield reduction of wheat was 0.5% day^{-1} of delay of sowing date from October 10 and maize yield was increased (through increasing kernel weight) by about 0.6% each day delayed from the harvest date of October 5 at Luancheng (Sun et al. 2007).

Figure 9 shows the average response of observed and simulated crop yield to delayed sowing time of wheat and harvesting time of maize. The simulation results give the same trend of yield change in response to the "Double-Delay" technology, which demonstrates that the model is able to capture the impact of changed sowing/harvesting time on crop yield.

Figure 10 shows the simulated percentage increase in grain yield of the wheat-maize double cropping system under two simulation scenarios (traditional planting pattern versus "Double-Delay" planting pattern). The results indicate that maize yield could be increased on average by 9% at Luancheng, 15% at Tai'an and 7% at Xinxiang if harvest date of maize was delayed for 7 days. Though there is a risk of yield loss of wheat due to late sowing, total yield of wheat-maize double cropping system could be increased by 4%–6% at all the three sites.

Figure 10 also shows that the "Double-Delay" technology could lead to increase in crop yield of the wheat-maize system in earlier years. However, it has only practiced in recent years because no-tillage or minimum tillage technology became widespread in China since 2002 (Zhang et al. 2004), which results in significant reduction in field preparation time between the harvest of summer maize and the sowing of winter wheat.

4 Discussion

In China, mean temperature has increased during the last decades particularly since the 1980s, with the largest increase in the northern part (Tao et al. 2003). While a number of

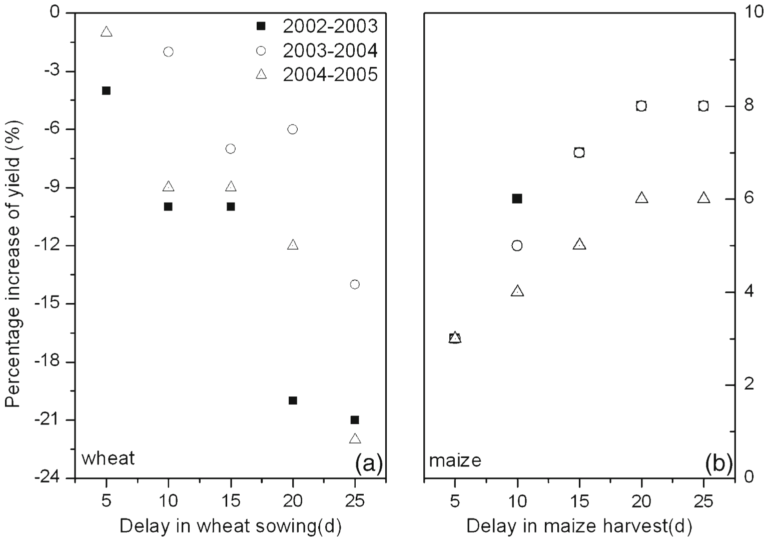


Fig. 8 Percentage increase of yield with delayed sowing time of wheat (**a**) and harvesting time of maize (**b**) from 2002 to 2005 at Luancheng (original data from Sun et al. 2007)

Fig. 9 Measured and simulated percentage increase of yield with the delay in wheat sowing and maize harvesting time, averaged from 2002 to 2005 at Luancheng

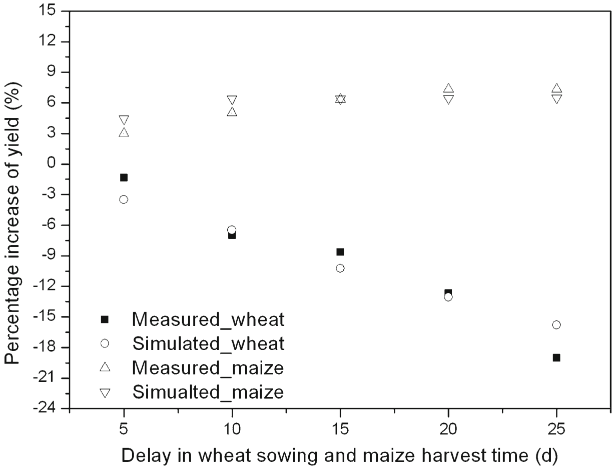
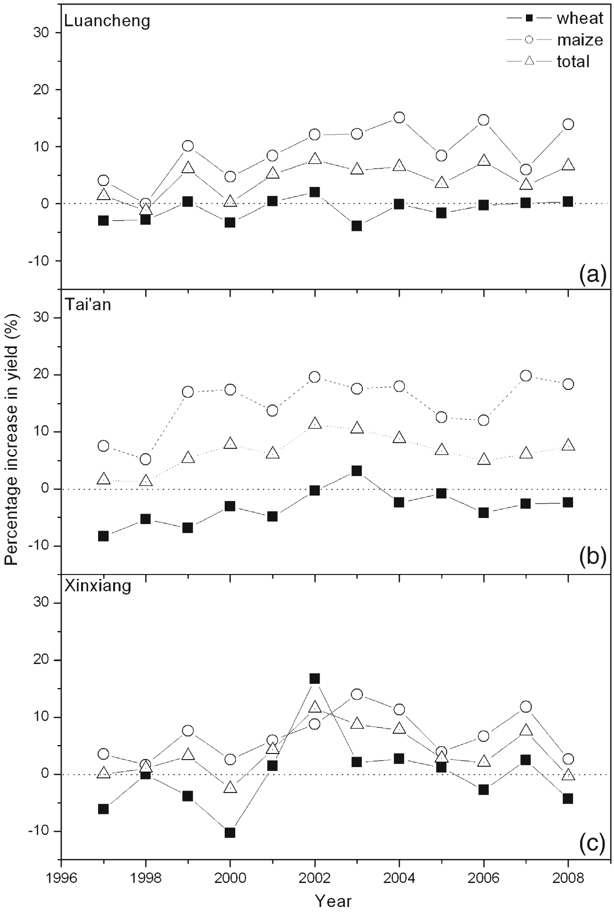


Fig. 10 The percentage increase in grain yield of winter wheat and summer maize simulated from 1997 to 2008 at Luancheng (**a**), Tai'an (**b**) and Xinxiang (**c**). The increase indicates the change of yield from traditional planting pattern to 'Double-Delay' planting pattern



studies showed the increase in temperature would reduce the length of growing period of wheat and maize and thereby lead to decline in yield (Tao et al. 2008; Wang et al. 2009b; Chen et al. 2010b), the actual yield change in the NCP shows the opposite. Improved crop varieties and management options have been able to steadily increase crop yield levels.

In the NCP, the warming in the past decades mainly occurred during the vegetative (pre-flowering) growth stage of wheat and maize. Similar phenomenon also occurred in the growth season of wheat in Australia and Argentina (Sadras and Monzon 2006). Although it had a potential to reduce the length of crop growth period and crop yield if no varietal change could have occurred, adoption of new crop varieties had been able to stabilize the length of pre-flowering period against the negative effect of warming and extend the length of the post-flowering (grain-filling period), which has led to increased crop yield (Liu et al. 2010). The modeling study of Kantolic et al. (2007) also indicated shortening pre-flowering period without changing the length of whole growth period would increase crop yields.

The results of Chen et al. (2010b) showed that the warming in the past decades has shortened the intercropping period between winter wheat and summer maize in Beijing. Our results confirm the findings also at other sites of NCP. These results indicated that the increase in temperature in winter in the past decades also lessened the season shortage problem to accommodate the wheat and maize crops within a year. The warming made it possible to delay the sowing time of wheat and harvesting time of maize, leading to the development of the "Double-Delay" technology. The yield reduction of wheat due to late planting (reduced length of growing season) could be partly compensated by increased planting density (Sun et al. 2007). The delayed sowing of wheat allows a longer duration of maize growth (longer grain filling period), or accommodation of longer season maize varieties. The increase in maize grain yield due to extended grain filling period thorough the "Double-Delay" technology outweighs the yield decline in wheat, resulting in an overall yield increase of the two crops by 5%.

For double cropping system, the management strategies should consider the yield advantages of the whole cropping system other than individual crops (Evans 1993). Monzon et al. (2007) indicated earlier sowing of soybean could increase the yield of wheat-soybean system in Argentina attributed to significant benefit for soybean and without yield reduction in wheat. The "Double-Delay" technology takes advantage of the warming climate, and leads to a more efficient use of the season to allow maize crop reach full maturity. In some years, it also avoids the over-growth of wheat before winter, which could lead to crop injury during cold winter and spring time (Sun et al. 2007). While improved irrigation, fertilization and crop varieties have contributed to the major increase in crop yield in the last three decades, maize yield increase in recent years since 2004 was thought to be partly due to the application of the "Double-Delay" technology especially in north part of NCP. Our results provide the scientific basis to explain the success. The success also suggests well planned adaption options could effectively mitigate the negative impact of adverse climate and increase the crop yield potential under global warming.

Other farming technologies, mainly increased use of farming machines, and minimum tillage technology also contributed to the adoption of the 'Double-Delay' management option. In the past, field preparation needed about more than 2 week from the harvest of summer maize to sowing of winter wheat in the North China Plain. Now, the time of field preparation was shortened significantly to about 7 days, which enabled longer season varieties to mature (Sun et al. 2007).

The changed planting pattern through the 'Double-Delay' also has the potential to increase water use efficiency in the North China Plain under limited irrigation condition. Due to the summer monsoon climate, about 70% of annual rainfall falls in the growth season of summer maize (Wang et al. 2010). Concentrated summer rainfall could meet water demand of maize crops in some wet years in large part of the NCP (Chen et al. 2010a).

The extension of maize growing period can make a better use of the summer rainfall. The rainfall in wheat growing season is much less than crop water demand, the shortened wheat growing length could also lead to less water needed to irrigate the wheat crop.

The ‘Double-Delay’ technology has shown to be a success to increase crop yields in the north part of NCP in recent years. However, the increase in crop yields is through better use of seasonal conditions and climate resources, which has to be supported by high inputs of irrigation water and fertilizers. How the resource use efficiencies have been changed under the “Double-Delay” technology, and how the technique is sustainable under future climate change require further studies to clarify.

Acknowledgements We sincerely acknowledge the Special Fund for agriculture profession (201103003), National Basic Research Program of China (2009CB118608) and the National Natural Science Foundation of China (No. 41101046). This work is also supported by National Basic Research Program of China (2005CB121106) and the Innovative Group Grant of the National Science Foundation of China (30821003). The authors acknowledge the anonymous referees for their valuable comments.

References

Carberry PS, Abrecht DG (1991) Tailoring crop models to the semi-arid tropics. In: Muchow RC, Bellamy JA (eds) Climatic risk in crop production: models and management in the semi-arid tropics and sub-tropics. Cab International, Wallingford, pp 157–182

Carberry PS, Muchow RC, McCown RL (1989) Testing the CERES-Maize simulation model in a semi-arid tropical environment. Field Crops Res 20:297–315

Che HZ, Shi GY, Zhang XY et al (2005) Analysis of 40 years of solar radiation data from China 1961–2000. Geophys Res Lett 32:1–5

Chen C (2008) Response of crop water productivity and water balance to climate variability/change in the North China Plain. PhD thesis, Graduate University of Chinese Academy of Sciences, Beijing, 170 pp

Chen L, Zhu W, Wang W et al (1998) Studies on climate change in China in recent 45 years. Acta Meteorol Sin 56:257–271

Chen C, Wang EL, Yu Q (2010a) Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agric Water Manage 97:1175–1184

Chen C, Wang E, Yu Q et al (2010b) Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Clim Change 100:559–578

Egli DB, Bruening WP (2000) Potential of early-maturing soybean cultivars in late plantings. Agron J 92:532–537

Ellis EC, Wang SM (1997) Sustainable traditional agriculture in the Tai Lake of China. Agric Ecosys Env 61:177–193

Evans LT (1993) Crop evolution adaptation and yield. Cambridge University Press, Cambridge, p 500

Howden SM, Soussana JF, Tubillo FN et al (2007) Adapting agriculture to climate change. PNAS 104:19691–19696

Ju XT, Xing GX, Chen XP et al (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. PNAS 106:3041–3046

Kantolic AG, Mercau JL, Slafer GA et al (2007) Simulated yield advantages of extending post-flowering development at the expense of a shorter pre-flowering development in soybean. Field Crops Res 101:321–330

Keating BA, Godwin DC, Watiki JM (1991) Optimising nitrogen inputs in response to climatic risk. In: Muchow RC, Bellamy JA (eds) Climatic risk in crop production: Models and management in the semi-arid tropics and sub-tropics. Cab International, Wallingford, pp 329–358

Keating BA, Wafula BM, Watiki JM (1992) Development of a modelling capability for maize in semi-arid eastern Kenya. In: A search for strategies for sustainable dryland cropping in semi-arid eastern Kenya (eds Probert ME), pp 138, Proceedings of a Symposium held in Nairobi, kenya

Keating BA, Meinke H, Probert ME et al (2001) NWheat: documentation and performance of a wheat module for APSIM. Tropical Agriculture Technical Memorandum. Indooroopilly, Queensland

Keating BA, Carberry PS, Hammer GL et al (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288

Lin E (1996) Agricultural vulnerability and adaptation to global warming in China. Water Air Soil Pollut 92:63–73

Liu Y, Wang E, Yang X et al (2010) Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Global Change Biol 16:2287–2299

Luo Q, Bellotti W, Williams M et al (2009) Adaptation to climate change of wheat growing in South Australia: analysis of management and breeding strategies. Agric Ecosys Env 129:261–267

Meinke H, Hammer GL, Van Keulen H et al (1998) Improving wheat simulation capabilities in Australia from a cropping systems perspective III. The integrated wheat model (I-WHEAT). Eur J Agron 8:101–116

Monzon JP, Sadras VO, Abbate PA et al (2007) Modelling management strategies for wheat-soybean double crops in the south-eastern Pampas. Field Crops Res 101:44–52

National Bureau of Statistics of China (2008) China agriculture yearbook. Agricultural Publishing House, Beijing

Peng S, Huang J, Sheehy JE et al (2004) Rice yields decline with higher night temperature from global warming. PNAS 101:9971–9975

Probert ME, Dimes JP, Keating BA et al (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow system. Agric Syst 56:1–28

Sadras VO, Monzon JP (2006) Modelled wheat phenology captures rising temperature trends: shortened time to flowering and maturity in Australia and Argentina. Field Crops Res 93:136–146

Smit B, Cai Y (1996) Climate change and agriculture in China. Global Enviro Change 6:205–214

Sun H, Zhang X, Chen S et al (2007) Effects of harvest and sowing time on the performance of the rotation of winter wheat–summer maize in the North China Plain. Ind Crop Prod 25:239–247

Tao F, Zhang Z (2010) Adaptation of maize production to climate change in North China Plain: quantify the relative contributions of adaptation options. Eur J Agron 33:103–116

Tao F, Yokozawa M, Hayashi Y et al (2003) Changes in agricultural water demands and soil moisture in China over the last half-century and their effects on agricultural production. Agric For Meteorol 118:251–261

Tao F, Yokozawa M, Xu YL et al (2006) Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric For Meteorol 138:82–92

Tao F, Yokozawa M, Liu J et al (2008) Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. Clim Res 38:83–94

Wang Q, Halbrendt C, Johnson SR (1995) Grain production and environmental management in China's fertilizer economy. J Environ Manage 47:283–296

Wang E, van Oosterom E, Meinke H et al (2003) The new APSIM-Wheat Model - performance and future improvements. In: Solutions for a better environment. Proceedings of the 11th Australian Agronomy Conference, Geelong, Victoria

Wang L, Zheng YF, Yu Q et al (2007) Applicability of agricultural production systems simulator (APSIM) in simulating the production and water use of wheat-maize continuous cropping system in North China Plain. Chin J Appl Ecol 18:2480–2486 (in Chinese)

Wang E, Yu Q, Wu D et al (2008) Climate, agricultural production and hydrological balance in the North China Plain. Int J Climatol 28:1959–1970

Wang H, Zhang M, Cai Y (2009a) Problems, challenges, and strategic options of grain security in China. Adv Agron 103:101–147

Wang J, Wang E, Luo Q et al (2009b) Modelling the sensitivity of wheat growth and water balance to climate change in southeast Australia. Clim Change 96:79–96

Wang J, Zhao T, Wang E et al (2010) Measurement and simulation of diurnal variations in water use efficiency and radiation use efficiency in an irrigated wheat-maize field in the North China Plain. NZJC&HS 38:119–135

Winter SR, Musick JT (1993) Wheat planting date effects on soil water extraction and grain yield. Agron J 85:912–916

Xiong W, Matthews R, Holman I et al (2007) Modelling China's potential maize production at regional scale under climate change. Clim Change 85:433–451

Xu FA, Zhao BZ (2001) Development of crop yield and water use efficiency in Fengqiu in the NCP of China. Acta Pedologica Sin 38:491–497 (in Chinese)

Yang Y, Yu Q, Wang J (2004) Spatio-temporal variations of principal climatic factors in North China and part of East China within past 40 years. Resour Sci 26:45–50 (in Chinese)

Zhang F, Zhao M, Zhang B (2004) Problem in the development of conservation tillage in North of China. J Agric Sci Technology 6:36–39 (in Chinese)

Zhang XY, Chen SY, Liu MY et al (2005) Improved water use efficiency associated with cultivars and agronomic management in the North China Plain. Agron J 97:783–790

Zhang Q, Gao Q, Herbert SJ et al (2010) Influence of sowing date on phonological stages, seed growth and marketable yield of four vegetable soybean cultivars in North-eastern USA. Afr J Agric Res 5:2556–2562

Zhou Y, He ZH, Sui XX et al (2007) Genetic improvement of grain yield and associated traits in the northern China winter wheat region from 1960 to 2000. Crop Sci 47:245–253