Modeling Wheat and Maize Productivity as Affected by Climate Variation and Irrigation Supply in North China Plain

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Agroclimatology

ABSTRACT

A modeling approach was used to analyze the response of crop productivity to irrigation in the North China Plain (NCP), where excessive use of water for irrigation has caused rapid decline in groundwater table. We calibrated and evaluated the farming systems model APSIM with data from three sites (Luancheng, Yucheng and Fengqiu). The calibrated model was applied to simulate the response of crop yield to climate variation and irrigation. The results show that the APSIM model was able to simulate growth and yield of wheat and maize in a double cropping system. Root mean squared error (RMSE) of yield and biomass simulations were 0.83 and 1.40 t ha^{-1} for wheat, 1.07 and 1.70 t ha^{-1} for maize, respectively. Soil water and ET were also reasonably predicted, with RMSE of 24.33 mm 1.49 mm d^{-1}, respectively. The simulated rainfed yield range was 0~6.1 t ha^{-1} for wheat and 0~9.7 t ha^{-1} for maize in the double cropping system. Each 60 mm additional irrigation increased crop yield by 1.2 t ha^{-1} and 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 >180 mm irrigation water was available, partition it to wheat and maize would lead to higher total yield than applying it only to wheat. Changing to a single crop system would lead to significantly lower annual total crop yield, although yield of the single crop could be increased due to increased stored soil moisture.

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 NCP (114–121°E and 32–40°N) is the largest agricultural area in China, known as "the bread basket of China" (Fig. 1). It covers an area of 320,000 km^2, 17.95 million ha of which is used for agriculture, and supports a population of more than 200 million. A dominant wheat-maize double cropping system has been developed in the last three to four decades, which provides about 50% of wheat and 30% of maize grains for the nation. The soil of the NCP is a mixture of river-laid alluvium and wind-deposited loess, with the dominant soil type of a loam of Aeolian origin (Zhang et al., 2005). The NCP has a typical continental monsoon climate with cold dry winter and hot humid summer. The minimum (January) and maximum (July) monthly average temperature was −6 to 0°C and 25 to 28°C, respectively. Annual precipitation is highly variable ranging from 300 to 1000 mm (Zhang and You, 1996). More than 70% of the total precipitation occurs in the summer months (from June–September), coinciding with the maize growing season. As a result, the spring time, that is, the active growing period of wheat, is very dry. Potential evapotranspiration (PET) of 800 to 900 mm of the two crops greatly exceeds mean annual precipitation in most part of NCP (Liu et al., 2002). Therefore, the relatively high crop yield in the past few decades has been achieved by irrigation development relying much on ground and surface water resources (Zhang et al., 2002). Excessive use of groundwater for irrigation has caused rapid decline of groundwater tables at an average rate of about 1 m yr^{-1} (Hu et al., 2005). Furthermore, the amount of available surface water from the Yellow River has been reduced significantly in recent decades due to lower rainfall and heavy upstream extraction for irrigation and other purposes (Xu, 2002).

A systematic study to capture crop productivity, as it responds to interannual 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. Agricultural production systems models capture the interaction between crop growth, soil and climate conditions as well as the impact of management practices such as irrigation and fertilization. A simulation approach with a robust model validated against local experimental data is an effective means to tease out the complex relationship between crop productivity, climate, and management options. Such an approach has been widely used for system study on agricultural systems performance as impacted by climate variability and management interventions (Elliott and Cole, 1989; Stapper and Harris, 1989; English et al., 1990; Meinke et al., 1993; Thornton et al., 1995; Mathews et al., 2002; Yu et al., 2006).

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Abbreviations: ET, evapotranspiration; LAI, leaf area index; NCP, North China Plain; PAWC, water storage capacity; PET, potential evapotranspiration; RMSE, root mean squared error; RUE, radiation use efficiency.

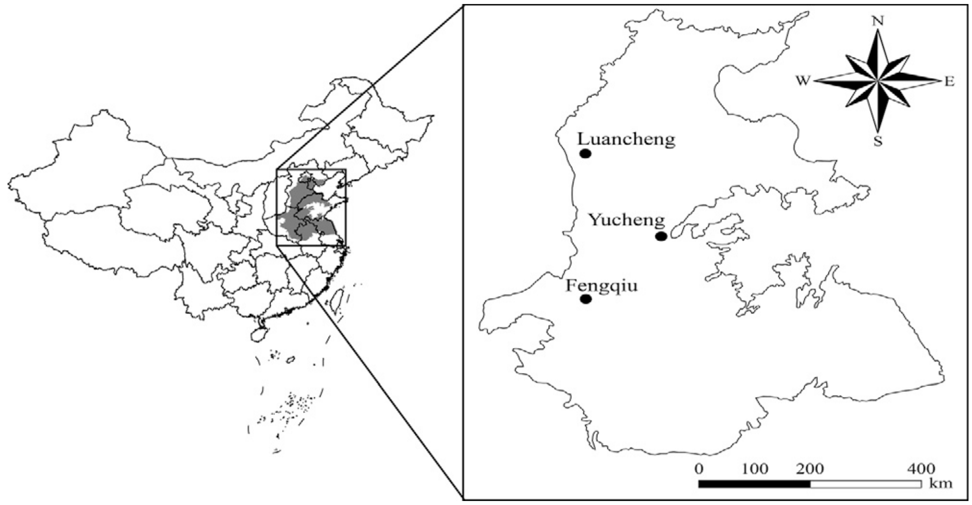

Fig. 1. The North China Plain and the locations of the three experimental sites (Luancheng, Yucheng, and Fengqiu) used in this study (from Gong, 1985).

Although, several studies have been performed in the NCP to simulate crop productivity to climate variations and irrigation management (Wang and Han, 1990; Wang et al., 2008; Wu et al., 2006, 2008), only two extreme conditions of irrigation water supply were considered, that is, full irrigation and no irrigation. Binder et al. (2008) used DSSAT-maize to quantify the production potential of summer and spring maize constrained by climate and soil in the NCP. Their simulations showed that yields of spring and summer maize were limited by water stress and the duration of the growing period, respectively. Fang et al. (2008) simulated water management effects in the wheat and maize double cropping system using the RZWQM model, and concluded that soil water at 50 to 60%of the field capacity in the 50-cm profile was adequate for obtaining acceptable yield levels. In another study (Fang et al., 2009), the RZWQM2 model was used to investigate irrigation strategies in the wheat-maize double cropping system. They found that, with limited irrigation water available (such as 200 or 250 mm yr^{-1}), 80% of the water applied to the critical wheat growth stages (stem extension, booting, grain filling) and 20% irrigated at maize sowing time is optimal for high crop yield and the least environmental impact in the area. However, there is still lack of systematic studies on how crop productivity will respond to different levels of irrigation water supply under the background of climate variations.

The agricultural production systems model APSIM (Keating et al., 2003) has been widely used in Australia (Probert et al., 1995; Asseng et al., 1998a, 1998b; Verburg and Bond, 2003; Wang et al., 2003; Lilley and Kirkegaard, 2007) and other countries (Asseng et al., 2000; Lyon et al., 2003; Sun and Feng, 2005) to evaluate management options in the face of climate risk. However, it has not been widely tested and applied to investigate the wheat and maize double cropping system in China except some scattered testing (Chen et al., 2004; Wang et al., 2007). Although, Wang et al. (2007) evaluated the model performance to simulate leaf area index (LAI), biomass, and soil water in the wheat-maize double cropping system with the experimental data from Yucheng site in the NCP, the grain yield and crop water use were not evaluated, which were more important for model performance evaluation when crop model was used to study crop production and water balance. They provided only qualitative or graphical analysis, but did not statistically assess the model performance. The APSIM model has not yet been evaluated in the NCP with multiple-year experimental data from different sites with different climate, soil, and crop varieties.

The objectives of this study are: (i) to evaluate the performance of APSIM for simulating crop yield and water balance in the wheat and maize double cropping system in the NCP and (ii) to investigate the response of crop yield to reduced irrigation water input in the wheat-maize double cropping system as well as in future possible wheat or maize single cropping systems.

MATERIALS AND METHODS

Experimental Sites and Data

Field data from three experimental stations (Fig. 1, Table 1) were used to calibrate and test the APSIM model: Luancheng Agro-ecosystem Station located in the northern part of the NCP, Yucheng Comprehensive Experimental Station located in the center of the NCP, and Fengqiu Agro-ecological Experimental Station located roughly in the west edge of the southern part of the NCP. They are three Agricultural Ecosystem Stations of

Table 1. Details of experimental sites.

Site	Latitude °N	Longitude °E	Annual rainfall	Wheat season rainfall	Maize season rainfall	Groundwater table
			mm			m
Luancheng	37.9	114.7	481†	116	365	32
Yucheng	36.1	116.0	582‡	145	437	2–4
Fengqiu	35.0	114.3	615§	246	369	2–4

† Average annual rainfall at Luancheng site was measured at the automatic weather station near the experimental field.

‡ Average annual rainfall at Yucheng site was measured at the automatic weather station near the experimental field.

§ Average annual rainfall at Fengqiu site was measured at the automatic weather station near the experimental field.

Chinese Ecological Research Network (CERN). At all three sites, the main cropping system was a winter wheat and summer maize double cropping rotation. In the rotation, the second crop was usually planted after the first one was harvested. The growing season for wheat is from early October to early June, and for maize from mid-June to late September. Average annual rainfall at the three sites ranged from 481 to 615 mm, most of which falls in maize growing season. At the three sites, soil types are loam and sandy loam, which are the dominant soil types in the NCP. Detailed soil parameters are given in Table 2. The soil texture was determined using the gravitometer method (Li, 1983). Bulk density (BD) was measured using the cutting ring method. Saturated volumetric water content (SAT) was determined by weighing the saturated samples, and then reweighing the samples after oven drying and cooling them. Drained upper limit (DUL) and lower limit (LL15) were determined as the water contents at −10 kPa and −1500 kPa suctions, respectively.

Field experiments were performed during 1998 to 2001 at Luancheng, 1997 to 2001 and 2002 to 2005 at Yucheng, and 2004 to 2006 at Fengqiu to measure the performance of the wheat-maize double cropping systems and their water use. The experiments at Luancheng (with two water treatments: irrigation applied during critical crop growth stages and irrigation only applied at sowing time) during 1997 to 2001 were described in detail by Zhang et al. (2004) and at Yucheng with irrigation treatments during 1997 to 2001 by Yu et al. (2006) and during 2002 to 2005 by Zhao et al. (2007). The measurements at Fengqiu were conducted in a regular crop monitoring experiment. Wheat variety Gaoyou 503 and maize variety Yandan 21 were planted at Luancheng. At Yucheng, wheat variety Zhixuan 1 and maize variety Yedan 22 were used during 1997to 2001 and wheat variety Keyu 13 and maize variety 981 during 2002 to 2005. At Fengqiu, the variety planted was wheat Zhengmai 9023 and maize Zhengdan 958.

Measurements included phenological stages, LAI, aboveground biomass, final grain yield, soil water content, and evapotranspiration (ET). Biomass and LAI for both wheat and maize were measured at 5- or 7-d intervals. Biomass was calculated by weighing air-dried samples. The LAI was measured with an electronic leaf-area meter. Soil water content measurements were available at two sites: at Luancheng measured using neutron probes down to 160 cm depth at 20 cm intervals, and at Yucheng down to 150 cm depth at 10 cm intervals. The ET was measured daily with weighing lysimeters filled with undisturbed soil with a precision of 0.02 mm d^{-1} at Luancheng (Wang et al., 2001; Zhang et al., 2002) and Fengqiu (Xie, 2001) and 0.04 mm d^{-1} at Yucheng (Yang et al., 2001). The lysimeter was located next to the experimental site at each of the three study sites, on which crop, soil and management practices such as irrigation and fertilizer were similar to those at the experimental site. Thus the ET measured with the lysimeter can be used to evaluate model performance for predicting ET of the wheat and maize double cropping system conducted in the field experiment.

Daily solar radiation, maximum and minimum temperature, and rainfall were collected from automatic weather stations near the three experimental sites.

Table 2. Soil characteristics at Luancheng, Yucheng, and Fengqiu station: saturated water content (SAT), drained upper limit (DUL), lower limit for plant available soil water (LL), and bulky density (BD).

Soil depth	Soil texture	SAT	DUL	LL	BD
cm		v/v			g cm^{-3}
Luancheng station					
0–20	loam	0.44	0.36	0.10	1.39
20–40	loam	0.44	0.35	0.11	1.50
40–80	loam	0.43	0.33	0.14	1.49
80–120	silty clay loam	0.44	0.34	0.13	1.54
120–160	clay loam	0.48	0.39	0.14	1.63
Yucheng station					
0–20	sandy loam	0.30	0.24	0.08	1.43
20–60	sandy loam	0.34	0.28	0.10	1.41
60–100	sandy loam	0.37	0.30	0.12	1.46
100–150	silty loam	0.39	0.32	0.13	1.49
Fengqiu station					
0–30	sandy loam	0.43	0.21	0.12	1.45
30–70	clay loam	0.42	0.31	0.14	1.46
70–150	sandy loam	0.47	0.36	0.15	1.38

APSIM Model

APSIM is an agricultural production system simulator developed for improving risk management under variable climate (McCown et al., 1996; Keating et al., 2003). The APSIM model is a component-based simulation framework and can simulate crop growth and development, soil water and N dynamics and the interactions between climate, soil, crop and management practices. It runs on a daily time-step with daily weather data including maximum and minimum temperature, rainfall, and solar radiation. In this study, APSIM version 5.3 was applied to simulate the phenological development, biomass growth, grain yield, and water use of wheat and maize crops as well as soil water dynamics in the double cropping system. Six built-in modules were used: Wheat, Maize, Soilwat2, Soiln2, SurfaceOM, Fertilize, Irrigate, and Manager. The Manager module, together with the Fertilize and Irrigate modules, was used for flexible specification of management options like crop sowing, residue management, tillage, irrigation, and fertilizer applications.

In the APSIM model, 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 vernalization and photoperiod in periods when crop is sensitive to vernalization 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, and it can be reduced by suboptimal temperatures, water, or N deficit. Grain yield is a function of grain number, grain filling rate, and assimilate retranslocation. The PET was calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972). Soil water characteristics are specified in terms of SAT, DUL, and LL15 of a sequence of soil layers. The number and thickness of each layer are specified by the user. The vertical water movements in the layered soil are simulated using a multi-layer

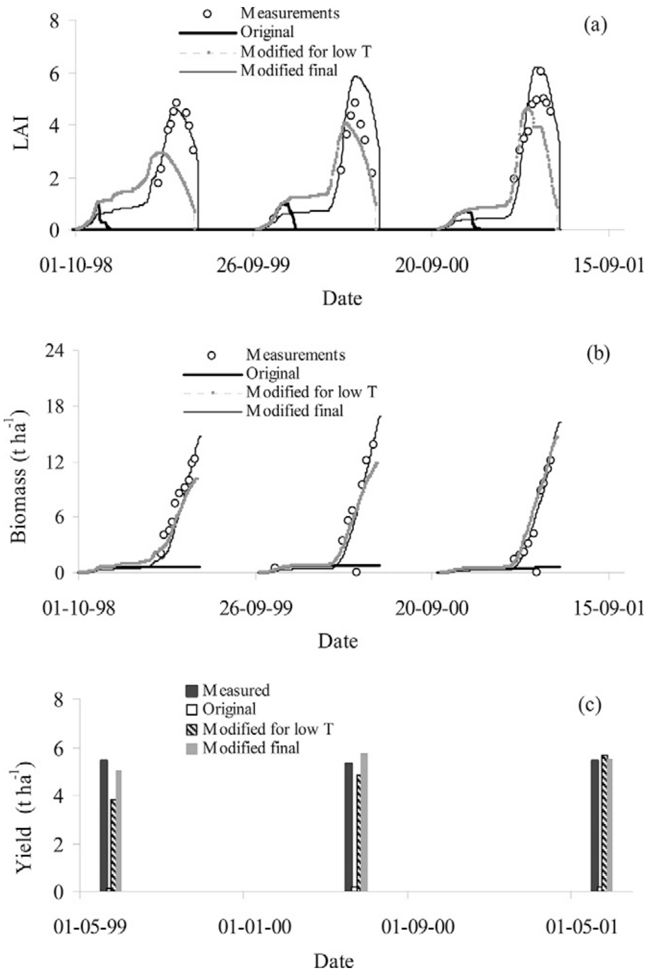

Fig. 2. (a) Measured and simulated leaf area index, (b) biomass, and (c) yield of wheat at Luancheng under irrigation applied during critical crop growth stages with the original and modified APSIM responses.

cascading approach, which is based on a water balance model described in detail by Probert et al. (1998). Runoff is estimated using a modified USDA curve number approach (Soil Conservation Service, 1972). The curve number for partitioning daily rainfall into runoff and infiltration was estimated from surface condition and slope following Littleboy (1997). Evaporation from the soil surface is calculated based on the concept of first and second stage evaporation (Ritchie, 1972). Crop water demand (potential transpiration) is estimated based on a transpiration efficiency (TE, biomass produced per unit water transpired) concept proposed by Tanner and Sinclair (1983).

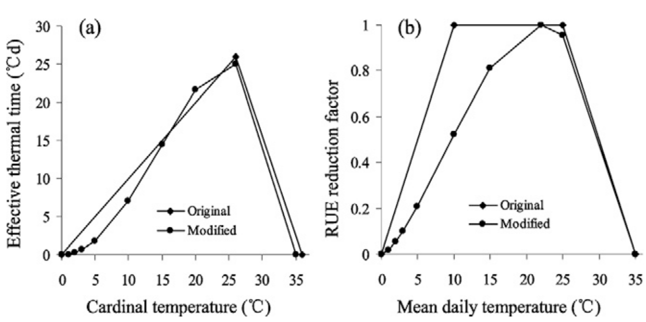

Fig. 3. The original and modified temperature response curves of (a) thermal time and (b) radiation use efficiency for wheat.

Daily radiation, maximum and minimum temperatures are required for 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/.

Model Calibration and Performance Evaluation

For model calibration, the experimental data from the irrigation treatment at Luancheng were used. First, cultivar parameters (Tables 3 and 4) were derived using a trial and error method to match the simulated crop anthesis and maturity dates to the observed ones. Then the model was run with the derived crop phenological parameters, and the performance was checked in terms of LAI, biomass, and yield simulations for both wheat and maize crops. The simulation results showed that the model severely underpredicted LAI, biomass, and yield of wheat (Fig. 2), and also underestimated the biomass and yield of maize. Detailed process-level analysis revealed that the underestimation was mainly due to the incorrect temperature response of physiological processes implemented in the model for wheat crop and lower radiation use efficiency (RUE) for maize crop.

In the original model, it assumes that all the green leaves of wheat will be killed when daily minimum temperature drops to below –15°C. In the NCP, this threshold temperature was found to be –20°C (Jin et al., 1994). Changing the threshold temperature from –15 to –20°C significantly reduced the low temperature induced leaf senescence and improved the simulation for wheat (Fig. 2). However, this change did not entirely eliminate the problem of significant underestimation, especially for maximum LAI and biomass (Fig. 2). Further modifications were made to the temperature response of thermal time calculation and the temperature response of RUE for wheat based on Wang and Engel (1998) and Porter and Gawith (1999) (Fig. 3), which led to further improvement of LAI, biomass, and grain yield simulations for wheat (Fig. 2). For maize crop, it was found that the underestimation was mainly due to low RUE. Therefore, the RUE for maize was Increased from 1.6 g MJ^{-1} in the current model to 1.8 g MJ^{-1} (Bastiaanssen and Ali, 2003; Tao et al., 2005), which significantly improved the biomass and yield simulations (Fig. 4).

For each specific crop cultivar, the cultivar parameters in Table 3 and Table 4 have to be derived to specify the cultivar differences in the simulation. The limited number of experimental years and the frequent change in crop cultivars made it impossible to derive these cultivar parameters for fully independent model calibration and validation. Thus, the cultivar parameters were derived using trial and error method based on all the available data, to ensure a correct simulation of phenological stages (mainly flowering and maturity) and reasonable harvest indices. Apart from these cultivar parameters, all other changes to the model were based on literature data, that is, were not derived to optimize the model performance. In that regard, all the experimental data (LAI, biomass, yield, and water use etc.) can be used to test the model performance, except for the phenology observations.

Specific soil characteristics required for the APSIM model such as SAT, DUL, LL15, and BD were from the three experimental sites (Table 2). Plant available soil water storage capacity (PAWC) to 150 cm depth (maximum rooting depth, set according to Zhang et al., 2006) was 350 mm for the Luancheng, 263 mm for Yucheng, and 204 mm for Fengqiu.

For the evaluation of model performance, six indices were used: (i) the coefficient of determination for $y = \beta x$ line [r^2 (1:1)], representing the true deviation of the model simulations from observations; (ii) the slope (β) of the regression line, presenting a possible over- or underestimation; (iii) RMSE, providing a measure of the absolute magnitude of the error; and (iv) model efficiency (ME), presenting variation in measured values accounted for the model. The parameters were calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_{\mathrm{i}} - O_{\mathrm{i}})^2}$$

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(P_{\mathrm{i}} - O_{\mathrm{i}})^2}{\sum_{i=1}^{n}(O_{\mathrm{i}} - O_{\mathrm{avg}})^2}$$

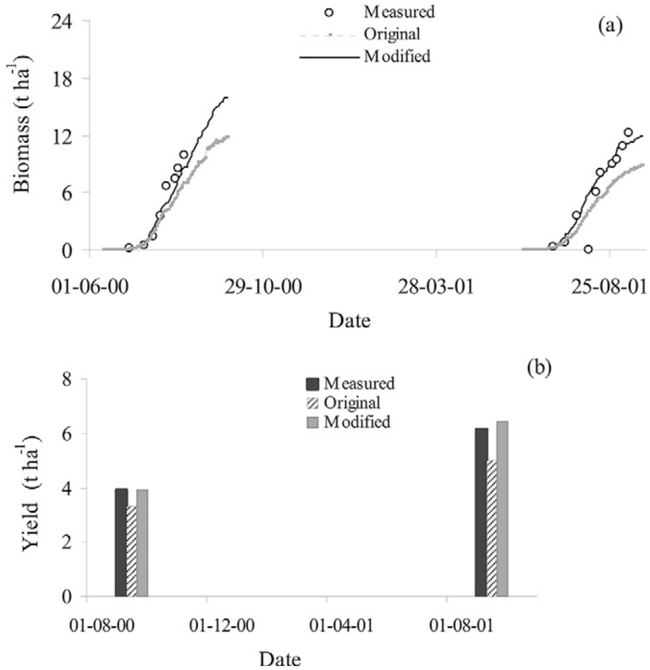

Fig. 4. (a) Measured and simulated biomass and (b) yield of maize at Luancheng under irrigation applied during critical crop growth stages with the original and modified RUE.

Modeling Response of Crop Yield to Limited Irrigation Water Supply under Variable Climate Conditions

The validated APSIM model was applied to simulate the responses of crop yield of the wheat-maize double or single cropping system to historical climate variation and different irrigation supplies at Luancheng County, where the Luancheng station is located. Luancheng county is a highly productive agricultural area, famous for its 15 t ha^{-1} yr^{-1} of grain production in one rotation of winter wheat and maize (Yang et al., 2006). However, the sustainability of agricultural systems has been affected by serious water shortage as a result of over-pumping groundwater for irrigation. The climate, soil, and crop conditions in this area are representative of the north NCP (Hu et al., 2005; Qiu et al., 2008).

Daily climate data from 1961 to 2005 were obtained directly from the weather station about 20 km away from the experimental site. One wheat cultivar (Gaoyou 503) and one maize cultivar (Yandan 21) were used in the simulations. The use of the fixed cultivars eliminates the impacts of other factors, and enables the investigation of the impact of climate variability and water supply levels on crop yields. Four scenarios of irrigation treatments were simulated. The split of irrigation water into wheat and maize season in each scenario and treatment is shown in Table 5.

- *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. This

Table 3. Derived values of cultivar parameters for Wheat at Luancheng (Variety Gaoyou 503), Yucheng (Variety Zhixuan 1, Keyu 13), and Fengqiu (Variety Zhengmai 9023).

Parameters	Derived values			
	Gaoyou 503	Xifeng 24	Keyu 13	Zhengmai 9023
Vern_sens†	1.7	1.5	1.5	1.8
photop_sens‡	2.3	2.0	2.0	2.0
startgf_to_mat§	500	500	420	420
grains_per_gram_stem¶	23.0	22.0	22.0	26.0
Potential_grain_filling_rate#	0.0023	0.0025	0.0023	0.0025
Phyllochron††	85	85	85	85

† Sensitivity to vernalization.

‡ Sensitivity to photoperiod.

§ Thermal time from beginning of grain filling to maturity (°Cd).

¶ Coefficient of kernel number per stem weight at the beginning of grain filling (g per stem).

Potential grain filling rate (g per kernel per day).

†† Phyllochron interval (°Cd/leaf appearance).

Table 4. Derived values of cultivar parameters for maize at Luancheng (Yandan 21), Yucheng (Yedan 22, 981), and Fengqiu (Zhengdan 958).

Parameters	Derived values			
	Yandan 21	Yedan 22	981	Zhengdan 958
Head_grain_no_max†	500	560	600	600
Grain_gth_rate‡	9	10	10	10
tt_emerg_to_endjuv§	240	240	240	280
photoperiod_slope¶	15	19	13	20
tt_flower_to_maturity#	700	700	650	600
tt_flower_to_start_grain††	120	160	130	160
RUE‡‡	1.8	1.8	1.8	1.8

† Maximum grain numbers per head.

‡ Grain filling rate (mg grain^{-1} d^{-1}).

§ Thermal time required from emergence to end of juvenile (°Cd).

¶ Photoperiod slope.

Thermal time required from flowering to maturity (°Cd).

†† Thermal time required from flowering to starting grain filling (°Cd).

‡‡ Radiation use efficiency.

Table 5. The amount of water assumed to be available for irrigation and its partition to each irrigation event according to crop growth stage and between wheat and maize.

Irrigation amount	Timing and amount of irrigation for wheat					Timing and amount of irrigation for maize			
	Sowing	Winter dormancy	Spring green up	Stem-extension	Grain-filling	Sowing	Stem-extension	Heading	Grain-filling
mm									
				Double cropped wheat and maize (DCIWM)					
0									
60	30					30			
120	40			40		40			
180	40			60		40	40		
240	40			60	60	40	40		
300	40	40		60	60	50	50		
360	60	60		60	60	60	60		
420	60	60	30	60	60	60	60	30	
480	60	60	60	60	60	60	60	60	
540	60	60	60	75	75	60	60	60	30
600	60	75	75	75	75	60	60	60	60
				Double cropped wheat and maize (DCIW)					
60	60								
120	60			60					
180	60			60	60				
240	60		60	60	60				
300	60	60	60	60	60				
360	70	70	70	80	70				
420	80	80	80	100	80				
				Single cropped wheat (SCIW)					
0									
60	60								
120	60			60					
180	60			60	60				
240	60		60	60	60				
300	60	60	60	60	60				
				Single cropped maize (SCIM)					
0									
60						60			
120						60	60		
180						60	60		60
240						60	60	60	60
300						75	75	75	75

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 crops (DCIW)*: total irrigation water supply ranged from 60 to 420 mm at 60 mm intervals—seven irrigation treatments in total. Irrigation was only applied to wheat crop. This scenario was designed to explore the performance of the double cropping system at reduced water supply conditions, and the impact of wheat irrigation on subsequent maize crop yield.
- *A single wheat system (SCIW)*: Only a single wheat crop every year and total irrigation water supply ranged from 0 to 300 mm at 60 mm intervals—six irrigation treatments in total. This scenario was designed to explore the performance of a single wheat cropping system when a summer fallow was kept to store soil water, and its response to different levels of irrigation.
- *A single maize system (SCIM)*: Only a single maize crop every year and total irrigation water supply ranged from 0 to 300 mm at 60 mm intervals—six irrigation treatments in total. This scenario was designed to explore the performance of a single maize cropping system when a winter fallow was kept to store soil water, and its response to different levels of irrigation.

The above irrigation scenarios were designed based on irrigation water requirement of wheat and maize and conventional agricultural practice in the NCP. Based on a wheat-maize rotation experiment conducted at Luancheng with fully irrigated treatment over 8 yr (1997–2005), Zhang et al. (2006) reported that irrigation water requirement was 300 mm for both wheat and maize in some extremely dry years, in which precipitation was <50% of the long-term average. Thus, the highest irrigation amount of 300 mm was applied for wheat or maize single cropping system, and 600 mm of irrigation water was applied in annual rotation of the two crops. The timing of irrigation was designed to roughly match the key developmental stages of wheat and maize. Generally, 60 mm of irrigation water was applied each time.

The above scenarios allow evaluation of the productivity of a double or single cropping system as it responds to variable climate, soil moisture storage, and irrigation water supply. The performance of the single cropping systems reflects the yield levels of possible future cropping systems when irrigation water becomes limited. The simulation results were used to generate yield responses to various irrigation levels under the variable climate background. Such response surfaces can assist in crop and water management under variable water supplies. Variability of the simulated crop yield was calculated as the coefficient of variation.

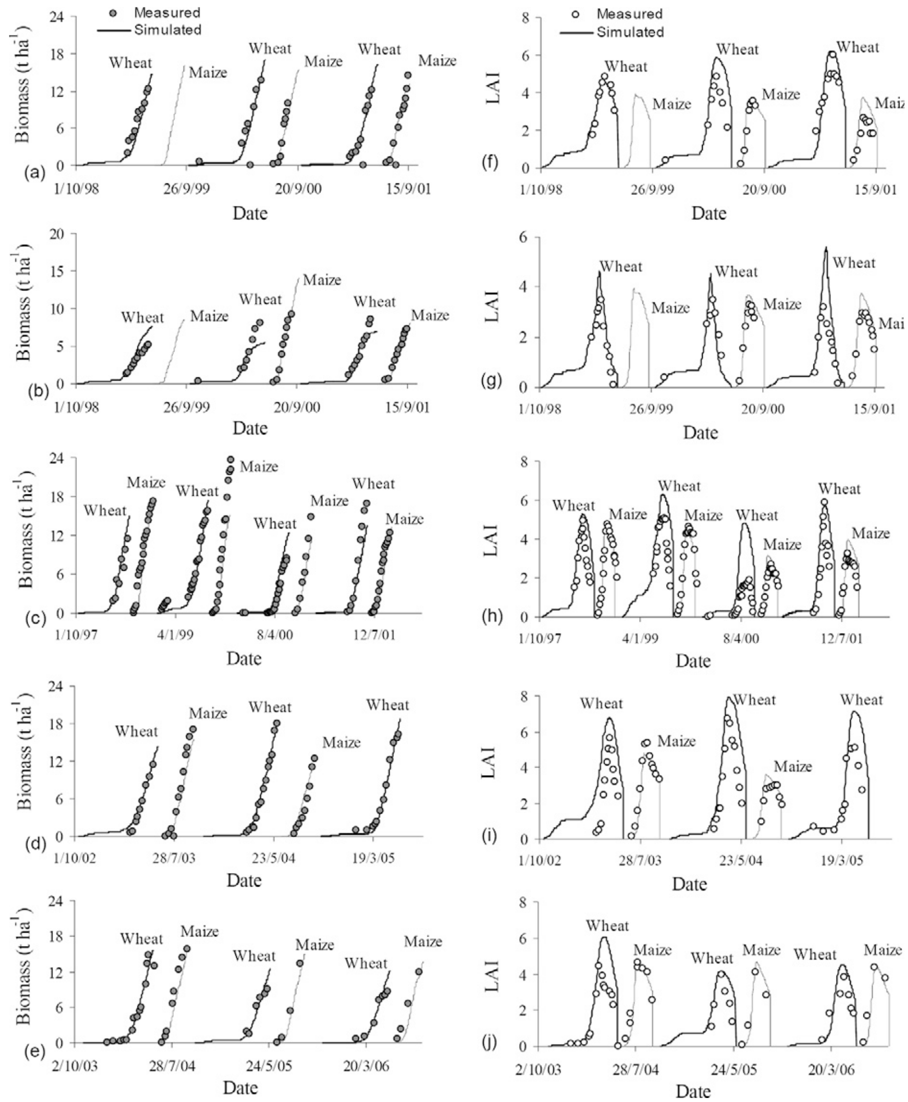

Fig. 5. Simulated and measured biomass and leaf area index of wheat and maize crops: (a) and (f) Luancheng irrigation applied during critical crop growth stages (1998–2001, measured data missing for maize in 1999), (b) and (g) Luancheng irrigation only applied at sowing (1998–2001), (c) and (h) Yucheng (1997–2001), (d) and (i) Yucheng (2002–2005), (e) and (j) Fengqiu station (2004–2006).

RESULTS

Model Performance

The performance of the calibrated APSIM model was shown in Fig. 5. In general, simulated aboveground biomass and LAI followed the measured pattern reasonably well at all three sites. For some seasons, there was a tendency to overestimate maximum LAI (Fig. 5f, g, h, i, j), but most of the LAI overestimation did not lead to overestimation of biomass due to the insensitivity of biomass production to LAI when LAI is greater than three (Asseng et al., 2004). The grain yield of both wheat and maize was reasonably well predicted (Fig. 6). The largest difference between simulated and observed grain yield occurred in 1999 for maize at Yucheng, with underestimation of 2.1 t ha^{-1}. A detailed examination of the observed data and harvest indices of maize revealed some mismatch between measured biomass and grain yield of maize, possibly due to measurement errors.

The total soil water in the 160-cm soil profile at Luancheng and in the150-cm profile at Yucheng was well simulated (Fig. 7). The discrepancy between simulated and measured soil water content during the 1998–1999 winter wheat growing season was probably caused by groundwater recharge in this extremely dry season (Yang et al., 2007). The patterns of measured ET were reasonably well simulated in most seasons (Fig. 8). For wheat growing seasons, the difference between simulated and measured cumulative ET ranged from –15.1% (underestimated) to 13.2% (overestimated). For maize growing seasons, the difference ranged from –18.8 to 24.9%.

The comparisons of simulated and measured values for biomass, LAI and grain yield, soil water and daily ET were presented in Fig. 9 and Table 6. The slope (β) indicated that the model tended to overestimate wheat LAI, but to slightly underestimate maize biomass and yield. When one extreme value was excluded (maize yield in 1999 at Yucheng), the overall performance of the model was very satisfactory, with r^2 (1:1) of 0.76 and 0.83 and RMSE of 0.8 and 1.3 t ha^{-1} for grain yield of wheat and maize, respectively. The relative small values of RMSE indicate that the model could reasonably simulate biomass, LAI and grain yield for both wheat and maize. The model could explain 93% of the variation in soil water content with a RMSE value of 24.33 mm. The values of the slope and ME were very close to 1. The model explained 61% of the variation in daily ET, with the RMSE value of 1.49 mm d^{-1} and ME of 0.51.

The above results indicate that the calibrated APSIM model can be used confidently to simulate the responses of crop yield in the wheat-maize double cropping system to climate variability and irrigation water supply. The model was used to generate the yield responses to different irrigation treatments as described below.

The Response of Crop Yield of the Wheat–Maize Double Cropping Systems to Irrigation under Climate Variability

Figure 10 shows the simulated yield range of wheat plus maize, wheat and maize in the double cropping systems when irrigation

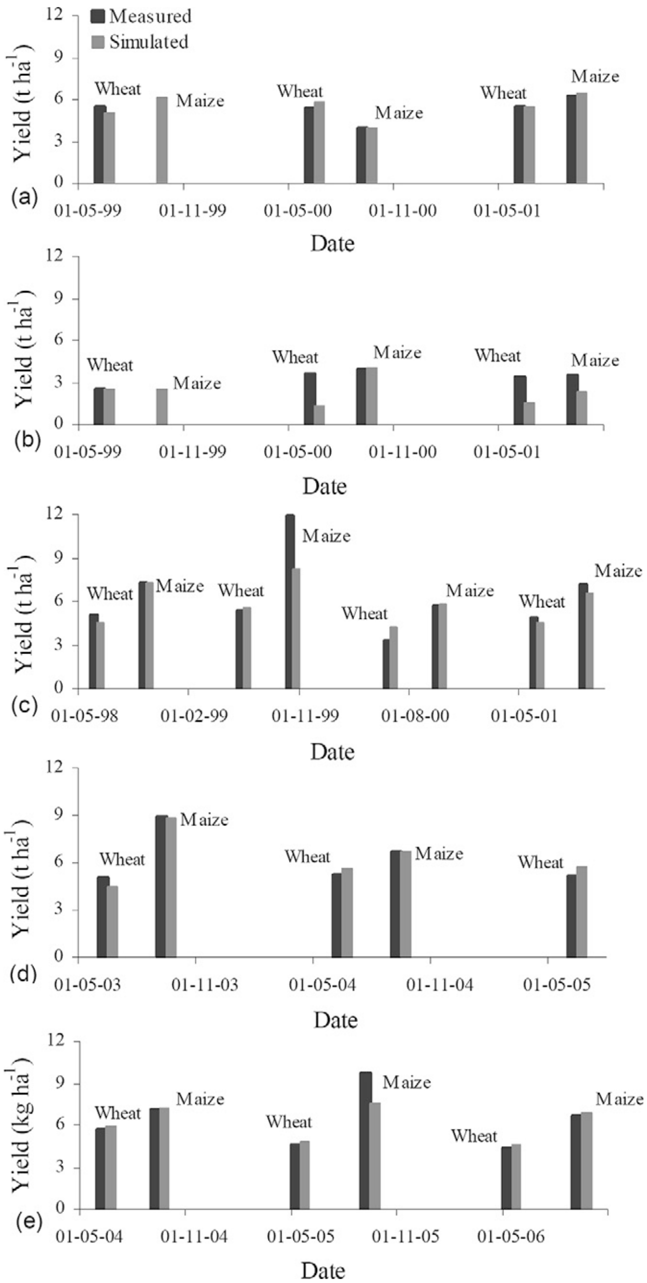

Fig. 6. Simulated and measured grain yield of wheat and maize at Luancheng (1998–2001, measured data missing for maize in 1999) under applied during (a) critical crop growth stages and (b) irrigation only applied at sowing, and at Yucheng (c) (1997–2001) (d) (2002–2005) and at (e) Fengqiu station (2004–2006).

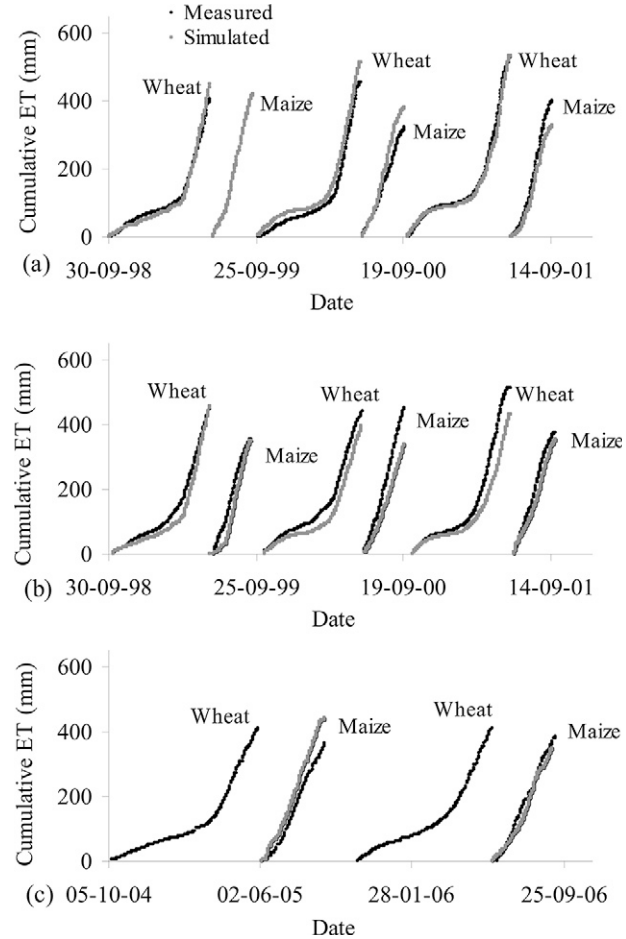

Fig. 7. Simulated and measured accumulative evapotranspiration of the wheat-maize double cropping system at (a) Luancheng under irrigation applied during critical crop growth stages treatment (1998–2001, measured data missing for maize in 1999), at (b) Yucheng (1998–2001), and (c) at Fengqiu station (2004–2006).

was applied to both crops (Fig. 10a, b, c and Table 5) or only to wheat crop (Fig. 10d, e, f and Table 5). Under the condition of no irrigation water available, simulated total grain yield of double cropped wheat and maize showed large interannual variation due to interannual climate variability, ranging from 0 to 15.8 t ha^{-1} with an average of 4.8 t ha^{-1} (Fig. 10a). Rainfed wheat yield ranged from 0 to 6.1t ha^{-1} (Fig. 10b), while rainfed maize yield ranged from 0 to 9.7 t ha^{-1} (Fig. 10c). Irrigation reduced interannual variability of crop yield caused by rainfall variability and increased the average crop yield almost linearly up to the irrigation amount of 480 to 540 mm (Fig. 10a, b, c). Irrigation mainly increased the lowest crop yield, which was the yield under drought years. When both wheat and maize were irrigated, the simulated lowest total crop yield was 0.1 t ha^{-1} under 60 mm irrigation and it increased to 9.5 t ha^{-1} when 600 mm irrigation water was applied; the highest total crop yield was 15.9 t ha^{-1} under 60 mm irrigation and only increased slightly with increase in irrigation amounts (Fig. 10a). The highest crop yield was normally achieved in wet years when rainfall could meet crop water demand. Thus, irrigation had little effects 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. On average, every 60 mm more irrigation application could increase total crop yield by 1.2 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. The variability of crop yield under rainfed conditions was 0.69 and it was reduced to 0.56 with 60 mm irrigation. When 480 to 600 mm irrigation was applied, the crop yield variability was the smallest with value around 0.13. Grain yield of wheat reached a stable level with a range of 5.8 to 8.6 t ha^{-1} under 330 mm irrigation (480 mm total irrigation for two crops) (Fig. 10b and Table 5) and that of maize reached a stable level with a range of 5.6 to 10.3 t ha^{-1} under 210 mm irrigation (540 mm total irrigation for two crops) (Fig. 10c and Table 5). 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, the wheat yield proportion attained the highest value of 46% and maize was the lowest with 54% (Fig. 10a, b, c). The simulated wheat yield response to water supply was comparable to that of Liu et al. (2005) derived from experimental data conducted in the same site. However, their response was derived vs. crop ET, while ours was derived vs. irrigation water supply.

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. 10d) were similar to those under the corresponding irrigation amounts when irrigation applied to both wheat and maize (Fig. 10a). But when irrigation was more than 180 mm, the average total crop yield was lower (Fig. 10d) due to the lower maize yield (Fig. 10f compared with Fig. 10c). 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. 10e). The increase in maize yield (Fig. 10f) with irrigation was due to the increased stored soil water left for maize from wheat in some years. 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.

The above results also enable us to optimize the scheduling of limited irrigation water between wheat and maize crops (including amounts and timing) to achieve the highest grain yields. Similar simulated results were obtained for the allocation of limited irrigation water between wheat and maize (Fang et al., 2009). They found that the total yield of wheat and maize increased with increased water allocation to wheat crop from 50:50 (wheat/maize) to 100:0 if 100 or 150 mm of water was available for irrigation. The highest total crop yield was obtained at an allocation ratio of 80:20 if 200 or 250 mm of water was available for irrigation.

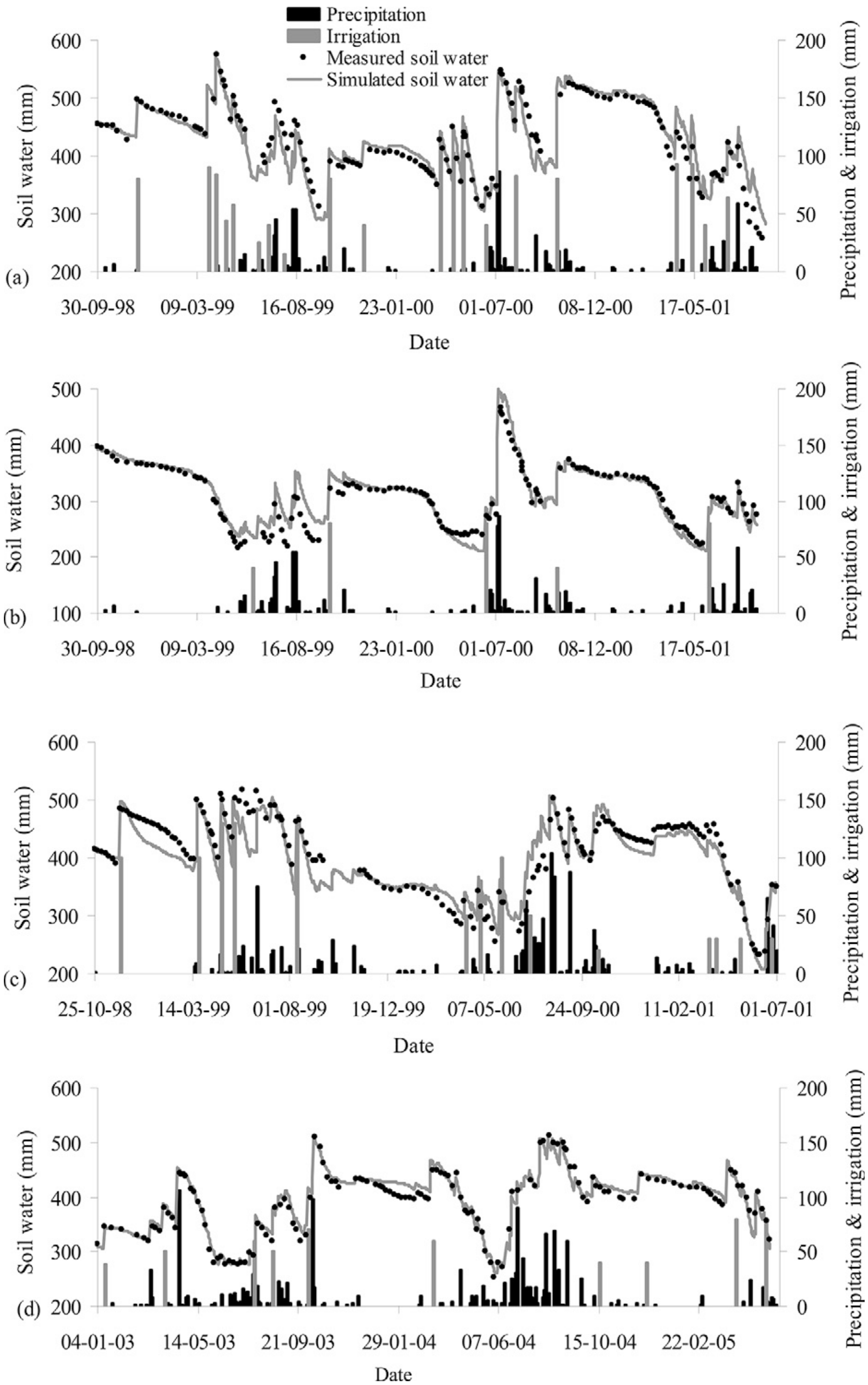

Fig. 8. Simulated and measured soil water in the 0 to 160 cm soil profile at Luancheng (1998–2001) under (a) irrigation applied during critical crop growth stages and (b) irrigation only applied at sowing, and the 0 to 150 cm soil profile at Yucheng (c) (1998–2001) and (d) (2003–2005).

The Response of Crop Yield of Wheat and Maize to Irrigation in Single Cropping Systems

When only wheat was grown each year, a summer fallow period would exist. Long fallowing can add substantially to subsoil moisture under specific soil and climatic conditions. Under rainfed conditions, simulated wheat grain yield ranged from 0.1 to 6.7 t ha^{-1} with an average of 2.9 t ha^{-1} (Fig. 11a). The growth of rainfed wheat would have to rely on stored soil moisture from the previous summer fallow period and the rainfall in the wheat growing season. On average, 130 mm water could be stored in the root-zone soil profile at wheat sowing time (Fig. 12a). The absence of a maize crop during the summer period resulted in 99 mm increase in stored soil moisture at wheat sowing time (Fig. 12a), which led to an increase of 1.7 t ha^{-1} in rainfed wheat yield, that is, 142% increase (Fig. 11a compared to Fig. 10b). The simulated contribution of stored soil water at sowing to rainfed wheat yield

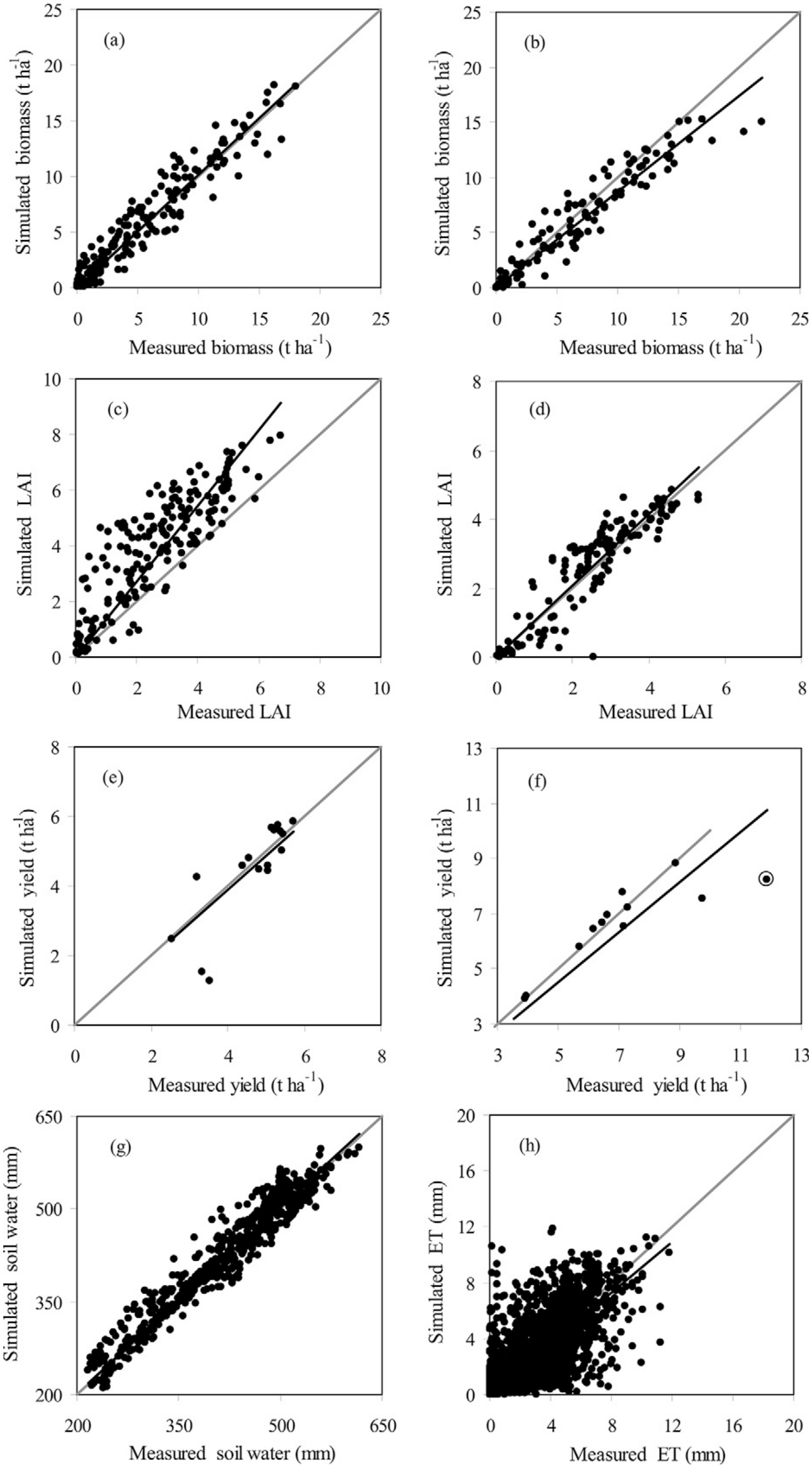

Fig. 9. Comparison of observed and simulated values of aboveground biomass of (a) wheat and (b) maize, (c) LAI of wheat and (d) maize, (e) grain yield of wheat and (f) maize, (g) soil water content and (h) evapotranpiration (ET) with all the data from Luancheng (1998–2001), Yucheng (1997–2001, 2002–2005) and Fengqiu (2004–2006). The circle in f indicates the extremely high maize yield, which was excluded

was similar to the results of Wang et al. (2008) that every 100 mm initial soil water could increase rainfed wheat yield by 1.0 to 2.0 t ha^{-1} depending on actual conditions The result under no irrigation in Fig. 11a represents the rainfed wheat yield range when single wheat was planted every year, indicating that stored soil water at sowing time and rainfall during growing season could support >4 t ha^{-1} wheat yield in 25% of the years, more than doubling rainfed wheat yield in the double cropping system (Fig. 10b). The lowest wheat yield was increased from 0.1 to 0.6 t ha^{-1} with 60 mm irrigation and the average wheat yield did not increase significantly under irrigation amount beyond 240 mm (Fig. 11a).

For single cropped maize, grain yield under no irrigation also had a large range from 0 to 10.6 t ha^{-1} with an average of 5.3 t ha^{-1} (Fig. 11b). An average of 120 mm of plant available water could be stored in the root-zone soil profile before sowing (Fig. 12a). The increase of 96.7 mm in stored soil moisture at sowing time (Fig. 12a) led to a rainfed maize yield increase of 1.8 t ha^{-1} (49.6%, Fig. 13b compared with Fig. 12f). Even with 60 mm irrigation, there was still a possibility of crop failure (Fig. 11b) due to the low summer rainfall and stored soil water at sowing. The lowest grain yield was increased to 5.7 t ha^{-1} when 180 mm irrigation was applied and this increased only marginally with more irrigation. The highest yield, 11.9 t ha^{-1} only occurred under 300 mm irrigation. This indicates that 180 mm irrigation could offset water deficit in most of maize seasons, except extremely dry seasons with very low soil water storage.

Rainfall during wheat growing season ranged from 40.5 to 281.0 mm with <140.0 mm in 75% years (Fig. 12b). In general, every 100 mm rainfall during this growing season increased rainfed wheat yield in a single cropping system by 1.3 t ha^{-1} (Fig. 13a). But there is a large uncertainty or risk associated with wheat yield due to the large variability in rainfall, as indicated by the low coefficient of determination of r^2 of 0.25. Maize growing season rainfall ranged from 159 to 1016 mm (Fig. 13b). Rainfed maize yield in a single cropping system also tended to increase with rainfall during its growing season, but not significantly (Fig. 13d). Rainfall during maize season only accounted for 9% of the variation in rainfed maize yield, which indicates that the variation in maize yield was related more to rainfall use efficiency than to the actual amount of rain due to the concentrated summer monsoon rainfall over the NCP.

Table 6. Evaluation results for APSIM predictions of leaf area index (LAI), aboveground biomass, grain yield, soil water, and evapotranspiration (ET) in the wheat–maize double cropping system at Luancheng, Yucheng, and Fengqiu sites in the North China Plain (NCP).

Model attribute	*n*†	X_{obs} (mean)‡	X_{sim} (mean)§	r^2¶	B#	RMSE††	ME‡‡
Wheat biomass, t ha^{-1}	153	0.03–17.9 (5.7)	0.07–18.2 (5.9)	0.91	1.36	1.40	0.90
Maize biomass, t ha^{-1}	113	0.03–21.8 (6.4)	0.01–15.3 (5.7)	0.91	0.87	1.70	0.89
Wheat LAI	180	0.03–6.7 (2.7)	0.14–7.6 (3.9)	0.61	1.35	1.66	–0.07
Maize LAI	118	0.04–5.3 (2.5)	0.01–4.9 (2.6)	0.84	1.03	0.60	0.80
Wheat grain yield, t ha^{-1}	16	2.6–5.7 (4.6)	1.3–5.9 (4.5)	0.76	0.99	0.83	0.40
Maize grain yield, t ha^{-1}	13	3.5–11.9 (6.8)	2.8–8.8 (6.3)	0.83	0.90	1.07	0.79
Soil water content, mm	624	215–616 (417)	210–598 (423)	0.93	1.01	24.33	0.93
Daily ET, mm	5254	0.01–11.84 (1.99)	0.01–11.81 (1.94)	0.61	0.91	1.49	0.51

† Number of paired data points.

‡ The range of the measured values (mean of observed values).

§ The range of the simulated values (mean of observed values).

¶ r^2 for the 1 to 1 line [r^2(1:1)].

Slope of linear regression (forced through origin).

†† Root mean squared error.

‡‡ Model efficiency.

Stored soil water at sowing for single cropped wheat ranged from 21 to 361 mm and it was more than 100 mm in 75% years (Fig. 12a). An average of 100 mm initial soil water has the potential to increase rainfed wheat yield by 2 t ha^{-1} (Fig. 13b). The variation in stored soil water at sowing accounted for about 64% of the variation in wheat yield (Fig. 13b). Stored soil water at sowing for single cropped maize was from 36 to 315 mm with more than 65.0 mm in 25% years. Rainfed maize yield increased with stored soil water at sowing at a rate of 0.03 t ha^{-1} mm^{-1} (Fig. 13e). About 42% of the variation of rainfed maize yield could be accounted for by the variation in initial soil water.

The wheat yield increase with stored soil moisture (Fig. 13b) is comparable to the water use efficiency estimated by French and Schultz (1984) (20 kg ha^{-1} mm^{-1}) in Australia. However, rainfall use efficiency is much lower (Fig. 13a) and the combined use efficiency of rainfall and stored moisture (Fig. 13c) for wheat was only half of that of the stored soil moisture. Rainfall and stored soil moisture together could explain 82% of the variation in grain yield of single cropped wheat (Fig. 13c), while it could only explain 27% of the variation in maize yield (Fig. 13f) due to the intensive and less efficient rainfall during the summer monsoon season.

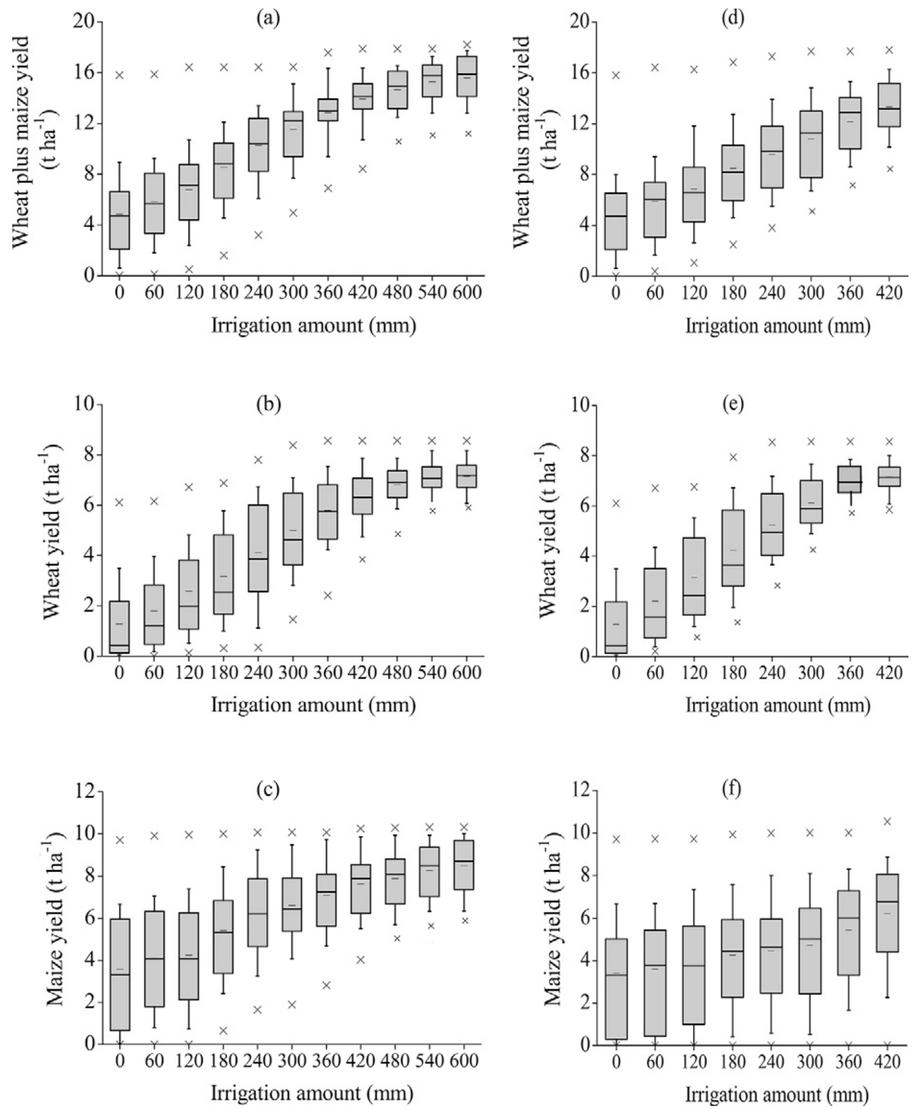

Fig. 10. Simulated yield response to different irrigation input levels for the wheat-maize double cropping system at Luancheng (1961–2005). (a), (b) and (c) show the grain yield of wheat plus maize, wheat, and maize, respectively when irrigation was applied to both crops (Scenario DCIWM); (d), (e), and (f) show the same yields when irrigation was applied only to wheat crop (Scenario SCIM). For details see text and Table 5. The box plots show the 0, 10, 25, 50, 75, 90, and 100 percentiles, the short line in the boxes show the mean.

SUMMARY AND CONCLUSIONS

This study is the first to provide the performance evaluation of APSIM against continuous multiseasonal data for a wheat-maize double cropping system from three experimental sites in the semiarid

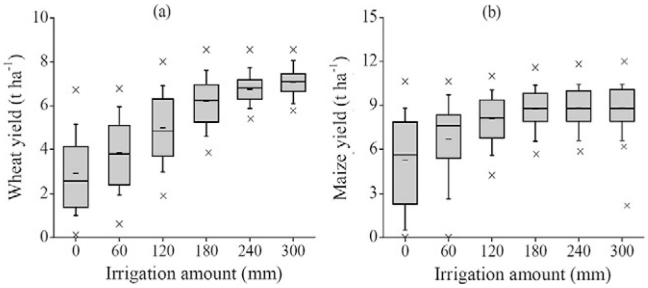

Fig. 11. Simulated grain yield of (a) wheat and (b) maize in a single cropping system under different levels of irrigation supply. See Fig. 12 caption for box plot values.

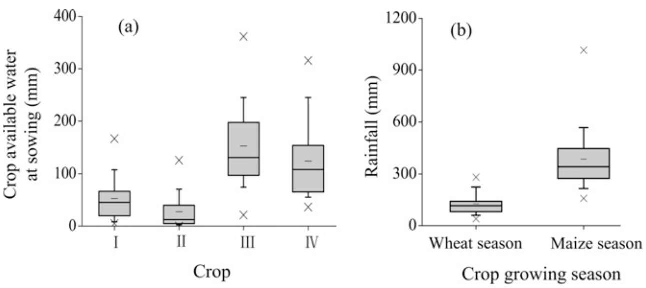

Fig. 12. (a) Simulated crop available soil water stored in the soil profile at sowing time of wheat under wheat-maize double cropping system (I), maize under wheat-maize double cropping system (II), wheat under single cropping system (III), and maize under single cropping system (IV). (b) Rainfall during the wheat and maize growing season from 1961 to 2005 at Luancheng. See Fig. 12 caption for box plot values.

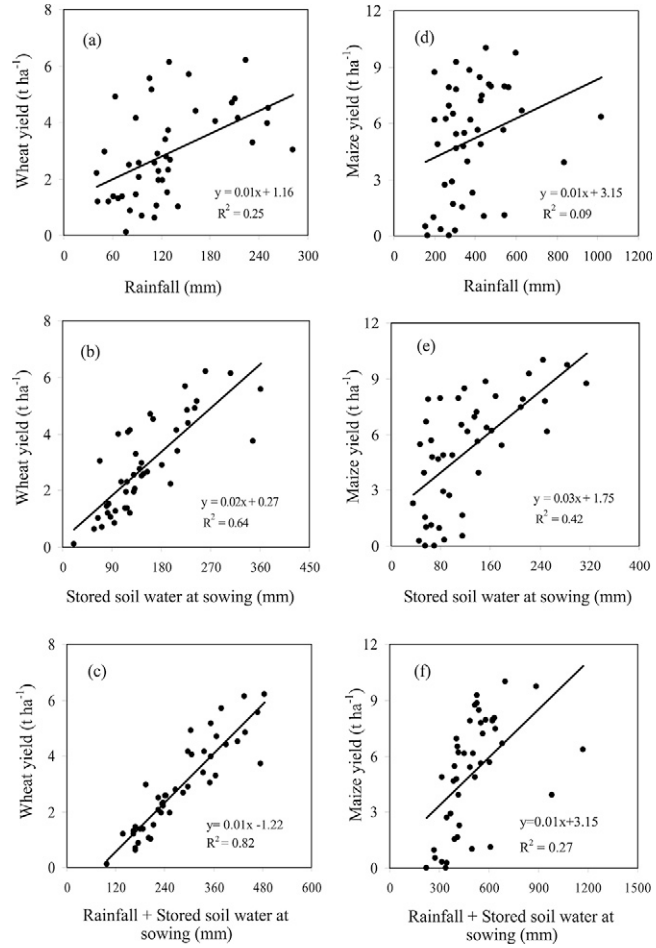

Fig. 13. (a) Relationship between wheat yield and rainfall, (b) wheat yield and stored soil water at sowing time, (c) wheat yield and rainfall + stored soil water at sowing time under single cropping system; (d) maize yield and rainfall, (e) maize yield and stored soil water at sowing time, (f) maize yield and rainfall + stored soil water at sowing time under single cropping system.

NCP of China. For better simulating the winter wheat production in the NCP, it was necessary to change the low temperature threshold for leaf area damage induced by low temperature, the temperature response of crop phenological development, and the temperature response of RUE. For maize, an increased RUE value to 1.8 g MJ^{-1} was required to better simulate the biomass and yield. The general good agreement of the simulated and measured values for crop LAI, biomass, and yield ET and soil water content indicate that 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. The RMSE values of grain yield, biomass, and LAI for wheat were 0.83 t ha^{-1}, 1.40 t ha^{-1}, and 1.66, respectively; while the corresponding values for maize were 1.07 t ha^{-1}, 1.70 t ha^{-1}, and 0.60, respectively. The RMSE of soil water content was 24.33 mm and of ET was 1.49 mm d^{-1}.

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}). 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. If single cropping has to be adopted under future reduced water availability, annual grain yield would be significantly reduced. But wheat yield under no irrigation increased by 2.5 times as compared with that in a double cropping system due to increased soil moisture at sowing as a result of the absence of the summer maize crop. Single crop maize yield under no irrigation was less than twice that in the double cropping system due to concentrated rainfall in maize growing season. For both single cropped wheat and maize, the simulated results indicate that stored soil water has more effect on promoting yield than the amount of rainfall from sowing to maturity. Although the rainfed yield of each individual crop increased in single cropping, the total annual gain yield would be much less if a single cropping system was adopted, no matter which crop was chosen. The single crop simulations enabled the exploration of the performance of single wheat or maize crop as affected by climate variations and the stored soil moisture at sowing in a scenario where future water availability cannot support two crops in a year.

The simulated responses reflect the effects of different levels of irrigation water supply on crop yield under the background of long-term climate variations through model extension with multiyear weather data. For any given level of irrigation water availability, we were able to produce a probability distribution of crop yield, which was caused by climate variations. It enables a better understanding of how wheat and maize crop yields vary with water availability and climate and provides insights for future agricultural decision making under conditions of reduced available water under variable climate.

In this study, we have taken into account the effects of climate and irrigation supply on the productivity of wheat and maize in the double and single cropping systems. The Luancheng County was taken as an example to represent the north NCP to analyze the yield responses to water supply levels. However, optimal management of water use for crop production and environmental protection is site specific, depending on the local climate (particularly rainfall) and soil type. Further studies through multiple site simulations taking into account the effects of the spatial variability of climate, soil, and hydrological conditions are needed to get a full picture across the NCP.

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