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Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain

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ABSTRACT

In the North China Plain (NCP), while irrigation using groundwater has maintained a high-level crop productivity of the wheat–maize double cropping systems, it has resulted in rapid depletion of groundwater table. For more efficient and sustainable utilization of the limited water resources, improved understanding of how crop productivity and water balance components respond to climate variations and irrigation is essential. This paper investigates such responses using a modelling approach. The farming systems model APSIM (Agricultural Production Systems Simulator) was first calibrated and validated using 3 years of experimental data. The validated model was then applied to simulate crop yield and field water balance of the wheat–maize rotation in the NCP. Simulated dryland crop yield ranged from 0 to 4.5 t ha^{-1} for wheat and 0 to 5.0 t ha^{-1} for maize. Increasing irrigation amount led to increased crop yield, but irrigation required to obtain maximum water productivity (WP) was much less than that required to obtain maximum crop yield. To meet crop water demand, a wide range of irrigation water supply would be needed due to the inter-annual climate variations. The range was simulated to be 140–420 mm for wheat, and 0–170 mm for maize. Such levels of irrigation applications could potentially lead to about 1.5 m year^{-1} decline in groundwater table when other sources of groundwater recharge were not considered. To achieve maximum WP, one, two and three irrigations (i.e., 70, 150 and 200 mm season^{-1}) were recommended for wheat in wet, medium and dry seasons, respectively. For maize, one irrigation and two irrigations (i.e., 60 and 110 mm season^{-1}) were recommended in medium and dry seasons, while no irrigation was needed in wet season.

1. Introduction

The North China Plain (NCP) is one of the most important agricultural production areas in China, with a continuous winter wheat–summer maize cropping system. Average annual precipitation in this region ranges from 470 to 910 mm (Wang et al., 2008c), and more than 70% of which falls during the summer months (July–September). Although the summer monsoon rainfall is favourable for maize growth, the lack of precipitation during wheat growing season (October to June) leads to frequent and severe water stress. Annual water demand of wheat and maize together amounts to 800–900 mm (Liu et al., 2002), which is much higher than annual precipitation in most part of the region. Even for maize, irrigation is still required due to the inter-annual rainfall variations and less rainfall than crop water demand in drought years. With the lack of surface water, groundwater has been used for irrigation for many years. As a result, groundwater levels have been persistently declining at an average rate of about 1 m year^{-1} (Hu et al., 2005), which is threatening the long-term agricultural and industrial development in the NCP. Therefore, it is necessary to develop optimal water management practices based on climatic conditions to avoid overuse of water resources, mitigate groundwater table decline and maintain a sustainable agricultural production. This requires knowledge of how crop yield, water productivity (WP) and water balance are influenced by climate variability and irrigation management.

Considerable experimental work has been done to investigate irrigation water use of winter wheat and/or maize crop in the NCP. At Luancheng County, Zhang et al. (2005) showed that irrigation applied once (at stem-extension) in wet seasons, twice (pre-winter and stem-extension stage) in normal seasons, and three times (pre-winter, stem-extension and flowering stage) in dry seasons (each 80 mm) could lead to optimum yield and maximum WP of winter wheat. Sun et al. (2006) draw the conclusion from

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experiments on irrigation during different growing stages of winter wheat that full irrigation to field capacity (FC) did not produce greater yield compared to treatments with some water stress in certain stages. Zhang et al. (2006) reported that minimum irrigation (only irrigate at sowing with no further irrigation afterwards) could increase WP of both wheat and maize compared with that under full irrigation. At Huantai County, Zhang and Yu (2003) found that three irrigations at pre-winter, at stem-extension and flowering stages (each 75 mm) were most efficient for wheat, while increased number of irrigations did not improve yield. However, these results were drawn from irrigation experiments conducted in a couple of years. They may not be representative of crop water requirements and field water balance beyond the experimental period due to the large inter-annual variations in climate (especially precipitation).

Agricultural system models have been proven to be useful tools to investigate the potential impacts of climate variability on crop productivity (Asseng et al., 1997; Keating et al., 2003; Meinke and Hammer, 1995; Meinke and Stone, 1997; Wu et al., 2006; Wang et al., 2008b,c) and field water balance (Asseng et al., 2001; Keating et al., 2002; Wang et al., 2008a), and how crop yield responds to water management strategies (Mo et al., 2005; Hartkamp et al., 1999). In the NCP, Mo et al. (2005) evaluated the spatial variations of crop yield, water consumption and WP with SVAT-crop growth model and found spatial patterns of these items closely related to water management patterns. Wu et al. (2006, 2008) simulated the impacts of climate on the temporal and spatial variability in grain yield and water demand of wheat and maize with WOFOST model. Yang et al. (2006) used DSSAT-wheat to simulate water use by wheat and put forward strategies of maximizing yield with the least amount of irrigation water. Wang et al. (2008c) estimated a sustainable water balance across NCP based on vegetation–climate interactions and analysed the water balance problems caused by the irrigated wheat–maize double cropping system. Although these studies provide useful understanding for the development of applicable water management practices, there is still a lack of systematic analysis on how crop productivity of a wheat–maize rotation, their WP and field water balance are affected by historical climate variability and irrigation management.

The objectives of this study are to use an agricultural system modelling approach to: (1) quantify the response of crop productivity and water balance to historical climate variability and irrigation, and (2) explore optimal water management strategies for wheat and maize in the NCP for the purpose of more efficient use of the limited water resources.

2. Materials and methods

2.1. Study site, soil and climate data

The Luancheng Agro-ecosystem station (37.9°N, 114.7°E, a.s.l. 50.1 m) was selected as the study site. It is located in Luancheng County in Hebei Province, representing the agricultural production and climatic conditions in the northern part of the NCP. The experimental station is one of the 36 agricultural ecosystem stations of Chinese Ecological Research Network (CERN).

The experimental site has a loam soil, with texture ranging from sandy loam in surface layers to light/median loam at 40–80 cm depth and to light clay below 80 cm. The soil profile properties are given in Table 1.

For the modelling study, daily meteorological data, including sunshine duration, maximum and minimum temperature and rainfall from 1961 to 2000, were obtained directly from the weather station about 20 km from the experimental plots described below. Sunshine duration was converted into solar radiation using the Ångström formula (Black et al., 1954; Jones, 1992).

2.2. Experimental data for model testing

Crop and soil data measured from wheat–maize double cropping experiments were used to test the model, which was carried out at the Luancheng Agro-ecosystem station from 1998 to 2001 (Zhang et al., 2004). Daily sunshine duration, maximum and minimum air temperature and rainfall during the experimental period were obtained from an automatic weather station near the experimental plots. Sunshine duration was also used to estimate solar radiation with above method. Three trial plots, each 50 m^2, were used as replicates. Crop varieties, sowing date, plant density and fertilizer were kept constant throughout the experiment (1998–2001). Winter wheat (variety Gaoyou No. 503) and maize (variety Yandan No. 21) were used. Wheat was sown at a rate of 150 kg ha^{-1} with 20 cm wide per row on 1 October, and maize was sown at a rate of 60 kg ha^{-1} on 2 June. Before sowing, ammonium phosphate and urea were applied for wheat at 300 and 150 kg ha^{-1}, respectively. Urea was applied for maize at a rate of 450 kg ha^{-1}. Leaf area index (LAI) was measured with CI-203 electronic leaf area meter (CID, Camas, WA) at 7-day intervals. Above-ground biomass was measured using oven-dry method at 7-day intervals. Grain yields were sampled from a subplot of 24 m^2. The straw of crop was removed after harvest.

Irrigation amount and timing during experiments are listed in Table 2. Irrigation applications were measured with a water meter. Soil water content was measured using a neutron probe (Institute of Hydrology, UK) down to 160 cm depth at 20 cm intervals, approximately every 5 days. Evapotranspiration (ET) was measured daily with a weighing lysimeter (rectangular surface area: 3 m^2, depth: 2.5 m, and weight with soil: 14 t) with a precision of 0.02 mm day^{-1} (Wang et al., 2001).

2.3. APSIM model and its parameterisation

The Agricultural Production Systems Simulator, APSIM (Keating et al., 2003) was used to simulate the winter wheat–summer maize double cropping system. A configuration of APSIM version 5.1 was used, including modules of Wheat, Maize, SoilWat2, $SoilN_2$, SurfaceOM and Manager. Further details on the model were described by Asseng et al. (1998), Keating et al. (2003) and Wang et al. (2003).

Firstly, APSIM was calibrated based on field-measured LAI, biomass and grain yield of wheat and maize in the double cropping sequence during 1998–2000 to determine the crop parameters with a trial-and-error method. The calibrated genetic coefficients

Table 1
Soil properties at experimental site at Luancheng Comprehensive Experimental Station.

Soil depth	0–20	20–40	40–60	60–80	80–100	100–120	120–160
Texture	Sandy loam	Sandy loam	Light loam	Medium loam	Light clay	Light clay	Light clay
BD (g/cm^3)	1.41	1.51	1.47	1.51	1.54	1.64	1.59
SAT (mm/mm)	0.44	0.46	0.43	0.43	0.44	0.44	0.48
DUL (mm/mm)	0.36	0.35	0.33	0.34	0.34	0.39	0.38
LL (mm/mm)	0.10	0.11	0.14	0.14	0.13	0.14	0.16

BD: bulky density; SAT: saturation; DUL: field capacity; LL: lower limit.

Table 2
Irrigation amount and dates during field experiments (1998–2001).

Crop	Date	Irrigation amount (mm)	Crop	Date	Irrigation amount (mm)
Wheat	25 September 1998	80.0	Wheat	4 April 2000	80.0
Wheat	2 December 1998	80.0	Wheat	24 April 2000	92.0
Wheat	26 March 1999	90.6	Wheat	9 May 2000	104.2
Wheat	8 April 1999	84.0	Maize	15 June 2000	40.0
Wheat	24 April 1999	54.0	Maize	11 August 2000	52.4
Wheat	5 May 1999	58.0	Wheat	8 October 2000	80.0
Maize	15 June 1999	25.0	Wheat	31 March 2001	118.0
Maize	30 June 1999	80.0	Wheat	18 April 2001	92.0
Maize	27 July 1998	15.0	Wheat	13 May 2001	92.0
Wheat	7 October 1999	80.0	Maize	9 June 2001	40.0
Wheat	1 December 1999	40.0	Maize	10 July 2001	64.0

Table 3
Derived values of parameters for APSIM-Wheat at Luancheng (Variety: Gaoyou 503).

Parameters	Values
vern_sens (sensitivity to vernalisation)	1.7
photop_sens (sensitivity to photoperiod)	2.3
Startgf_to_mat (thermal time from beginning of grain-filling to maturity (°Cd)	500
Grains_per_gram_stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem)	23.0
Potential_grain_filling_rate (potential grain-filling rate (g per kernel per day))	0.0023
Phyllochron (Phyllochron interval (°Cd/leaf appearance))	85

for wheat and maize were listed in Tables 3 and 4, respectively. The calibrated model was then validated using the experimental data during 2000–2001. After validation, the model was run with historical weather records (1961–2000) to assess effects of climate variability and irrigation managements on crop yield, WP and water balance components.

2.4. Modelling the system performance under different irrigation schedules and different climatic seasons

Five irrigation treatments were modelled for wheat and three for maize. The timing of irrigation was designed to roughly match the key developmental stages of wheat and maize, which approximates the conventional practice. In each treatment, if the total soil water content in the soil profile up to 120 cm fell below 60% of FC during a certain stage of crops (as described below), water was added to the soil up to 80% of FC.

The treatments for wheat are as follows:

- Zero irrigation—no irrigation applied, used to evaluate crop yield supported by seasonal rainfall.
- One irrigation—only applied at sowing.
- Two irrigations—applied at sowing and during stem-extension stage.
- Three irrigations—applied at sowing, during stem-extension and grain-filling stages.
- Four irrigations–applied at sowing, during turning green, stem-extension and grain-filling stages.

Table 4
Derived values of parameters for APSIM-Maize at Luancheng (Variety: Yandan 21).

Parameters	Values
Head_grain_no_max (maximum grain numbers per head)	500
Grain_gth_rate (grain-filling rate (mg/grain/day))	9
tt_emerg_to_endjuv (thermal time (TT) required from emergence to end of juvenile (°Cd))	240
photoperiod_slope (change in TT required to floral initiation per hour photoperiod increase)(°C/hour)	15
tt_flower_to_maturity (thermal time required from flowering to maturity (°Cd))	700
tt_flower_to_start_grain (thermal time required from flowering to starting grain-filling (°Cd))	120

For maize, the one irrigation option assumed irrigation was applied at sowing, while two-irrigation treatment assumed irrigation was applied at sowing and during stem-extension stage.

Crop WP is calculated as grain yield (GY) produced per unit of water consumed by ET during the growing season:

$$\mathrm{WP} = \frac{\mathrm{GY}}{\mathrm{ET}} \tag{1}$$

Mean daily temperature and solar radiation, and total precipitation from June to September and from October to May were calculated to represent climatic conditions during growing seasons of maize and wheat, respectively. Due to the large inter-annual variability in precipitation, winter wheat and maize growing seasons were divided into three categories based on the precipitation percentiles from 1961 to 2000, i.e., wet (higher than 75%), medium (between 25% and 75%) and dry (below 25%) seasons.

2.5. Potential impact of irrigation water use on groundwater table

In Luancheng County, about 75% of the land area is covered by irrigated crop fields, which is roughly equal to the area of shallow groundwater. There is no significant variation in soil types, elevation and physical geomorphology. So the whole study area can be treated as a large uniform irrigated crop field. In order to quantify the relative impacts of irrigation applications under climate variability on groundwater table, lateral seepage from the Taihang Mountains and vertical infiltration from waterlogged pond were not taken into consideration in the calculation, though they are the significant sources of groundwater recharge in this area. Potential changes in groundwater table due to its extraction for irrigation can be simply calculated as

$$\Delta \mathrm{h} = \frac{q}{\mu} \tag{2}$$

here Δh is the change in groundwater table (m); q is the net extraction of groundwater (m), i.e., the difference between the amount of groundwater used for irrigation and the recharge by deep drainage; and μ is the specific water yield and is set to 0.15 according to Mao and Liu (2001) and Mao et al. (2005).

3. Results and discussions

3.1. Model calibration and validation

The performance of the model was evaluated by comparing simulated LAI, above-ground biomass, grain yield, soil water

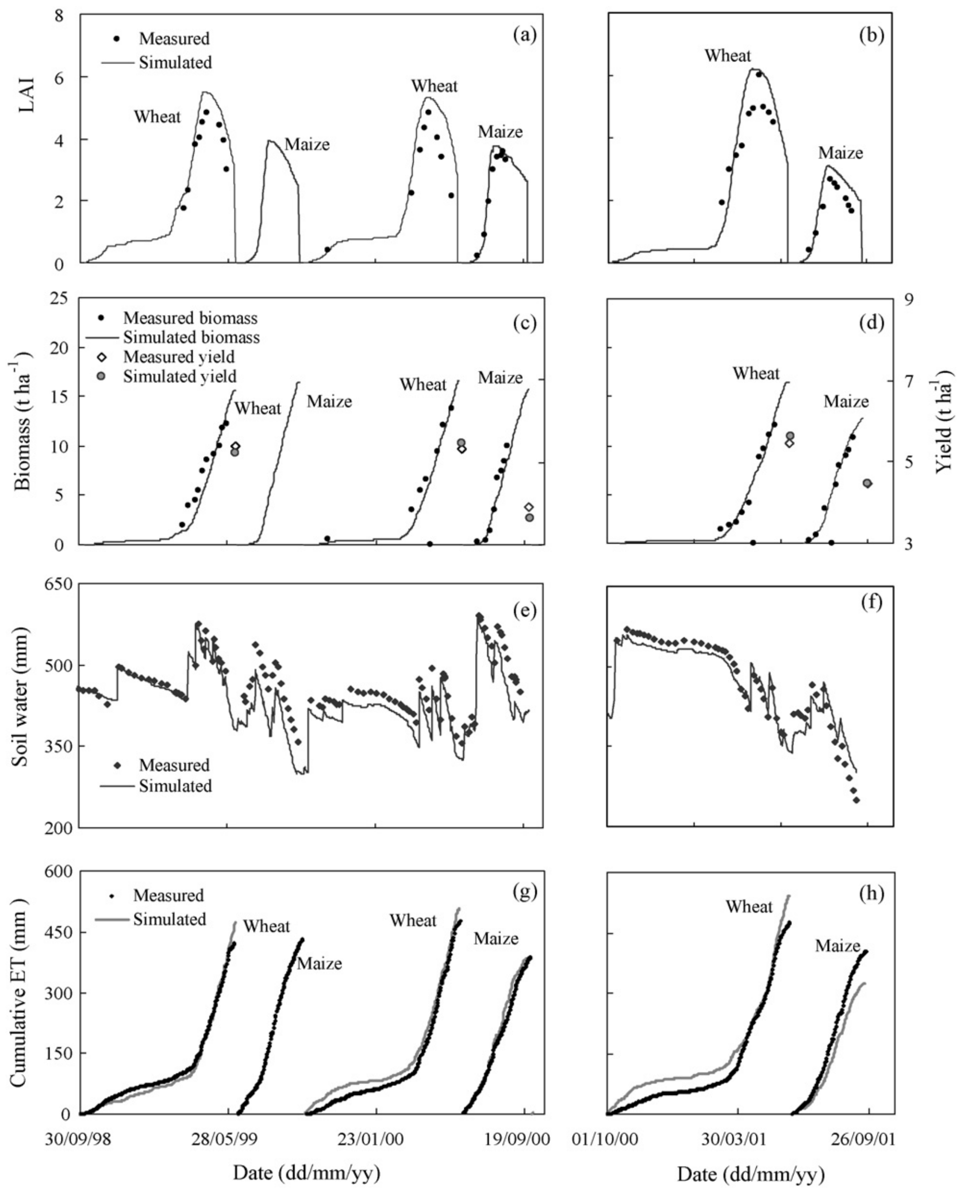

Fig. 1. Comparison of observed and APSIM simulated LAI (a and b), above-ground biomass and yield (c and d), soil water content (e and f) in the 0–160 cm soil profile and cumulative ET (g and h) at the Luancheng station. a, c, e and g show the calibration results using experimental data from the growing season 1998–2000; and b, d, f and h show the validation results using data from the 2000–2001 growing season.

content and cumulative ET during wheat and maize growing seasons (Fig. 1). In general, LAI simulations of wheat and maize closely followed the observations (Fig. 1a and b). Simulations of biomass accumulation and grain yield also agreed well with the measurements (Fig. 1c and d). Some overestimation in above-ground biomass of wheat occurred due to the overestimation of LAI. The model was able to explain the yearly difference in grain yield. The largest difference between simulated and observed grain yield occurred in 2000 for maize with underestimation of 0.3 t ha^{-1}. The simulated soil water content in the 0–160 cm depth (Fig. 1e and f) corresponded well with measured values. Cumulative ET patterns during wheat and maize growing seasons also corresponded well with the measured values (Fig. 1g and h), though some disagreements between simulated and observed cumulative ET occurred at the end of the growing season in the validation period (2000–2001).

Agreement between observations and simulations of LAI, above-ground biomass, soil water contents was described by the slope and the coefficient of determinations (R^2) of the original regression lines (Fig. 2). The model was able to explain more than 90% of the variation in crop biomass (Fig. 2c and d) and yield (Fig. 2e), and more than 84% of the variation in soil water content (Fig. 2f). All the slopes of the regression lines are close to 1.0, except for the soil water (0.84) due to a couple of low soil moisture values. If those low soil moisture values were excluded, the slope of the regression line for soil water became very close to 1.0. Considering possible errors in the measurement data, the performance of the model is therefore considered to be satisfactory for the simulation of crop growth, water use in wheat–maize double cropping systems in the study area.

3.2. Analysis of climate variations from 1961 to 2000

The variations of climate variables during wheat and maize growing seasons from 1961 to 2000 were shown in Fig. 3. Mean temperature during wheat seasons ranged from 6.4 to 9.9 °C with a

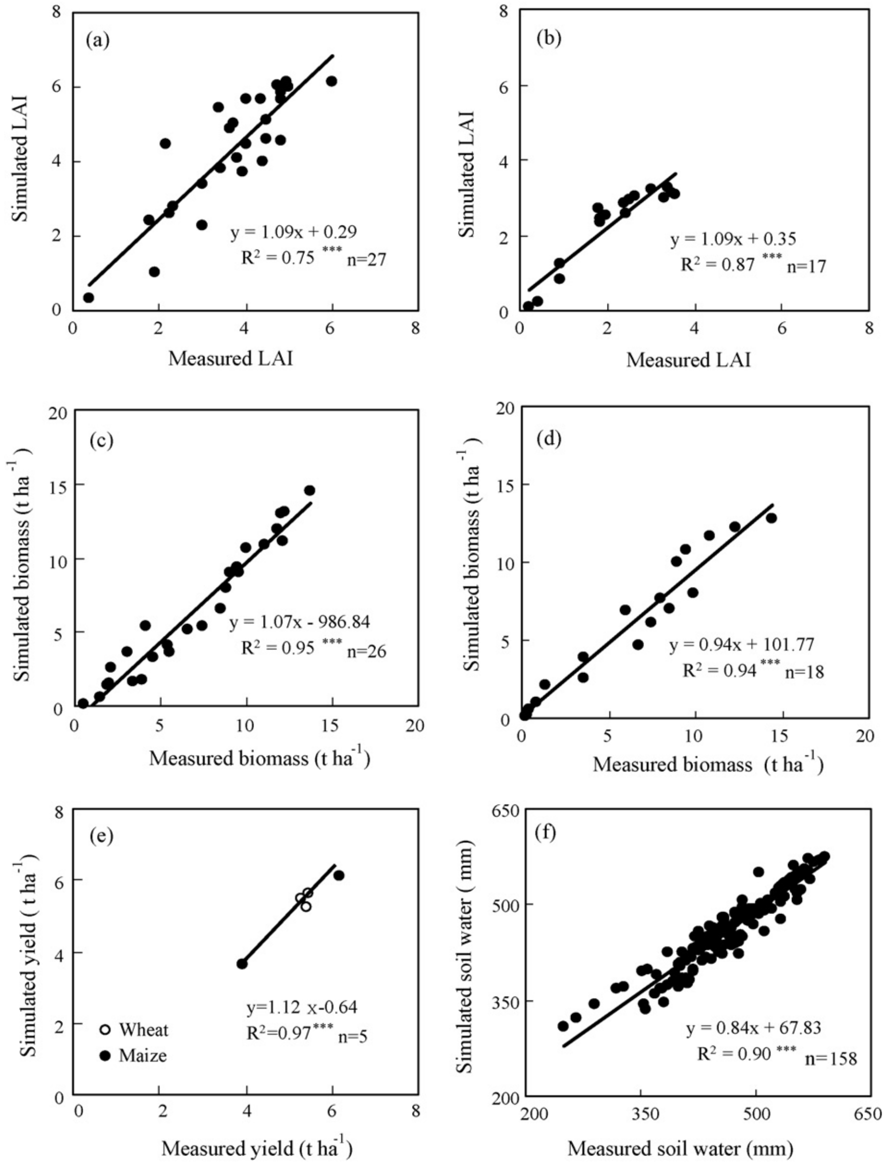

Fig. 2. Relationship between observed and simulated values of LAI, above-ground biomass of wheat (a and c) and maize (b and d), grain yield for wheat and maize (e) and soil water (f) from 1998 to 2001 at Luancheng station. Significant at $^{***}P < 0.001$; significant at $^{*}P < 0.05$.

standard deviation of 0.76 °C, and that during maize seasons varied between 23.6 and 27.5 °C with a standard deviation of 0.74 °C. Solar radiation during wheat and maize seasons ranged from 10.0 to 13.2 MJ $m^{-2}d^{-1}$ and 12.7 to 20.2 MJ $m^{-2}d^{-1}$, with standard deviations of 0.88 and 1.57 MJ $m^{-2}d^{-1}$, respectively. Precipitation had the biggest variability. During wheat seasons, precipitation ranged between 40.0 and 285.0 mm with a standard deviation of 58.8 mm. It was less than 150.0 mm in 80% of seasons. Precipitation during maize seasons was between 150.0 and 1020.0 mm with a standard deviation of 172.8 mm. It was less than 400.0 mm in 60% of seasons.

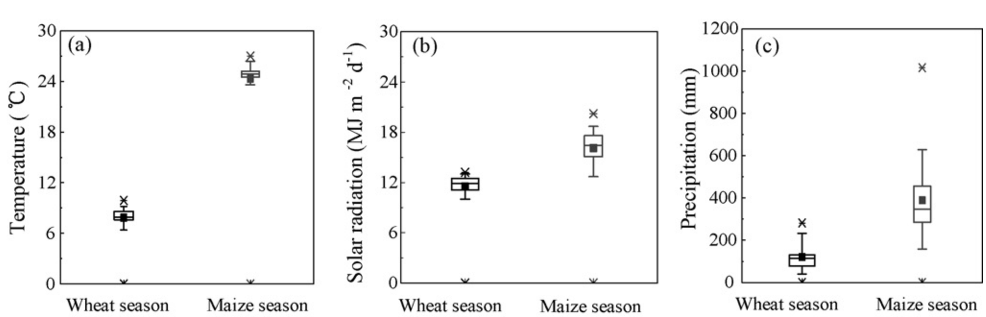

Fig. 3. Mean daily air temperature (a), global radiation (b) and total rainfall (c) during the wheat and maize growing seasons from 1961 to 2000 at Luancheng. The box plots show the 5, 25, 50, 75 and 95 percentiles. The dots and lines in the box plots indicate the mean and medium, respectively. The crosses indicate the minimum and maximum.

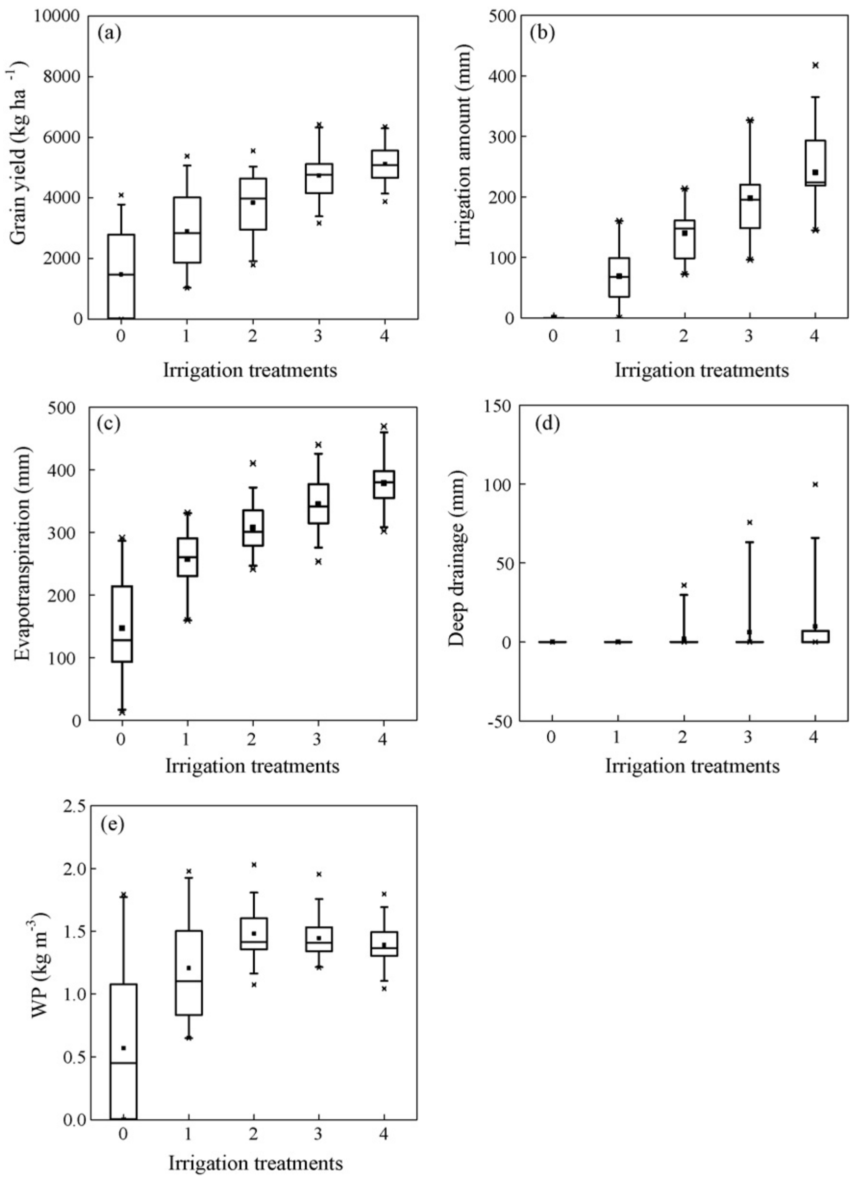

Fig. 4. Simulated grain yield (a), irrigation water demand (b), evapotranspiration (c), deep drainage (d) and water productivity (e) of wheat from 1961 to 2000 at Luancheng. 0, 1, 2, 3, 4 refer to zero-, one-, two-, three- and four-irrigation treatments. The box plots show the 5, 25, 50, 75 and 95 percentiles. The dots and lines in the box plots indicate the mean and medium, respectively. The crosses indicate the minimum and maximum.

3.3. Grain yield and water balance in response to water management under climate variability

Simulation results for grain yield and water balance components in response to irrigation under historical climate variations were shown in Fig. 4 for wheat and Fig. 5 for maize. The range of rain-fed wheat yield was large and ranged from 0 to 4.5 t ha^{-1}, indicating a significant impact of climate (rainfall) variability. Increasing irrigation amount increased wheat yield and reduced yield variability (Fig. 4a). Wheat yields were increased significantly when one, two or three irrigations were applied. However, there was only a small increase from three to four irrigations.

Even with summer monsoon rainfall, maize yield under no irrigation also varied greatly due to large inter-annual variability of rainfall, ranging from 0 to 5.0 t ha^{-1}. A large difference in maize yields was shown between no irrigation and one irrigation in many seasons due to low rainfall (Fig. 5a).

Irrigation water demand under each irrigation treatment varied greatly due to inter-annual variability in rainfall. With decreased number of irrigations, the irrigation water (plus rainfall) only met crop water demand during certain part of the growing season. The variations in the amount of water required in each treatment (to fill the soil up to 80% of FC) indicated that the soil water content at these crop stages varied from year to year. Under one-irrigation treatment, irrigation water demand for wheat was less than 30, 70 and 90 mm in 25%, 50% and 75% of seasons, respectively (Fig. 4b). The average value was 70 mm. It ranged from 70 to 220 mm under the two-irrigation treatment with an average of 140 mm. The average was 200 and 240 mm under three and four irrigations, respectively. The maximum value amounted to 330 mm under three irrigations and 420 mm under four irrigations. Irrigation water demand for maize under one irrigation ranged from 0 to 140 mm with an average of 60 mm, while that under two irrigations had a range of 0–170 mm and averaged 110 mm (Fig. 5b).

Under no irrigation, the range of crop ET was mainly determined by rainfall. ET increased with the increase in irrigation application. Maximum ET for wheat under no irrigation was 290 mm, whereas it reached 330, 410, 440 and 470 mm under one, two, three and four irrigations, respectively (Fig. 4c). As for maize, maximum ET was 370, 400 and 430 mm under no irrigation, one irrigation and two

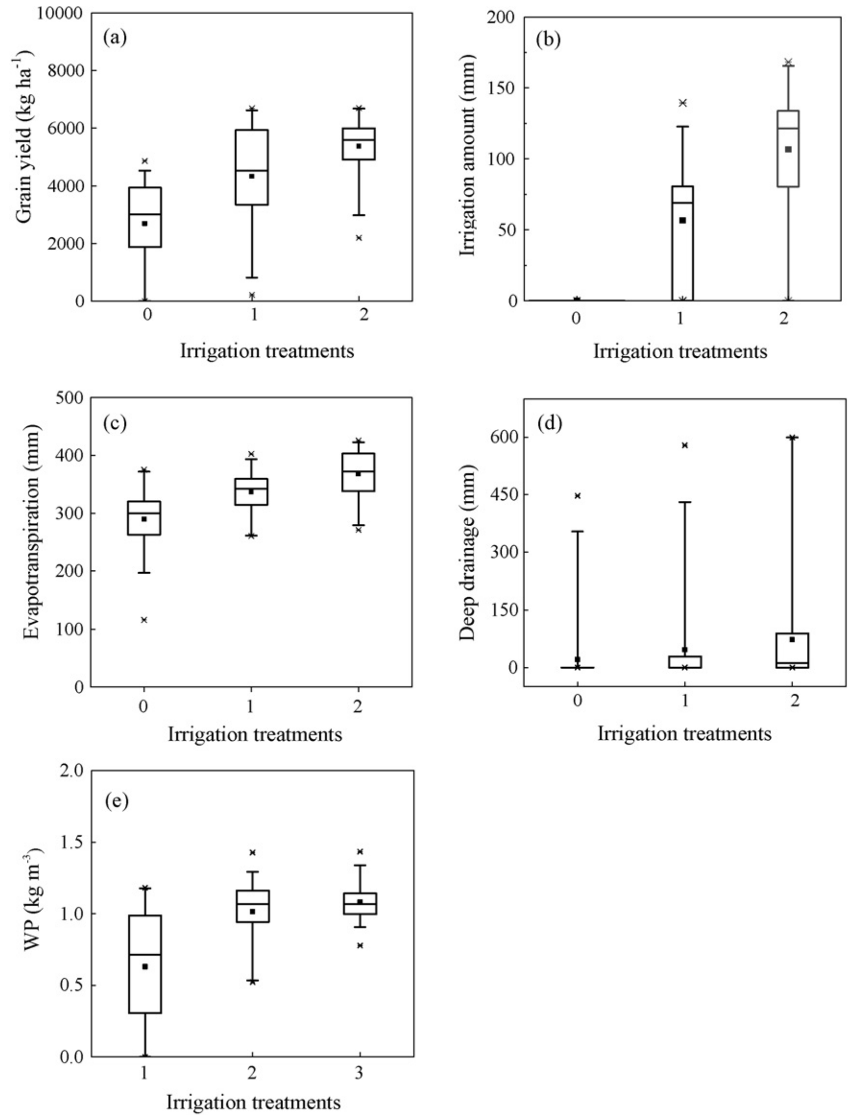

Fig. 5. Simulated grain yield (a), irrigation water demand (b), evapotranspiration (c), deep drainage (d) and water productivity (e) of maize from 1961 to 2000 at Luancheng. 0, 1, 2 refer to zero-, one- and two-irrigation treatments. The box plots show the 5, 25, 50, 75 and 95 percentiles. The dots and lines in the box plots indicate the mean and medium, respectively. The crosses indicate the minimum and maximum.

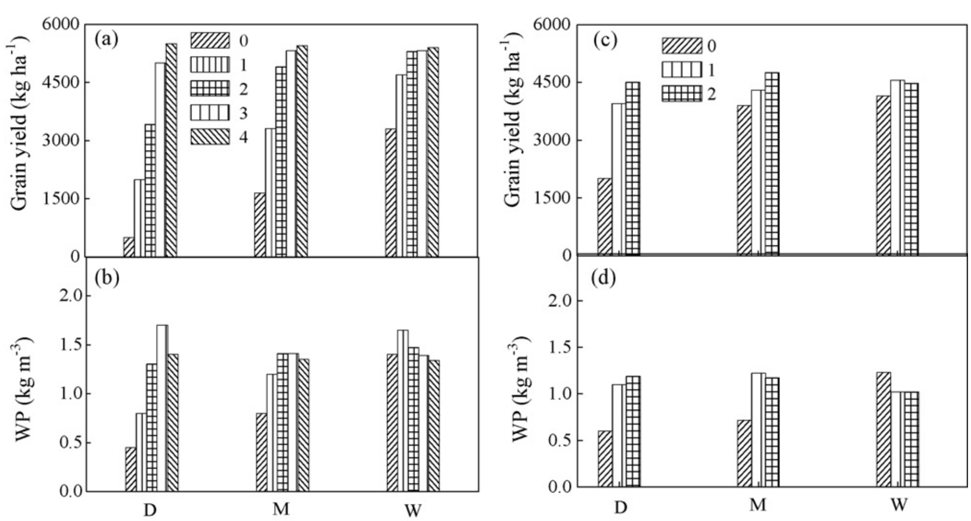

Fig. 6. Average of simulated grain yield and water productivity of wheat (a and b) and maize (c and d) as affected by different irrigation scenarios and season types at Luancheng. 0, 1, 2, 3, 4 refer to zero-, one-, two-, three- and four-irrigation treatments. D: dry season; M: medium season; W: wet season.

irrigations, respectively (Fig. 5c). On average, wheat ET under zero, one, two, three and four irrigations were 150, 260, 310, 350 and 380 mm, respectively. The average ET of maize was 290, 330 and 370 mm, respectively.

The simulated responses of crop yield to irrigation treatments or water consumption (ET) were very similar to those of Zhang and Yu (2003), Liu et al. (2005) and Zhang et al. (2005). Those previous studies derived their results either from a number of year's experiments or discontinuous modelling, while this study continuously simulated the wheat–maize double cropping system from 1961 to 2000 and provided results on both the mean values under historical climatology and the variations caused by historical climate variability.

Due to the relatively low rainfall during the wheat season, little deep drainage occurred under all irrigation schedules except for four irrigations in rainy seasons (Fig. 4d). During the maize season, deep drainage occurred when rainfall plus irrigation exceeded the water demand for maize (Fig. 5d). Even with summer rainfall, little deep drainage occurred in more than 80% of seasons under no irrigation, implying that the possibility for recharging groundwater under a continuous wheat–maize double cropping system was low.

Using a simple soil water balance model, Kendy et al. (2003, 2004) calculated annual recharge from irrigated cropland to unconfined alluvial aquifers underlying Luancheng County for 1949–2000. Their modelled recharge rates ranged from 5 to 109 cm year^{-1}, depending on the quantity of precipitation and irrigation applied, similar to the mean results shown in Fig. 5d. The results here further emphasised the fact that areal recharge is not a constant fraction of precipitation plus irrigation, but rather the fraction increases as the water inputs increase (Kendy et al., 2004).

3.4. Crop water productivity under different water management and climate conditions

WP of wheat (Fig. 4e) and maize (Fig. 5e) under no irrigation were low and varied greatly, and WP was lower than 1.0 kg m^{-3} for wheat and 0.9 kg m^{-3} for maize in 75% of seasons. The average of wheat WP reached maximum value under the two-irrigation treatment (Fig. 4e), and declined under three and four irrigations. The average values of wheat WP were 0.52, 1.24, 1.56, 1.42 and 1.40 kg m^{-3} for no, one, two, three and four irrigations, respectively. There was only a small difference in maize WP between one and two irrigations (Fig. 5e). Applying two irrigations for maize did not increase WP, though it increased the average yield.

Figs. 4e and 5e show the WP of wheat and maize as affected by both climate variability and irrigation management. For a given irrigation level, a wide range of crop yield existed due to impact of inter-annual climate variability, which also led to difference in WP. If the results in Fig. 4c and e were put together to analyse the response of WP to total ET, it is very similar to the relationship derived in Liu et al. (2005).

The variations of simulated grain yield, irrigation water demand, ET, WP suggest that in optimizing agricultural water management one should consider the climate variability, especially the amount and distribution in time of precipitation, and soil water content to schedule irrigation. Another consideration is that a more efficient irrigation water use would be achieved with maximal WP rather than crop yield under the water resource limited conditions in the NCP.

3.5. Optimal irrigation management in crop seasons under different climatic seasons

As shown in Fig. 6, grain yield of both wheat and maize increased with the increase in irrigation application, but the increase became smaller with increasing water supply depending on the season types (Fig. 6a and c). Maximum WP did not occur in the treatment with the highest irrigation application and there was a significant irrigation–season type interactions (Fig. 6b and d). For wheat, maximum WP was obtained under three irrigations (about 200 mm) in dry season, two irrigations (about 150 mm) in medium season and one irrigation (about 70 mm) in wet season, respectively. For maize, WP was the maximum under two irrigations (about 110 mm) in dry season, one irrigation (about 60 mm) in medium season, and no irrigation in wet season, respectively. Therefore, these irrigation schedules were recommended for wheat and maize for more effective utilization of the limited water resources.

The simulations also showed that, even under optimal irrigation schedule, winter wheat and maize rotation still needed large amounts of irrigation in most years, especially in wheat seasons. This means that groundwater table would continue to fall if irrigation practices continue. For a long-term perspective, changing cropping system or reducing wheat planting area might be an option to avoid over consumption of water resource.

3.6. The impact of climate variability and irrigation on groundwater table

Fig. 7 shows the potential change in the depth of groundwater table in response to different irrigation treatments. Inter-annual rainfall variation largely drove the variation in water demand for irrigation, i.e., the groundwater pumping, leading to different changes in groundwater table in different years. For example, in

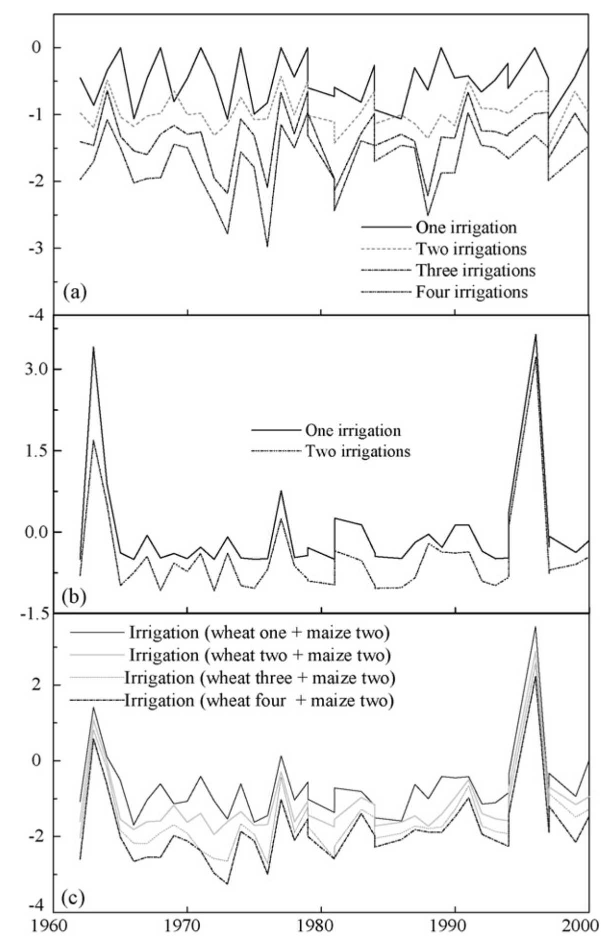

Fig. 7. The change in groundwater table under different water management strategies during wheat season (a), maize season (b) and a rotation year (c) from 1961 to 2000 at Luancheng.

the three wheat seasons with high rainfall (1964, 1969 and 1990), the average of groundwater table decline was 0.9 m per season even under the four-irrigation treatment (Fig. 7a) while in the three seasons with low rainfall (1976, 1982 and 1989), groundwater table declined about 2.0 m per season on average due to more groundwater mining for irrigation to meet higher crop water demand. In maize seasons with high rainfall, such as 1963 and 1996, groundwater was predicted to be recharged because groundwater use for irrigation was less than the deep drainage (Fig. 7b). When a rotation year was considered, the average groundwater table decline was 0.7, 1.0, 1.3 and 1.5 m $year^{-1}$ if two irrigations for maize were combined with one-, two-, three- and four- irrigations for wheat, respectively (Fig. 7c).

The simulated rate of groundwater table decline under lower irrigation levels in Fig. 7c roughly matches the observed decline in aquifer levels (about 1 m $year^{-1}$ over a prolonged 28-year period) in Luancheng County (Zhang et al., 2003). Higher irrigation levels with the efforts to meet the crop water demand of both wheat and maize would lead to further decline of groundwater table, up to 1.5 m $year^{-1}$, similar to the value estimated by Kendy et al. (2004). The simulation results of this study allows further scenario analysis to explore how irrigation management interacts with climate variability to affect crop yield, WP and hydrological balance in the study area. The decline would be smaller if other sources of groundwater recharge, such as lateral seepage from the Taihang Mountain and vertical infiltration from waterlogged pond are considered. The simulated results of this study give information about the relative impacts of irrigation management and climate variability on groundwater table.

4. Conclusions

Crop yield, water productivity and field water balance are strongly influenced by climate variability and irrigation water management in the NCP. An agricultural system modelling is an effective means to investigate the response of such items to historical climate variations and irrigation. The calibration and validation of the APSIM model showed that it could reasonably reproduce the dynamics of winter wheat and summer maize growth, yield, water use and the change of soil water in the study area. Simulation results using the validated model combined with historical climate records and irrigation scenarios showed that climate variability greatly affected crop yield and irrigation water demand. Dryland crop yield ranged from 0 to 4.5 t ha^{-1} for wheat and 0 to 5.0 t ha^{-1} for maize. Increasing irrigation amount led to increased crop yield, but the irrigation amount required to obtain maximum WP was much less than that required for obtaining maximum crop yield. To meet crop water demand, irrigation water requirement for wheat ranged from 140 to 420 mm per season, while for maize 0–170 mm per season. An attempt to supply enough water to meet the crop water demand with such levels of irrigation could lead to about 1.5 m $year^{-1}$ decline in groundwater table in the study area when other sources of groundwater recharge were not considered.

Under the climate and the limited water resource conditions in the region, one, two and three irrigations (i.e., 70, 150 and 200 mm $season^{-1}$) based on soil water status were recommended for wheat in wet, medium and dry seasons respectively for maximising WP. For maize, no irrigation was applied in wet season, while one-irrigation and two-irrigations (i.e., 60 and 110 mm $season^{-1}$) were recommended in medium and dry seasons.

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