Quantifying Climate and Management Effects on Regional Crop Yield and Nitrogen Leaching in the North China Plain

Q. X. Fang,* L. Ma,* Q. Yu, C. S. Hu, X. X. Li, R. W. Malone, and L. R. Ahuja

Better water and nitrogen (N) management requires better understanding of soil water and N balances and their effects on crop yield under various climate and soil conditions. In this study, the calibrated Root Zone Water Quality Model (RZWQM2) was used to assess crop yield and N leaching under current and alternative management practices in a double-cropped wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) system under long-term weather conditions (1970–2009) for dominant soil types at 15 locations in the North China Plain. The results provided quantitative long-term variation of deep seepage and N leaching at these locations, which strengthened the existing qualitative knowledge for site-specific management of water and N. In general, the current management practices showed high residual soil N and N leaching in the region, with the amounts varying between crops and from location to location and from year to year. Seasonal rainfall explained 39 to 84% of the variability in N leaching (1970–2009) in maize across locations, while for wheat, its relationship with N leaching was significant ($P < 0.01$) only at five locations. When N and/or irrigation inputs were reduced to 40 to 80% of their current levels, N leaching generally responded more to N rate than to irrigation, while the reverse was true for crop yield at most locations. Matching N input with crop requirements under limited water conditions helped achieve lower N leaching without considerable soil N accumulation. Based on the long-term simulation results and water resources availability in the region, it is recommended to irrigate at 60 to 80% of the current water levels and fertilize only at 40 to 60% of the current N rate to minimizing N leaching without compromising crop yield.

The North China Plain (NCP, Fig. 1) is the most important wheat and maize production region in China; however, high water and N fertilizer inputs are critical for maintaining the high crop yields in the region (Zhang et al., 2011; Fang et al., 2010a). The current N fertilizer and irrigation management practices have led to serious N losses to surface and groundwater (Chen et al., 2005; Ju et al., 2009; Sun et al., 2012) and over-exploitation of groundwater in the region (Hu et al., 2010b; Qiu, 2010), resulting in a decrease in the groundwater table of 0.8 m yr^{-1} from 1978 to 2008 in some areas (Fang et al., 2010a). Similar problems associated with agricultural N losses to the environment and water resources have been reported worldwide (Galloway et al., 2008; Nolan et al., 2002). These environmental problems are threatening the sustainability of agricultural production and require optimum water and N management for high crop yields and lower N losses.

Various irrigation and/or N fertilizer management strategies have been investigated via field experiments in the NCP for their effects on the soil water and N balances and crop yield (Cui et al., 2010; Fang et al., 2010a; Ju et al., 2009; Zhang et al., 2011). These studies revealed a great potential for increasing irrigation or N use efficiency by improving on the current management practices in the region. For example, deficit irrigation management can increase water use efficiency and maintain a high crop yield in the area (Zhang et al., 2006; Fang et al., 2010a). Reducing N application rates and varying in-season N applications showed promise for improving N use efficiency and reducing N losses to the environment (Fang et al., 2006; Meng et al., 2012). Recently, an integrated soil–crop system management was proposed for achieving high crop yields and resource use efficiency by matching agricultural inputs to crop requirements in amount, time, and space (Chen et al., 2011b). Similar research has been conducted in other countries (Dinnes et al., 2002; Drinkwater et al., 2007; Schlegel et al., 2005). Stone et al. (2010) developed functions for the maize yield response to both irrigation and N fertilizer rates on a Coastal Plain soil in South Carolina, which were useful to guide site-specific irrigation and N management for both high

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*Corresponding author (fqx01@163.com; Liwang.Ma@ars.usda.gov).

Q.X. Fang, Qingdao Agricultural Univ., Qingdao, 266109 China; L. Ma and L.R. Ahuja, USDA-ARS, Agricultural Systems Research Unit, Fort Collins, CO 80526; Q. Yu, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101 China; C.S. Hu and X.X. Li, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, 286 Huaizhong Rd., Shijiazhuang 050021, China; and R.W. Malone, National Lab. for Agriculture and the Environment, Ames, IA 50011. Assigned to Associate Editor Qingli Ma.

Abbreviations: NCP, North China Plain.

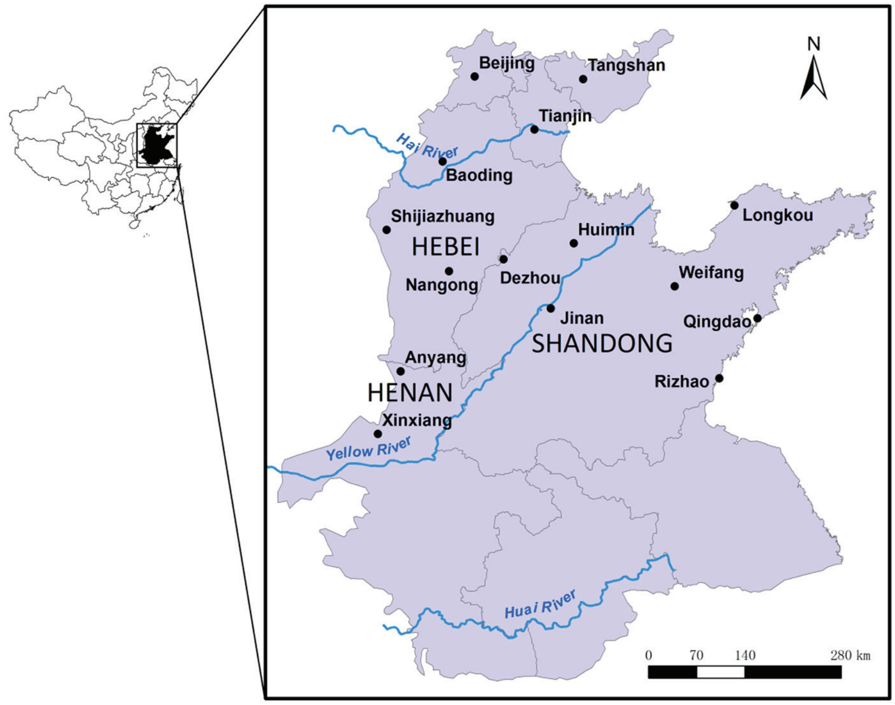

Fig. 1. The 15 selected locations in the North China Plain. These selected locations are located in the North China District based on agricultural water requirements as defined by Shi and Lu (2001).

crop yields and natural resource conservation. Recently, a "4R" (right source, right rate, right time, and right place) nutrient stewardship framework was developed for horticultural crops (Mikkelsen, 2011). These nutrient management frameworks can be potentially applied for precision irrigation and N management for high crop yields and low N losses.

The coupled effects of water and N on crop yield and N loss are complex due to the high variability in climate and soil conditions, and most field studies have not accounted for a wide range of climate and soil variations, although many studies showed significant interactions among soil, climate, and management on crop yield and N leaching (Girma et al., 2007; Ju et al., 2009; Lilburne et al., 2003; Lobell et al., 2004). Such interactions result in high temporal and spatial variation in N leaching and crop yield across different areas (Hall et al., 2001; Zhu and Chen, 2002) and limit the extension of field experimental results to other locations and the development of site-specific management practices (Chen et al., 2011b).

System models in conjunction with good field experimental data can aid our understanding of these interactions across different soil and climate conditions (Ma et al., 2007a). In Iowa, Malone et al. (2007a) and Ma et al. (2007b) used the RZWQM2 model to quantify the effects of various N and tillage management practices on N loss through tile drainage across different climate conditions. In the NCP, Hu et al. (2006) calibrated the RZWQM2 at the Luancheng Ecological Station (Hebei Province), evaluated various N management effects on crop yield and N leaching, and proposed alternate N application rates for a wheat–maize rotation system in the area. Fang et al. (2008, 2010b) used RZWQM2 to explore the effects of alternative irrigation and N management practices on crop yield and N balance at the Yucheng Ecological Station (Shandong Province) using long-term historical weather data and provided useful guidelines for irrigation and N management strategies for the wheat–maize rotation system. Li et al. (2007b) proposed a water and N management model (WNMM) for irrigated cropping systems in the NCP, which was later used to explore N and crop yield in desert oases in northwestern China (Hu et al., 2010a). Most of these studies focused on a single site and climate condition and did not investigate the effects of soil, climate, and management on crop yield or N balance across multiple locations.

In this study, we simulated long-term crop yield and N leaching to deep seepage using RZWQM2 and long-term weather data from 1970 to 2009 for the dominant soil types at 15 locations in the NCP. The objectives were to (i) characterize and assess the long-term soil water and N balance under current and alternative irrigation and N management conditions in the region; (ii) identify the main factors (climate and management) controlling N leaching and crop yield under the current and alternative management practices at these locations; and (iii) propose reasonable N and irrigation management guidelines for different locations in the region based on simulated crop responses to various irrigation and N management scenarios.

Materials and Methods

Study Area and Soil and Climate Conditions in the North China Plain

The study areas were spread across three provinces of Henan, Hebei, and Shandong, and two cities of Tianjin and Beijing (Fig. 1). The region was recognized as the North China District based on its agricultural water requirement (Shi and Lu, 2001). The soil is formed mainly from the sediments of the Huang, Huai, and Hai rivers (Fig. 1), and the main soil type is calcareous alluvial and alkaline (Xiong and Xi, 1965). The annual rainfall varies from 40 to 90 cm, and the annual potential free surface evaporation is from 180 to 200 cm (1961–2009). About 70% of the rainfall occurs in the summer, and the rest occurs in the spring and fall. This uneven distribution of annual rainfall leads to a water deficit for winter wheat and a relatively sufficient water supply for summer maize. The long-term average annual air temperature ranges from 9 to 15°C across the region, and the minimum and maximum air temperature generally occur in February and July, respectively.

In this study, 15 locations were selected for the long-term simulations from 1961 to 2009 (Fig. 1). The soil type and physical characteristics for the 15 locations were set according to Xiong and Xi (1965). These soil types included loamy sand, sandy loam, silt loam, loam, clay loam, silty clay, and clay (Table 1), which account for most agricultural areas in the region. The historical weather data from 1961 to 2009 were obtained from 15 weather stations at these locations (Fig. 1), including daily maximum and minimum air temperature, sunshine duration, vapor pressure, wind speed, and rainfall, and the weather data were processed according to Wu et al. (2006).

Current Agricultural Management Practices in the Region

Winter wheat and summer maize are the two main crops in the region. The common planting date is early October for wheat and early June for maize, forming a wheat–maize double-cropping system without a fallow period. Irrigation and N fertilizer management are the main inputs for the cropping system, and levels of irrigation and N application practiced by local farmers vary greatly across the region. Thus, we used average N and irrigation management for each of the 15 locations based on agricultural survey data and a previous study in the region (Wu et al., 2006).

Irrigation management differs greatly in timing and amount from year to year and from location to location. We used the averaged condition for Beijing (39.93° N, 116.28° E), Tianjin (39.10° N, 117.17° E), Hebei Province (including Baoding [38.85° N, 115.52° E], Tangshan [39.67° N, 118.15° E], Shijiazhuang [38.03° N, 114.42° E], and Nangong [37.37° N, 115.38° E]), Shandong Province (including Jinan [36.68° N, 116.98° E], Longkou [37.62° N, 120.32° E], Qingdao [36.07° N, 120.33° E], Rizhao [35.38° N, 119.53° E], Huimin [37.50° N, 117.53° E], Dezhou [37.43° N, 116.32° E], and Weifang [36.70° N, 119.08° E]), and Henan Province (including Anyang [36.12° N, 114.37° E] and Xinxiang [35.32° N, 113.88° E]) according to Shi and Lu (2001) and Fang et al. (2010a) (Fig. 1; Table 2). The areas for Beijing and Tianjin are 1.6×10^4 and 1.2×10^4 ha, respectively, and the areas for Hebei, Shandong, and Henan provinces are 18.9×10^4, 15.7×10^4, and 16.7×10^4 ha, respectively. The irrigation timing was set at the planting, jointing stage, and grain-filling stage for wheat (three irrigations) and the silking stage for maize (one irrigation) based on a previous study in the region (Fang et al., 2010a). Farmers' common practices include 7.5 to 10 cm of water per irrigation event (Shi and Lu, 2001) and split applications of N at planting and at the middle growth stages of both wheat and maize (Table 2). These water and N management practices, referred to as the current agricultural management practices in the region, were used as the RZWQM2 simulation baseline and compared with the alternative management scenarios by reducing N and/or water application rates to 40 to 80% of their current levels.

RZWQM2 Parameterization and Evaluations

The RZWQM is a comprehensive agricultural system model, and detailed information on the model can be found in Ahuja et al. (2000). The CERES-maize and CERES-wheat crop models incorporated in RZWQM2 by Ma et al. (2006) were used for the current model applications. The RZWQM2 has been evaluated for simulating soil water, soil N, crop growth, and grain yield in the wheat–maize double-cropping system in the region, such as at Yucheng Ecological Station (Fang et al., 2008, 2010b; Yu et al., 2006), Luancheng Ecological Station (Hu et al., 2006), Beijing (Wang and Huang, 2008), Xinxiang in Henan province (Zhu and Ren, 2011), and Tianjin (Wang et al., 2012). These model evaluations and applications showed better model predictions of soil water and crop yield and relatively poor predictions of soil N dynamics and crop N uptake, which warranted further improvement of the model as discussed by Fang et al. (2008) and Hu et al. (2006).

The soil parameters for RZWQM2 simulations were based on either the available soil physical and nutrient data for the 15 locations or default values based on soil texture (Table 1). Initial soil nutrient status was determined by the model for the 15 locations based on the soil organic matter contents (Table 1) using a procedure similar to that of Fang et al. (2008). As discussed above, these soil types used for simulations were typical for these locations; we did not consider the soil variations within each location. It was beyond the scope of this study to address variability within a location, which also requires detailed soil mapping and GIS connectivity of the model. Rather, we focused on water and N interactions among the 15 locations given the differences in soil and weather conditions.

Table 1. Soil types and organic matter content, bulk density, saturated hydraulic conductivity (K_{sat}), and soil water content at 33 kPa ($\theta_{1/3}$) used for RZWQM2 at these 15 locations in the North China Plain. The ranges in organic matter and bulk density refer to the different soil layers (0–120 cm) based on Xiong and Xi (1965); K_{sat}, $\theta_{1/3}$, and other soil parameters were estimated by RZWQM2 for these different soil layers based on soil texture.

Location	Soil type	Organic matter	Bulk density	K_{sat}	$\theta_{1/3}$
		%	g cm^{-3}	cm h^{-1}	cm^3 cm^{-3}
Anyang	loamy sand	0.21–1.02	1.41–1.51	6.11–12.28	0.10–0.19
Baoding	silt loam	0.17–0.78	1.32–1.42	0.32–0.68	0.28–0.31
Beijing	loam–silt loam	0.39–1.10	1.33–1.40	0.30–1.20	0.20–0.37
Dezhou	silt loam–clay	0.58–0.86	1.41–1.54	0.06–2.59	0.19–0.38
Huimin	silt loam–silty clay	0.50–1.00	1.33–1.37	0.09–0.68	0.28–0.37
Jinan	sandy loam–loamy sand	0.14–1.15	1.33–1.40	0.43–6.11	0.19–0.25
Longkou	loam	0.51–1.14	1.41–1.51	0.23–1.32	0.23–0.32
Nangong	silt loam	0.29–0.73	1.41–1.54	0.68–1.32	0.23–0.29
Qingdao	loam–sandy loam	0.46–0.95	1.41–1.51	0.23–2.59	0.19–0.34
Rizhao	clay loam–clay	0.41–1.57	1.39–1.42	0.06–0.23	0.31–0.38
Shijiazhuang	silt loam	0.57–1.05	1.41–1.54	0.23–0.68	0.28–0.31
Tangshan	silty clay loam	0.43–1.13	1.33–1.40	0.09–0.15	0.34–0.37
Tianjin	silt loam–silty clay	0.43–0.95	1.33–1.40	0.09–0.68	0.28–0.37
Weifang	silt loam	0.61–1.24	1.41–1.54	0.15–0.68	0.28–0.34
Xinxiang	loam	0.36–1.10	1.41–1.51	1.32–2.59	0.19–0.23

Table 2. Current irrigation amount and timing (TI, cm) used in RZWQM2 based on Shi and Lu (2001) and the current N inputs (TN, kg N ha^{-1}) based on the National Bureau of Statistics of China (2010) across the 15 locations in the North China Plain.

Location	Wheat							Maize				
	Irrigation				N inputs			Irrigation		N inputs		
	Planting	Jointing	Grain filling	Total	Planting	Jointing	Total	Silking	Total	Planting	Silking	Total
	cm				kg N ha^{-1}			cm		kg N ha^{-1}		
Anyang	8.0	8.0	8.0	24.0	100	100	200	8.0	8.0	80	80	160
Baoding	7.5	7.5	7.5	22.5	100	90	190	7.5	7.5	60	70	130
Beijing	10.0	10.0	10.0	30.0	100	100	200	10.0	10.0	80	80	160
Dezhou	7.5	7.5	7.5	22.5	150	100	250	7.5	7.5	75	100	175
Huimin	7.5	7.5	7.5	22.5	150	125	275	7.5	7.5	125	125	250
Jinan	7.5	7.5	7.5	22.5	150	100	250	7.5	7.5	100	100	200
Longkou	7.5	7.5	7.5	22.5	150	150	300	7.5	7.5	100	100	200
Nangong	7.5	7.5	7.5	22.5	100	80	180	7.5	7.5	80	80	160
Qingdao	7.5	7.5	7.5	22.5	150	150	300	7.5	7.5	100	100	200
Rizhao	7.5	7.5	7.5	22.5	150	175	325	7.5	7.5	100	125	225
Shijiazhuang	7.5	7.5	7.5	22.5	175	125	300	7.5	7.5	125	125	250
Tangshan	7.5	7.5	7.5	22.5	125	90	215	7.5	7.5	90	60	150
Tianjin	10.0	10.0	8.0	28.0	100	60	160	8.0	8.0	60	50	110
Weifang	7.5	7.5	7.5	22.5	150	125	275	7.5	7.5	80	100	180
Xinxiang	8.0	8.0	8.0	24.0	100	100	200	8.0	8.0	80	80	160

The crop genetic parameters for the CERES-maize and CERES-wheat crop models in RZWQM2 were initialized based on previous studies (Yu et al., 2006; Fang et al., 2008, 2010b). The parameters related to crop phenology (P1V and P1D for wheat and P1 and P2 for maize in Table 3) were adjusted according to the planting, flowering, and maturation dates at the 15 locations (Jin, 1991). Other parameters for yield components (such as grain weight and grain number) differ greatly among the crop cultivars adopted at the different locations. For simplicity, we used the same values for all 15 locations based on the common crop cultivar types from previous studies in the region and the surveyed crop yield across the region (Jin, 1991) (Table 3). The specific crop cultivar parameters for each location were consistent during the simulation period from 1961 to 2009.

The historical irrigation and N management practices from 1961 to 2009 were set according to the agricultural survey data during this period (National Bureau of Statistics of China, 2010) and were used to further test RZWQM2 performance at these 15 locations. The simulated long-term yield was compared with national surveyed crop yield data from 1978 to 2009 when surveyed yield data were available. Because the survey crop yield data were from multiple fields under both irrigated and rainfed field conditions, two long-term scenarios of irrigated and rainfed conditions were created; the ratio between irrigated and rainfed

Table 3. Crop genetic parameters used in RZWQM2 across the 15 locations.

Parameter†	Description	Value
Wheat		
P1V	relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 d of vernalization is sufficient for all cultivars	35–55
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)	25–45
P5	relative grain-filling duration based on thermal time (degree days above a base temperature of 1°C), where each unit increase above zero adds 20 °C d to an initial value of 430 °C d	480
G1	kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis, g^{-1}	32
G2	kernel filling rate under optimum conditions, mg d^{-1}	40
G3	unstressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases, g	1.5
PHINT	phyllochron interval, °C	85
Maize		
P1	thermal time from seedling emergence to the end of the juvenile phase during which the plants are not responsive to changes in photoperiod, °C d	170–240
P2	extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at the maximum rate (considered to be 12.5 h), d	0.2–0.8
P5	thermal time from silking to physiological maturity,°C d	700
G2	maximum possible number of kernels per plant	800
G3	grain-filling rate during the linear grain-filling stage and under optimum conditions, mg d^{-1}	7.0
PHINT	phyllochron interval, °C d	48

† The crop parameters of PIV and PID for wheat and P1 and P2 for maize were determined based on the crop growth stages and growth periods across the 15 locations (Jin, 1991). In general, higher values for these parameters were associated with longer growth periods.

crop areas ranged from 0.3 to 0.7 for these 15 locations according to the agricultural hydrology survey data (Shi and Lu, 2001; Wu et al., 2006). Specifically, we compared the average survey and simulated crop yield for five regions (Beijing, Tianjin, Hebei Province, Shandong Province, and Henan Province) because the same irrigation management was used for the five regions.

RZWQM2 Applications in the Region

Long-Term Evaluation of Current Management Practices

Using the current irrigation and N fertilizer management (Table 2), the long-term management effects (1970–2009) on crop yield and N leaching at the 15 locations were assessed and the main climate factors controlling crop yield and N leaching in NCP were identified for each location based on the long-term simulations from 1970 to 2009.

Alternative Management Effects

To explore the alternative irrigation and N fertilizer management scenarios for higher crop yield and lower N leaching at these 15 locations, various scenarios with reduced irrigation and/or N rates were designed to evaluate the responses of crop yield and N leaching at each location using the long-term weather data from 1961 to 2009 (Table 4). These alternative N and irrigation management scenarios were based on previous field experimental results in the region (Cui et al., 2008; Fang et al., 2006; Li et al., 2007a; Liu et al., 2003). Although the model runs began in 1961, only simulation results from 1970 through 2009 were used in the analysis, which allowed the initial soil C and N pools to stabilize (Fang et al., 2008). Scenarios that reduced N leaching with comparable crop yield as the baseline simulation were selected as better water and N management practices for each location.

Multivariate Regression Analysis and Statistics Method

Multivariate regression equations were developed for each location. This analysis was used to evaluate the effects of climate and management factors on the predicted variations in seasonal N leaching to deep seepage and crop yield under current management scenarios (Table 2) or alternative management scenarios (Table 4) for each location. The simulated crop yield and N leaching during the wheat or maize seasons from 1970 to 2009 was predicted as a function of seasonally based climate variables: total seasonal rainfall (*rainw* in the wheat season or *rainm* in the maize season), total seasonal monthly average temperature (*temw* in the wheat season or *temm* in the maize season), and total seasonal monthly radiation (*radw* in the wheat season or *radm* in the maize season). The N application rate and irrigation amount for the wheat (*Nratew* and *irriw*, respectively) or maize seasons (*Nratem* and *irriw*, respectively) were also used in the regression analysis for the alternative management scenarios (Table 4) but not for the current management scenarios (Table 2) because the irrigation and N rates were the same for each location. The developed regression equation was used for identifying the most controlling factor for seasonal variation in crop yield or N leaching. A stepwise procedure of RSREG in SAS (Freund and Littell, 1991) was used for these variable selections ($P < 0.01$), which combines forward-selection and backward-elimination steps for variable selection. The detailed regression development processes can be found in Malone et al. (2007b).

Spearman's rank correlation coefficient (ρ) was used to describe the correlation between these climate and management variables and model outputs among locations because these variables were generally skewed. The climate and management variables included rainfall, air temperature, radiation, irrigation, and N application rate. The model outputs included N leaching and crop yield. The coefficient of determination (R^2) was used to evaluate the performance of the model and multivariate regression equations.

Results and Discussion

Comparisons between Predicted Crop Yield and Survey Data in the Region

The comparisons between the long-term simulated crop yield and the survey yield data from 1978 to 2009 at the five regions are shown in Fig. 2. The simulated wheat yield showed a similar increase trend as the survey data from 1978 to 2009 (mainly associated with increased N application rates across these years) at Beijing city ($R^2 = 0.50$, $n = 32$, $P < 0.001$), Tianjin city ($R^2 = 0.49$, $n = 32$, $P = 0.001$), Hebei Province ($R^2 = 0.58$, $n = 32$, $P < 0.001$), Shandong Province ($R^2 = 0.70$, $n = 32$, $P < 0.001$), and Henan Province ($R^2 = 0.57$, $n = 32$, $P < 0.001$). Similar increase trends between simulated maize yield and survey data across these years were found at the five regions but with lower correlation ($R^2 = 0.39$ for Beijing at $P < 0.001$, $R^2 = 0.42$ for Tianjin at $P < 0.001$, $R^2 = 0.39$ for Hebei at $P < 0.001$, $R^2 = 0.36$ for Shandong at $P < 0.001$, and $R^2 = 0.38$ for Henan at $P < 0.001$). The lower R^2 values were mainly due to underpredicted maize yield from 1978 to 1998 at Beijing and overpredicted maize yield from 1978 to 1998 in other regions (Fig. 2). Across the regions, a significant positive linear relationship between the predicted average crop yield and averaged survey data was found from 1978 to 2009 ($R^2 = 0.63$ for both wheat and maize, $n = 32$, $P < 0.001$). The discrepancy between predicted and survey crop yields was probably associated with the long-term simulations without considering crop cultivar improvement during this

Table 4. Alternative irrigation and N management for the wheat–maize rotations based on the current irrigation (TI) and N (TN) management (baseline conditions for each site are shown in Table 2).

Treatment	Irrigation	Nitrogen
	% of TI	% of TN
10TI10TN	100	100
10TI8TN	100	80
10TI6TN	100	60
10TI4TN	100	40
8TI10TN	80	100
8TI8TN	80	80
8TI6TN	80	60
8TI4TN	80	40
6TI10TN	60	100
6TI8TN	60	80
6TI6TN	60	60
6TI4TN	60	40
4TI10TN	40	100
4TI8TN	40	80
4TI6TN	40	60
4TI4TN	40	40

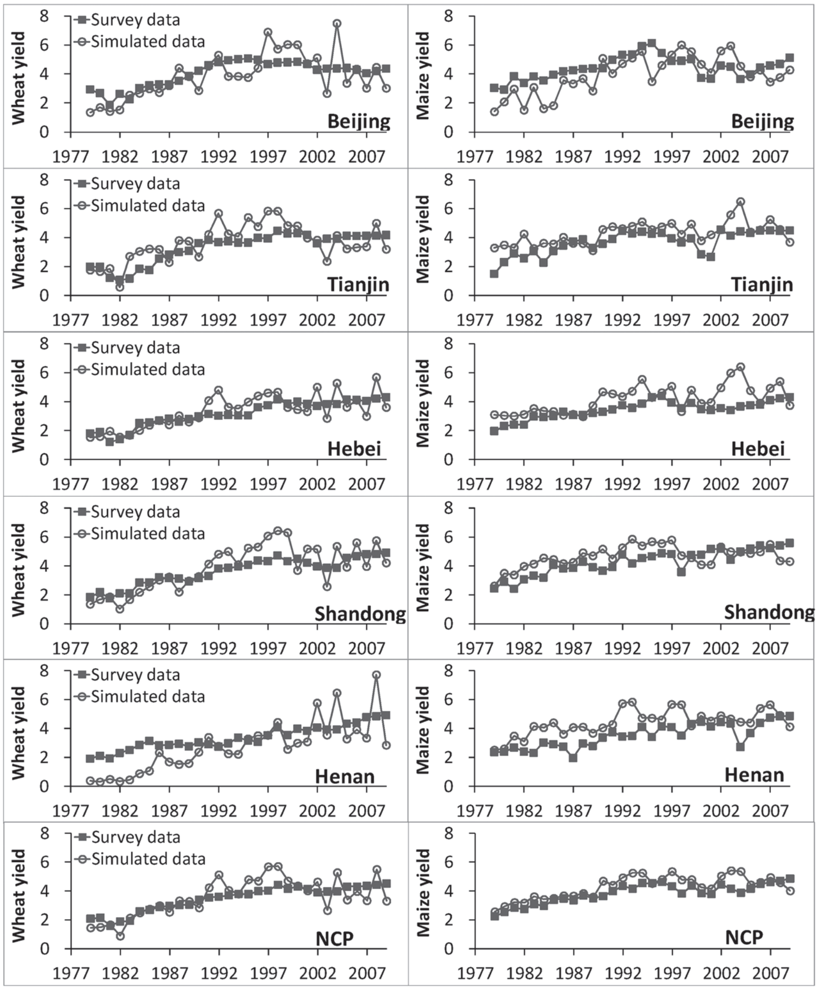

Fig. 2. Comparisons between surveyed crop yield (Mg ha^{-1}) and yield predicted by RZWQM2 using historical irrigation and N fertilizer management from 1970 to 2009 in the North China Plain (NCP). Jinan, Longkou, Qingdao, Rizhao, Huimin, Dezhou, and Weifang locations are in Shandong Province; Baoding, Tangshan, Shijiazhuang, and Nangong locations are in Hebei Province; and Anyang and Xinxiang locations are in Henan Province. All 15 locations were also used for the comparison of regional average crop yields across the NCP. Note: the historical irrigation and N management from 1978 to 2009 and surveyed crop yields (wheat and maize) at these locations from 1978 to 2009 are from the National Bureau of Statistics of China (2010). The surveyed crop yields for these areas were calculated from multiple field measurements across the region (>60,000 samples at the national level).

period. The simulated values showed higher yearly variations than the survey data mainly due to the fact that the survey crop yield was obtained from many fields with different soil and crop cultivars at each location.

Predicted Nitrogen Leaching and Crop Yield under Current Management Practices

Long-Term Water and Nitrogen Balances across the Fifteen Locations

The predicted average annual water seepage below 120 cm from 1970 to 2009 varied from 4.7 cm at Nangong to 26.1 cm at Beijing (Table 5). Annual evapotranspiration ranging from 59.0 to 83.8 cm was comparable with the field measurement values of 50 to 85 cm under various management conditions (Fang et al., 2010a) and simulated results using a process-based crop growth model with remotely sensed data and GIS in NCP (Mo et al., 2005).

Across the 15 locations, the predicted average deep seepage below 120 cm was 13.6 cm, runoff was 4.9 cm, and evapotranspiration was 70.1 cm. A significant positive correlation between average annual irrigation and predicted average annual deep seepage was found ($\rho = 0.60$, $n = 15$, $P = 0.02$). No significant correlation was observed between seepage and average annual rainfall ($\rho = 0.06$, $n = 15$, $P = 0.83$) or between seepage and average annual rainfall plus irrigation ($\rho = 0.40$, $n = 15$, $P = 0.14$). Similar results were obtained between runoff and average annual rainfall ($\rho = 0.33$, $n = 15$, $P = 0.24$) and between runoff and average annual rainfall plus irrigation ($\rho = 0.04$, $n = 15$, $P = 0.90$). For example, at Rizhao (clay loam–clay soil) with the highest annual rainfall and at Nangong (silt loam soil) with the lowest annual rainfall, comparable average annual seepages (7.7 cm for Rizhao and 4.7 cm for Nangong) were simulated but with different simulated average annual runoff (27.9 cm at Rizhao vs. 4.8 cm at Nangong) (Table 5). This result was mainly due to differences in soil type and hydraulic parameters (such as saturated hydraulic conductivity) among these locations (Table 1). Across these locations, a significant correlation was observed between predicted average annual seepage plus runoff and average annual rainfall plus irrigation ($\rho = 0.63$, $n = 15$, $P = 0.01$).

The predicted average annual N leaching below 120 cm from 1970 to 2009 ranged from 89.4 kg N ha^{-1} at Tianjin to 288.8 kg N ha^{-1} at Shijiazhuang. These values were generally higher than the field measurements reported in NCP (Zhu and Chen, 2002), but some field experiments showed annual N leaching amounts of 250 kg N ha^{-1} at high N application rates in NCP (Ju et al., 2006; Fang et al., 2006). The model-predicted annual N leaching below 120 cm in Table 5 was comparable to the field-observed data in the literature across NCP (Fig. 3). A significant correlation between model-predicted and observed data was found among these locations ($\rho = 0.63$, $n = 10$, $P = 0.05$), but the model-predicted N leaching was higher than field-observed data by about 25% across the locations (Fig. 3). The lower observed soil N leaching in the field experiments may be associated with the deeper than 120 cm observation depth (>150-cm depth reported from these field experiments). For example, the obviously lower field-observed N leaching at the Nangong location than predicted by the model was probably associated with the observed N leaching depths of 200 cm. Another possible reason is that the field-observed data were from short-term experiments (<5 yr) without accounting for the different climate conditions in NCP. In addition, field measurements may not represent the whole field due to spatial variability. The simulated high soil N denitrification, such as at Rizhao, Dezhou, and Huimin, was probably due to the high soil water content (lower soil O_2 concentration) in the clay soil with a

Table 5. Annual soil water balance and inorganic N balances in the 0- to 120-cm depth simulated by RZWQM2 from 1970 to 2009 under current management conditions (Table 2) at the 15 locations.

Location	Soil water balance						Soil N balance							
	Rainfall	Irrigation	ET	Seepage	Runoff	Balance†	NF	NP	ND	NV	NM	NR	NL	Balance‡
	cm						kg N ha^{-1}							
Anyang	54.7	31.8	66.5	25.5	1.1	−6.6	357.5	270.6	3.9	19.0	111.2	0.1	149.0	26.1
Baoding	59.5	29.8	69.8	13.7	0.3	5.5	317.5	271.6	11.8	34.3	129.4	0.0	125.7	3.5
Beijing	55.7	39.8	77.1	26.1	0.1	−7.8	357.5	301.9	8.8	37.1	125.6	0.0	122.6	12.7
Dezhou	54.7	29.8	71.2	12.5	5.9	−5.1	421.3	280.8	76.7	31.8	132.2	1.1	145.3	17.8
Huimin	56.5	29.6	71.2	5.4	7.5	2.0	521.3	295.0	72.9	9.7	136.0	1.4	250.8	27.5
Jinan	58.0	29.8	83.8	12.3	0.2	−8.5	443.8	283.6	48.5	31.7	159.5	0.0	213.4	26.1
Longkou	55.3	27.8	72.0	9.0	4.6	−2.5	496.3	316.1	16.4	10.5	127.5	0.8	239.1	40.9
Nangong	47.4	29.8	78.4	4.7	4.8	−10.7	337.5	256.9	32.9	3.3	122.2	0.8	139.2	26.6
Qingdao	70.0	29.4	70.7	18.6	5.3	4.8	496.3	290.4	45.3	11.5	124.1	0.9	251.6	20.7
Rizhao	79.2	28.1	59.0	7.7	27.9	12.7	546.3	330.0	132.8	0.0	135.5	5.6	186.6	26.8
Shijiazhuang	51.4	29.3	68.2	10.3	4.2	−2.0	520.6	226.4	9.3	89.5	111.8	0.7	288.8	17.7
Tangshan	58.2	29.8	59.5	19.3	0.4	8.8	361.9	273.2	66.1	15.2	114.3	0.0	115.1	6.6
Tianjin	53.6	35.3	66.7	14.7	0.2	7.3	267.5	266.2	12.2	10.8	121.5	0.0	89.4	10.4
Weifang	59.8	29.8	74.4	8.6	4.9	1.7	451.3	291.2	16.7	2.9	134.8	0.9	255.7	18.7
Xinxiang	58.2	31.8	62.3	16.3	5.7	5.7	357.5	268.5	8.7	5.1	119.7	1.0	179.2	14.7
Avg.	58.1	30.8	70.1	13.6	4.9	0.3	416.9	281.5	37.5	20.8	127.0	0.9	183.4	19.8

† Rainfall + irrigation − evapotranspiration (ET) − seepage − runoff.

‡ N fertilizer (NF) + N mineralization (NM) − N uptake (NP) − N denitrification (ND) − N volatilization (NV) − N in runoff (NR) − N leaching in seepage (NL).

lower saturated hydraulic conductivity and higher field capacity (Table 1). The simulated soil N denitrification was comparable with the reported values from other studies, such as at Beijing (Ju et al., 2009) and Shijiazhuang (Hu et al., 2006). The simulated positive soil N balance and high N leaching indicated a soil N surplus in NCP (Table 5) and was consistent with the increased NO_3–N concentration in the groundwater in the 1980s (Liu et al., 2005; Zhu and Chen, 2002). Reducing the N application rate is essential to reducing N leaching, as reported from field experimental studies (Fang et al., 2006; Ju et al., 2009; Zhang et al., 2011). The long-term high N application rate can lead to a higher N leaching potential due to high soil inorganic N accumulations (e.g., >500 kg N ha^{-1} in 0–120-cm soil depth at Jinan, Huimin, Longkou, Qingdao, Weifang, and Shijiazhuang). Similar results were also found in field studies after several years of high N application rates (Ju et al., 2009; Li et al., 2007a) and were reported in a previous simulation study in NCP (Fang et al., 2008). Therefore, reducing the residual soil inorganic N is critical to mitigating the N leaching risk (Cui et al., 2008).

Long-Term Variations in Predicted Crop Yield across the Fifteen Locations

The developed multivariate regressions from seasonally based variables (e.g., seasonal rainfall) described 17 to 68% of the variation in the predicted wheat yield from 1970 to 2009 and 15 to 55% of the variation in the predicted maize yield across the 40 yr (Table 6). The effect of seasonal rainfall on the predicted wheat yield was significant at $P < 0.05$, except for Qingdao and Xinxiang, where its effect was significant at the $P <$ 0.1 level. Regression analysis also showed that monthly rainfall, monthly temperature, and monthly radiation in February and March were critical factors for the predicted wheat yield at most locations, which was consistent with the frequent spring droughts occurring at the stem extension stage of wheat in NCP as reported by Fang et al. (2010a). For predicting maize yield, seasonal monthly averaged air temperature was the primary factor at all locations ($P < 0.05$), and seasonal rainfall was not effective in predicting maize yield (Table 6). The result confirmed that seasonal rainfall was the most limiting factor for predicting the wheat yield but not for predicting the maize yield, as reported from previous studies in NCP (Fang et al., 2010a; Zhang et al., 2006).

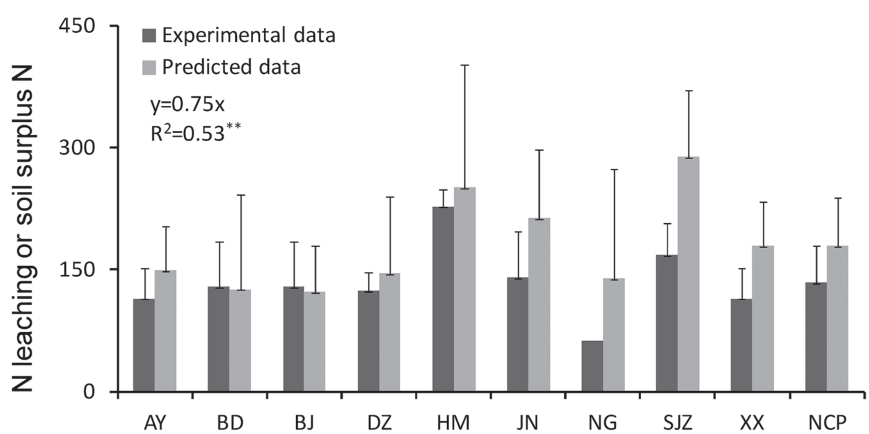

Fig. 3. Comparisons between field-observed and RZWQM2-predicted N leaching below the 120-cm depth or soil surplus N (kg N ha^{-1}) at locations in the North China Plain (NCP, Fig. 1) for which data on field-observed N leaching below the 150- to 200-cm depth were available: Anyang (AY) and Xinxiang (XX) (Bi et al., 2003; Zhu et al., 2005), Beijing (BJ) and Baoding (BD) (Liu et al., 2003; Ju et al., 2009), Dezhou (DZ) (Fang et al., 2006), Huimin (HM) (Ju et al., 2006), Jinan (JN) (Chen et al., 2011a), Nangong (NG) (Hu et al., 2004), and Shijiazhuang (SJZ) (Hu et al., 2006; Li et al., 2007a). The vertical bars for the location data indicate seasonal variation in the field-observed data and model-predicted data, while the vertical bars for the NCP-averaged data indicate the spatial variation across the region.

Table 6. The seasonally based climate variables selected for the multivariate regression for RZWQM2-simulated crop yield and N leaching during the cropping season from 1970 to 2009 for the 15 locations under current management conditions (Table 2, the current N application rate and irrigation amount were not considered in the regression analysis because they were same for each location).

Location	Wheat†				Maize‡			
	Yield		N leaching		Yield		N leaching	
	Selected variables	R^2	Selected variables	R^2	Selected variables	R^2	Selected variables	R^2
Anyang	*rainw***, *temw***	0.19	*rainw**	0.14	*temm**	0.16	*rainm***, *radm***	0.62
Baoding	*rainw* **, *temw***	0.56	*rainw***	0.69	*temm***	0.21	*rainm***	0.63
Beijing	*rainw***, *temw***	0.68	*rainw***, *temw***	0.38	*temm***, *radm***	0.55	*rainm***, *temm***, *radm***	0.84
Dezhou	*temw***, *radw***, *rainw**	0.36	*rainw***	0.84	*temm**	0.15	*rainm***	0.73
Huimin	*rainw***	0.18	*rainw**, *radw**	0.87	*temm**	0.16	*rainm***, *temm***	0.61
Jinan	*rainw***, *radw***, *temw***	0.35	–§	–	*temm**, *radm**	0.30	*rainm***, *temm***, *radm***	0.79
Longkou	*temw***, *rainw**	0.49	*rainw**, *temw**	0.16	*temm**	0.36	*rainm***, *temm***	0.56
Nangong	*rainw**, *temw**	0.39	*rainw**, *radw**	0.20	*temm***	0.45	*rainm***, *temm***, *radm***	0.74
Qingdao	*temw**	0.20	*rainw**	0.13	*temm**, *radm**	0.32	*rainm***, *radm***	0.41
Rizhao	*rainw**, *temw**	0.22	–	–	*temm***, *radm***	0.46	*rainm***	0.39
Shijiazhuang	*rainw**, *temw**	0.36	*rainw**, *radw**	0.44	*temm***	0.39	*rainm***	0.83
Tangshan	*rainw***	0.22	*rainw***, *temw***	0.39	*temm***	0.45	*rainm***, *temm***	0.37
Tianjin	*temw***, *radw***, *rainw**	0.36	*rainw***	0.90	*temm***	0.24	*rainm***, *temm***	0.59
Weifang	*rainw***	0.17	*rainw**	0.06	*temm***	0.28	*rainm***, *temm***	0.63
Xinxiang	*temw***, *radw***	0.28	–	–	*temm**, *rainm**, *radm**	0.35	*rainm***	0.55

* Variable selected at the $P = 0.05$ level because no variable was included at the $P = 0.01$ level.

** Variable selected at the $P = 0.01$ level.

† *rainw*, *radw*, and *temw* are total seasonal rainfall, total seasonal monthly average radiation, and total seasonal average monthly air temperature during the wheat season from October to June of the next year.

‡ *rainm*, *radm*, and *temm* are total seasonal rainfall, total seasonal monthly average radiation, and total seasonal average monthly air temperature during the maize season from June to September. Variables were selected at $P = 0.05$ level.

§ No variable was included at the $P = 0.05$ level.

Long-Term Variations in Predicted Nitrogen Leaching across the Fifteen Locations

The predicted N leaching differed greatly between the wheat and maize seasons (Fig. 4), similar to results from previous studies (Fang et al., 2006; Hu et al., 2006; Liu et al., 2003). As shown in Table 6, the multivariate regressions showed that seasonal rainfall was a primary factor at the $P < 0.01$ level for predicting seasonal N leaching during the wheat season from 1970 to 2009 at Baoding, Beijing, Dezhou, Tangshan, and Tianjin. At other locations, the effects of seasonal rainfall on the predicted N leaching were significant at the $P < 0.05$ level, except for Jinan, Rizhao, and Xinxiang, where seasonal rainfall had no effect on the predicted N leaching at the $P < 0.05$ level (Fig. 4a). We also found that total rainfall in October was the key factor for predicting N leaching at $P < 0.01$ for all locations except for Anyang ($P = 0.05$ level). The N applied before wheat planting in October can be highly potentially leachable due to the lower crop N requirement during the early growth stage. For predicting seasonal N leaching during the maize season from 1970 to 2009, seasonal rainfall was significant at $P < 0.01$ level in predicting N leaching at all 15 locations (Table 6; Fig. 4b) and explained 37 to 84% of the seasonal variations in N leaching across the seasons. This result indicates that seasonal rainfall was the most important factor controlling N leaching variation during the maize season in NCP. Similar results were also reported from experimental studies (Fang et al., 2006; Liu et al., 2003).

As shown in Fig. 4b, the predicted higher seasonal N leaching (>400 kg N ha^{-1}) occurred in some maize seasons with high seasonal rainfall at these locations even with a lower N leaching potential (such as Baoding, Nangong, and Dezhou). Such high seasonal N leaching was mainly the result of the simulated high inorganic N accumulation in the soil profiles from previous years under the current N application rates at these locations; a similar result was also reported from field experiments by Zhu et al. (2005). These simulation results indicate that a high N application rate in the previous wheat season can contribute to high soil residual N and subsequent high N leaching potential in the following maize season when seasonal rainfall is high (Fang et al., 2006; Liu et al., 2003). In this context, optimizing N management for reducing N leaching should account for the N carryover effects between the wheat and maize seasons.

Quantifying Management and Climate Effects under Alternative Management

RZWQM2-Simulated Effects of Nitrogen and Irrigation Management

The RZWQM2-predicted long-term average crop yield generally increased with N application rate or irrigation amount but differed among these locations and between wheat and maize seasons due to the different soil and climate (such as rainfall) conditions (Fig. 5). Both irrigation amount and N application rate were important for the predicted wheat and maize yields (e.g., Fig. 5a and 5b for the Tianjin location), and similar responses of crop yield to irrigation amount and N application rate were found at most locations (Fig. 5g and 5h) except for Shijiazhuang and Anyang. These results were consistent with field experimental results in NCP (Cui et al., 2010; Fang et al., 2010a). At Shijiazhuang (Fig. 4e and 4f), however, irrigation alone was the most influential factor for both simulated wheat and maize yields, indicating an adequate N supply to meet crop

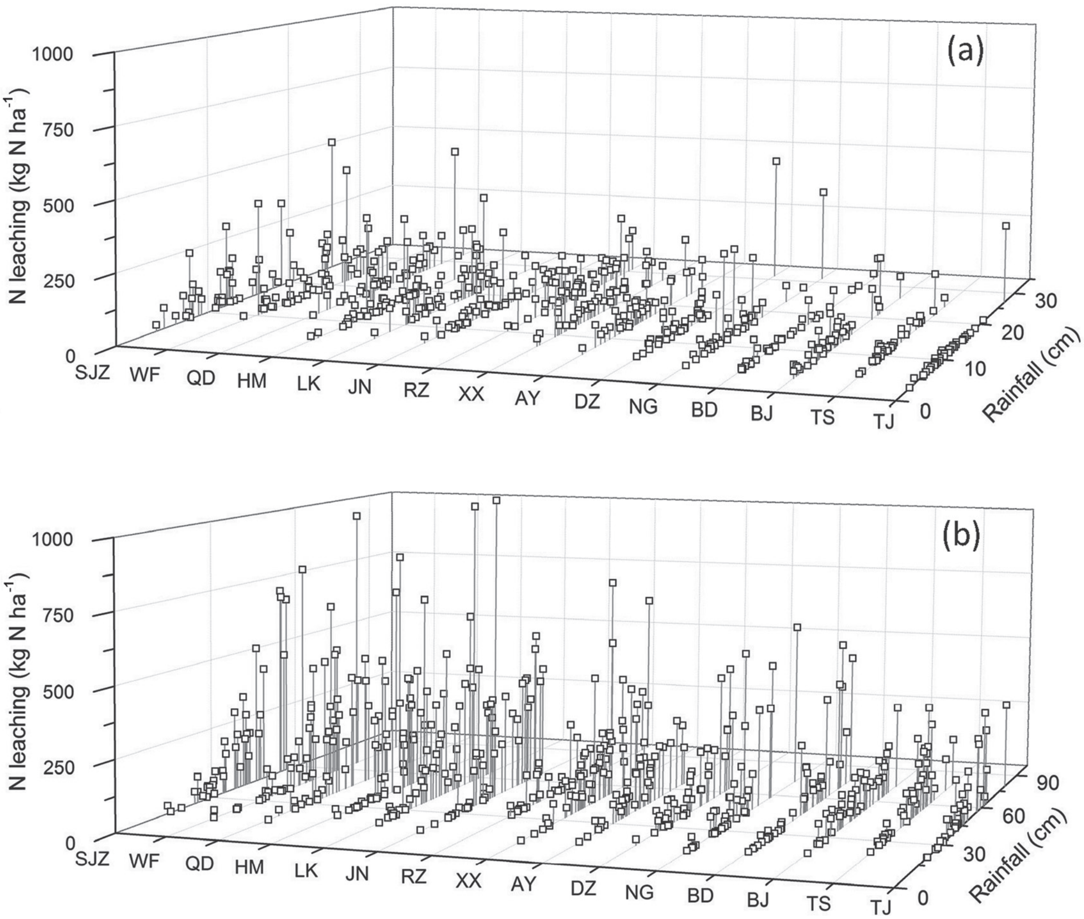

Fig. 4. Relationships between predicted temporal seasonal N leaching below 120 cm and total seasonal rainfall in (a) wheat and (b) maize seasons from 1970 to 2009 under current management conditions at the 15 locations: Shijiazhuang (SJZ), Weifang (WF), Qingdao (QD), Huimin (HM), Longkou (LK), Jinan (JN), Rizhao (RZ), Xinxiang (XX), Anyang (AY), Dezhou (DZ), Nangong (NG), Baoding (BD), Beijing (BJ), Tangshan (TS), and Tianjin (TJ).

requirements even at 40% of the current N application rate. At Anyang (Fig. 5c), only the N rate was influential for the predicted wheat yield.

At most locations, the predicted crop yield maximized at about 60 to 80% of the current N rates (Fig. 5a, 5b, 5g, and 5h), except for Anyang with the highest yield level at 100% of the current N application rate (Fig. 5c and 5d) and Shijiazhuang with the highest yield at 40% of the current N application rate (Fig. 5e and 5f). These results indicate a high potential for reducing the N application rate without compromising the crop yield at most locations. The predicted crop yield (wheat and maize) maximized at 100% of the current irrigation amount across these locations, however, and reducing irrigation amount generally decreased crop yield, especially for wheat. Due to the increased water resource deficit and groundwater crisis (Liu and Xia, 2004; Qiu, 2010), reducing the current irrigation amount will be unavoidable in NCP (Fang et al., 2010a; Li., 2010). In this context, 80% of the current irrigation amount is preferred to cope with the water resource crisis, which resulted in about 5 to 15% reductions in the predicted wheat yield across these simulation years. The 5 to 10% reduction in the predicted wheat yield due to a 20% reduction in the irrigation amount was higher than observed in many experiments, where no or little reduction in wheat yield was observed when irrigation was reduced by 20 to 25% from the highest irrigation levels (Fang et al., 2010a; Zhang et al., 2006). One reason for this discrepancy is that the short-term field experimental results did not account for long-term climate variations, and another reason is that the full irrigation levels in these field experiments were generally higher than the current simulations (full irrigation as the highest irrigation level) and probably overirrigated (Fang et al., 2010a). The lower accuracy in simulating crop yields under soil water stress conditions as reported by Fang et al. (2010b) can also contribute to the discrepancy in predicted wheat yield under these different irrigation levels.

The responses of RZWQM2-simulated long-term average N leaching below 120 cm to the alternative N and irrigation managements (Table 4) varied greatly among these locations or between wheat and maize seasons associated with the different soil, climate (such as rainfall), and crop yield levels (Fig. 6). In general, the predicted N leaching decreased significantly with a reduced N application rate in both the wheat and maize seasons but differed in response to reduced irrigation due to the complex interactions between irrigation amount and N rate on both crop yield (N uptake) and N leaching. The predicted N leaching during the wheat season changed little with reducing irrigation amount at 40 and 60% of the current N application rates (Table 4), but decreased with reduced irrigation at 80 and 100% of current N application rates (80%TN or 100%TN in Table 4) across the locations (Fig. 6a). At Qingdao, Rizhao, and

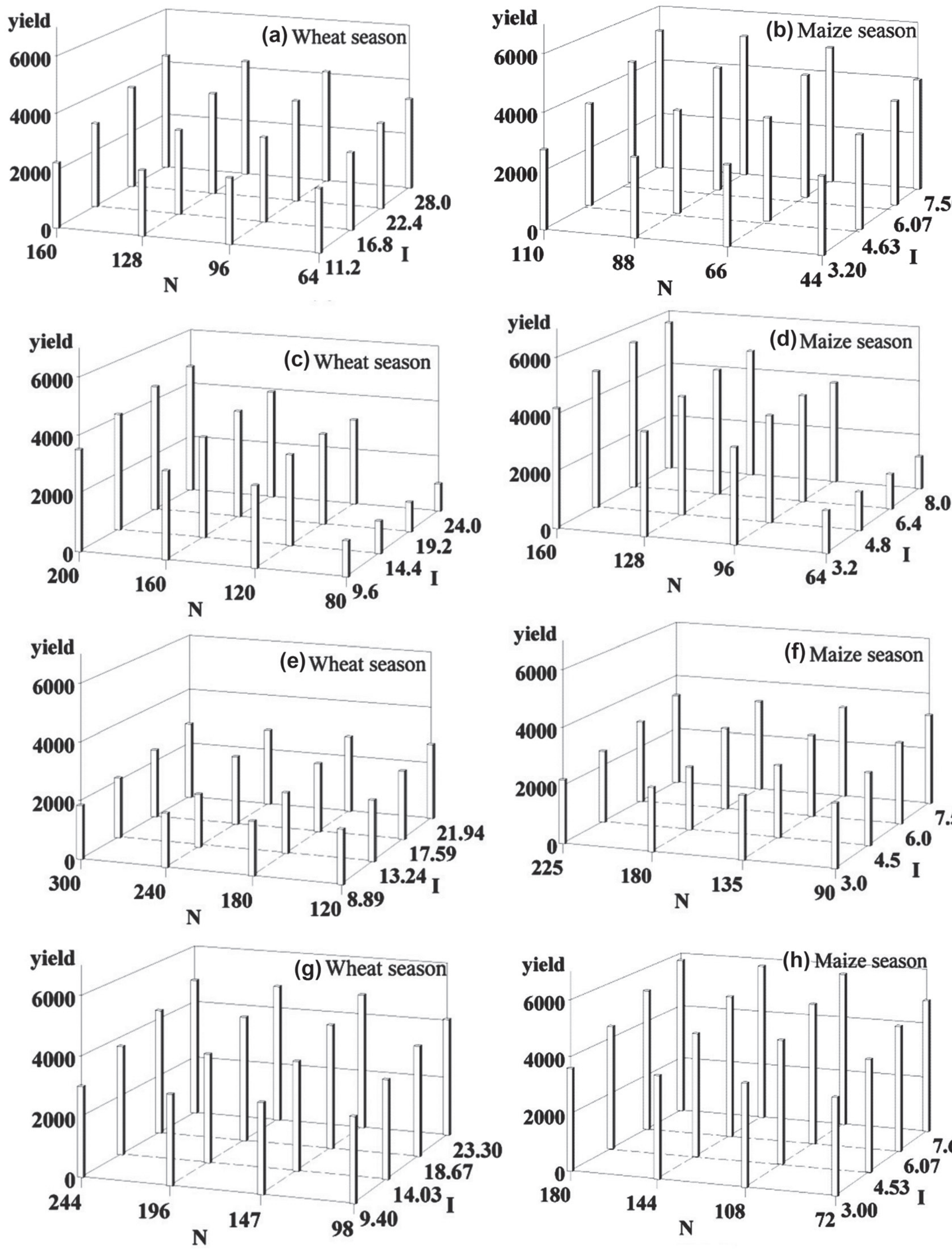

Fig. 5. Response of the predicted average crop yield (kg ha^{-1}) from 1970 to 2009 to N application rates (N, kg N ha^{-1}) and irrigation (I, cm) in wheat and maize seasons as simulated by RZWQM2 under the alternative management practices in Table 4 (based on a response of increase, decrease, or no response) for: (a,b) Tianjin, (c,d) Anyang, (e,f) Shijiazhuang, and (g,h) all remaining locations.

Tianjin (Fig. 6b), however, no obvious response of predicted N leaching to reduced irrigation during the wheat season was observed. Predicted N leaching during the wheat seasons did not decrease with increase in irrigation amount and wheat yield at these locations (Fig. 5a), mainly due to the high potential for deep seepage with high seasonal irrigation amounts. This result provided a useful guideline for matching limited agricultural water with reasonable N input levels at these different locations.

Similar to the wheat seasons, no or little response of predicted N leaching was found at 40% of current N application rates with irrigation during the maize seasons. At higher N application rates, the predicted N leaching showed an increase (such as at Dezhou, Jinan, Nangong, Rizhao, and Shijiazhuang, Fig. 6c), a decrease (such as at Tianjing and Tangshan, Fig. 6d), or no obvious response (such as at Anyang, Beijing, Baoding, Longkou, Qingdao, Weifang, Huimin, and Xinxiang, Fig. 6e) with increasing irrigation. The decrease in predicted N leaching during the maize seasons with increasing irrigation as shown in Fig. 6d was mainly due to the increased crop yield (N uptake) with increased irrigation levels (e.g., Fig. 5b for Tianjin). The predicted higher N leaching during the maize season required more specific and precise management to match maize water and

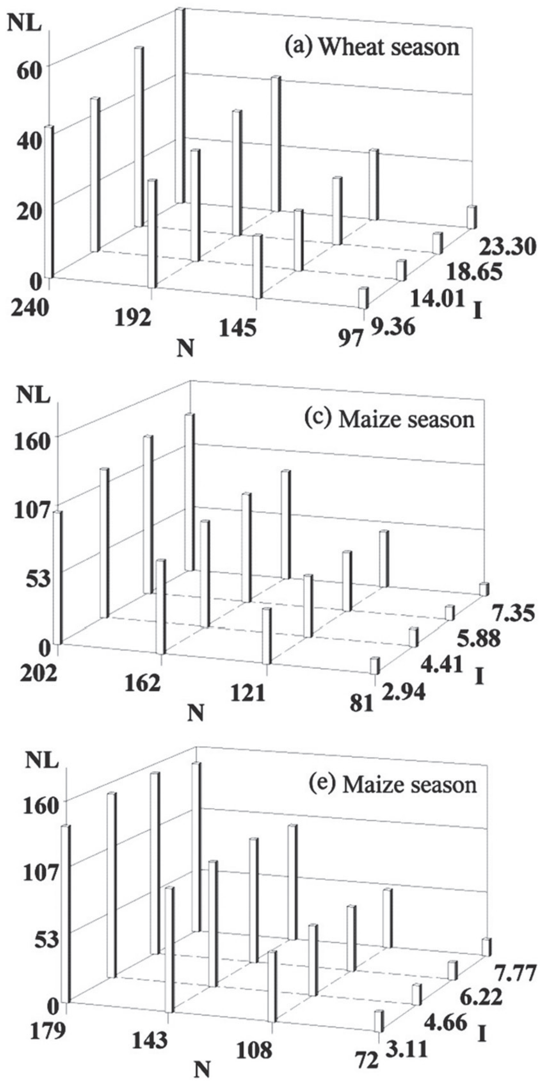

Fig. 6. Response of the RZWQM2-simulated long-term average N leaching below 120 cm (NL, kg N ha^{-1}) from 1970 to 2009 to N application rates (N, kg N ha^{-1}) and irrigation (I, cm) in wheat and maize seasons under the alternative management practices in Table 4 (based on a response of increase, decrease, or no response) for: (a) all locations except for Qingdao, Rizhao, and Tianjin, which are averaged in (b); (c) Dezhou, Jinan, Nangong, Rizhao, and Shijiazhuang; (d) Tianjin and Tangshan; and (e) Anyang, Beijing, Baoding, Huimin, Longkou, Qingdao, Weifang, and Xinxiang.

N demand with N inputs at these locations, such as accounting for residual soil N after wheat harvest and variable and multiple N and irrigation applications (Chen et al., 2011b; Cui et al., 2008; Meng et al., 2012)

Based on the above long-term simulation results under various alternative management scenarios among the 15 locations (Table 4), reasonable irrigation and N management practices, with lower N leaching by >50% and lower crop yield by <18%, were proposed for the 15 locations considering the balance between crop yield and N leaching under limited water conditions (Table 7). These selected management scenarios call for 40 to 60% of current N application rates and 80% of the current irrigation amount at most locations (Fig. 5 vs. 6). At Anyang and Xinxiang with a high rainfall amount, the irrigation amount can be as low as 60% of the current amount (e.g., Fig. 5c and 5d for Anyang). At locations with a high N leaching potential and lower response of crop yield to N rate, such as Shijiazhuang, Weifang, Rizhao, Longkou, Huimin, and Jinan (e.g., Fig. 5e and 5f for Shijiazhuang), 40% of the current N application rate was recommended, while at other locations, 60% of the current N application rate was recommended for maintaining high crop yields (e.g., Fig. 5g and 5h). It is difficult, however, to reduce N leaching without significantly comprising crop yield at Anyang due to the similar responses of predicted N leaching and crop yield to N application rate (e.g., Fig. 5c and 5d vs. 6a and 6e).

Identifying Important Variables for Crop Yield and Nitrogen Leaching

Based on the alternative management scenarios (Table 4), the management and climate effects on predicted seasonal N leaching or crop yield from 1970 to 2009 were quantified for identifying the important variables using multivariate regressions for each location. In general, the developed regression equations explained more variations in predicted N leaching during the maize seasons than the wheat seasons at most locations but explained less variation in maize yield than wheat yield (Table 8). Seasonal rainfall and irrigation were identified as the most controlling factors (with the highest partial R^2) for predicted wheat yield at each location, and N rate was critical only at

Table 7. Selected best irrigation and N management practices for wheat and maize cropping systems at the 15 locations based on the long-term simulations of the alternative management treatments in Table 4.

Location	Alternative treatment	Wheat season		Maize season		Annual reduction†	
		N rate	Irrigation	N rate	Irrigation	N leaching	Crop yield
		kg N ha^{-1}	cm	kg N ha^{-1}	cm	——— % ———	
Anyang	6TI6TN	120	14.4	96	4.8	64.2	18.0
Baoding	8TI6TN	120	18.0	80	6.0	66.1	6.4
Beijing	8TI6TN	120	24.0	100	8.0	73.4	8.4
Dezhou	8TI6TN	150	18.0	100	6.0	65.3	4.0
Huimin	8TI4TN	100	18.0	100	6.0	89.8	7.5
Jinan	8TI4TN	100	18.0	100	6.0	88.2	7.2
Longkou	8TI4TN	120	18.0	80	5.0	94.5	12.6
Nangong	8TI6TN	110	18.0	100	6.0	73.9	6.7
Qingdao	8TI6TN	180	18.0	120	6.0	62.0	3.7
Rizhao	8TI4TN	130	18.0	90	5.4	95.4	9.0
Shijiazhuang	8TI4TN	120	18.0	90	6.0	79.8	5.2
Tangshan	8TI6TN	96	18.0	60	6.0	49.1	5.1
Tianjin	8TI6TN	96	22.0	70	6.4	80.9	7.6
Weifang	8TI4TN	110	18.0	72	6.0	93.9	10.6
Xinxiang	6TI6TN	120	14.4	100	4.8	72.2	7.8

† Annual reductions in yield (wheat and maize) and N leaching during the growing season calculated between these alternative management treatments (Table 4) and current management scenarios (Table 2).

three locations (Anyang, Beijing, and Xinxiang). For predicted maize yield, seasonal temperature was the most important factor, with a partial R^2 of 0.11 to 0.50 at most locations, and rainfall plus irrigation was critical only at Jinan and Xinxiang (Table 8). Nitrogen rate was less important (with low partial R^2) for explaining variations in the predicted maize yield at these locations (e.g., Fig. 5b, 5f, and 5h). For the predicted N leaching during the wheat seasons, N rate was the most controlling factor at all locations, and rainfall or irrigation was important only at four locations (Anyang, Baoding, Beijing, and Tangshan). Seasonal N rate and rainfall were the most important factors for the predicted N leaching during the maize seasons at all locations, and irrigation plus rainfall was critical at Longkou, Qingdao, and Rizhao. These results indicate great potential for mitigating N leaching without significantly compromising crop yield by reducing the current N application rates in the

Table 8. The most influential management and climate variables selected ($P < 0.01$ with highest partial R^2 value) for the multivariate regression of the RZWQM2-simulated crop yield and N leaching during the growing season from 1970 to 2009 at the 15 locations under the alternative management conditions (Table 4). A single variable with the highest partial R^2 value was selected for some regression analyses, while two variables were selected for others to show an interaction between the two variables with the highest partial R^2 values.

Location	Wheat†				Maize‡			
	Yield		N leaching		Yield		N leaching	
	Selected variable	Partial R^2	Selected variable	Partial R^2	Selected variable	Partial R^2	Selected variable	Partial R^2
Anyang	*riw*, *Nratew*	0.49	*Nratew*, *irriw*	0.36	*temm*	0.24	*Nratem*, *rainm*	0.62
Baoding	*riw*	0.43	*Nratew*, *riw*	0.27	*temm*	0.22	*Nratem*, *rainm*	0.66
Beijing	*riw*, *Nratew*	0.60	*Nratew*, *riw*	0.42	*temm*, *radm*	0.47	*Nratem*, *rainm*	0.68
Dezhou	*riw*, *temw*	0.39	*Nratew*, *radw*	0.22	*temm*	0.11	*Nratem*, *rainm*	0.68
Huimin	*riw*	0.41	*Nratew*, *radw*	0.14	*temm*	0.19	*Nratem*, *rainm*	0.57
Jinan	*riw*, *radw*,	0.30	*Nratew*	0.11	*radm*, *rim*	0.29	*Nratem*, *rainm*	0.70
Longkou	*riw*	0.60	*Nratew*	0.28	*temm*, *radm*	0.41	*Nratem*, *rim*	0.67
Nangong	*riw*, *radw*	0.29	*Nratew*	0.13	*temm*	0.47	*Nratem*, *rainm*	0.52
Qingdao	*irriw*	0.17	*Nratew*, *temw*	0.18	*temm*, *radm*	0.18	*Nratem*, *rim*	0.59
Rizhao	*riw*, *rainw*	0.39	*Nratew*	0.27	*radm*	0.30	*Nratem*, *rim*	0.55
Shijiazhuang	*riw*, *temw*	0.46	*Nratew*, *radw*	0.17	*temm*	0.41	*Nratem*, *rainm*	0.56
Tangshan	*riw*, *radw*	0.30	*Nratew*, *irriw*	0.18	*temm*, *radm*	0.50	*Nratem*, *rainm*	0.56
Tianjin	*riw*	0.45	*Nratew*, *temw*	0.15	*temm*	0.21	*Nratem*, *rainm*	0.67
Weifang	*riw*	0.34	*Nratew*	0.19	*temm*	0.39	*Nratem*, *rainm*	0.65
Xinxiang	*irriw*, *Nratew*	0.21	*Nratew*	0.34	*temm*, *rim*	0.17	*Nratem*, *rainm*	0.67

† Climate variables *rainw*, *radw*, and *temw* are total seasonal rainfall, total seasonal monthly average radiation, and total seasonal monthly average air temperature during the growing season from October to June of the next year; management variables (Table 4) *Nratew* is seasonal N application rate and *irriw* is seasonal irrigation amount during the growing season *riw* is rainfall plus irrigation during the growing season.

‡ Climate variables *rainm*, *radm*, and *temm* are total seasonal rainfall, total seasonal monthly average radiation, and total seasonal monthly average air temperature during the growing season from June to September; management variables (Table 4) *Nratem* is seasonal N application rate and *irrim* is seasonal irrigation amount during the growing season; *rim* is rainfall plus irrigation during the growing season.

wheat–maize rotation system at most locations, which has been confirmed in many field experiments in NCP (Liu et al., 2003; Fang et al., 2006; Cui et al., 2010).

At locations where N rate was a dominant controlling factor for both the predicated crop yield and N leaching during the wheat season, such as Anyang, Beijing, and Xinxiang, it is important to reduce the N rate carefully to avoid a significant reduction in wheat yield (e.g., Fig. 5c vs. 6a for Anyang). On the other hand, at Anyang, Baoding, Beijing, and Tangshan, where irrigation was the main controlling factor for both predicted crop yield and N leaching during the wheat seasons, extremely high irrigation should be avoided to reduce the N leaching potential (e.g., Fig. 5c and 5g vs. 6a).

Conclusions and Remarks

The intensified agricultural systems in the NCP has led to high N losses to groundwater resources. Irrigation and N management practices play an important role in controlling soil N and water balances in such cropping systems. We assessed the long-term soil water and N balance for the wheat–maize double-cropping system under current management conditions for the dominant soil types at 15 locations in NCP. The results showed an obvious soil N surplus at these locations from 1970 to 2009 under the current management conditions. Seasonal rainfall can explain 39 to 84% of the predicted variability in seasonal N leaching during the maize seasons from 1970 to 2009 at these locations, while in the wheat seasons, significant correlations ($P < 0.01$) between seasonal N leaching and rainfall were found at only five locations. Seasonal rainfall explained more seasonal variation in wheat yield than maize yield across these simulation years (1970–2009) at the 15 locations.

Simulation studies of reducing the current N and/or irrigation rates to 40 to 80% of their current levels showed that N leaching responded more to changes in the N application rate than the irrigation rate, while the reverse was true for crop yield at most locations. Under lower irrigation levels, both N leaching and crop yield showed less response to N rate. These results suggest that matching the N application rate with the crop requirement under limited available water conditions is essential to achieving acceptable crop yields with the lowest N leaching in NCP. These simulation studies also showed that 40 to 60% of the current N application rate and 60 to 80% of the current irrigation amount should be recommended for these 15 locations, considering the N leaching potential, crop yield level, and water availability in NCP.

The multivariate regression analysis for the alternative management scenarios showed that N application rate was the most important factor for the predicted N leaching variations among the locations, and seasonal rainfall was also important for the predicted N leaching across maize seasons at these locations. Seasonal rainfall and irrigation were the most influential factors for the predicted wheat yield variation, while seasonal temperature or radiation was most important for the predicted maize yield. Reducing the N rate at high irrigation rates is a key measure to achieve high crop yields with low N leaching in the cropping system in NCP, but any management recommendation should be site specific to account for local soil and weather conditions.

These simulation results revealed the complexity of water and N interactions across 15 locations in the NCP due to differences in soil and weather conditions. Some of the simulation results may be counterintuitive. For example, N leaching significantly ($P < 0.01$) correlated with rainfall during the wheat seasons at five out of the 15 locations due to the relative dry weather conditions in NCP and lower N leaching potential. Another outcome of this simulation study is the quantification of proposed water and N management to meet certain environmental criteria (N leaching) without compromising crop yield. The results of this study may be used to develop decision support tools for water and N management in the NCP.

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