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Exploring optimal irrigation and nitrogen fertilization in a winter wheat-summer maize rotation system for improving crop yield and reducing water and nitrogen leaching

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A B S T R A C T

Irrigation and nitrogen (N) fertilization play important roles in grain yield. However, amounts supplied in excess of crop demand are responsible for water and N leaching during intensive agricultural production. A three-year winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) rotation experiment involving varied irrigation and N fertilization treatments was conducted in the Jinghui Canal irrigation area of Guanzhong Plain in China. To develop a more sustainable agroecosystem taking into account crop yields, deep percolation and N leaching, the RZWQM2 model was used to simulate crop production. Various irrigation and N fertilization strategies were simulated to obtain high crop yields and to reduce water and N leaching in different precipitation years, using long-term historical weather data spanning 57 years (1961–2017). The simulated soil water and NO_3-N content, grain yield, water and nitrogen use efficiencies (with nRMSE values ranging from 5.3–25.1 %), and the simulated crop biomass and N uptake (with RE values ranging from -16.4–18.3 %) were in good agreement with observed data. Simulated LAI values were acceptable (with RMSE ranging from 0.31 to 1.68 and index of agreement, *d*, ranging from 0.28 to 0.94), with the poorer simulations occurring with water and N stress. Maize seedling stage and wheat jointing stage were the phases most sensitive to water deficit, and optimal irrigation schedules could be adjusted according to variable precipitation and other climate changes. The best irrigation strategies for maize in the Guanzhong Plain were irrigation applied at the seedling stage in wet and normal years, and two irrigations applied at the seedling and jointing stages in dry years. The best irrigation strategies for wheat were two, three, and four irrigations applied in wet, normal, and dry years, respectively. Irrigation at different crop growth stages significantly influenced N leaching and nitrogen use efficiency. Increasing N input led to greater water use efficiency and less deep percolation water. Considering the interactive effects of water and N input on yield, deep percolation, and N leaching, the most appropriate N application rates in all precipitation years were 140 kg N ha^{-1} for maize and 240 kg N ha^{-1} for wheat, coupled with the recommended irrigation strategies. Improving water and N management can significantly reduce deep percolation of water and N leaching while maintaining agricultural productivity and environmental sustainability.

1. Introduction

Water is vital essential element for crop development and yield. Water scarcity has become a global systemic risk (Sun et al., 2016). The total water resources of China are 2876 billion m^3, accounting for 6 % of global water resources. Agricultural water accounts for 62.3 % of China's total water consumption, and shows a decreasing trend (Ministry of Water Resources of the People's Republic of China, 2016). Agricultural irrigation is the largest water consumer in China. The insufficient water resource challenges the sustainability of conventional agricultural practices and is a major factor limiting agricultural production in China (Dadrasan et al., 2015; Kang et al., 2017). This situation stresses the urgent need to identify reasonable irrigation management recommendations to improve crop water use efficiency (WUE) and achieve reductions in deep percolation below the crop root zone, while maintaining high grain yields. Meanwhile, the influence of

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climate change and interannual variations of precipitation in time and space result in large fluctuations in annual crop water demand, causing interannual changes in appropriate irrigation strategies.

In addition to water, nitrogen is another important component affecting crop growth and yield (Wang et al., 2017; Zhang et al., 2015b). From 1980–2012, the total consumption of N fertilizers in China increased by ~158 %, from 9.3–24.0 million t, yet total grain yield increased by only ~70 % (Yang et al., 2017). The large use of N fertilizers substantially exceeded crop demand for N and did not significantly increase crop yields and N uptake, leading to low N use efficiency (Cui et al., 2010b; Li et al., 2016) and potential environmental risks (Cui et al., 2013b). Accumulation of NO_3-N in soil profile not absorbed by crops was serious and prevalent in wheat–maize cropping system in China (Fang et al., 2006), leading to very serious environmental risks, such as N_2O emissions from agricultural fields (Zhang et al., 2013), soil degradation (Vashisht et al., 2015), and groundwater contamination (Fang et al., 2006; Gu et al., 2013).

Generally, the need for food security and environmental protection is the paradox for N fertilizer use. Zhao et al (2006) showed a dramatically decreasing NO_3–N movement to deeper soil profile by optimizing N fertilization, while keeping the higher grain yield. Thus, a balancing between grain yield and the risk of N loss is a common aim for us (Liu et al., 2018). However, climate change and differences in soil types and other factors can lead to variations in management practices such as N application rates used and irrigation amounts applied in different regions (Ju et al., 2004). Wang et al. (2017) concluded that appropriate N application rate for wheat production should be around 185 kg N ha^{-1}, using data obtained from the literature and from field experiments, and considering agricultural production and environmental impacts. Zhang et al. (2015c) recommended a reasonable N application rate for maize of 150–240 kg N ha^{-1} in the North China Plain. Huang et al. (2018) recommended seasonal N application rates of 190 and 150 kg N ha^{-1} for winter wheat and summer maize production, respectively, in China's Huang-Huai-Hai Plain. In the Guanzhong Plain of China, Yang et al. (2017) suggested proper N application rates for winter wheat and summer maize of 150–170 and 180 – 200 kg N ha^{-1}, respectively, in the winter wheat-summer maize rotation system. LÜ et al. (2019) recommended 175 and 214 kg N ha^{-1} for wheat and maize, which resulted in low environment stress and produced yields of 6799 and 7518 kg ha^{-1}, respectively. Furthermore, accumulation of NO_3-N in soil profile could be leached to deeper soil profile in conjunction with deep water percolation due to heavy precipitation in summer and unreasonable irrigation practices such as over-flooding. The implementation of appropriate N application rates coupled with reasonable irrigation schedules is essential for reducing deep percolation below the crop root zone and decreasing soil residual nitrate levels (Huang et al., 2018).

Agricultural system models have been developed as tools to simulate crop responses to water and N treatments and to extend the results of field experiments to different soil types, management practices, and climate change (Ma et al., 2001). For example, the Root Zone Water Quality Model 2 (RZWQM2, version 2.10.2010; Ahuja et al., 2000), Agricultural Production Systems Simulator (APSIM; Keating et al., 2003), Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003), Denitrification-Decomposition model (DNDC; Li et al., 1992), etc., were developed to simulate crop growth as influenced by water and N management practices. RZWQM2 (Ahuja et al., 2000; Ma et al., 2001; Qi et al., 2011) integrates physical, biological, and chemical process including hydrology, chemistry, nutrients, pesticides, crop growth, and management practices. In this study we used RZWQM2 to simulate crop development, soil water content, deep percolation and N concentration in the root zone, and grain yield. Using RZWQM, Thorp et al. (2007) concluded that reducing N application rate from 180 to 130 kg N ha^{-1} could reduce nitrate loss by 18 %. Fang et al. (2008) found that an N application rate of 200 kg N ha^{-1} for wheat/maize in conjunction with irrigation at 50 % of field capacity in the 0 – 50 cm soil layer was suitable in the winter wheat-summer maize rotation system. A long-term simulation (1961–1999) with the RZWQM2 model by Fang et al. (2010) found that preseason irrigation of wheat should be delayed to the critical water requirement growth stage, and that preseason irrigation for maize was needed in 40 % of the years. They also reported that an irrigation water ratio of 4:1 between wheat and maize could improve both water use efficiency (WUE) and crop yield in the North China Plain. Li and Sun (2016) used the RZWQM2 model to optimize single irrigation treatments in order to obtain high maize yield and WUE in northeast of China. Sun et al. (2018) used the RZWQM2 model to explore water and N transport processes and nitrate leaching into groundwater over 10 years in a summer maize-winter wheat rotation system in the North China Plain. Jeong and Bhattarai (2018) showed the need for accommodative N application rate as a result of the regional differences in agricultural systems, and used RZWQM2 to determine best management practices for nitrogen applications, focusing on rate, time, and placement. However, few studies have considered the effects of different precipitation years over the long-term historical weather record on the productivity of the winter wheat-summer maize rotation system widely used in China, and the effects of deep percolation of irrigation water and N leaching on wheat and maize productivity in order to determine the optimal irrigation and N application rates. Also, the differences in crop yields, water and nitrogen use efficiency, and water and N leaching due to various irrigation water amounts and N application rates have not been reported for different precipitation years.

The Guanzhong Plain in the Shaanxi Province of Northwest China, located in a semiarid to sub-humid climate zone, is a vital grain production area in the northwest region (Zhao et al., 2018). It covers nearly 20 % of the area of the province (34,000 km^2), while provides more than 50 % of the total food produced in the province (Yang et al., 2017). The winter wheat-summer maize rotation planting pattern is common in the region due to abundant solar radiation and optimal temperatures favorable for crop growth (Yang et al., 2017). Due to high potential evapotranspiration (ET), precipitation is not sufficient to meet crop water requirements in this area and irrigation (usually more than 75 mm) becomes essential for agricultural production (Li et al., 2013; Xu et al., 2019). In addition to this, annual rainfall in the region, mainly concentrated in August and September, has over the past 50 years varied widely from 288 mm to 959 mm, causing difficulties in precise agricultural irrigation management. To obtain high yields in this region, farmers usually use N fertilizers in amounts exceeding crop demand (Chang et al., 2014; Zhang et al., 2015a). High N inputs in conjunction with flood irrigation could result in severe N leaching (Fang et al., 2008).

This objectives of this study were to: (1) calibrate and validate RZWQM2 for accurate assessment of soil water content and soil NO_3-N content, plant growth, WUE, and N-use efficiency (NUE) in response to different irrigation and N fertilization treatments; (2) simulate and determine the optimal irrigation strategies considering crop yields, deep percolation, N leaching loss, irrigation water use efficiency (IWUE), WUE, and NUE in different precipitation years using historical weather data spanning 57 years (1961–2017); and (3) analyze the interactive effects of water applications and N input on crop yields, WUE, deep percolation, and N leaching, and determine optimal irrigation and N management under different precipitation years.

2. Materials and methods

2.1. Site description

The Jinhui Canal irrigation area (34°25′20″–34°41′40″N, 108°34′34″–109°21′35″E), supplied directly from the Jinghe River, is located in the Guanzhong Plain, Xianyang, Shaanxi Province of China, at 350–450 m above mean sea level, and covers 97,000 hm^2. The site is located in a semiarid to sub-humid climate zone, with annual rainfall and average potential evapotranspiration of approximately 535 and 1212 mm, respectively (Li et al., 2013). The experiments were conducted from 2012 to 2015 at the Shiqiao site (34°35′N, 108°43′E), located in the upper zone of the Jinghui Canal irrigation area with "Lou" soil (loess with a silty loam texture; 22.7 % clay, 48.0 % silt, 29.3 % sand).

2.2. Field experiment

The cropping system of the investigated region uses the winter wheat-summer maize rotation, with summer maize (cultivar 'Wuke 2′) grown from June to October and winter wheat (cultivar 'Xinong 979′) grown from October to the following June. Winter wheat was planted in rows spaced 20 cm apart on 13 October in 2012 and 2013 and 18 October 2014. Summer maize was planted at 60,000 plants ha^{-1} in rows spaced 65 cm apart on 13 June in 2013 and 2014. Water from the Jinghe River was used for irrigation employing the common practice for this region of flood irrigation. During the 2012–2013 wheat growing season, we instituted different water treatments with 90 mm of irrigation applied at different growth stages. Different irrigation amounts (90 and 120 mm) with different N application rates were applied during the 2013–2015 experimental period (Table 1). Each treatment during 2012–2015 was replicated three times. Plots were 21.6 m × 3.5 m, and all experimental treatments were randomly assigned to the plots. Urea (46 % N) and ammonium dihydrogen phosphate fertilizer were used, with half of the total N application incorporated into the soil before planting and the rest applied at the jointing stage of wheat and maize.

In each plot, leaf area index (LAI) for maize and wheat was measured five or six times during the respective growing seasons using the LAI-2000 Plant Canopy Analyzer (Li-Cor, Inc, Lincoln, NE, USA). Grain yields were harvested and measured at physiological maturity (4 June 2012, 7 June 2013, and 8 June 2014 for winter wheat; 7 October in 2013 and 2014 for summer maize) from 4 m^2 areas in each plot and adjusted to 13 % water content. Aboveground biomass was also measured at physiological maturity by oven–drying plant samples at 75 °C for 72 h. N content of the crops at physiological maturity was measured using the AA3 Continuous Flow Analytical System (Bran + luebbe Company, Germany).

Soil samples, used to measure soil water content and NO_3-N concentration, were collected at different crop growth periods before and after each irrigation and after precipitation. Three random locations in each plot, were sampled and then mixed well to form one sample for each plot. The samples were taken from the soil surface to a depth of 100 cm at 10 cm intervals, and from 100 to 200 cm at 20 cm intervals using an auger. The gravimetric soil water content was determined by oven drying at 105 °C for 8 h. Soil volumetric water content was determined by multiplying the measured gravimetric soil water content by the soil bulk density (measured by ring sampler at various soil depths). Soil NO_3-N concentration was measured by ultraviolet and indophenol blue colorimetry using an EV300PC ultraviolet spectrophotometer (Thermo Electron, USA).

Daily meteorological data, including temperatures, wind speed, relative humidity, sunshine hours, and precipitation from 2012 to 2015 were obtained directly from the Jinghui Canal weather station about 14 km away from the experimental site. Because daily total solar radiation data were not available, solar radiation was calculated from the daily sunshine hours using the Angstrom equation (Ampratwum and Dorvlo, 1999; Angstrom, 1924; He et al., 2013; Ji et al., 2014).

Table 1
Irrigation (W or I) and nitrogen (N) levels used as treatments in the wheat-maize double-cropping system from 2012 to 2015, Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

Planting year	Crops		Irrigation (mm)				Nitrogen application (kg N ha^{-1})
			Stage 1	Stage 2	Stage 3	Stage 4	
Oct 2012-Jun 2013	Wheat	W_1	90	0	0	0	200
		W_2	90	0	90	0	200
		W_3	90	90	90	0	200
		W_4	90	0	90	90	200
		W_5	90	90	0	90	200
		W_6	90	90	90	90	200
Jun 2013-Jun 2014	Maize	W_9N_0	90	0	90	0	0
		W_9N_{120}	90	0	90	0	120
		W_9N_{240}	90	0	90	0	240
		$W_{12}N_0$	120	0	120	0	0
		$W_{12}N_{120}$	120	0	120	0	120
		$W_{12}N_{240}$	120	0	120	0	240
	Wheat	W_9N_0	90	90	90	0	0
		W_9N_{120}	90	90	90	0	120
		W_9N_{240}	90	90	90	0	240
		$W_{12}N_0$	120	120	120	0	0
		$W_{12}N_{120}$	120	120	120	0	120
		$W_{12}N_{240}$	120	120	120	0	240
Jun 2014-Jun 2015	Maize	I_1N_0	90	90	0	0	0
		I_1N_1	90	90	0	0	120
		I_1N_2	90	90	0	0	240
		I_1N_3	90	90	0	0	360
	Wheat	I_1N_0	90	90	90	0	0
		I_1N_1	90	90	90	0	120
		I_1N_2	90	90	90	0	240
		I_1N_3	90	90	90	0	360
		I_2N_0	90	0	90	0	0
		I_2N_1	90	0	90	0	120
		I_2N_2	90	0	90	0	240
		I_2N_3	90	0	90	0	360

Note: Summer maize stages 1–4 represent seedling, jointing, tasseling, and filling stages (varied irrigation applied on June 17 and August 12 in 2013 and June 17 and July 19 in 2014). Winter wheat stages 1–4 represent seedling, wintering, jointing, and filling stages (varied irrigation applied on November 6, January 6, March 8 and May 6 during 2012–2013; October 22, January 5 and April 1 during 2013–2014 and October 21, January 15 and March 10 during 2014–2015); 50 % of the total N applied was incorporated into the surface soil before sowing and the rest at the jointing stage of wheat and maize.

Table 2
Physical and chemical parameters at various depths for soil layers from the Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

Soil layer (cm)	Clay (%)	Sandy (%)	Silt(%)	Bulk density (g/cm^3)	Saturated hydraulic conductivity (cm/hr)	Field capacity (m^3/m^3)	Permanent wilting point (m^3/m^3)
0–20	24.5	31.5	44.0	1.300	4.62	0.278	0.140
20–40	22.5	30.5	47.0	1.300	3.32	0.309	0.164
40-60	21.0	29.0	50.0	1.322	2.82	0.297	0.166
60–80	22.0	30.0	48.0	1.322	2.12	0.294	0.156
80–100	22.0	29.0	49.0	1.450	1.62	0.326	0.153
100–130	18.5	16.5	65.0	1.440	1.40	0.332	0.157
130–160	17.0	18.0	65.0	1.400	1.40	0.348	0.164
160–200	21.5	16.0	62.5	1.480	1.50	0.332	0.157

A one-way analysis of variance (ANOVA) was used to examine the differences in biomass, grain yield, and aboveground nitrogen uptake for winter wheat and summer maize by using SPSS Statistics 22.0 (https://www.ibm.com/analytics/academic-statistics-software). Statistically significant comparisons were identified using Least Significant Difference (LSD) tests.

2.3. Model calibration and validation

We used the 2014–2015 experimental data set to calibrate the model and the remaining data from 2012 to 2014 for model validation. Ma et al. (2003) recommended calibrating soil water first, followed by soil N and crop growth. The soil properties of each layer are listed in Table 2. We measured the particle size distribution (clay, sand, and silt percentages), field capacity, and permanent wilting point of soil. The saturated hydraulic conductivity for each soil layer was estimated according to Rawls et al. (1982), then slightly adjusted manually to improve the simulation of soil water content. Then we calibrated the C/N module of RZWQM2 according to Ma et al. (1998) and Fang et al. (2008) to establish the initial size of different C/N pools in order to adjust the soil NO_3-N content. After calibration of the soil parameters, we calibrated the crop genetic coefficients for the CERES-Wheat and CERES-Maize crop models used within RZWQM2 using the measured grain yields, biomass, LAI, and N uptake. The calibrated crop parameters are shown in Table 3.

To evaluate the accuracy of the simulation results for soil water content and soil NO_3-N content, as well as crop production, we used the root mean square error (*RMSE*), normalized *RMSE* (*nRMSE*), mean relative error (*MRE*), and index of agreement (*d*) parameters described in Eq.s (1)–(4):

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

$$nRMSE = \frac{RMSE}{O_{avg}} \quad (2)$$

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{P_i - O_i}{O_i}\right) \times 100\% \quad (3)$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - O_{avg}| + |O_i - O_{avg}|)^2} \quad (4)$$

where P_i and O_i are the i^{th} predicted and observed values, O_{avg} is the average of the observed values, and n is the number of data pairs.

The accuracy of the simulation results was quantitatively assessed by classifying them into four categories: excellent ($nRMSE < 10$ %), good ($10\ \% < nRMSE < 20$ %), fair ($20\ \% < nRMSE < 30$ %), and poor ($nRMSE > 30$ %) (Bannayan and Hoogenboom, 2009). The d index ranges from 0 to 1, with 1 indicating perfect agreement between the simulated and observed data, $d < 0.50$ suggesting partial inconsistency in the model predictions, and 0 indicating no agreement (Willmott, 1982).

2.4. Model application

After calibration and validation, the model was applied to determine the reasonable irrigation and fertilization practices in the summer maize-winter wheat rotation system using long-term historical weather data (1961–2017) obtained from the National Meteorological Information Center (http://data.cma.cn/). First, the drought index (*DI*) was calculated using the following equation:

$$DI = (P - M)/\sigma \quad (5)$$

where P is the annual precipitation, M is the average annual precipitation over the period 1961–2017, and σ is the standard error. *DI* is used to distinguish wet ($DI > 0.35$), normal ($-0.35 \le DI \le 0.35$), and dry ($DI < -0.35$) precipitation years (Guo et al., 2012).

In this study, *DI* for maize was calculated using the precipitation values for the summer maize growing season (June to September) and for the winter wheat growing season (October to the next May) for the experimental location. Then 15 wet years with average precipitation (AP) of 496 mm, 21 normal years (333 mm AP), and 20 dry years

Table 3
Calibrated values of crop genetic coefficients used for winter wheat and summer maize by RZWQM2.

Wheat parameters	Calibrated value
PIV (Optimum vernalizing temperature, required for vernalization, days)	41.5 (5-65)
PID (Photoperiod sensitivity coefficient, % reduction/h near threshold)	54 (0-95)
P5 (Thermal time from the onset of linear fill to maturity, °C days)	452.0 (300-800)
G1 (Kernel number per unit stem + spike weight at anthesis, #/g)	25 (15-30)
G2 (Potential kernel growth rate, mg/(kernel day))	39 (20-65)
G3 (Tiller death coefficient. Standard stem + spike weight when elongation ceases, g)	1.7 (1-2)
PHINT (Phyllochron interval, °C days)	88 (60-100)
Maize parameters	
P1 (Thermal time from seedling emergence to the end of juvenile phase, °C days)	160 (100-400)
P2 (Delay in development for each hour that daylength is above 12.5 hours, days)	0.75 (0-4)
P5 (Thermal time from silking to physiological maturity, °C days)	770 (600-1000)
G2 (Maximum possible number of kernels per plant, #)	750 (500-1000)
G3 (Kernel filling rate during the linear grain filling stage and under optimum conditions, mg/(kernel day))	9.0 (5-12)
PHINT (Phyllochron interval, °C days)	60 (30-75)

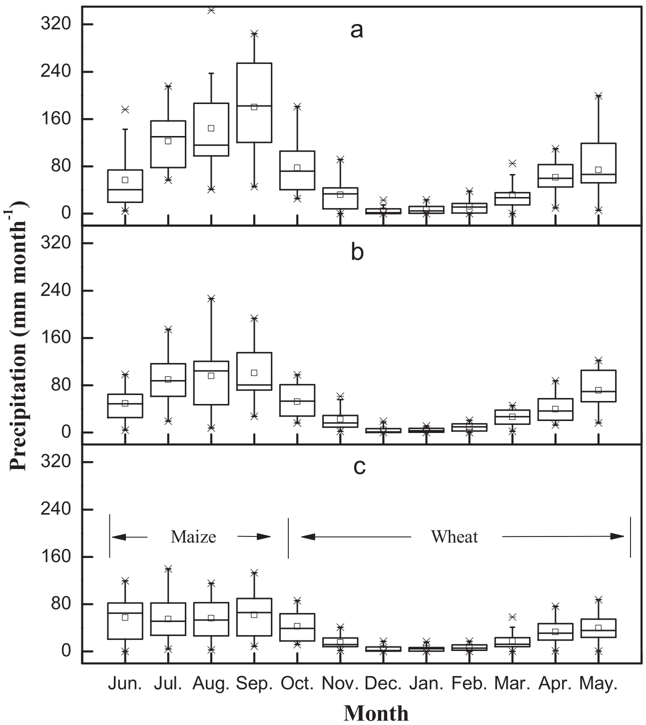

Fig. 1. Monthly precipitation in wet (a), normal (b), and dry (c) precipitation years for maize and wheat growing seasons at Guanzhong Plain, Shaanxi Province, China (1961–2017). The bottom and top of each box plot are the 25th and 75th percentiles. The line within each box is the 50th percentile. The ends of the lower and upper whiskers are the 5th and 95th percentiles, the lower and upper stars are the minimum and maximum values. The small square within each box is the mean.

(228 mm AP) for the maize growing season, and 19 wet years (303 mm AP), 15 normal years (232 mm AP), and 22 dry years (168 mm AP) for the wheat growing season were obtained. The monthly precipitation in dry, normal, and wet years is shown in Fig. 1.

The entire summer maize growing season was divided into seedling-jointing, jointing-tasseling, tasseling-filling, and filling-ripening periods, and the wheat growing season was divided into tillering-jointing, jointing-boot, boot-filling, and filling-ripening periods. Based on the meteorological data of different precipitation years, 16 scenarios of irrigation treatments were designed with 90 mm applied at various growth stages of each crop (Table 4). One treatment was a no-irrigation rainfed treatment (S1). Four treatments consisted of one irrigation application (S2-S5). Six treatments consisted of two irrigation applications (S6-S11). Four treatments consisted of three irrigation applications (S12-S15). The final treatment was four irrigation applications (S16). The effects of these treatments varying in amount and timing of applied irrigation on grain yields, deep percolation below the 120 cm soil depth, WUE, IWUE, NUE, and N leaching were determined in order to identify reasonable irrigation strategies in different precipitation years.

The grain yield, deep percolation, and N leaching values were simulated using the RZWQM2 model. The WUE and IWUE parameters were determined as follows: the WUE (kg m^{-3}) was calculated as grain yield (Y) divided by evapotranspiration (ET) during the growing season:

$$WUE = Y/10ET \tag{6}$$

The IWUE was calculated as the ratio of the difference between irrigated yield and average rainfed yield (ΔY) and applied irrigation (I):

$$IWUE = \Delta Y/I \tag{7}$$

The NUE (kg kg^{-1}) was calculated as crop yield produced per unit of N fertilizer absorbed by crops (N_{uptake}):

Table 4
Irrigation amounts (mm) for sixteen simulation scenarios (S1–S16) in the wheat-maize double-cropping system.

Scenarios	Growth stage 1	Growth stage 2	Growth stage 3	Growth stage 4
S1(rainfed)	0	0	0	0
S2	90	0	0	0
S3	0	90	0	0
S4	0	0	90	0
S5	0	0	0	90
S6	90	90	0	0
S7	90	0	90	0
S8	90	0	0	90
S9	0	90	90	0
S10	0	90	0	90
S11	0	0	90	90
S12	90	90	90	0
S13	90	90	0	90
S14	90	0	90	90
S15	0	90	90	90
S16	90	90	90	90

Note: Summer maize growth stages 1–4 represent seedling-jointing, jointing-tasseling, tasseling-filling, and filling-ripening stages. Winter wheat growth stages 1–4 represent tillering-jointing, jointing-boot, boot-filling, and filling-ripening stages.

$$NUE = Y/N_{uptake} \tag{8}$$

Finally, we intentionally removed the irrigation treatments that had little effect on yields and WUE but could cause greater deep percolation under the same irrigation amount. We analyzed the response of crop yields, N leaching, deep percolation, and WUE to different N inputs (from 0 to 240 kg N ha^{-1} for maize and from 0 to 300 kg N ha^{-1} for wheat) under four water input levels with 0 mm, 90 mm (seedling stage), 180 mm (seedling + jointing stage), and 270 mm (seedling + jointing + tasseling stage) for maize; and 90 mm (jointing stage), 180 mm (jointing + boot stage), 270 mm (jointing + boot + filling stage), and 360 mm (tillering + jointing + boot + filling stage) for wheat to evaluate the effect of the N application rate and interactive effects of water and N input on yield, N leaching, deep percolation, and WUE, in order to identify the appropriate irrigation and N fertilization management in different precipitation years.

3. Results and discussion

3.1. Model calibration and validation

3.1.1. Soil water content

Fig. 2 shows the simulated and measured soil water contents in eight soil layers of the I_1N_2 treatment during the maize and wheat growing seasons in 2014 and 2015. The predictions of soil water content were good (*RMSE* = 0.016–0.039; *nRMSE* = 5.7–14.2 %) for all soil depths, except for the top depth (20 cm) (*RMSE* = 0.059; *nRMSE* = 21.6 %). In particular, the simulated values agreed well with the measured values ($d > 0.6$), except for the 160 cm depth. The simulated water contents at the top soil depth showed a poorer match with the measured data than those at deeper depths. This result was consistent with the findings of Yu et al. (2006); Hu et al. (2006), and Fang et al. (2008) for the North China Plain. The main reason for this discrepancy was that water dynamics in the surface soil layer are more complex than in deeper soil layers because of high temporal variations in porosity, conductivity, and other properties (Hu et al., 2006), which causes greater model uncertainty associated with soil parameter and processes. In addition, the discrepancy may also be due to error in the measured soil volumetric water content, which was calculated from the measured gravimetric soil water content and the soil bulk density. Bulk density changes in response to the cultivation, irrigation, and precipitation conditions (Cai et al., 2016; Xu et al., 2019). Furthermore, the

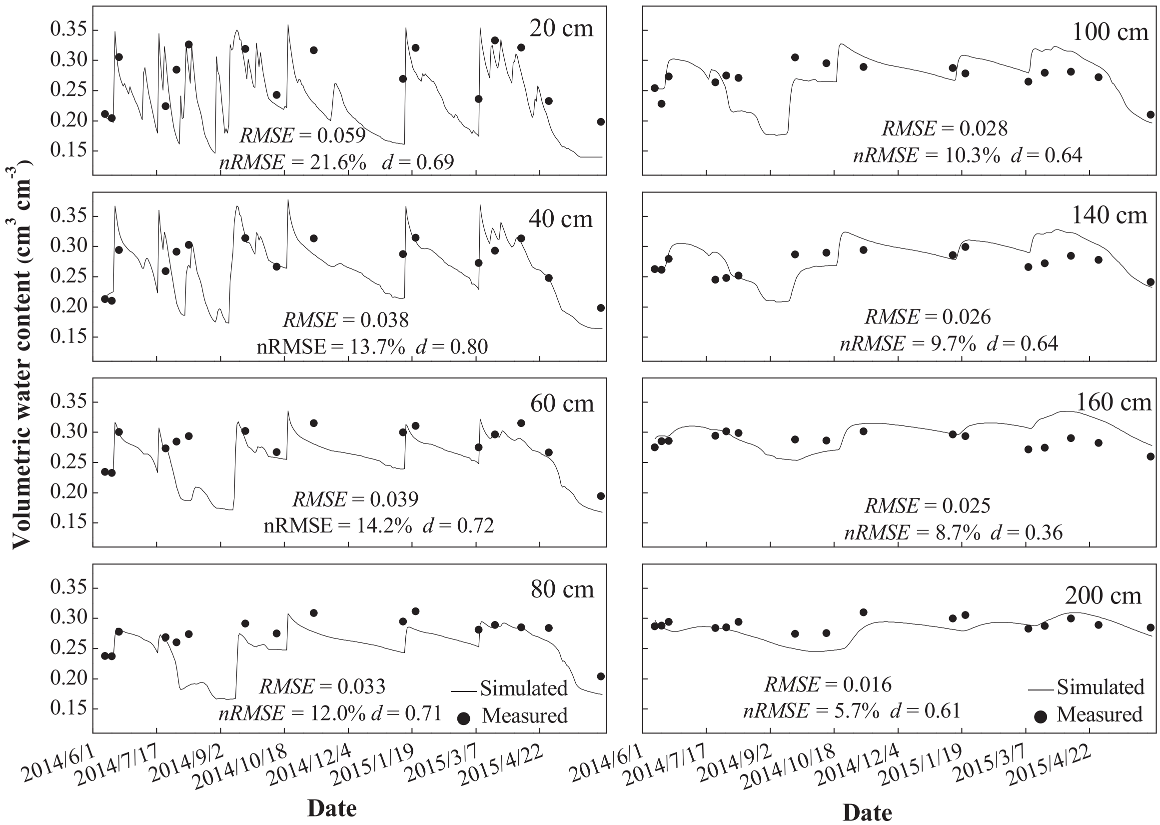

Fig. 2. Measured and RZWQM2-simulated and volumetric soil water contents at different soil depths for the I_1N_2 (see Table 2) treatments during the maize and wheat growing seasons in 2014 and 2015 at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

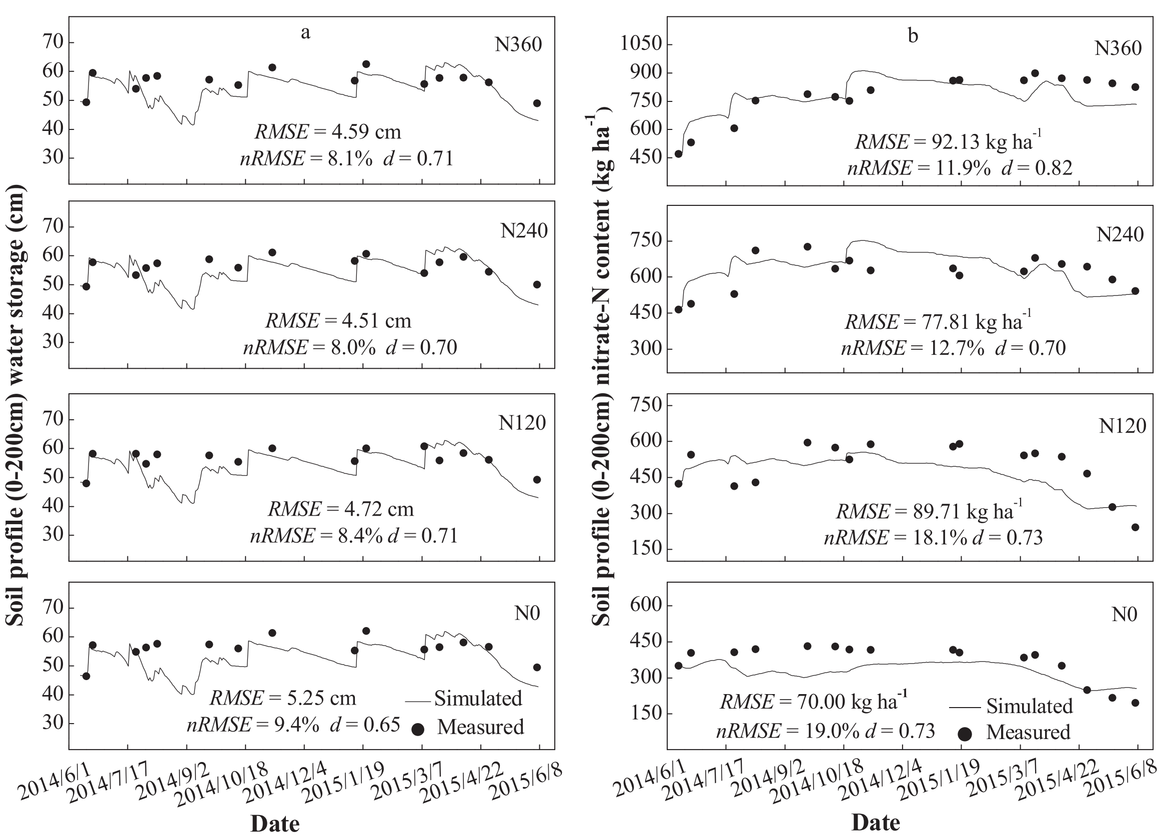

Fig. 3. Measured and RZWQM2-simulated profile (0–200 cm depth) soil water storage (a) and NO_3-N content (b) in the wheat-maize double-cropping system under different irrigation and nitrogen fertilization treatments from 2014–2015 at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

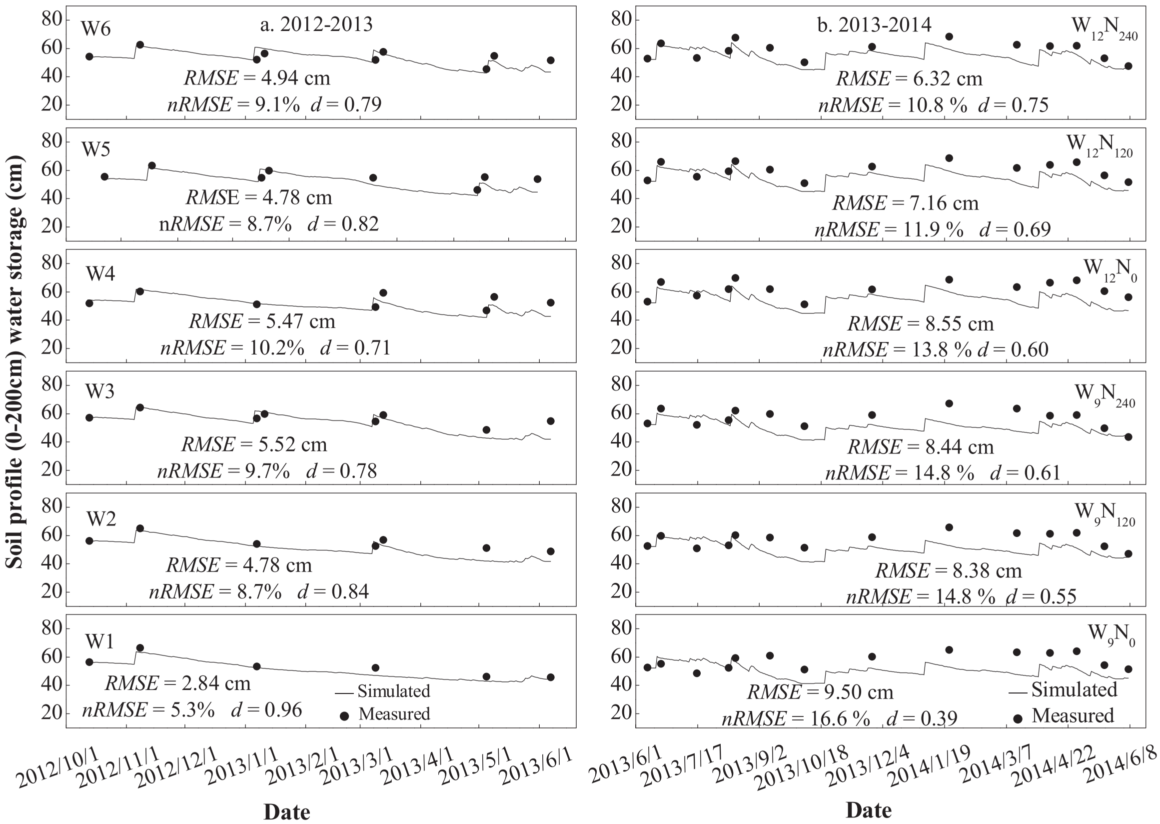

Fig. 4. Measured and RZWQM2-simulated profile (0–200 cm depth) soil water storage in the wheat-maize double-cropping system under different irrigation and nitrogen fertilization treatments from 2012 to 2013 (a) and from 2013 to 2014 (b) at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

soil water contents in the 0–80 cm layers changed more drastically in the summer maize than in the winter wheat growing period. This was because more than 55 % of the precipitation during the measurement period occurred during the maize growing period. As shown in Fig. 3a, the simulated total profile (0–200 cm) soil water storage for different N fertilization treatments was simulated with excellent accuracy (*RMSE* = 4.51–5.25 cm, *nRMSE* = 8.0–9.4 %), and the simulated results were in good agreement with the measured values (d = 0.65–0.71).

The predicted and measured soil water contents obtained for the model validation data sets in the wheat-maize rotation system from 2012 to 2014 are shown in Fig. 4. The *RMSE* and *nRMSE* values ranged from 2.84 to 5.52 cm and 5.3 %–10.2 %, respectively, for different irrigation treatments during 2012–2013, and were comparable to the *RMSE* and *nRMSE* results obtained from the model calibration. The values of d ranged from 0.71 to 0.96, with similar trends shown by the simulated and measured soil water values. The accuracy of the simulation results for the 2013–2014 period was good (*nRMSE* = 10.8–16.6 %), and most simulated values agreed well with the measured values (d = 0.55–0.75), except those corresponding to the W_9N_0 treatment (d = 0.39).

3.1.2. Soil NO_3-N content

Fig. 5 shows the simulated and measured soil NO_3-N concentrations at different times during the maize and wheat growing seasons of 2014–2015 in different soil layers of the I_1N_2 treatment. The simulated soil NO_3-N concentrations showed reasonable agreement with the measured values (*RMSE* = 3.14–6.82 mg kg^{-1} and *MRE* = -19.9 % –1.6 %).

A continuous downward movement of NO_3-N occurred in the 0 – 200 cm soil profile during the maize-wheat rotation. Nitrate mainly accumulated in soil layers between 20 and 60 cm, with a peak at 40 cm on 10 August. In contrast, after maize harvest on 12 October, nitrate accumulated in soil layers between 60 and 120 cm, with a peak at 80 cm. During the subsequent wheat growing season, some additional nitrate continued to move downward to depths below 120 cm in response to rain and several irrigation events, and accumulated in the 130–160 cm layer by the wheat harvest date. This NO_3-N fraction that accumulated below 120 cm would be difficult to be used by crops and poses a high risk of leaching into much deeper soil layers.

As shown in Fig. 3b, the simulated total NO_3-N contents in the 0–200 cm soil profile for all N treatments were in reasonable agreement with the measured profile NO_3-N content. The *RMSE* values ranged from 70.0–92.1 kg ha^{-1}, slightly larger than the value of 50.4 kg ha^{-1} in the 0 – 100 cm profile reported by Fang et al (2008) for the North China Plain. However, the accuracy of the simulated results was still good (*nRMSE* = 11.9 %–19.0 %). The d values ranged from 0.70 to 0.82, denoting similar trends between the simulated and measured soil NO_3-N content. Significant variation in NO_3-N distribution in 0 – 200 cm soil profile was observed among the different N treatments, and increased NO_3-N storage was observed with increasing N fertilization, especially for the treatment with 360 kg N ha^{-1} applied per crop. Similar to the calibration results observed in 2014–2015, the validation results of the wheat-maize rotation system subjected to different treatments during the 2013–2014 growing season were of good accuracy (*RMSE* = 75.62–95.87 kg ha^{-1} and *nRMSE* = 12.9 %–18.9 %) and in good agreement with the measured values (d = 0.56-0.82) (Fig. 6).

The present results revealed an increase in both the simulated and measured soil NO_3-N content after crop harvest (NO_3-N residue; NR) (Figs. 3b and 6) in the 0 – 200 cm soil profile for N application rates above 120 kg N ha^{-1} for maize and 240 kg N ha^{-1} for wheat. The NR of treatments with 120 kg N ha^{-1} for maize and 240 kg N ha^{-1} for wheat remained approximately unchanged, denoting the correct N balance. The NR was observed in soil after crop harvest, especially for maize crops, even when no N was applied. This could be attributed to amounts of N left in deeper layers before maize was planted that could not be utilized by the crop. In addition, precipitation and mineralization of

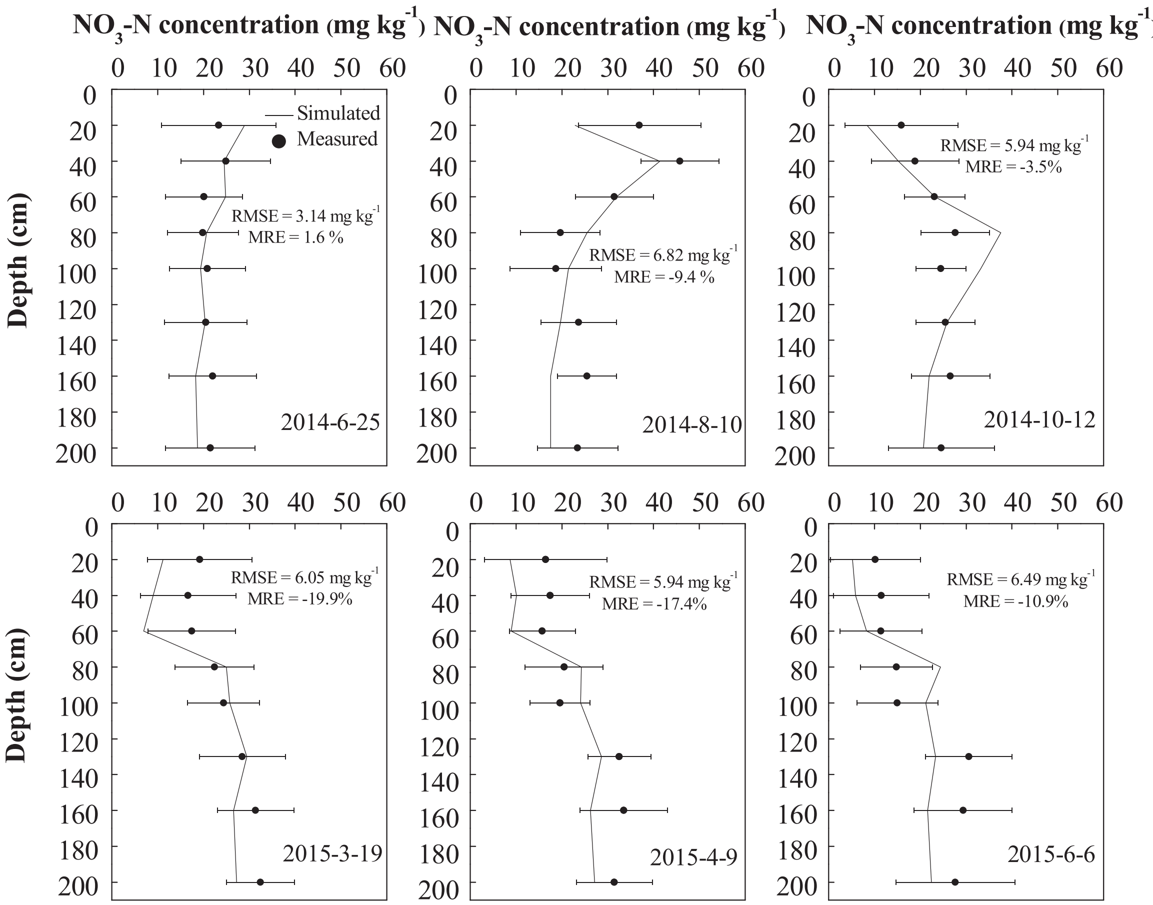

Fig. 5. Measured and RZWQM2-simulated NO_3-N concentrations in different soil layers of I_1N_2 treatment for maize and wheat, respectively, during 2014–2015 growing season at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China, and the error bars represent one standard error around the mean.

organic N could be crucial sources of soil N under these conditions. Dai et al. (2015) reported the same observation in the Loess Plateau of China. The soil NR values were above 400 kg N ha^{-1} before we planted maize in the experimental area due to higher N applied by the local farmers of the region.

3.1.3. Plant growth

The simulated values of aboveground biomass were underestimated for both maize (*MRE* = -5.4 %) and wheat (*MRE* = -10.9 %) during the 2014–2015 crop seasons. The relative errors ranged from -14.3 %–18.3 % for maize, and -16.4 % to -0.1 % for wheat (Table 5). Simulated maize grain yield was overestimated by 6.5 %, whereas wheat grain yield was underestimated by 1.7 %, with relative errors ranging from 1.3 %–15.4 % for maize and -11.1 %–10.4 % for wheat. The simulated aboveground N uptake deviated from the observed values by 5.8 % for maize and -1.5 % for wheat. The corresponding relative errors for maize and wheat ranged from 1.3 %–11.0 % and -11.6 %–7.1 %, respectively.

The biomass, crop yield, and aboveground N uptake values for maize and wheat were at their minimum when N application rate was 0 kg N ha^{-1}, and they did not significantly increase ($P > 0.05$) with increasing N fertilizer inputs from 120 to 360 kg N ha^{-1}, indicating the absence of significant effects on maize growth once the N application rate was above 120 kg N ha^{-1}. Similarly, wheat grain yield did not significantly increase ($P > 0.05$) with increasing N fertilizer inputs from 120 to 360 kg N ha^{-1} for both high and low irrigation treatments, indicating that over-fertilization (> 120 kg N ha^{-1}) did not significantly increase grain yields. However, we found no significant effect of the irrigation treatment on wheat biomass, grain yield, or aboveground N uptake, although higher values were obtained for high irrigation treatments. In particular, the aboveground N uptake values of maize and wheat remained high when N application rate was 0 kg N ha^{-1}, due to high levels of N mineralization (Fang et al., 2006) and high soil nitrate accumulation (Fig. 3b), so that farmers do not need to apply N fertilizers before planting crops (Cui et al., 2010a).

Fig. 7 shows the simulated and observed values of maize LAI during the 2013 and 2014 growing seasons and of wheat LAI during the 2012–2013, 2013–2014, and 2014–2015 growing seasons. The observed and simulated maize LAI followed similar trends over time, with *RMSE* and *d* values ranging from 0.31 to 0.57 and from 0.71 to 0.91, respectively. Wheat LAI during the 2012–2015 period was best predicted during the 2014–2015 season (*RMSE* = 0.54–1.2; *d* = 0.62–0.94), whereas the wheat LAI predictions for the other two years were slightly poorer (*RMSE* = 0.79–1.68; *d* = 0.51–0.86 in 2013–2014, and *RMSE* = 0.97–1.58, *d* = 0.28–0.87 in 2012–2013). Overall, LAI values simulated by RZWQM2 model were acceptable, but results under water and N stress were not good. The underestimated LAI values of the W_9N_{240} and W_9N_{120} treatments in 2013–2014 and of the W_4 and W_1 treatments in 2012–2013 were considered to be the main sources of error in the simulated values, and this result was in agreement with previous studies (Dejonge et al., 2011; Fang et al., 2009; Song et al., 2015).

Fig. 8 shows the simulated and observed wheat and maize grain yields for different irrigation and N fertilization treatments in the wheat-maize rotation system from 2012 to 2015. Measured wheat yields for the different treatments in the 2012–2013, 2013–2014, and 2014–2015 growing seasons ranged from 5274 to 7906 kg ha^{-1}. Simulation results were in good agreement with the measured data (*RMSE* = 711.3 kg ha^{-1}, *nRMSE* = 11.1 %, R^2 = 0.76, and *d* = 0.87). Similarly, measured maize yields for the different treatments ranged from 5850 to 7120 kg ha^{-1} during the 2013–2014 and 2014–2015 growing seasons,

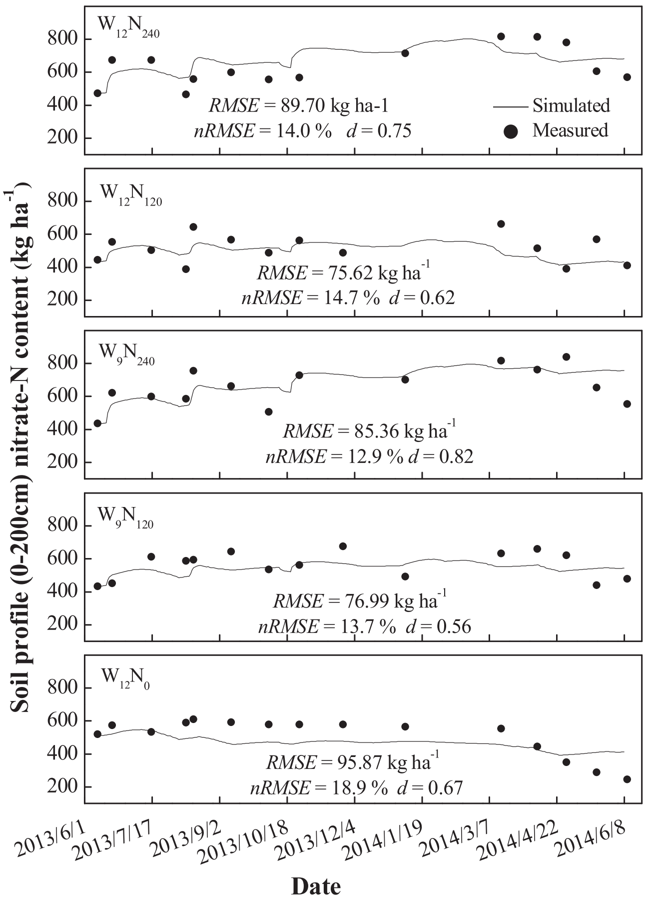

Fig. 6. Measured and RZWQM2-simulated soil NO_3-N content in the 0 – 200 cm soil profile under different irrigation and nitrogen fertilization treatments in the wheat-maize double–cropping system during the 2013–2014 growing season at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

with excellent agreement between simulated and measured values ($RMSE$ = 473.9 kg ha^{-1}, $nRMSE$ = 7.2 %, R^2 = 0.34, and d = 0.72).

3.2. Characteristics of ET, WUE, deep percolation, NUE, plant N uptake, and N leaching

Table 6 shows the simulated and observed WUE and NUE values, along with the simulated ET, deep percolation, N leaching, and plant N uptake results, obtained for the wheat-maize rotation system under different irrigation and N fertilization treatments during 2012–2015. The simulated WUE of maize was in close agreement with the observed values and the accuracy of the simulated results was good ($nRMSE$ = 10.2–14.7 %) during the growing seasons of 2013 and 2014. However, the accuracy of the corresponding model predictions obtained for wheat varied from excellent in 2014–2015 ($nRMSE$ = 7.7 %) to fair in 2013–2014 ($nRMSE$ = 25.1 %) and 2012–2013 ($nRMSE$ = 23.1 %). The WUE values were underestimated for the $W_{12}N_{240}$ and $W_{12}N_{120}$ treatments in 2013–2014 and for the W_6 treatment in 2012–2013. One possible reason was that simulated yields were a little higher than measured. Another possible reason was that there may have been some field sampling errors for these treatments. These two reasons were considered the main sources of error in the model predictions. The WUE of both maize and wheat increased with increasing N application rate due to the increase in grain yield and water use (Ji et al., 2014). Similarly, there was excellent agreement between the simulated and observed maize NUE values during the 2014 ($nRMSE$ = 3.3 %) and 2015 (5.7 %) growing seasons. As for the wheat NUE values, the accuracy of the simulation results was excellent for 2014–2015 ($nRMSE$ = 5.3 %) and good for 2013–2014 ($nRMSE$ = 19.9 %). The NUE for wheat appeared to decrease with increasing N application rate.

Evapotranspiration increased with increasing irrigation amount for both maize and wheat (Table 6). For the same total water amount, the irrigation treatment applied during the wheat regreening-jointing period led to a significantly increased ET (W4, W3 > W5) during the 2012–2013 wheat growing season. The N application rate had no significant ($P > 0.05$) effect on the ET of maize or wheat when it was above 120 kg ha^{-1}. Precipitation and irrigation significantly affected the amount of deep percolation below the root zone. Deep percolation increased with increasing irrigation amount for both maize and wheat. During 2013–2014, deep percolation increased significantly as irrigation amount increased from 90 to 120 mm, indicating that the irrigation amount had a significant effect on water movement in the soil profile. Irrigation at the winter tillering stage (W3 and W5) significantly increased the deep percolation for the same irrigation amount (W5, W4,

Table 5

Comparisons of measured and simulated biomass, grain yield, and aboveground plant nitrogen uptake across irrigation (I) and nitrogen (N) treatments applied from 2014–2015 in the Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

	Biomass ($\times 10^3$ kg ha^{-1})			Grain yield ($\times 10^3$ kg ha^{-1})			Aboveground nitrogen uptake (kg ha^{-1})		
	Observed	Simulated	RE (%)	Observed	Simulated	RE (%)	Observed	Simulated	RE (%)
Maize									
I_1N_3	15.35 ± 1.62 a	13.16	−14.3	7.10 ± 0.53 a	7.21	1.6	160.4 ± 14.42 a	162	1.0
I_1N_2	15.24 ± 1.84 a	13.16	−13.7	7.12 ± 0.48 a	7.21	1.3	159.1 ± 14.11 a	162	1.8
I_1N_1	14.95 ± 1.77 a	13.16	−12.0	6.95 ± 0.69 ab	7.21	3.7	147.8 ± 17.72 a	162	9.6
I_1N_0	10.82 ± 1.51 b	12.80	18.3	5.98 ± 0.55 b	6.90	15.4	146.3 ± 15.52 a	162	10.7
Wheat									
I_1N_3	15.65 ± 2.13 a	14.29	−8.7	7.52 ± 0.35 a	7.90	5.1	231.4 ± 14.6 a	237.5	2.6
I_1N_2	15.58 ± 2.45 a	14.28	−8.3	7.35 ± 0.43 ab	7.89	7.4	232.5 ± 16.8 a	237.5	2.2
I_1N_1	14.28 ± 1.68 ab	14.26	−0.1	7.14 ± 0.31 ab	7.88	10.4	203.6 ± 10.4 b	218	7.1
I_1N_0	12.16 ± 1.81 b	10.59	−12.9	5.84 ± 0.38 c	5.54	−5.1	161.9 ± 13.9 c	143.1	−11.6
I_2N_3	14.34 ± 1.72 ab	11.99	−16.4	6.95 ± 0.38 ab	6.18	−11.1	212.1 ± 9.9 ab	197.7	−6.8
I_2N_2	14.24 ± 1.78 ab	11.99	−15.8	6.89 ± 0.48 ab	6.18	−10.3	215.3 ± 9.1 ab	197.7	−8.2
I_2N_1	13.97 ± 1.39 ab	11.98	−14.2	6.72 ± 0.50 b	6.17	−8.2	196.1 ± 12.8 b	197.7	0.8
I_2N_0	11.57 ± 1.13 b	10.34	−10.6	5.43 ± 0.39 c	5.33	−1.8	156.7 ± 16.4 c	160.1	2.2

Note: Different letters in the same column in the same section of the table (upper and lower sections) indicate statistically significant difference as tested by LSD (0.05), and the ± represent one standard error around the mean.

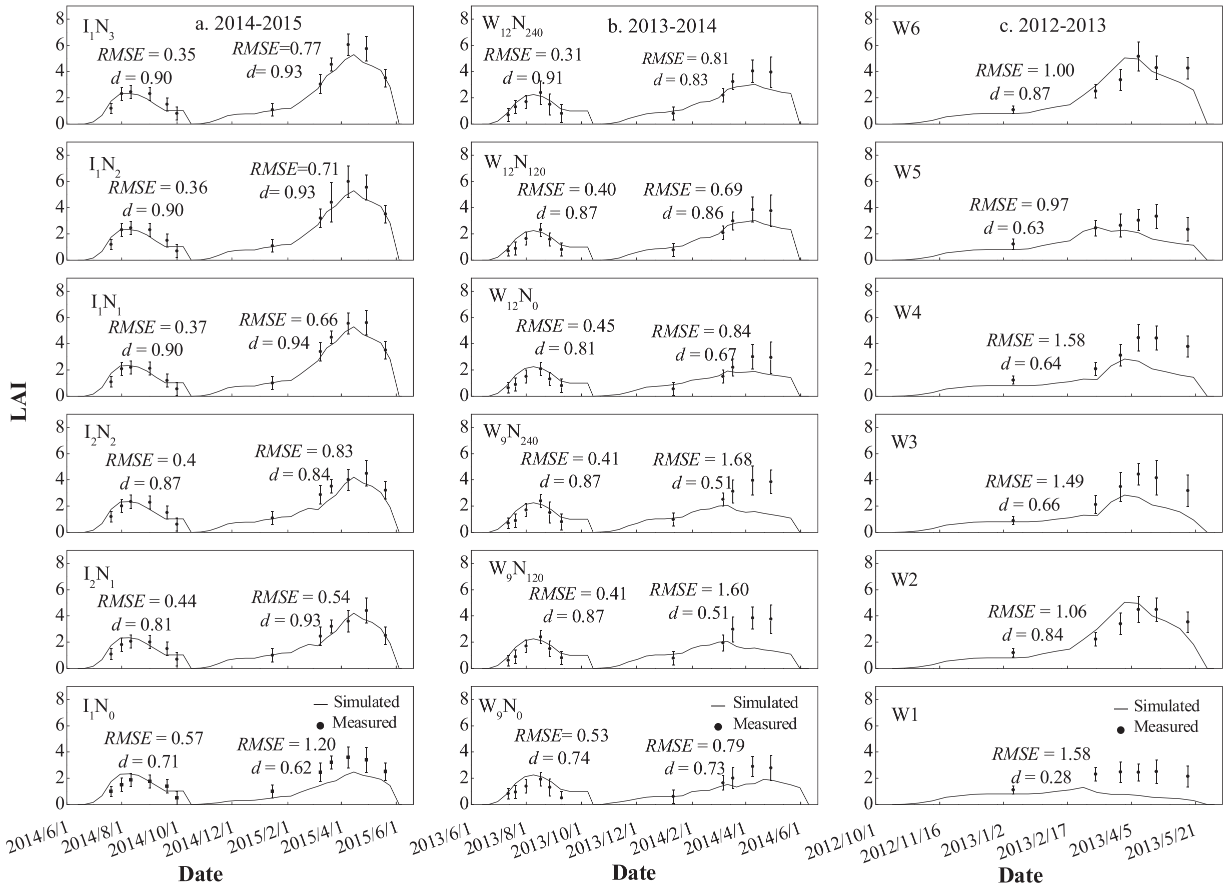

Fig. 7. Measured and RZWQM2-simulated leaf area index (LAI) values under different irrigation and nitrogen fertilization treatments in the wheat-maize double-cropping system from 2012 to 2015 at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China. Error bars represent one standard error around the mean.

and W3) during 2012–2013 (Table 6), mainly because wheat consumed less water during the seedling period, and the soil water content remained higher for a long time after the irrigation, causing larger amounts of deep percolation (58 mm for W5 and 60 mm for W3). Deep percolation ranged from 81 mm to 139 mm for all treatments during the 2014–2015 wheat growing season, which was greater than observed in other years when deep percolation ranged from 11 to 60 mm. This was mainly due to high precipitation after irrigation was applied at the jointing stage, causing large amounts of deep percolation. Similarly, the N leaching amounts increased with increasing deep percolation and N application rate, and showed marked interannual differences.

3.3. Irrigation and nitrogen management

3.3.1. Response to irrigation management for different precipitation years

Maize yields did not show much difference in response to varied

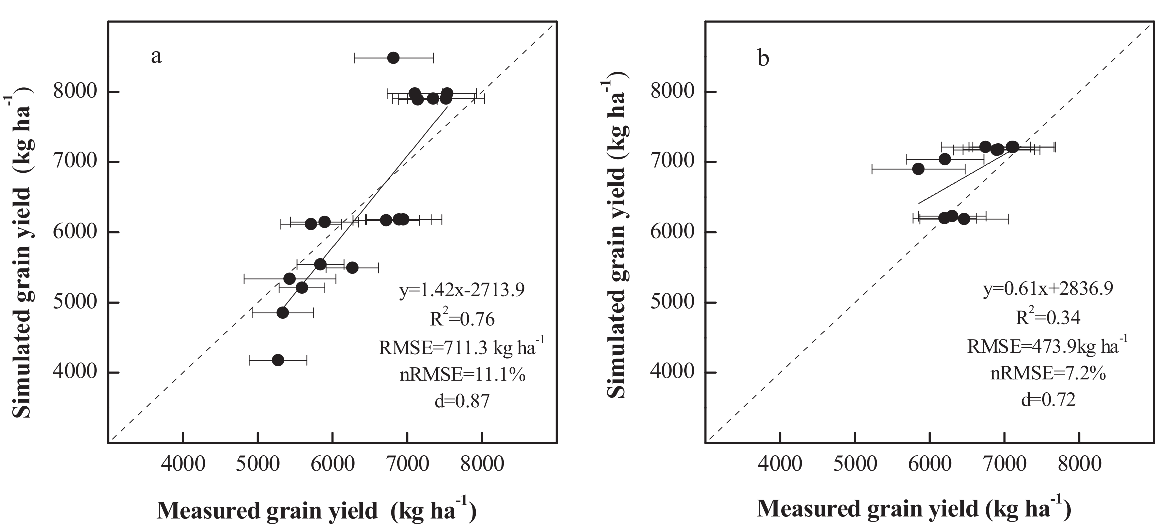

Fig. 8. Measured and RZWQM2-simulated grain yields for wheat (a) and maize (b) under varying irrigation and nitrogen fertilization treatments in the wheat-maize double-cropping system from 2012 to 2015 at Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China. Error bars represent one standard error around the mean.

Table 6
Total applied irrigation and precipitation water (W_{in}), simulated evapotranspiration (ET), deep percolation water (DP), total plant nitrogen (N) uptake, N leaching, and simulated (Sim.) and observed (Obs.) water use efficiency (WUE) and N use efficiency (NUE), for the wheat-maize double-cropping system from 2012 to 2015 in the Jinghui Canal irrigation area at Xianyang, Shaanxi Province, China.

Treatment		W_{in} (mm)	ET (mm)	DP (mm)	WUE ($kg\ m^{-3}$) Sim.	Obs.	N ($kg\ ha^{-1}$)	N uptake ($kg\ ha^{-1}$)	N leaching ($kg\ ha^{-1}$)	NUE Sim.	Obs.
2014–2015											
I_1N_3	wheat	371	429	119	1.84	1.73	360	237.5	211.4	33.3	32.5
I_1N_2			429	119	1.84	1.71	240	237.5	174.1	33.2	31.6
I_1N_1			429	119	1.84	1.65	120	218	140.7	36.2	35.1
I_1N_0			403	139	1.37	1.34	0	143.1	91.1	38.7	36.1
I_2N_3		281	378	81	1.63	1.80	360	197.7	147.1	31.3	32.8
I_2N_2			378	81	1.63	1.78	240	197.7	122.9	31.3	32.0
I_2N_1			378	81	1.63	1.74	120	197.7	99.4	31.2	34.3
I_2N_0			368	87	1.45	1.44	0	160.1	61.5	33.3	34.7
I_1N_3	maize	578	465	20	1.55	1.40	360	162	26.5	44.5	44.3
I_1N_2			465	20	1.55	1.42	240	162	24.6	44.5	44.8
I_1N_1			465	20	1.55	1.34	120	162	22.3	44.5	45.7
I_1N_0			467	190	1.48	1.21	0	162	14.2	42.6	40.0
2013–2014											
W_9N_{240}	wheat	489	452	11	1.35	1.39	240	104.3	14.4	56.7	46.5
W_9N_{120}			452	11	1.35	1.38	120	104.2	12.9	56.7	55.3
W_9N_0			445	11	1.31	1.14	0	92	11.3	58.0	69.9
$W_{12}N_{240}$		579	524	53	1.68	1.20	240	174.8	64.3	53.0	53.8
$W_{12}N_{120}$			524	53	1.69	1.22	120	174.8	56.1	53.0	58.8
$W_{12}N_0$			507	58	1.35	1.05	0	116.6	52.8	57.0	81.6
W_9N_{240}	maize	331	455	16	1.36	1.58	240	171	13.1	36.2	38.4
W_9N_{120}			456	16	1.36	1.55	120	171	13.0	36.3	39.0
W_9N_0			457	15	1.36	1.54	0	171	12.5	36.4	39.9
$W_{12}N_{240}$		391	473	42	1.52	1.66	240	171	33.8	41.9	43.3
$W_{12}N_{120}$			473	42	1.52	1.66	120	171	33.1	41.9	43.4
$W_{12}N_0$			476	40	1.48	1.52	0	171	31.4	41.2	39.3
2012–2013											
W_6	wheat	516	513	60	1.65	1.13	200	174.8	46.9	48.5	–
W_5		426	409	58	1.19	1.13	200	63.5	45.2	76.4	–
W_4		426	431	39	1.28	1.05	200	169.2	28.9	32.5	–
W_3		426	438	60	1.40	1.59	200	117.5	46.8	52.3	–
W_2		336	365	39	1.15	1.20	200	114	28.8	36.7	–
W_1		246	261	38	0.8	1.11	200	28.4	28.4	73.6	–

irrigation management in wet (6930 – 7683 kg ha^{-1}) and normal years (7595 – 8809 kg ha^{-1}) (Figs. 9a1 and b1). Maize yields in wet and normal years decreased by an average 8.5 % and 12.7 % ($P < 0.05$), respectively, under the rainfed condition (S1). Precipitation during the maize season was mainly concentrated in July, August, and September in the wet years (496 mm) and normal years (333 mm) (Fig. 1). Thus, irrigation at the seedling stage was the key to achieving high maize yields, and the greatest values of IWUE in wet and normal years (Figs. 9a4 and b4) were seen with irrigation at the seedling stage. In dry years, maize yields decreased on average by 38.7 % under the rainfed condition and showed more drastic fluctuations to different irrigation treatments (Fig. 9c1). A single irrigation could not produce a high maize yield, although it could result in a large IWUE if the irrigation occurred at the seedling or jointing stage (Figs. 9c4). If two irrigations could be applied to maize, they should be applied at the seedling and jointing stages to ensure higher yields in dry years. Irrigating at the maize grain-filling stage led to the lowest IWUE and did not significantly ($P > 0.05$) increase production compared with rainfed yields for all the precipitation years. This was partially because more rainfall occurred in the maize grain-filling stage, and that rainfall was enough to meet the crop water demand. Another reason could be that maize yields were significantly decreased when maize was subjected to water stress at early growth stages when higher temperature and drought conditions are frequent in dry years (Song et al., 2016).

Deep percolation during maize growth significantly ($P < 0.05$) increased with increasing irrigation water due to the fact that total water input was much greater than crop water requirement under high levels of irrigation (Figs. 9a2, b2, and c2). Greater values of deep percolation were achieved by irrigating during the maize seedling stage in normal and dry years (S2 > S3, S4, S5; S6, S7, S8 > S9, S10, S11; S12, S13, S14 > S15), mainly because less than 90 mm water was used by maize and the remaining soil water percolated out of the root zone. Deep percolation is a vital component of the water balance in hydrologic processes (Xu et al., 2017) and can also contribute to N loss through leaching and runoff (Bouman et al., 2007; Sato et al., 2009), In our study, N leaching amount was strongly correlated with deep percolation, demonstrating that changes in N leaching were consistent with changes in deep percolation.

WUE and NUE responses to irrigation were similar to yield responses to irrigation (i.e., not significant in wet and normal years due to relatively abundant precipitation), and ranged from 2.32-2.48 kg m^{-3} for WUE and 45.9–47.9 for NUE in wet years (Figs. 9a3 and a6), and 2.43-2.65 kg m^{-3} for WUE and 47.6–50.4 for NUE in normal years (Figs. 9b3 and b6). In dry years, WUE values exhibited a much different response to varied irrigation management (Fig. 9c3), showing the same change trend as observed for maize yield. Results showed that irrigating in the maize seedling and jointing stages could significantly increase grain yield and WUE in dry years of the Guanzhong Plain. Similar results were obtained by Chen et al. (2011). In our study, total amount of irrigation had no significant ($P > 0.05$) effect on NUE, but irrigation time had a great influence on NUE. Irrigating at the maize jointing and boot stages could significantly ($P < 0.05$) increase NUE (Fig. 9c6) because adequate water at the jointing and boot stages could increase N accumulation and N distribution ratio in stem and leaves, thus benefitting N assimilation and absorption by maize in later stages (Miao et al., 2011).

Simulated wheat yields showed greater responses to different irrigation treatments than maize yields for all precipitation years (Figs. 10a1, b1, and c1). It was more difficult to meet the wheat water requirement due to the lower rainfall during the wheat growing seasons (average 303 mm for wet years, 232 mm for normal years, and 168 mm for dry years). Rainfed wheat yields averaged 5110, 3963, and 2776 kg

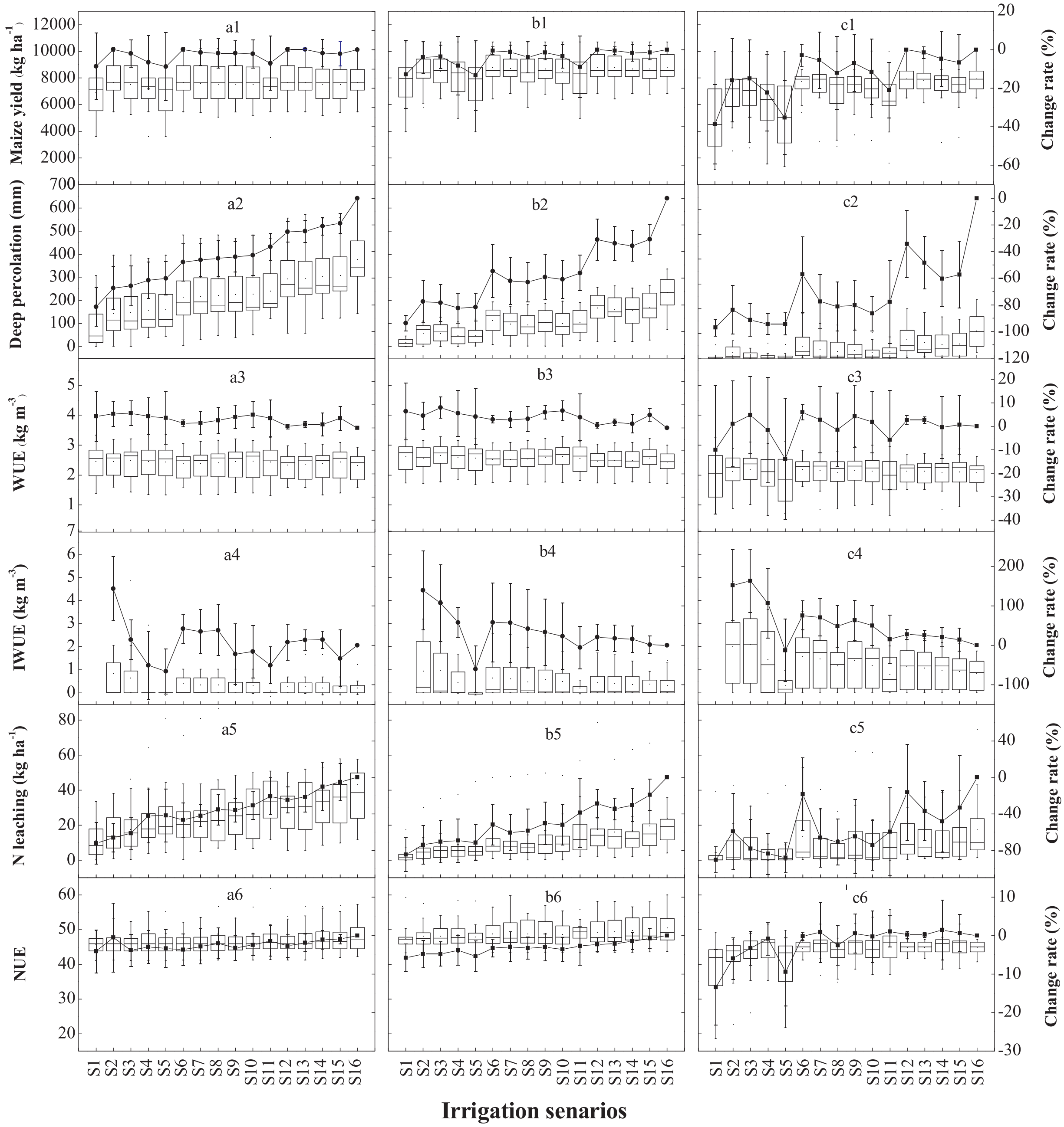

Fig. 9. RZWQM2-simulated maize yield, deep percolation, water use efficiency (WUE), irrigation water use efficiency (IWUE), N leaching, and NUE (box plots), and corresponding change compared with S16 (solid circles) obtained using the RZWQM2 model for irrigation treatments (see Table 4 for definitions of scenarios S1-S16) in different precipitation years, based on long-term weather data from 1961 to 2017 in the Guanzhong Plain. Panels a1–a6, b1–b6, and c1-c6 represent simulated results in wet years, normal years, and dry years, respectively. The bottom and top of each box plot are the 25th and 75th percentiles. The line within each box is the 50th percentile. The ends of the lower and upper whiskers are the 5th and 95th percentiles. The dot within each box is the mean. Error bars associated with the solid circles represent one standard error around the mean.

ha^{-1} in wet, normal, and dry years, respectively, and were reduced by 37.9 %, 57.10 %, and 72.5 % compared with yields under adequate irrigation conditions. Irrigation at the jointing stage for all precipitation years could increase wheat yields significantly ($P < 0.05$), and produced the highest IWUE (2.87 kg m^{-3} for wet, 3.07 kg m^{-3} for normal, 2.82 kg m^{-3} for dry years) (Figs. 10a4, b4 and c4), indicating that the jointing stage was the critical wheat growth stage for irrigation in the Guanzhong Plain. Results were similar to those presented by Zheng et al. (2016) who concluded that the wheat jointing phase was the most sensitive phase to water deficit, followed by the anthesis phase, and Zhou et al. (2018) who found irrigation applied at the wheat jointing stage could significant increase wheat yield. To avoid significantly lower wheat yields, two irrigations during the jointing-boot and boot-filling stages were necessary to meet the water demand of wheat in wet years. During normal precipitation years, three irrigations during the jointing-boot, boot-filling, and filling-ripening stages are recommended, while in dry years four irrigations are recommended.

Deep percolation during wheat growth exhibited consistent trends in all precipitation years (Figs. 10a2, b2 and c2). Greater values of deep percolation were produced by irrigating during the wheat tillering-jointing period (S2 > S3, S4, S5; S6, S7, S8 > S9, S10, S11; S12, S13, S14 > S15). This greater deep percolation was probably because the combination of excess water stored in the soil and irrigation water was far beyond the wheat water requirement during that period of time,

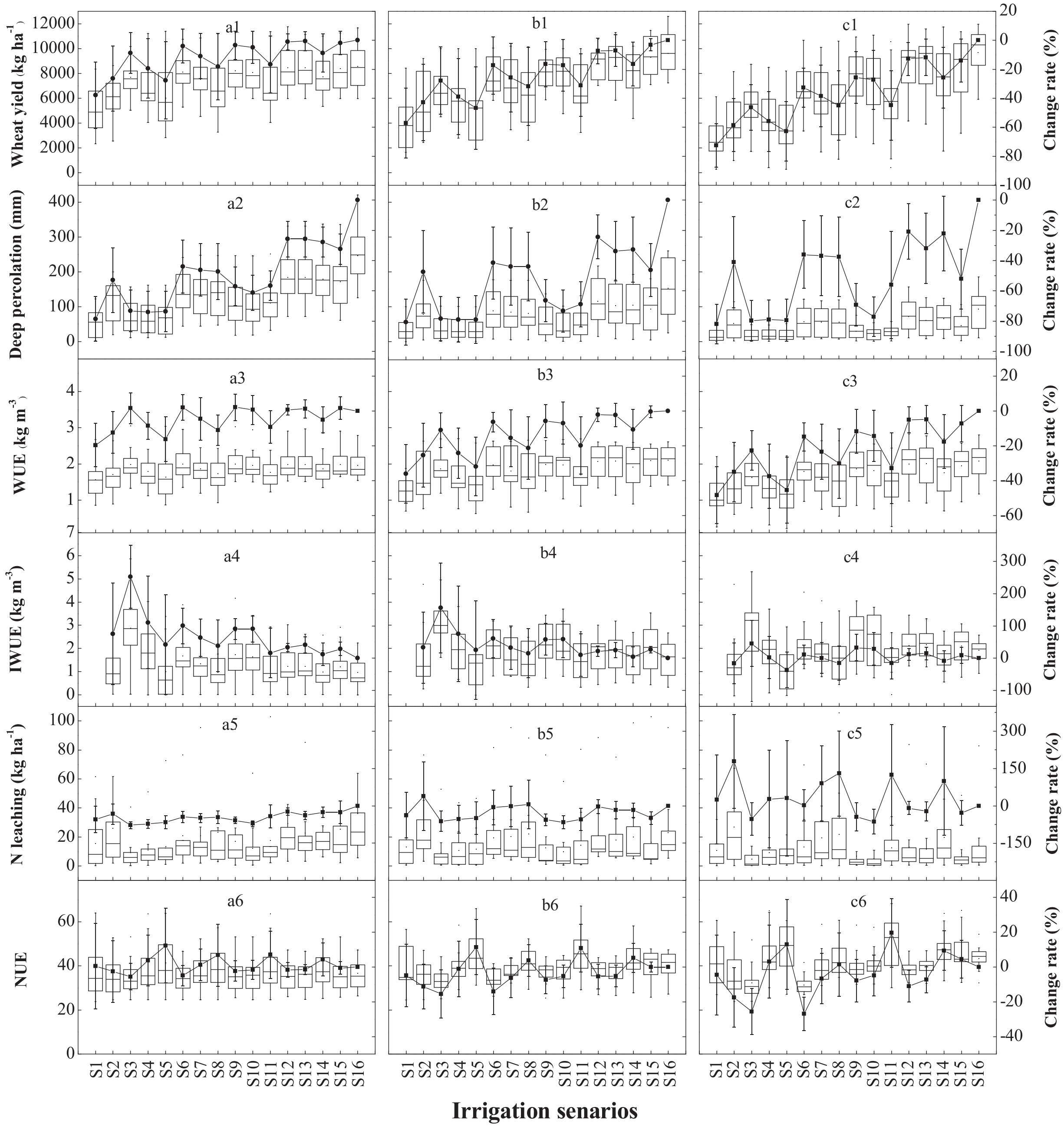

Fig. 10. RZWQM2-simulated winter wheat yield, deep percolation, water use efficiency (WUE), irrigation water use efficiency (IWUE), N leaching, and NUE (box plots), and corresponding change compared with S16 (solid circles) obtained using the RZWQM2 model for irrigation treatments (see Table 4 for definitions of scenarios S1-S16) in different precipitation years, based on long-term weather data from 1961 to 2017 in the Guanzhong Plain. Panels a1–a4, b1–b4, and c1-c4 represent simulated results in wet years, normal years, and dry years, respectively. The bottom and top of each box plot are the 25th and 75th percentiles. The line within each box is the 50th percentile. The ends of the lower and upper whiskers are the 5th and 95th percentiles. The dot within each box is the mean. Error bars associated with the solid circles represent one standard error around the mean.

resulting in a higher potential risk of percolation out of the root zone. Similarly to what was observed during the maize growing season, the trend of N leaching amounts was consistently and strongly related to deep percolation amounts during the wheat growing season. There was no significant difference ($P > 0.05$) in the amount of N leaching in different precipitation years. In particular, greater values of N leaching with irrigation during the wheat tillering-jointing period were caused by simultaneous influence of greater amounts of deep percolation and greater fertilization applied during the period.

WUE values for wheat showed differing responses to varied irrigation management in wet years (1.56-2.00 kg ha^{-1} m^{-3}), normal years (1.36-2.10 kg ha^{-1} m^{-3}), and dry years (1.11-2.08 kg ha^{-1} m^{-3}), and the change trend was consistent with the change trend observed for wheat yield (Figs. 10a3, b3 and c3). Irrigating during the jointing-boot and boot-filling growth stages improved wheat WUE in our study, mostly because irrigation at the jointing and boot stages corresponded to pre- and post-anthesis water consumption, optimized the canopy structure, and ensured wheat physiological water demand post-anthesis, all of which was beneficial for improving grain yield and WUE (Xu et al., 2018). Similarly to results observed for maize, NUE values were little influenced by total irrigation amount, but irrigation date had a much greater influence on NUE (Figs. 10a6, b6, and c6). It appeared that irrigating during the boot-filling and filling-ripening stages could increase NUE significantly ($P < 0.05$), while, irrigating during the

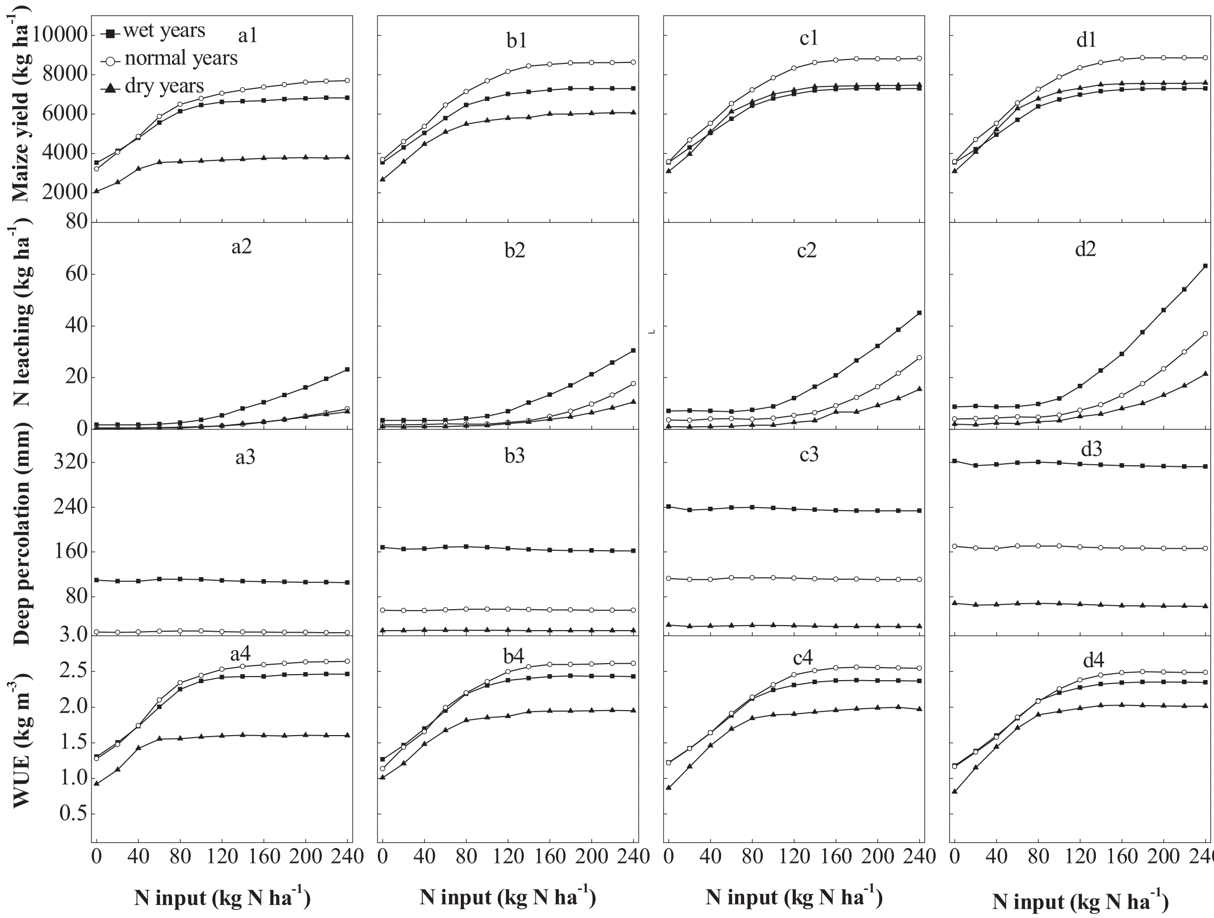

Fig. 11. RZWQM2-simulated summer maize yield, N leaching loss, deep percolation, and water use efficiency (WUE) for different irrigation amounts (0 − 270 mm) and nitrogen fertilization rate (0 − 240 kg N ha^{-1}) in different precipitation years, based on long-term weather data from 1961 to 2017 in the Guanzhong Plain. Panels a1–a4, b1–b4, c1-c4, and d1-d4 represent simulated maize production under 0, 90, 180, and 270 mm application of irrigation, respectively.

jointing-boot stage could decrease NUE. Adequate water supply in the jointing stage could promote wheat vegetative growth and negative affect the nitrogen absorption by grain, while irrigation in the reproductive growth stage of winter wheat could improve the nitrogen absorption by grains (Meng et al., 2016).

3.3.2. Interactive effects of irrigation and nitrogen management

Average simulated summer maize yields (Figs. 11a1-d1) in all three precipitation year categories were affected by the N application rate. Yields initially increased sharply with increasing N application rate and then increased more slowly once N application rate reached a certain value. This type of response is well described by a linear-plus-plateau model (Liu et al., 2016; Yang et al., 2017). In wet and normal years, as previously discussed, due to abundant precipitation, N application rate became the main factor affecting maize yields. Increasing irrigation and nitrogen application amounts did not significantly ($P > 0.05$) increase maize yields when irrigation amount was greater than 90 mm, and the interaction effect of irrigation and nitrogen on yield was not significant. Under the non-irrigated condition in dry years, average maize yield increased significantly ($P < 0.05$) to 3555 kg ha^{-1} as N application rate increased from 0 to 60 kg N ha^{-1}, but there was no significant difference ($P > 0.05$) in yield for N application rates greater than 60 kg N ha^{-1}. When irrigation amounts of 90, 180, and 270 mm were applied, average maize yield increased significantly ($P < 0.05$) to 5796, 7393, and 7499 kg ha^{-1} as N application rate increased from 0 to 120 kg N ha^{-1}, 0–140 kg N ha^{-1}, and 0–140 kg N ha^{-1}, respectively, and no significant increases in yield were seen as N application rate increase above those values. Similar results were simulated for wheat (Figs. 12a1-d1), and the highest grain yields were obtained with high irrigation amounts and high N application rates. In dry years, the critical N application rates were 200, 220, 240, and 260 kg N ha^{-1}, with 90, 180, 270, and 360 mm irrigation applied, respectively. Wheat yields increased significantly ($P < 0.05$) to 4716, 6610, 7772, and 9106 kg ha^{-1} as N application rate increased to the critical values. Similar results were found in wet and normal years. Results indicated that water input promoted the absorption and utilization of nitrogen by crops. Therefore, N fertilizer application rate should be adjusted according to water conditions experienced by the crop.

WUE values for maize and wheat were mainly affected by yields and total evapotranspiration (Xu et al., 2018). Maize WUE (Figs. 11a4-d4) and wheat WUE (Figs. 12a4-d4) increased with increasing N application rate, which showed that changes in WUE were consistent with changes in crop yields. Results indicated that N fertilizer input could increase both crop growth and evapotranspiration, but had a greater influence on increasing crop yields, thus increasing WUE. For a given N fertilizer application rate, wheat WUE showed an increasing trend ($P < 0.05$) as irrigation amount increases in dry years. For example, with 240 kg N ha^{-1} applied, WUE increased from 1.53 kg m^{-3} to 1.75, 1.83, and 1.90 kg m^{-3} as irrigation increased from 90 to 360 mm. In contrast, WUE showed a slightly decreasing trend with the increasing irrigation amount for maize in wet and normal years and for wheat in wet years. For example, with 140 kg N ha^{-1} applied to maize in normal years, WUE decreased from 2.42 kg m^{-3} to 2.40, 2.35, and 2.32 kg m^{-3} as irrigation increased from 90 to 270 mm. Considering that increased N application rate increases WUE, farmers should avoid unreasonable applications of irrigation that would reduce WUE.

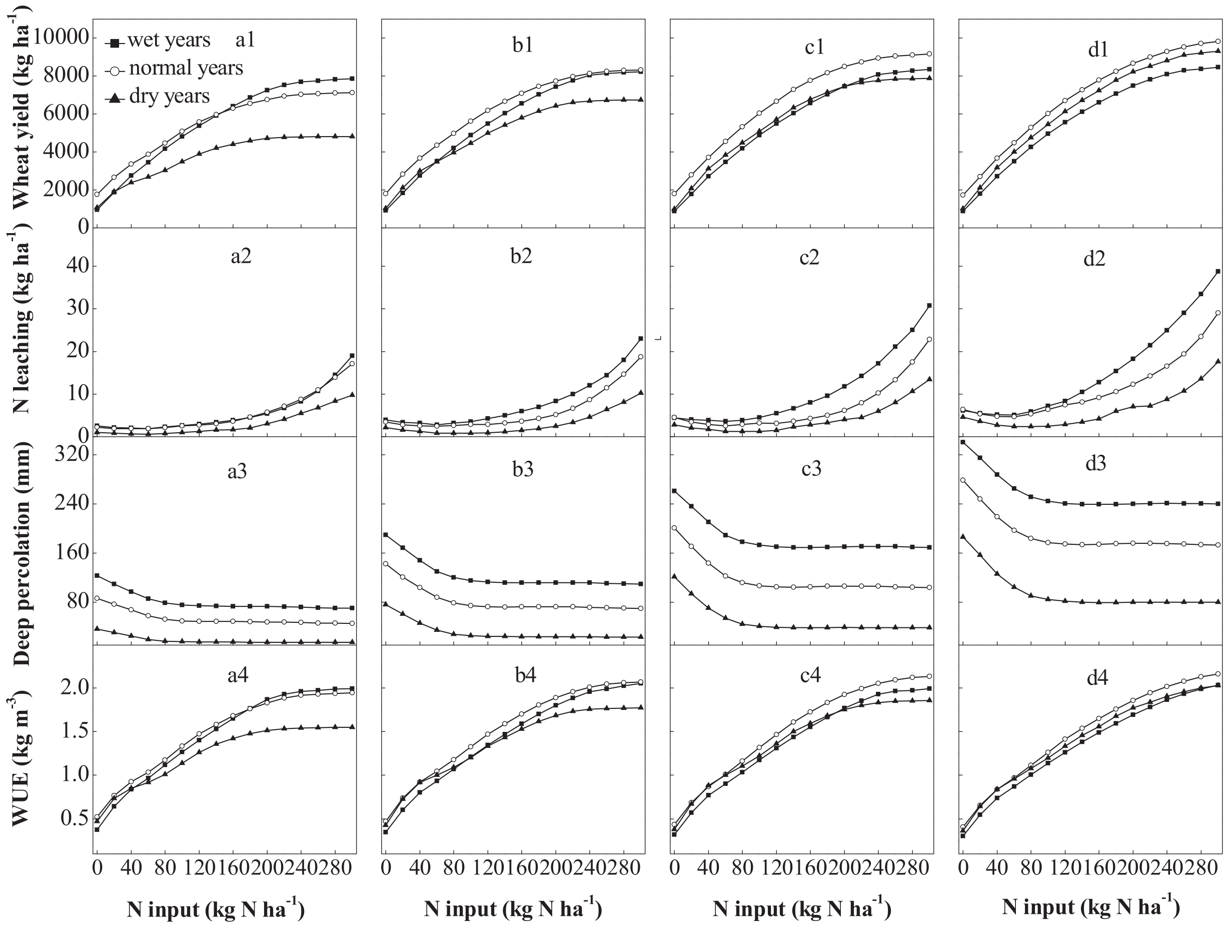

Fig. 12. RZWQM2-simulated winter wheat yield, N leaching loss, deep percolation, and water use efficiency (WUE) for different irrigation amounts (90 – 360 mm) and nitrogen fertilization rate (0 – 240 kg N ha^{-1}) in different precipitation years, based on long-term weather data from 1961 to 2017 in the Guanzhong Plain. Panels a1–a4, b1–b4, c1-c4, and d1-d4 represent simulated maize production under 90, 180, 270, and 360 mm of applied irrigation, respectively.

The N application rate is the main factor affecting N leaching, with N leaching values increasing with increasing N fertilizer application rate (Zhang et al., 2015c; Wang et al., 2017). In our study, simulated N leaching clearly increased with increasing N application rate for both maize (Figs. 11 a2-d2) and wheat (Figs.12a2-d2). In contrast to the yield response observed for increasing N application, we found that N leaching for both maize and wheat increased slowly initially as N application rate increased and then increased more sharply with further increases in N application rate. For example, with 90 mm of irrigation applied to summer maize in wet years (Fig. 11b2), average N leaching increased from 3.4–6.9 kg ha^{-1} as N application rate increased from 0 to 120 kg ha^{-1}. Then, as N application rate increased from 120 to 240 kg N ha^{-1}, N leaching increased sharply from 6.9–30.5 kg ha^{-1}. The main reason for this result was that nitrogen absorption by crops reaches a maximum value at the point where N amount exceeds a critical value, causing more and more nitrogen to be stored in the soil, resulting in much greater N leaching. Similarly, N leaching increased as water input increased and deep percolation increased for maize (Figs. 11a3-d3) and wheat (Figs. 12a3-d3). Previous studies reported that increasing irrigation significantly increased deep percolation and nitrate leaching (Li et al., 2015). In our study, deep percolation increased with increasing irrigation amounts for both maize and wheat. Deep percolation in wheat increased from 14 to 80 mm as irrigation increased from 90 to 360 mm with the 240 kg N ha^{-1} application rate in dry years. Furthermore, deep percolation in wheat decreased with increasing N application rate. For example, deep percolation decreased from 75 to 23 mm for wheat in dry years when N application rate increased from 0 to 300 kg N ha^{-1} with the 180 mm irrigation amount (Fig. 12b3). This finding was probably due to the higher N application rate promoting crop growth, thus increasing crop water consumption, and thus reducing the amount of deep percolation.

Identifying reasonable irrigation and fertilization is of great importance for obtaining higher grain yields with lower environmental risks (Yang et al., 2017). Excessive N fertilization does not result in significant increases in yield but leads to wasted resources and increased environmental risks (Chen et al., 2014; Cui et al., 2013b; Jeong and Bhattarai, 2018). One of the most important risk factors is leached NO_3-N, which could contaminate groundwater and cause water eutrophication (Gu et al., 2013; Le et al., 2010). Understanding the balance between the effects of N fertilization and irrigation on deep percolation, N leaching, WUE, and grain yields under different precipitation regimes is thus a crucial task. The present simulation results suggest that 140 kg N ha^{-1} fertilizer application rate coupled with 90 mm irrigation amount in wet and normal years, and 140 kg N ha^{-1} fertilizer rate coupled with 180 mm irrigation amount in dry years were optimal strategies for maize, and 240 kg N ha^{-1} fertilizer application rate coupled with 180, 270 and 360 mm irrigation amount in wet, normal, and dry years, respectively, were appropriate irrigation and nitrogen management for wheat.

4. Conclusions

An appropriate N application rate coupled with suitable irrigation schedules should be implemented to obtain high grain yields while reducing deep percolation and N leaching in the intensively cropped farming practice of the maize-wheat rotation system in China. The present simulation results, obtained with a calibrated RZWQM2 model for different precipitation years from 1961 to 2017, showed that higher irrigation and N application rates could produce higher yields. However, these management practices could also result in lower WUE, IWUE, and NUE values along with significant deep percolation of water and N leaching. Identifying reasonable irrigation schedules and N application rates could increase WUE, IWUE, and NUE values along with considerably reducing deep percolation and N leaching while maintaining high grain yields. The optimal irrigation recommendations determined in this study could be adjusted according to variations in precipitation years and climate change, especially for wheat growth. Irrigation and rainfall promote the absorption and utilization of nitrogen by crops, and N fertilizer application rate should be adjusted according to variations in water availability to crops. Considering grain yields and environmental effects, reasonable N application rates for summer maize and winter wheat in the Guanzhong Plain of China were estimated to be 140 and 240 kg N ha^{-1}, respectively, when coupled with recommended irrigation management in different precipitation years. These rates resulted in a considerable reduction in N loss with only slightly lower grain production, showing that it is possible to strike a balance between substantially increased food production and minimum environmental impacts in this region.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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