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Irrigation strategies to improve the water use efficiency of wheat–maize double cropping systems in North China Plain

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A B S T R A C T

Water is the most important limiting factor of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) double cropping systems in the North China Plain (NCP). A two-year experiment with four irrigation levels based on crop growth stages was used to calibrate and validate RZWQM2, a hybrid model that combines the Root Zone Water Quality Model (RZWQM) and DSSAT4.0. The calibrated model was then used to investigate various irrigation strategies for high yield and water use efficiency (WUE) using weather data from 1961 to 1999. The model simulated soil moisture, crop yield, above-ground biomass and WUE in responses to irrigation schedules well, with root mean square errors (RMSEs) of 0.029 $\mathrm{cm^3\,cm^{-3}}$, 0.59 $\mathrm{Mg\,ha^{-1}}$, 2.05 $\mathrm{Mg\,ha^{-1}}$, and 0.19 $\mathrm{kg\,m^{-3}}$, respectively, for wheat; and 0.027 $\mathrm{cm^3\,cm^{-3}}$, 0.71 $\mathrm{Mg\,ha^{-1}}$, 1.51 $\mathrm{Mg\,ha^{-1}}$ and 0.35 $\mathrm{kg\,m^{-3}}$, respectively, for maize. WUE increased with the amount of irrigation applied during the dry growing season of 2001–2002, but was less sensitive to irrigation during the wet season of 2002–2003. Long-term simulation using weather data from 1961 to 1999 showed that initial soil water at planting was adequate (at 82% of crop available water) for wheat establishment due to the high rainfall during the previous maize season. Preseason irrigation for wheat commonly practiced by local farmers should be postponed to the most sensitive growth stage (stem extension) for higher yield and WUE in the area. Preseason irrigation for maize is needed in 40% of the years. With limited irrigation available (100, 150, 200, or 250 mm per year), 80% of the water allocated to the critical wheat growth stages and 20% applied at maize planting achieved the highest WUE and the least water drainage overall for the two crops.

1. Introduction

Winter wheat–summer maize double cropping is the main cropping system in the North China Plain (NCP) and accounts for about one fourth of national food production by using high-yielding cultivars with fertilizer and water applications. Water is the most limiting factor in this cropping system due to the low and uneven distributions of annual rainfall (Liu and Wei, 1989; Liu et al., 2001). High irrigation is necessary to maintain high yield levels under these variable climatic conditions, but results in a decline in the groundwater table and water quality (Liu et al., 2001). Therefore, it is essential to optimizing irrigation strategies for high crop production and water use efficiency (WUE), which is usually defined as grain yield production per unit evapotranspiration (Wang et al., 2002), to conserve water resource in this water-limited region.

Research in the NCP, as across the world, has shown that scheduling irrigation based on crop responses to water stress at different growth stages can improve WUE (Wang et al., 2002; Zhang et al., 2004a,b; Fang et al., 2007). However, crop production and WUE generally show a high variation in response to irrigation across seasons and regions, mainly due to varying annual rainfall, soil type, and other agronomic practices (Wang et al., 2002; Zwart and Bastiaanssen, 2004). Therefore, the experimental results are site- and season-specific and may not be applicable to other growing seasons and other locations with different climate and soil conditions.

In addition, most of the field experiments conducted in the NCP focused only on wheat seasons when water deficits generally occurred, without considering the influence of the previous maize crop and its associated growing conditions. Under water-limited conditions, initial soil water at planting is important for crop

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Table 1
Soil properties of the experimental field used for the RZWQM2 simulations at Yucheng Ecological Station.

Soil layer (cm)	Soil bulk density (g cm^{-3})	Organic matter content (%)	Sand (%)	Silt (%)	Clay (%)	Saturated hydraulic conductivity (cm h^{-1})	Soil water content at 33 kPa (cm^3 cm^{-3})	Soil Water Content at 1500 kPa (cm^3 cm^{-3})	Soil root growth factor (SRGF)
0–10	1.28	1.08	12.8	65.1	22.1	5.50	0.19	0.09	1.00
10–60	1.39	1.08	11.3	67.0	21.7	1.32	0.23	0.12	0.54
60–100	1.40	0.76	28.3	58.0	13.7	0.68	0.29	0.14	0.14
100–120	1.39	0.61	24.5	63.0	12.5	0.32	0.29	0.14	0.01

germination, emergence and plant establishment (Li et al., 2001; Zhang et al., 2004a,b), and is influenced substantially by the amount and distribution of rainfall and water use by the previous crop due to essentially no fallow between crops (Varvel, 1994; Norwood, 2000; Nielsen et al., 2002). However, it is still not clear how seasonal rainfall, irrigation, and water use by maize influence the soil water balance, yield and WUE in subsequent wheat season in this area. This knowledge can provide useful insights to improving irrigation managements and WUE of double cropping systems.

In order to address these issues, process-based simulation models of cropping systems provide a powerful tool to extend and enhance these experimental results for site-specific alternative managements over long-term climate conditions. RZWQM2 combined the Root Zone Water Quality Model (RZWQM) with the Decision Support System for Agrotechnology Transfer (DSSAT, Hoogenboom et al., 2004) crop growth modules (Jones et al., 2003) and is a powerful tool to address crop production, soil water balance and other environmental issues (Ma et al., 2006). In the DSSAT crop growth modules, two crop water stress factors for photosynthesis and crop growth were defined from the ratio of potential root water uptake to potential transpiration, where potential root water uptake is calculated from soil water availability and plant root distribution (Ritchie, 1998). In the RZWQM2, plant root distribution is calculated from DSSAT crop growth modules, and soil water dynamic and potential transpiration are calculated from RZWQM (Ma et al., 2006). The RZWQM coupled with the DSSAT has been used to quantify and analyze experimental results and to propose alternative water and N management practices In the NCP (Yu et al., 2006; Fang et al., 2008). However, the RZWQM2 with DSSAT4.0 crop growth modules has not been evaluated for crop responses to soil water stress under various irrigation managements across growth stages in the NCP. In addition, long-term weather data were not used to propose alternative irrigation practices to cope with the high variations in rainfalls in the area.

The objectives of this study were (1) to evaluate RZWQM2 for its prediction of soil water balance and crop yield in response to growth stage based irrigation treatments from 2001 to 2003; and (2) to propose alternative irrigation strategies in terms of timing, amounts, and allocations of a fixed amount of water between wheat and maize seasons for high WUE and less water drainage using long-term (1961–1999) weather data.

2. Materials and methods

2.1. Site description

The field experiment was conducted at Yucheng Ecological Station (Latitude 36°50′N, Longitude 116°34′E, and altitude 20 m) in the NCP from 2001 to 2003. It is one of the 36 agricultural ecosystem stations of the Chinese Ecological Research Network (CERN). The double cropping system is from early October to early June next year for wheat and from early June to late September for maize. The soil is formed from the sediments carried by the Yellow River and is silty, calcareous, alkaline, and rich in phosphorus and potassium (Table 1). Influenced by the monsoon climate, the area is characterized by high temperature and high rainfall in the summer with a mean annual rainfall of 515 mm. Seventy to eighty percent of the rainfall occurs from July to late September during the maize growing season. Only 20–30% occurs from October to early June during the wheat season. Groundwater table ranged from 2 to 4 m at experiment site, which can result in a certain groundwater recharge during dry seasons (Yang et al., 2007). Rainfall was much lower in 2001–2002 (292 mm) than in 2002–2003 (562 mm) (Fig. 1).

2.2. Crop and irrigation treatments

A typical wheat–maize double cropping system with varieties, and planting densities that are commonly used by the farmers in the NCP were selected with maize planted in June and winter wheat planted in October. The maize variety, Nongda 108, was sown at a density of 6.6 seedings m^{-2} with 67 cm row spacing after winter wheat harvest. Before planting maize, 200 kg N ha^{-1} of nitrogen (N) fertilizer as urea was applied with irrigation water in each plot in order to establish a good seedling emergence. The wheat variety, 93–52, was sown at a rate of 250 seedings m^{-2} with 25 cm row spacing on 4 October each year. Before sowing winter wheat, 300 kg N ha^{-1} of urea and 5000 kg ha^{-1} chicken manure were incorporated into the 0–30 cm soil followed with irrigation.

The experiment was carried out in 2.58 m × 2.58 m plots with concrete walls to 1.8 m depth to eliminate the exchanges of soil water between plots. Four irrigation treatments with three replicates each were designed based on wheat growth stages of planting (I), stem elongation (S), booting (B), and grain filling (G) (Table 2). The treatments were arranged in randomized block design with three replications. Two (I, IS) of the four treatments were under rain-out shelters from stem extension (jointing) to maturity in the first winter wheat season (2001–2002), which resulted in severe soil water stress in these treatments due to no

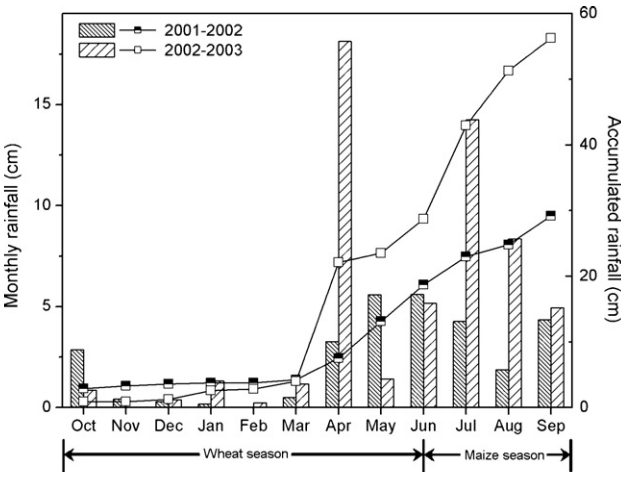

Fig. 1. Monthly rainfall and accumulations from 2001 to 2003 at Yucheng Ecological Station.

Table 2
Irrigation (mm) treatments for the wheat–maize double cropping system from 2001 to 2003. I: irrigation at wheat and maize planting; S: irrigation at stem extension stage; B: irrigation at booting stage; and G: irrigation at grain filling stage.

Treatments[a]	Winter wheat season				Maize growth season		
	Before planting	Stem extension	Booting	Grain filling	Before planting	Stem extension	Flowering
ISBG	100	60	60	60	100		
ISB	100	60	60		100	60	90
IS	100	60			100	60	90
I	100				100		

[a] Two treatments of I and IS were under rain-out shelters from stem extension stage to maturity in the 2001–2002 wheat season. Additional irrigation at stem extension (60 mm) and flowing (90 mm) were applied for IS and ISB treatments only for the 2002 maize season. Treatments were named after irrigation scheduling in the wheat seasons.

rainfall received. Irrigation water was applied using the surface flood method delivered through plastic pipe that was 40 mm in diameter and recorded with a water meter. There were 5 m buffering zones between plots, where the same crop as in the plot was planted.

2.3. Measurements and analyses

Rainfall, maximum and minimum temperatures, and solar radiation were measured daily at a meteorological station on the experimental site. Soil moisture was measured at 10 cm intervals to a 150 cm depth using a neutron moisture meter (CNC503D2 developed by the Institute of Modern Physics, Chinese Academy of Sciences), with a separate calibration for the top 20 cm soil layer. Aluminum access tubes were placed in the middle of each plot. Neutron measurements were taken at weekly intervals, with additional measurements following irrigation and rainfall events.

At harvest, plants in 2 m^2 for winter wheat and 15–20 plants from a row for maize were sampled in each plot to determine the ratio of above-ground biomass to grain yield. Yield components including grain number per m^2 (spike numbers per m^2 × grains of spike), and grain weight were determined from sub samples with about 15 plants for winter wheat and 5 plants for maize. Evapotranspiration (ET) was estimated from soil water balance [rainfall + irrigation − increases in soil water storage − drainage − runoff]. Runoff was zero in this study. Drainage was estimated from excess water beyond field capacity for each irrigation and rainfall event. WUE was then calculated from grain yield (GY) and ET (WUE = GY/ET) (Zhang et al., 2004a,b). Detail descriptions of the experimental results are given in Fang et al. (2007).

2.4. Model calibrations and applications

As Boote (1999) suggested, the measured soil water content (5–7 day intervals), crop phenology, grain yield and biomass from the highest irrigation treatment (ISBG) (including two wheat and two maize seasons from 2001 to 2003) were used for model calibrations, and the other three treatments (ISB, IS and I) were used for evaluation. The parameters controlling soil water dynamics were calibrated before the crop genetic parameters (Hanson et al., 1999; Ma et al., 2003). During calibrations, the initial values for soil properties and crop parameters were set according to the results from Yu et al. (2006) and Fang et al. (2008), and then, via trial and error method (Godwin et al., 1989), these parameters values were adjusted slightly to minimize root mean-squared error (RMSE) and optimize graphical fits between simulated and measured data.

In RZWQM2, soil physical and hydraulic properties are needed for each soil horizon, where hydraulic properties are defined by the Brooks and Corey (1964) functions with slight modifications (Ahuja et al., 2000). Therefore, the default soil hydraulic properties for a silt loam soil provided in the model were first used as initial values for model calibrations. These initial values over-predicted soil water content in the top soil layers (0–60 cm). We then calibrated the soil water contents at 33 and 1500 kPa suction based on other studies in the literature on the same experimental site (Yu et al., 2006; Yuan et al., 2003) to improve soil water simulation (Table 1). Finally, based on the results from Zhang (1999) and Zhang et al. (2004a,b) in the NCP, the soil root growth factor (SRGF) in each soil layer was calibrated to further improve soil moisture predictions (Table 1).

The new crop genetic coefficients for DSSAT4.0 were based on a previous study at the experimental station (Yu et al., 2006). First, we slightly adjusted the cultivar parameters P1V, P1D, P5 and PHINT for wheat and P1, P2, P5 and PHINT for maize to match the simulated and measured crop phenology (emergence, flowering and maturity) by trial and error within the ranges given in Table 3. The other cultivar parameters were calibrated to improve the agreements between the simulated and measured crop yield and biomass. The genetic coefficients that resulted in the lowest RMSE values were chosen (Table 3). Mean Difference (MD), coefficient of determination (r^2), and the Nash-Sutcliffe model efficiency (NSME) (Nash and Sutcliffe, 1970) were also used to evaluate simulation results.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{1}$$

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{2}$$

$$r^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})}{\left[\sum_{i=1}^{n}(O_i - O_{avg})^2\right]^{0.5}\left[\sum_{i=1}^{n}(P_i - P_{avg})^2\right]^{0.5}}\right\} \tag{3}$$

$$\mathrm{NSME} = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \tag{4}$$

where P_i is the ith predicted value, O_i is the ith observed value, O_{avg} and P_{avg} are the average of observed and simulated values, respectively, and n is the number of data pairs.

For model application, four long-term simulations with historical weather data (1961–1999) obtained from Jinan city about 40 km away from Yucheng station were conducted by (1) running the calibrated model under rainfed condition for each crop season with the same initial soil moisture without carrying over soil moisture from season to season. The initial soil moisture at 10% intervals from 0% to 100% of soil crop available water (CAW) (water content at 33 kPa − water content at 1500 kPa) was used to investigate the effects of initial soil moisture at planting on crop yield, WUE and soil water balance; (2) running the calibrated model continuously from 1961 to 1999 under rainfed conditions to investigate the effects of the seasonal rainfalls and their distributions on initial soil water for

Table 3
Genetic coefficients developed for winter wheat (cv. 93-52) and maize (cv. Nongda108) in the RZWQM2. Values given in brackets are the ranges used in parameter calibration.

No.	Wheat parameters	Initial values[a]	Final values
P1V	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars.	60	50 (45–75)
P1D	Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h).	70	60 (30–70)
P5	Relative grain filling duration based on thermal time (degree days above a base temperature of 1 °C), where each unit increases above zero adds 20° days to an initial value of 430° days.	430	440 (380–480)
G1	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (1/g).	50	27 (20–50)
G2	Kernel filling rate under optimum conditions (mg/day).	25	25 (20–43)
G3	Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g).	1.0	1.5 (1.0–4.5)
PHINT	Phyllochron interval (°C).	85	80 (75–90)

No.	Maize parameters	Initial values	Final values
P1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days).	140	230 (140–260)
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days).	0.9	0.4 (0.2–1.0)
P5	Thermal time from silking to physiological maturity (degree days).	735	830 (650–900)
G2	Maximum possible number of kernels per plant.	837	760 (650–900)
G3	Grain filling rate during the linear grain filling stage and under optimum conditions (mg/day).	11.0	6.0 (5.0–11.0)
PHINT	Phyllochron interval (degree days).	38	39 (35–65)

[a] Initial values in the column were obtained from Yu et al. (2006).

the subsequent crop season; (3) running the calibrated model with additional irrigation timing and amounts designed according to the field experimental design in the NCP (Zhang et al., 2004a,b; Li et al., 2005) for their long-term effects on soil water balance, crop yield, and WUE; and (4) running the calibrated model to optimize allocation of limited water between the wheat and maize growing seasons for high production and WUE in the double cropping system at four given limited available water amounts (100, 150, 200, and 250 mm per year). All scenarios had urea-N applications of 200 kg N ha^{-1} before each maize planting and 300 kg N ha^{-1} before each wheat planting.

3. Results and discussion

3.1. Model calibration

Predicted soil water storage (SWS) in the 0–120 cm profiles over time showed similar trends to the measured values for the ISBG treatment with an overall RMSE of 2.85 cm (9.7%) and a MD (mean difference) of 0.1 cm (Fig. 2, Table 4). Across the seasons, the model under-predicted soil water content during winter (December–March) with a negative NSME value (−0.069). This discrepancy was probably caused by groundwater recharge at high groundwater table (Yang et al., 2007), which was not simulated by the model. The SWS in the 0–120 cm profiles was under-predicted with MDs of −1.52 and −0.86 cm for the two wheat seasons, respectively, which was due to under-prediction of soil water content at the soil depths deeper than 60 cm during the two winter seasons (data not shown). Similar under-predicted soil water contents during winter season were also reported by Fang et al. (2008) at the experiment site. For the 2003 maize season, the SWS in the 0–120 cm profiles was over-predicted with a RMSE of 5.37 cm (15.2%) and a MD of 3.69 cm. The model slightly under-predicted soil water content in the dry season (2001–2002) with a MD of −0.007 cm^{-3} cm^{-3}, while in the normal season of 2002–2003, the model slightly over-predicted soil water content with a MD of 0.012 cm^{-3} cm^{-3}. These results are comparable with similar studies by Yu et al. (2006) and Fang et al. (2008).

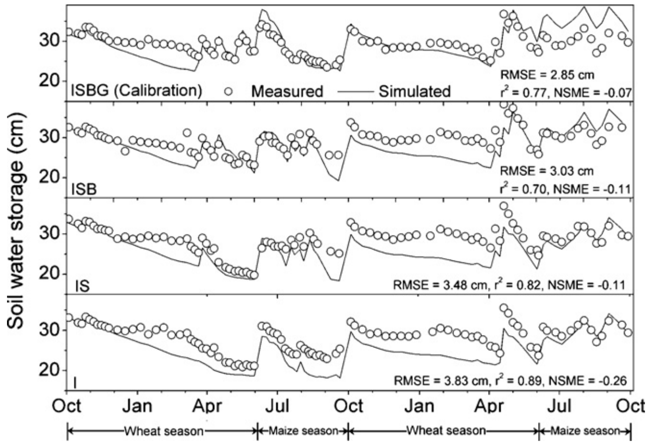

Fig. 2. Comparison between measured soil water storage (SWS) in the 0–120 cm profile for the four irrigation treatments and simulated values by RZWQM2 in the wheat–maize double cropping system from 2001 to 2003.

Evapotranspiration (ET) estimated from the soil water balance (considering deep drainage) of treatment ISBG is compared with model simulation values, where estimated water losses to drainage across seasons showed similar trends as the simulated values (R^2 = 0.96, n = 4; Table 5). The ET from RZWQM2 simulation was under-predicted by 1.0% for the wheat season and over-predicted by 3.5% for the maize season in the dry year of 2001–2002 (annual rainfall of 290 mm), and was over-predicted by 10.9% for the wheat season and by 10.1% for the maize season in the normal year of 2002–2003 (annual rainfall of 560 mm). The relatively high deviation of RZWQM2-predicted ET from the calculated ET in the second rotation (2002–2003) was mainly due to the difference in estimated and simulated deep drainages (Table 5). The WUE was under-predicted by 6.3% for the wheat season and by 11.2% for maize season in the dry year of 2001–2002, and was under-predicted by 9.0% for the wheat season and over-predicted by 1.4% for the maize season in the normal year of 2002–2003 (Table 5).

Simulated crop growth stages (emergence, flowering and physiological maturity) were within 5 days of the observed dates (Table 6). During the 2001–2002 crop seasons, above-ground biomass was under-predicted by 5.1% and 0.6% for wheat and maize, respectively. However, during the 2002–2003 crop seasons, it was over-predicted by 8.5% for wheat and under-predicted by

Table 4
Root mean square error (RMSE) and mean difference (MD) for soil water content ($cm^3\ cm^{-3}$) in the different layers or soil water storage (SWS) in the 0–120 cm soil profile predicted by the RZWQM2 from 2001 to 2003.

Treatment	Soil layers										SWS(cm)	
	0–30 cm		30–60 cm		60–90 cm		90–120 cm		0–120 cm			
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
ISBG (Calibration)	0.012	0.041	−0.015	0.038	0.013	0.032	−0.006	0.025	0.001	0.034	0.10	2.85
ISB	0.031	0.054	−0.020	0.042	−0.012	0.032	−0.042	0.049	−0.011	0.044	−1.28	3.03
IS	0.018	0.044	−0.025	0.045	−0.040	0.049	−0.040	0.048	−0.022	0.047	−2.62	3.48
I	0.018	0.042	−0.035	0.047	−0.039	0.051	−0.050	0.056	−0.027	0.049	−3.19	3.83
Mean values[a]	0.022	0.047	−0.027	0.045	−0.030	0.044	−0.044	0.051	−0.020	0.047	−2.36	3.44

[a] Mean values were calculated from the last three treatments for validations.

Table 5
Comparison between estimated soil water losses, evapotranspiration (ET), water use efficiency (WUE) and the simulated values by the RZWQM2 in the wheat–maize double cropping system from 2001 to 2003 at Yucheng Ecological Station in the NCP[a].

Crop	Treatment	M_{yield} (Mg ha^{-1})	S_{yield} (Mg ha^{-1})	E_{D+R} (mm)	S_{D+R} (mm)	E_{ET} (mm)	S_{ET} (mm)	E_{WUE} (kg m^{-3})	S_{WUE} (kg m^{-3})
Wheat (2001–2002)	ISBG	5.35	4.94	0.0	12.3	375.8	372.2	1.42	1.33
	ISB	5.24	5.33	0.0	17.8	335.2	379.5	1.56	1.40
	IS	2.69	3.41	0.0	16.1	242.5	240.8	1.11	1.42
	I	1.84	1.98	0.0	19.4	183.3	184.6	1.00	1.07
Maize (2002)	ISBG	4.43	4.07	0.0	14.0	247.9	256.5	1.79	1.59
	ISB	6.45	6.45	0.0	1.5	344.1	405.6	1.87	1.59
	IS	4.99	6.16	0.0	0.7	337.5	392.0	1.48	1.57
	I	3.34	3.47	0.0	0.7	202.1	243.3	1.65	1.43
Wheat (2002–2003)	ISBG	5.29	5.34	89.8	54.2	364.7	404.4	1.45	1.32
	ISB	4.41	4.60	90.2	43.4	324.0	366.8	1.36	1.25
	IS	4.31	4.47	67.7	41.8	291.1	352.3	1.48	1.27
	I	4.07	3.02	36.0	35.5	264.1	291.7	1.54	1.04
Maize (2003)	ISBG	6.03	6.73	89.0	52.3	274.5	302.3	2.20	2.23
	ISB	6.00	6.73	4.3	13.1	337.0	299.3	1.78	2.25
	IS	6.37	6.73	0.8	0.5	339.3	298.2	1.88	2.26
	I	6.56	6.73	3.3	0.4	329.0	301.7	1.99	2.23
RMSE[b]		0.53		18.0		41.5		0.28	
NSME[b]		0.88		−0.31		0.60		0.54	
r^{2}[b]		0.88		0.86		0.83		0.74	

[a] M_{yield} is measured yield; S_{yield} is simulated yield; E_{D+R} is estimated water losses to drainage by comparing each irrigation or rainfall with the difference between field water capacity and soil water storage (0–120 cm) at the time; S_{D+R} is simulated water losses to drainage and runoff; E_{ET} is estimated ET; S_{ET} is simulated ET; E_{WUE} is estimated WUE with M_{yield} and E_{ET}; S_{WUE} is simulated WUE with S_{yield} and S_{ET}.

[b] RMSE, r^2 and NSME are root mean standard error, coefficient of determination and Nash-Sutcliffe model efficiency, which are calculated from the three treatments (ISB, IS, and I) for model validation.

Table 6
Comparison between observed phenology, yield components and harvest index and simulated values by the RZWQM2 in treatment ISBGI (calibration) at Yucheng Ecological Station from 2001 to 2003.

Items	Wheat (2001–2002)		Maize (2002)		Wheat (2002–2003)		Maize (2003)	
	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
Emergence (dd/mm/yy)	08/10/01	10/10/01	13/06/02	14/06/02	08/10/02	11/10/02	14/06/03	14/06/03
Flowering (dd/mm/yy)	06/05/02	2/05/02	08/08/02	12/08/02	10/05/03	07/05/03	10/08/03	14/08/03
Physiological maturity (dd/mm/yy)	31/05/02	01/06/02	20/09/02	24/09/02	05/06/03	08/06/03	30/09/03	28/09/03
Grain weight per grain (g $grain^{-1}$)	0.025	0.037	0.178	0.192	0.025	0.026	0.258	0.236
Grain number (Grain m^{-2})	19997	15675	2280	2288	21338	20100	2608	2674
Yield (kg ha^{-1})	4942	5345	4066	4429	5335	5293	6729	6029
Biomass (kg ha^{-1})	12772	13137	10526	10971	14819	14304	15489	14455
Harvest index (kg kg^{-1})	0.39	0.41	0.39	0.40	0.36	0.37	0.43	0.42

2.2% for maize (Fig. 3A). Simulated grain yields deviated from measured values by −7.5% for wheat and −8.2% for maize during 2001–2002, whereas, wheat and maize grain yields were over-estimated by 0.8% and 2.5% for the 2002–2003 growing seasons (Fig. 3B). Grain weight was under-predicted by 32% but grain number was over-predicted by 28% for the 2001–2002 wheat season (Table 6). For the 2002–2003 wheat season, grain weight was under-predicted by 4% and grain number was over-predicted by 6%. For the two maize seasons, simulated grain weight and number deviated from measured values by −7% and 9%, respectively. Overall, under-predicted biomass and grain yields were consistent with the under-predicted soil water contents for the two crops (Table 4). Overall RMSEs of simulated above-ground biomass and grain yield of treatment IBSG were 0.80 and 0.33 Mg ha^{-1}, respectively, in the two years. Simulated harvest index was within ±5% of measured values in the two years. Thus,

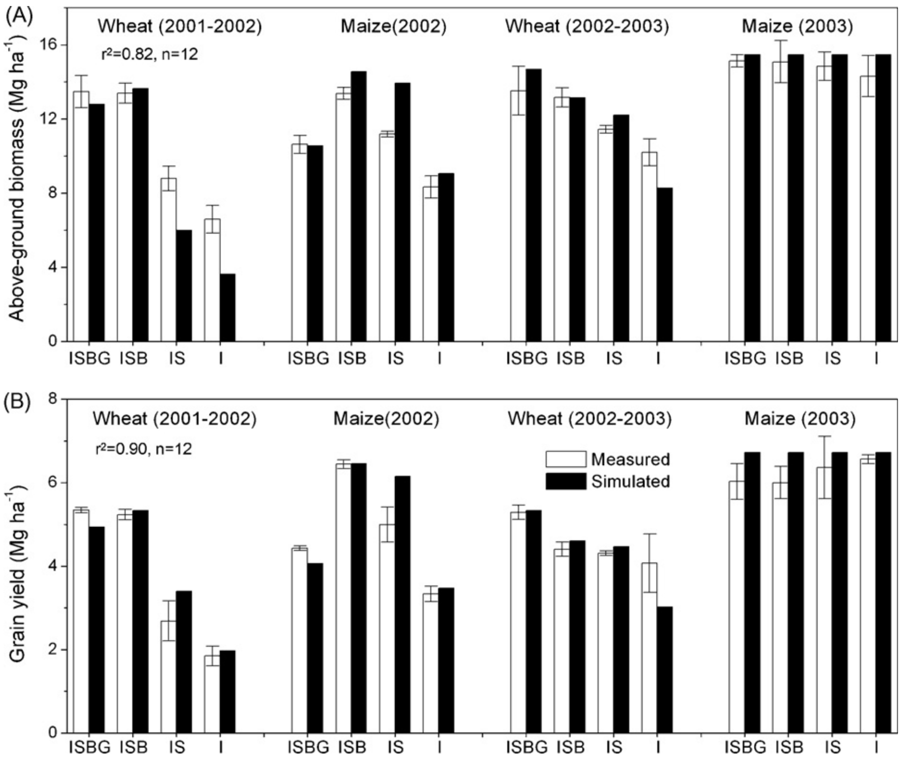

Fig. 3. Comparison between measured above-ground biomass (A) and grain yield (B) and simulated values by RZWQM2 in the wheat–maize double cropping system from 2001 to 2003. Error bars represent one standard deviation calculated from the measured data.

there is a need for further improvement in yield component predictions by improving the responses of photosynthate translocations between different organs to water stress at different stages in the model.

3.2. Model evaluation

Similar to the calibration results, predicted soil water contents in each soil layer and SWS in the 0–120 cm soil profile responded well to measured soil water from 2001 to 2003 (r^2 = 0.70, 0.82 and 0.89 for the three treatments, n = 59, Fig. 2), in spite of higher RMSEs than calibration. Mean RMSE and MD of simulated soil water content across the three treatments for the two years were 0.047 and −0.020 cm^3 cm^{-3}, respectively. For simulated SWS in the 0–120 cm soil profile, the mean RMSE and MD were 3.43 and −2.36 cm, respectively (Table 4). At low irrigation levels (treatments IS and I), SWS in the 0–120 cm soil profile was generally under-predicted for the dry year of 2001–2002 and the 2002–2003 wheat season (Fig. 2), mainly due to the groundwater recharge under dry conditions as reported by Yang et al. (2007). Similar to the calibration result, the under-predicted soil water during winter (December to March) caused negative NSME values (−0.11, −0.11 and −0.26 for treatments ISB, IS and I, respectively). When these data were removed, the NSME values increased to 0.39, 0.37 and 0.16, respectively.

The simulated ET showed a similar trend with the estimated values based on the soil water balance across the three irrigation treatments and growing seasons (r^2 = 0.83 and NSME = 0.60, Table 5). The RMSE of the simulated ET across the three treatments was 2.57 cm (10.0%) for wheat and 5.33 cm (21.2%) for maize during the 2001–2002 crop seasons. During the 2002–2003 crop seasons, the RMSE of simulated ET were 4.59 cm (12.8%) for wheat and 3.58 cm (10.6%) for maize. Overall, the model over-predicted ET for the period from 2001 to 2003, except for the 2003 maize season. Improving water drainage predictions and considering groundwater recharge in the model are need for improving the ET simulations in the area. The simulated WUE had a similar trend as the estimated values (r^2 = 0.74, and NSME = 0.53) with a RMSE of 0.28 across the three treatments from 2001 to 2003. Both simulated and estimated results showed that irrigation increased WUE in the dry year of 2001–2002, but in the wet year of 2002–2003, WUE was less sensitive to supplemental irrigation mainly due to the high seasonal rainfall (Table 5).

The measured and simulated above-ground biomass and crop yields followed similar trends to measured values (similar responses to the different irrigation treatments) from 2001 to 2003 across the three treatments (r^2 = 0.90 and NSME = 0.88 for yield; r^2 = 0.82 and NSME = 0.73 for biomass, Fig. 3). Mean RMSEs of simulated yield and biomass across the three treatments were 0.53 and 1.78 Mg ha^{-1} for wheat, and 0.65 and 1.29 Mg ha^{-1} for maize, respectively. The considerable under-prediction of wheat biomass for treatment I was associated with the under-prediction of soil water content in the 0–120 cm soil profiles (Table 4). On average, the model simulated grain yield and above-ground biomass with RMSEs of 0.59 and 2.05 Mg ha^{-1} for the two wheat seasons, and 0.71 and 1.50 Mg ha^{-1} for the two maize seasons from 2001 to 2003. These results were comparable with other studies reported by Yu et al. (2006) and Hu et al. (2006) in the NCP.

3.3. Model applications to extend experimental results

3.3.1. Long-term simulation with and without resetting initial soil moisture at planting

In the NCP, flood irrigation before planting is commonly used by the local farmers to promote germination and crop establishment due to the low and uneven seasonal rainfall (Li et al., 2001, 2005; Zhang et al., 2004a,b). The amount of preseason irrigation is generally 80–100 mm, which is high compared to the low water requirements during the early crop growth stages. The question is how often this pre-season irrigation is needed on a long-term basis

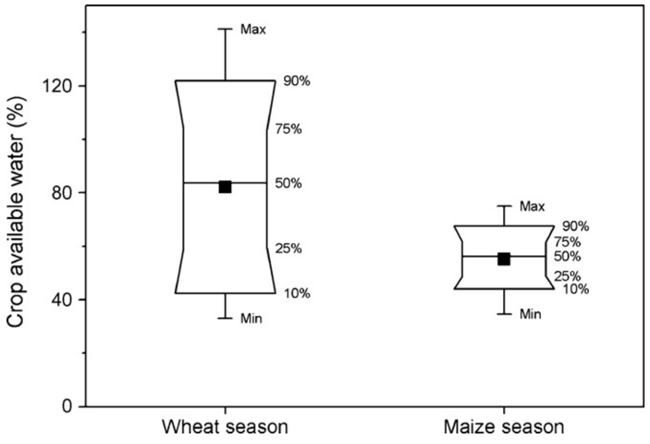

Fig. 4. Simulated initial crop available water (CAW) at crop planting under rainfed conditions by RZWQM2 with or without resetting initial soil water in the wheat–maize double cropping system from 1961 to 1999.

(Zhang et al., 1999; Li et al., 2005). Simulation results reported here assumed uniform irrigation in the field without considering uneven water distribution in the field when flood irrigation method was used.

Simulated grain yield increased from 0.65 ± 0.60 to 1.61 ± 0.85 Mg ha^{-1} (147%) for wheat and from 3.64 ± 1.75 to 4.59 ± 1.37 Mg ha^{-1} (20%) for maize when the initial soil moisture levels at planting was increased from 0 to 100% of CAW. However, when initial soil moisture was not reset at planting, simulated mean initial soil moisture at planting from 1961 to 1999 was 82% of CAW for the wheat seasons and 56% of CAW for the maize seasons (Fig. 4). About 55% of wheat seasons across the 38 years were simulated with higher initial soil moisture at planting than 80% of CAW, and 40% of the simulated maize seasons had higher initial soil moisture at planting than 60% of CAW (Fig. 4). Corresponding average rainfed yields (1.27 ± 0.80 Mg ha^{-1} for wheat and 4.12 ± 1.41 Mg ha^{-1} for maize) were 80% and 90% of the maximum yields simulated with 100% CAW initial soil water level at planting for wheat and maize, respectively. This result suggests that initial soil moisture at planting is generally adequate for wheat germination and establishment in the NCP due to the high rainfall during the previous maize season. The low rainfed wheat yields even under high initial soil moisture at planting were mainly due to the severe drought stresses later in the growing season (Zhang et al., 1999, 2004a,b). Therefore, irrigation before wheat planting, commonly practiced by local farmers, should be saved in most seasons for the later crop growth stages. For maize, irrigation may be required under very low initial soil moisture conditions (Fig. 4), but the high subsequent rainfalls can compensate for the initial slow growth caused by early water stresses, providing that a successful germination occurs. Experimental evidence of no significant impact of initial soil moisture on maize yield was also reported by Zhang et al. (2004a,b) in the NCP. The simulations also showed that high initial soil water at planting reduced maize yield variation from 48% to 30%.

There were obvious increases in simulated deep drainage from 0.03 ± 0.10 to 1.09 ± 0.54 cm for the wheat season and from 0.22 ± 0.74 to 4.62 ± 5.30 cm for the maize season as initial soil moisture at planting increased from 0% to 100% of CAW. The high drainage during the maize seasons is caused by the high seasonal rainfall. For half of the simulated wheat seasons, drainage simulation was higher without resetting initial soil water at planting (82% of CAW initial soil water averaged from seasons) than with resetting initial soil water at 80% of CAW. However, for the maize seasons, the model simulated similar drainages across the seasons (1.75 ± 3.37 cm) without resetting initial soil water conditions (56% of CAW initial soil water averaged across seasons) as with resetting initial soil water at 60% of CAW (1.69 ± 3.30 cm). Since maize yield was less sensitive to initial soil water at planting, irrigation before planting maize may not be needed to reduce deep drainage and nutrient losses in the cropping systems as suggested by field experimental results (Liu et al., 2003; Fang et al., 2006).

The simulated coefficients of variation for yield from 1961 to 1999 ranged from 53% to 93% for wheat and from 30% to 48% for maize among the different initial soil moisture levels, indicating that the amount and distribution of the growing season rainfall had a significant impact on crop growth and ultimately yields. To study the relationship between rainfall pattern and yield in more detail, rainfall was calculated for five periods in the wheat season (P1, planting to before winter; P2, winter season; P3, turn green to booting; P4, booting to flowering; P5, flowering to end of grain filling) and three periods in the maize season (P1, planting to jointing; P2, jointing to silking stage; P3 silking to maturity). For wheat, grain yields were significantly ($p < 0.01$) related to rainfall during P3 and P4 periods, suggesting that soil water conditions during these periods substantially influenced wheat yield level, and irrigation should be supplied in these periods for higher yield and WUE, which is consistent with field experiments in the NCP (Li et al., 2005; Fang et al., 2006). Maize yield was only significantly ($p < 0.001$) related to rainfall in the P1 period (planting to jointing). Other metrological factors such as solar radiation and air temperature can also contribute to high yield variations in the area (Li et al., 2002) since seasonal rainfalls are generally adequate for maize growth.

3.3.2. Irrigation scheduling

The third long-term simulation experiment was designed to investigate the most reasonable irrigation schedules for the double cropping system in the NCP (Table 7). The simulated grain yield, WUE, drainage, and N leaching averaged from 1961 to 1999 for various irrigation schedules in the cropping system are presented in Fig. 5. Large differences in wheat yield occurred with irrigation timing, mainly associated with the uneven distributions of rainfall during the crop seasons (Fig. 5A), and higher yield was obtained when a single irrigation was applied at stem extension stage than when it was applied at booting or grain filling stage. Similar results were observed for WUE. These results indicate that stem extension stage is the most sensitive growth stage of wheat to water stresses, and a single irrigation applied at this stage can be used more

Table 7
Irrigation (mm) scenarios designed for long-term simulation from 1961 to 1999. I: irrigation at planting wheat and maize; S: irrigation at stem extension stage; B: irrigation at booting stage; and G: irrigation at grain filling stage.

Treatments	Winter wheat season				Maize season
	At planting	Stem extension	Booting	Grain filling	At planting
With irrigation at planting					
I	75				75
IS	75	60			75
IB	75		60		75
IG	75			60	75
ISB	75	60	60		75
ISG	75	60		60	75
IBG	75		60	60	75
ISBG	75	60	60	60	75
Without irrigation at planting					
S	0	60			0
B	0		60		0
G	0			60	0
SB	0	60	60		0
SG	0	60		60	0
BG	0		60	60	0
SBG	0	60	60	60	0

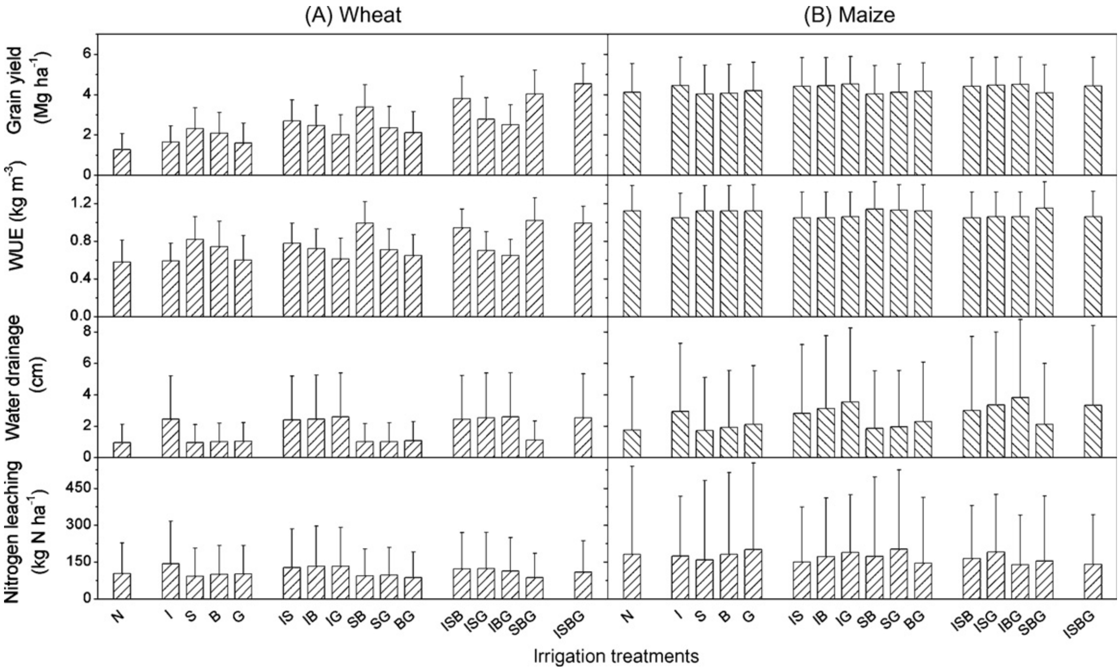

Fig. 5. Grain yield, water use efficiency (WUE), water drainage, and N leaching for wheat (A) and maize (B) seasons as influenced by irrigation schedules simulated by RZWQM2 from 1961 to 1999 (vertical bars represent one standard deviation calculated from the data from 1961 to 1999).

efficiently by the crop. However, in short-term field experiments, the most sensitive stages of wheat to water stresses were extended from stem extension to grain filling stage (Zhang et al., 1999; Li et al., 2005). Higher crop yield and water use efficiency could be obtained when two irrigations were applied at stem extension and booting stages than applied at stem extension and grain filling stages or booting and grain filling stages. Three irrigations after planting (SBG and ISBG) produced higher wheat yields than two irrigations, but did not increase WUE (Fig. 5A).

Preseason irrigation can increase grain yield by 12–30% for wheat and only 8–9% for maize, but drainage increased by 128–154% in the wheat season and 57–71% in the maize season (Fig. 5). WUE increased slightly for wheat and decreased slightly for maize when preseason irrigation was applied. If the preseason irrigation was removed from the I and IS treatments and applied in the most sensitive growth stage of stem extension, yield increased by about 30% and WUE by about 27% with 60% reduction in drainage (see treatments S and SB).

Preseason irrigation resulted in higher drainage and N leaching in the wheat season (Fig. 5A). However, the high drainages and N leaching along with high variations across seasons generally occurred in the maize season regardless of irrigation treatments (Fig. 5B), which is in agreement with field experimental observations in the region (Liu et al., 2003; Fang et al., 2006). At the same time, irrigation applied in later growth stages of wheat resulted in slightly higher drainage in the subsequent maize seasons. Therefore,

Table 8
Irrigation strategies for the wheat–maize double cropping system in the NCP at four limited available water levels (100, 150, 200, 250 mm).

Available water levels	Crop	Growth stages	Partitioning of water between wheat and maize seasons					
			50:50	60:40	70:30	80:20	90:10	100:0
100 mm	Wheat	Stem extension	50	60	70	80	90	100
		Booting						
		Grain filling						
	Maize	Before planting	50	40	30	20	10	0
		Jointing						
150 mm	Wheat	Stem extension	75	90	50	60	60	70
		Booting			55	60	75	80
		Grain filling						
	Maize	Before planting	75	60	45	30	15	0
		Jointing						
200 mm	Wheat	Stem extension	50	60	70	70	60	60
		Booting	50	60	70	90	60	60
		Grain filling					60	80
	Maize	Before planting	50	40	30	40	20	0
		Jointing	50	40	30			
250 mm	Wheat	Stem extension	60	70	55	60	60	70
		Booting	65	80	60	80	85	90
		Grain filling			60	60	80	90
	Maize	Before planting	60	50	30	50	25	0
		Jointing	65	50	45			

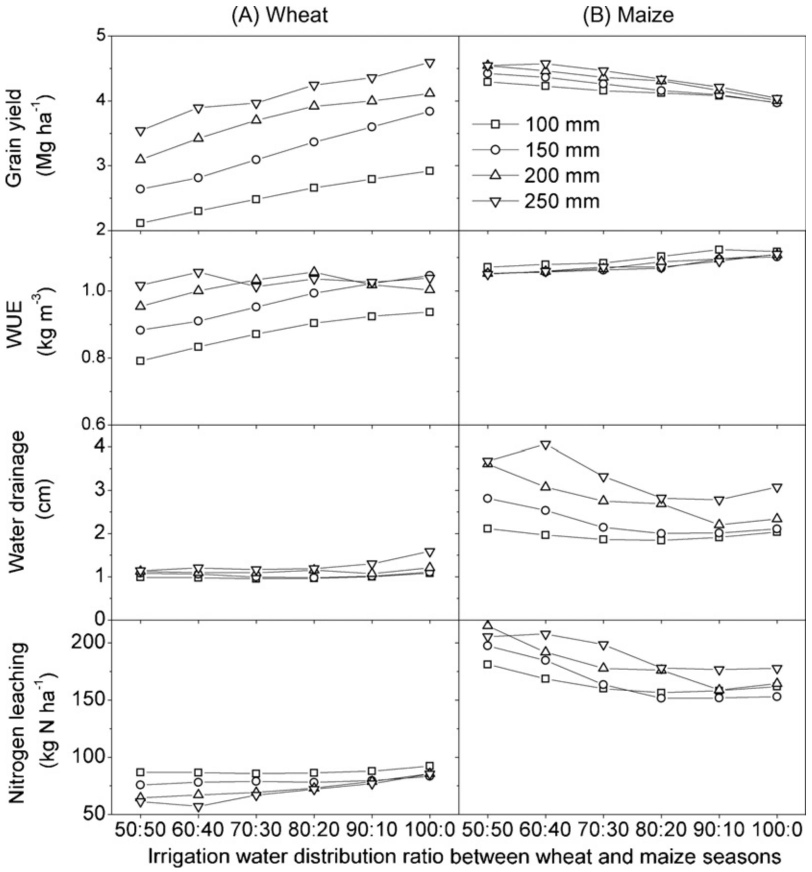

Fig. 6. Grain yield, water use efficiency (WUE), water drainage, N leaching for wheat (A) and maize seasons (B) at the four limited available water levels (100 mm, □; 150 mm, ○; 200 mm, △; 250 mm, ▽) simulated by RZWQM2 from 1961 to 1999.

irrigation scheduling should take into account the interactions between maize and wheat seasons on soil water balance to achieve higher yield and WUE in the double cropping systems.

3.3.3. Optimizing limited available water between maize and wheat seasons

The fourth long-term simulation was designed to optimize the limited water between wheat and maize seasons for high WUE and minimum drainage. Water distribution between the wheat and maize seasons was tested at six ratios: 50:50; 60:40; 70:30; 80:20; 90:10; 100:0, and the irrigation timings and amounts are shown in Table 8. Wheat yields increased linearly with the distribution ratios varying from 50:50 to 100:0 (Fig. 6), whereas maize yield decreased slightly. WUE of wheat increased with the irrigation ratio from 50:50 to 100:0 at 100 and 150 mm available water, whereas at 200 and 250 mm available water level, WUE reached the highest values at the ratios of 80:20 and 60:40, respectively. For maize, WUE increased slightly with the irrigation ratio varying from 50:50 to 100:0 and with a decrease in available water from 250 to 100 mm (Fig. 6B).

Simulated water drainage and N leaching in the wheat seasons showed little difference among the six distribution ratios and among the available water levels, except for the 250 mm water level, where drainage and N leaching increased with the distribution ratio varying from 80:20 to 100:0. Simulated water drainage and N leaching in the maize seasons was generally higher than in the wheat seasons, and showed a decrease as the distribution ratio varied from 50:50 to 80:20 and an increase as the distribution ratio varied from 80:20 to 100:0.

Combining both the wheat and maize seasons in a year, crop yield increased with the distribution ratio varying from 50:50 to 100:0 at 100 and 150 mm available water, but reached the highest values at the distribution ratio of 80:20 at both 200 and 250 mm available water. WUE reached the highest values at a ratio of 80:20. Drainage and N leaching were the lowest for the distribution ratio of 80:20 at 100, 150 and 250 mm available water and the lowest for the distribution ratio of 90:10 at 200 mm available water. Therefore, we can conclude that the most reasonable distribution ratio for available water between the wheat season and the maize season was 80:20 at the four limited available water levels to obtain the highest crop yield and WUE and the lowest water drainage.

4. Summary and conclusions

RZWQM2 adequately simulated soil moisture, crop yield and above-ground biomass in response to various irrigation practices (four treatments from 2001 to 2003) in the NCP, with RMSEs of 0.029 $cm^3\ cm^{-3}$, 0.59 and 2.05 $Mg\ ha^{-1}$ for wheat and 0.027 $cm^3\ cm^{-3}$, 0.71 and 1.51 $Mg\ ha^{-1}$ for maize, respectively. The high correlations and model efficiency between simulated and measured crop yield ($r^2 = 0.90$ and NSME = 0.87) and between simulated and measured aboveground biomass ($r^2 = 0.82$ and NSME = 0.70) showed that the model correctly simulated crop responses to irrigation scheduling at various growth stages. The relatively low accuracy in simulating WUE of maize was mainly associated with the low accuracy in predicted ET. Further improvements in simulating water drainages and groundwater recharge by the model are required to improve predictions of soil water and ET in the area.

Effective irrigation strategies for wheat–maize rotation in the NCP should not only improve the WUE, but also mitigate agricultural pressures on the environment, such as declines in groundwater levels and increased N leaching. Based on the long-term simulation results from 1961 to 1999, irrigation water at wheat planting in more than 55% of the growing seasons should be postponed to later sensitive growth stages to achieve higher crop yield and WUE, and lower soil water drainage and N leaching. Irrigation at stem extension stage of wheat is the most effective for increasing grain yield and WUE, and two irrigations applied at stem extension and booting stages are the most desirable. In the maize seasons, high seasonal rainfall generally induces high soil water drainage and nutrient leaching losses in the region (Liu et al., 2003; Fang et al., 2006). Therefore, provided that reasonable initial soil water exists at maize planting, no irrigation is recommended for maize to reduce water drainage and N leaching. In addition, an 80:20 allocation of limited irrigation water between wheat and maize seasons is optimal for high crop yield and WUE and low drainage in the double cropping systems in the NCP.

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