18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Modeling the response of wheat and maize productivity to climate variability and irrigation in the North China Plain

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Abstract: The North China Plain (NCP) is the largest agricultural production area in China, accounting for about 50% of wheat and 30% of maize grain production in China, with a dominant wheat-maize double cropping system. Due to the concentrated summer monsoon rainfall and inter-annual climate variability, irrigation is required to support the high productivity of the wheat-maize system, especially for the wheat crop and in the northern part of the plain, where excessive use of ground- and surface water for irrigation has caused rapid decline of groundwater tables and severe reduction of available surface water from the Yellow River. The productivity of the double cropping system and its reliance on decreasing water supplies under the variable climate need to be assessed. There is still a lack of systematic studies on how the productivity of the wheat-maize system could respond to different levels of reduced irrigation water supply.

A modeling approach is used in this study to analyze the response of wheat and maize productivity to climate variability and irrigation in the NCP. Firstly, we calibrated and evaluated the farming systems model APSIM for simulating the wheat-maize double cropping system with detailed field experiments conducted at three experimental sites (Luancheng, Yucheng and Fengqiu), which can represent the conditions of climate, soil and crop production in the NCP. The experiments covered 31 crop growing seasons, four genotypes of wheat and four of maize, and detailed measurements of leaf area index (LAI), above-ground biomass, grain yield, soil water and evapotranspiration (ET). The validated model was then applied to simulate the response of crop yield of the wheat-maize double cropping system to climate variability and irrigation water supply with historical climate data from 1961-2005 at Luancheng site.

The APSIM model could explain 73% of the variation in crop yield, with a root mean square deviation (RMSD) of 1.0 t ha^{-1} for grain yield, 1.5 t ha^{-1} for biomass and 1.3 m^2/m^2 for LAI. The RMSD values of simulated soil water and ET were 24.3 and 1.5 mm, respectively. The results revealed that the APSIM model is able to capture the observed responses of crop growth, yield and water use of the wheat-maize double cropping systems to climate variability and irrigation management in the NCP.

The simulated rain-fed wheat yield at Luncheng site ranged from 0 to 6.1 t ha^{-1} and rain-fed maize yield ranged from 0 to 9.7 t ha^{-1}. Each 60 mm additional irrigation increased crop yield by 1.2 t ha^{-1} and up to 540 mm irrigation would be required to achieve the yield potential of 7.1 t ha^{-1} for wheat and 8.3 t ha^{-1} for maize. If more than 180 mm water was available for irrigation, a partition of the water to maize would lead to higher total yield than applying it only to wheat.

Keywords: *Grain yield, Water balance, Double cropping system, APSIM, Model validation*

1. INTRODUCTION

The long term sustainability of agricultural systems needs to be assessed in the face of historical climate variability and future climate change. This is particularly the case when cropping systems are intensive and rely heavily on irrigation water supply where natural water resources are limited. The North China Plain (NCP) is the largest agricultural area in China, accounting for about 50% of wheat and 30% of maize produced in the nation with a dominant wheat-maize double cropping system. Due to the concentrated summer monsoon rainfall (80% falls in Jun-Sep) and inter-annual climate variability, irrigation is required to support the high productivity of the wheat-maize system, especially for wheat and in the northern part of the plain, where excessive use of ground- and surface water for irrigation has caused rapid decline of groundwater tables (Hu et al., 2005) and severe reduction of available surface water from the Yellow River (Xu, 2002). Although there have been several studies on crop water demand (Liu et al., 2002; Wang et al., 2008) and crop productivity under rain-fed and fully irrigated conditions (Wang and Han, 1990; Wang et al., 2008; Wu et al., 2006, 2008), there is still lack of systematic studies on how the productivity of the wheat-maize system could respond to different levels of reduced irrigation water supply.

A systematic study to capture crop productivity, as it responds to inter-annual climate variability and irrigation water supply, requires long-term crop yield data under various irrigation treatments. Experimental data are limited and an experimental approach for such a study is impractical. A robust model validated against local experimental data can be an effective means to tease out the complex relationship between crop productivity, climate and management options. The agricultural production systems model APSIM (Keating et al., 2003) has been widely used in Austraila to evaluate management options in the face of climate risk. APSIM allows flexible specification of cropping systems and management options and is well suited for the proposed study. However, it has not been widely tested in China and applied to investigate the wheat-maize double cropping system, and no detailed evaluation was done for its performance apart from some scattered testing (Chen et al., 2004; Wang et al., 2007).

The objectives of this study are: (1) to evaluate the performance of the APSIM model to simulate the wheat-maize double cropping system against a range of detailed field experiments taken at three different experimental sites in the NCP, and (2) to use the validated APSIM model to investigate the response of crop yield of the wheat-maize double cropping system to reduced water availability at different irrigation levels under the variable climate in the NCP in order to gain a better understanding of crop yield levels under future reduced water supply.

2. MATERIALS AND METHODS

2.1. Study sites and data

Field data from three experimental sites (Figure 1) were used for model verification: Luancheng (37.9^{o}N, 114.7^{o}E), Yucheng (36.1^{o}N, 116.0^{o}E), and Fengqiu (35.0^{o}N, 114.3^{o}E). They are three of 36 agricultural ecosystem stations of the Chinese Ecological Research Network (CERN). At all three sites, the cropping system is a winter wheat and summer maize double cropping rotation. Soil types are loam and sandy loam which are the dominant soil types in the NCP.

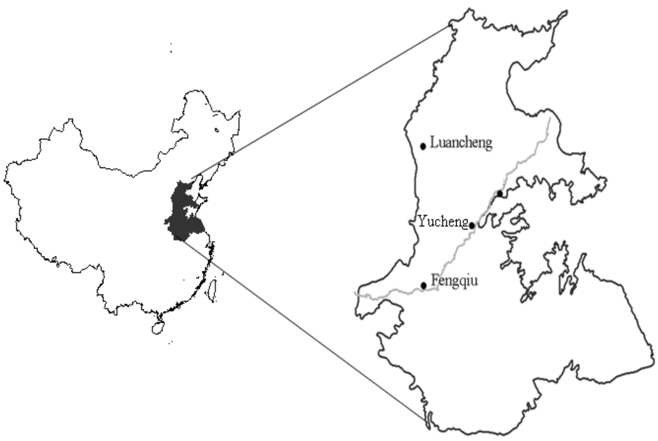

Figure 1. The North China Plain and the three study sites

Crop and soil measurements were from the field experiments carried out during 1998-2001 at Luancheng, 1997-2001 and 2002-2005 at Yucheng, and 2004-2006 at Fengqiu. The experiments at Luancheng with two water treatments (irrigated and rain-fed) have been described in detail by Zhang et al. (2004) and at Yucheng with irrigated treatment during 1997-2001 by Yu et al. (2006) and during 2002-2005 by Zhao et al. (2007). The measurements at Fengqiu were conducted in a regular crop monitoring experiment. Measurements included phenological stages, leaf area, above-ground biomass, final grain yield, soil water content and evapotranspiration (ET). Biomass and leaf area index (LAI) for both wheat and maize were measured at 5- or 7-day intervals. Soil water content measurements were available at two sites, with neutron probes down to 160 cm depth with 20 cm intervals at Luancheng, and to 150 cm depth with 10 cm intervals at Yucheng. ET was measured daily with weighing lysimeters with a precision of 0.02 mm day^{-1} at Luancheng and Fengqiu and 0.04 mm day^{-1} at Yucheng. Solar radiation, maximum and minimum temperature and rainfall were collected from automatic meteorological stations near the experimental sites.

2.2. The APSIM model, its calibration and verification

APSIM is an agricultural production system simulator developed and used for improving risk management under variable climate (Keating et al., 2003). APSIM version 5.3 was tested to study the yield responses of wheat and maize to climate variability and irrigation water supply. Field measurement data in wheat-maize rotations conducted at the three experimental sites were used to calibrate the model and test its performance.

Specific soil characteristics required for the APSIM model such as saturated water content, drained upper limit, lower limit for plant available soil water and bulky density were obtained from detailed soil analysis from three experimental sites. Plant available water capacity (PAWC) to 150 cm depth (maximum rooting depth) was 335 mm for the Luancheng, 341 mm for Yucheng and 204 mm for Fengqiu. The nutrient properties were set based on literature or the default values in the module. The calibrated genetic coefficients for the wheat and maize cultivars planted in the experiments are listed in Table 1 and 2, respectively. These parameters were derived using a trial and error method based on field observed phenological stages, LAI, biomass and grain yield of wheat and maize during 1999-2000 at Luancheng, during 1998-1999 and 2002-2003 at Yucheng and during 2004-2005 at Fengqiu. After calibration, the APSIM model was then run for all cropping seasons for model evaluation.

Table 1 Derived parameters for APSIM-Wheat at Luancheng (Gaoyou 503), Yucheng (Zhixuan 1, Keyu 13) and Fengqiu (Zhengmai 9023).

Parameters	Cultivars			
	Gaoyou 503	Xifeng 24	Keyu 13	Zhengmai 9023
vern_sens[a]	1.7	1.5	1.5	1.8
photop_sens[b]	2.3	2.0	2.0	2.0
startgf_to_mat[c]	500	500	420	420
grains_pg_stem[d]	23.0	22.0	22.0	26.0
Pot_grain_fil_rate[e]	0.0023	0.0025	0.0023	0.0025
Phyllochron[f]	85	85	85	85

[a]Sensitivity to vernalisation
[b]Sensitivity to photoperiod
[c]Thermal time from beginning of grain filling to maturity (□d)
[d]Coefficient of kernel number per stem weight at anthesis (g/stem)
[e]Potential grain filling rate (g/kernel·d)
[f]Phyllochron interval (□d/leaf appearance)

Table 2 Derived values of parameters for APSIM-Maize at Luancheng (Yandan 21), Yucheng (Yedan 22, 981) and Fengqiu (Zhengdan 958)

Parameters	Cultivars			
	Yandan 21	Yedan 22	981	Zhengdan 958
Head_grain#_max[a]	500	560	600	600
Grain_gth_rate[b]	9	10	10	10
tt_emerg_endjuv[c]	240	240	240	280
photoperiod_slope[f]	15	19	13	20
tt_flower_to_mat[e]	700	700	650	600
tt_flow_st_grain[f]	120	160	130	160

[a]Maximum grain numbers per head
[b]Grain filling rate (mg/grain/day)
[c]Thermal time (TT) from emergence to end of juvenile stage (EJV) (℃d)
[d]Increase in TT with photoperiod from EJV to floral initiation (℃d/hour)
[e]Thermal time required from flowering to maturity (℃d)
[f]Thermal time required from flowering to starting grain filling (℃d)
[g]Radiation use efficiency[f]Phyllochron interval (□d/leaf appearance)

Other changes in the model include: the low temperature of -15^{o}C, which causes total leaf death, was changed to -20^{o}C (Jin et al., 1994); Temperature responses of thermal time were modified based on Wang and Engel (1998); Maize radiation use efficiency was modified from 1.6 to 1.8 g MJ^{-1} to improve biomass and yield simulation.

For model performance, the coefficient of determination regression line that was forced through the origin was used, which represents the true deviation of the model simulations from observations. The slope (β)

presents a possible over- or underestimation. The root mean square~~d~~ deviation (RMSD) was calculated to provide a measure of the absolute magnitude of the prediction error.

2.3. Modelling crop yield responses to climate variability and irrigation water supply

After the verification showing confidence in the simulation of crop yield and water use, the APSIM model was applied to simulate the responses of crop yield of the wheat-maize double cropping system to historical climate variation and different irrigation treatments at Luancheng. Daily climate data from 1961 to 2005 were obtained directly from the weather station about 20 km away from the experimental site. Two scenarios of irrigation treatments were simulated.

- A wheat-maize double cropping system with irrigation water applied to both crops (DCIWM): total irrigation water supply ranged from 0 (rain-fed treatment) to 600 mm at 60 mm intervals – 11 irrigation treatments in total. More water was applied to wheat due to the drier wheat season. The scenario was designed to investigate the yield response of wheat and maize at different water supply levels.
- A wheat-maize double cropping system with irrigation water applied only to wheat (DCIW): total irrigation water supply ranged from 60 to 420 mm at 60 mm intervals – 7 irrigation treatments in total. This scenario was designed to explore the performance of the double cropping system at reduced water supply, and the impact of wheat irrigation on subsequent maize yield.

The above scenarios allow evaluation of the productivity of a double cropping system as it responds to climate variability and irrigation water supply. The simulation results were used to generate the yield responses to various irrigation levels.

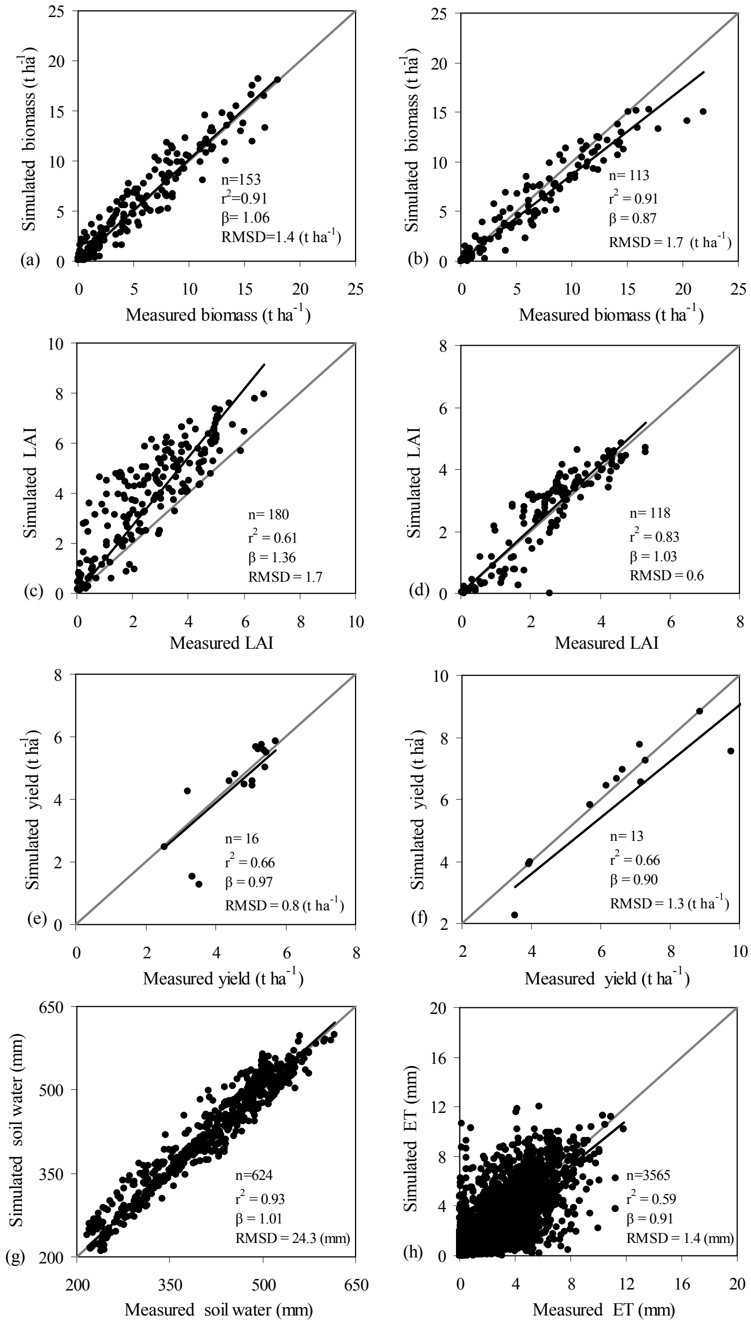

Figure 2 Comparison of observed and simulated values of above-ground biomass of wheat (a) and maize (b), LAI of wheat (c) and maize (d), grain yield of wheat (e) and maize (f), soil water content (g) and evapotranpiration (ET) (h) with all the data from Luancheng (1998-2001), Yucheng (1997-01, 2002-05) and Fengqiu (2004-06).

3. RESULTS

3.1. Model verification

Figure 2 shows the statistical comparison of all simulated and observed values. The model tended to overestimate wheat LAI (Fig. 2c), but to slightly underestimate maize biomass and yield (Fig. 2b, f). The overall performance of the model to simulate crop growth and water use was very satisfactory, with a coefficient of determination r^2 (1:1) of 0.73 and RMSD of 1.0 t ha^{-1} for grain yield of wheat and maize. The RMSD for biomass of two crops simulation was 1.5 t ha^{-1} and for LAI was 1.3. The high r^2 (1:1) value and β values very close to 1.0 indicated close matches of simulated to measured values for biomass (Fig. 2a, b), LAI (Fig. 2d), grain yield (Fig. 2e, f) and crop water use (Fig. 2h) and soil water dynamics (Fig. 2g). It is always difficult to simulate daily crop ET due to its great variation, which led to the scattering of the daily ET in Fig. 2h.

The above results indicate that the calibrated APSIM model can be used confidently to simulate the responses of wheat and maize yield to the impact of climate variability and to irrigation water supply.

3.2. Response of crop yields to irrigation under climate variability

Figure 3 shows the simulated yield range of wheat plus maize when irrigation was applied to both crops (Fig. 3a) or only to wheat crop (Fig. 3d). Under the condition of no irrigation water available, simulated total grain yield of double cropped wheat and maize showed large inter-annual variation due to inter-annual climate variability, ranging from 0 to 15.8 t ha^{-1} with an average of 4.8 t ha^{-1} (Fig. 3a). Rain-fed wheat yield ranged from 0 to 6.1 t ha^{-1} (Fig. 3b), while rain-fed maize yield from 0 to 9.7 t ha^{-1} (Fig. 3c). Irrigation reduced inter-annual variability of crop yield caused by rainfall variability and increased the average crop yield almost linearly up to the irrigation amount of 480-540 mm (Fig. 3a, b, c). Irrigation mainly increased the lowest crop yield, which was the yield under dried years. When both wheat and maize were irrigated, the simulated lowest crop yield was 0.1 t ha^{-1} under 60 mm irrigation and it was increased to 9.5 t ha^{-1} when 600 mm irrigation water was applied, while the highest yield was 15.9 t ha^{-1} under 60 mm irrigation and only increased slightly with increase in irrigation amounts (Fig. 3a). The highest crop yield was normally achieved in wet years when rainfall could meet crop water demand. Thus, irrigation had little effects on crop yield in those years. Lack of increase in the average yield of wheat and maize when irrigation amount was above 540 mm indicates that 540 mm irrigation could meet crop water demand in most years.

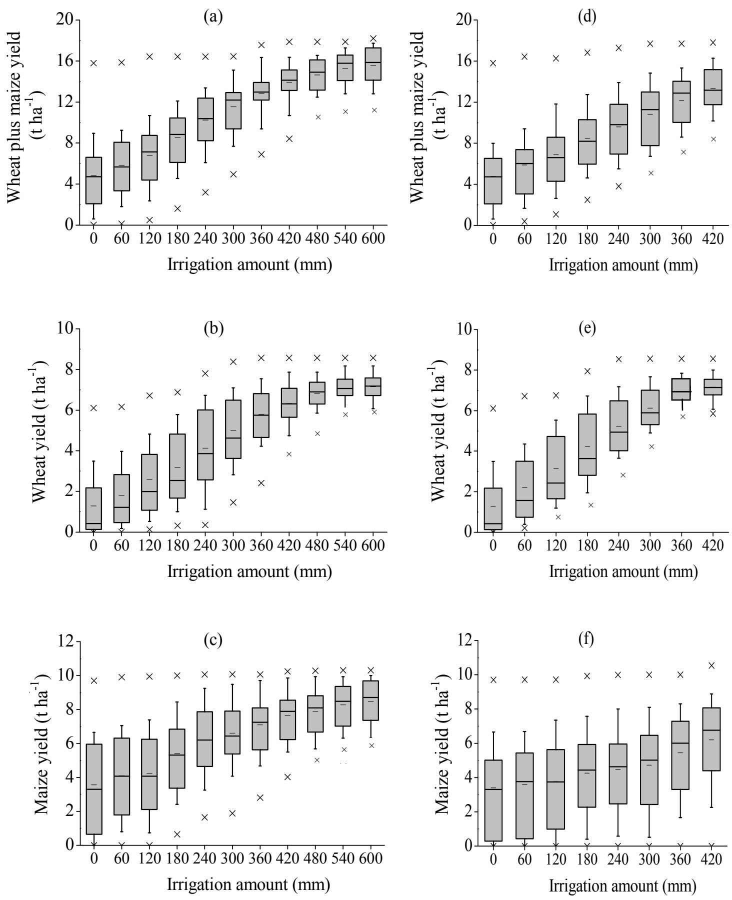

Figure 3. Simulated yield response to different irrigation levels of the wheat-maize double cropping system at Luancheng (1961-2005). (a), (b) and (c) show the grain yield of wheat plus maize, wheat, and maize respectively when irrigation was applied to both crops (Scenario DCIWM); (d), (e), and (f) show the same yields when irrigation was applied only to wheat crop (Scenario SCIM). Details see text. The box plots show the 0, 10, 25, 50, 75, 90 and 100 percentiles, the short line in the boxes show the mean.

On average, every 60 mm more irrigation application could increase crop yield by 1.2 t ha^{-1}. The variation of crop yield under rain-fed conditions was 0.69 and it was reduced to 0.56 with 60 mm irrigation. When 480-600 mm irrigation was applied, the crop yield variability was the smallest with value around 0.13. Wheat yield reached a stable level with a range of 5.8 to 8.6 t ha^{-1} under 330 mm irrigation (Fig. 3b) and that of maize reached a stable level with a range of 5.6 to 10.3 t ha^{-1} under 210 mm irrigation (Fig. 3c). Under 60 mm irrigation, average wheat yield accounted for 31% of total crop yield and maize yield accounted for 69%, while under 600 mm irrigation, this proportion of wheat yield attained the highest value of 46% and maize was the lowest with 54% (Fig.3a, b, c).

When irrigation was only applied to wheat crop in the double cropping system, the ranges of crop yield under 60 to 180 mm irrigation (Fig. 3d) were similar to those under the corresponding irrigation amounts when irrigation applied to both wheat and maize (Fig. 3a). But when irrigation was more than 180 mm, the average total crop yield was lower (Fig. 3d) due to the lower maize yield (Fig. 3f compared with Fig. 3c). This indicated that even the concentrated summer monsoon rainfall could not meet maize crop water demand in some years. This also implied that a certain partition of irrigation water to maize crop could lead to higher total crop yield. Under this scenario, wheat yield attained stable levels with the range of 5.9 to 8.6 t ha^{-1} when 360 mm of irrigation was applied (Fig. 3e). The increase in maize yield (Fig. 3f) with irrigation was due to the increased soil water left from wheat season. The proportion of average wheat yield accounting for the total grain yield increased from 37% under 60 mm irrigation to 54% under 600 mm irrigation.

4. DISCUSSION AND CONCLUSION

APSIM has been proven to perform well in simulating crop growth and development, grain yield and soil water and N dynamics in various cropping systems in Australia (Meinke et al., 1998; Probert et al., 1998; Wang et al., 2003b; Lilley and Kirkgaard, 2007) and other places (Asseng, et al., 2000; Nelson et al., 1998; Robertson et al., 2000; Moeller et al., 2007). This study provides the verification of APSIM against continuous multi-seasonal data of the wheat-maize double cropping system from three experimental sites in the semi-arid NCP of China. The good agreement of the simulated and measured values of crop LAI, biomass and yield, ET and soil water content indicate the robustness of the model in simulating the productivity and water use of the double cropping system in China. For simulating the winter wheat varieties, it was necessary to change the low temperature threshold for leaf area cold damage and the temperature response of crop phenological development. For maize crop, an increased RUE value to 1.8 g MJ^{-1} was required to better simulate the biomass and yield. With the cultivar parameters for wheat and maize derived, the calibrated model was then able to simulate the leaf area dynamics, biomass and yield and water use in response to different levels of irrigation water supply under the NCP climate.

The simulated wheat yield response to water supply (Fig. 3b) was comparable to that of Liu et al. (2005) derived from experimental data. However, their response was derived versus crop ET, while ours versus irrigation water supply. In our study, the simulated responses reflect the effects of irrigation water supply on crop yield under the background of long-term climate variability. For any given level of irrigation water, we were able to produce a probability distribution of crop yield (Fig. 3). The range (or variation) of crop yield under a given irrigation level was caused by climate variability. Such a response surface extends the knowledge of yield response to irrigation management obtained from several year's experimentation to cover the full impact of long-term climate variability. It enables a better understanding of how wheat and maize yield varies with water availability and climate.

It can be concluded that, once properly calibrated, the APSIM model is able to capture the observed responses of crop growth, yield and water use of the wheat-maize double cropping system to climate variations and irrigation management at the three experimental sites in the NCP. It can be used to generate yield responses to climate variability and irrigation water supply levels. Under the Luancheng climate, in a wheat-maize double cropping system, rainfed wheat yield ranged from 0 to 6.1 t ha^{-1} (mean 1.2 t ha^{-1}) and maize yield ranged from 0 to 9.7 t ha^{-1} (mean 3.5 t ha^{-1}). Each 60 mm addition of irrigation would lead to an increase in yield by 1.2 t ha^{-1} and up to 540 mm irrigation water would be required to achieve the full yield potential of 7.1 t ha^{-1} for wheat and 8.3 t ha^{-1} for maize (total 15.3 t ha^{-1}). It should be emphasized that this amount of water would not be fully used by crops, some will be lost by drainage, particularly in the treatments with high irrigation amounts. If more than 180 mm water was available for irrigation, a partition of the water to wheat and maize would lead to higher total yield than applying it only to wheat.

ACKNOWLEDGMENTS

We acknowledge the funding support from the National High Technology Research and Development Program of China (Grant # 2008AA10Z215), Chinese Academy of Sciences International Partnership Project "Human Activities and Ecosystem Changes" and the CSIRO-MOE Research Fellowship Program.

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