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Case study of developing an integrated water and nitrogen scheme for agricultural systems on the North China Plain**

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A b s t r a c t. Appropriate irrigation and nitrogen fertilization, along with suitable crop management strategies, are essential prerequisites for optimum yields in agricultural systems. This research attempts to provide a scientific basis for sustainable agricultural production management for the North China Plain and other semi-arid regions. Based on a series of 72 treatments over 2003-2008, an optimized water and nitrogen scheme for winter wheat/summer maize cropping system was developed. Integrated systems incorporating 120 mm of water with 80 kg N ha^{-1} N fertilizer were used to simulate winter wheat yields in Hebei and 120 mm of water with 120 kg N ha^{-1} were used to simulate winter wheat yields in Shandong and Henan provinces in 2000-2007. Similarly, integrated treatments of 40 kg N ha^{-1} N fertilizer were used to simulate summer maize yields in Hebei, and 80 kg N ha^{-1} was used to simulate summer maize yields in Shandong and Henan provinces in 2000-2007. Under the optimized scheme, 341.74 10^{7} mm ha^{-1} of water and 575.79 10^{4} Mg of urea fertilizer could be saved per year under the wheat/maize rotation system. Despite slight drops in the yields of wheat and maize in some areas, water and fertilizer saving has tremendous long-term eco-environmental benefits.

K e y w o r d s: water saving, nitrogen, winter wheat, summer maize, management

INTRODUCTION

Water and nitrogen (N) are critical elements of all forms of life. Both are essential in agricultural systems to produce crops for feed, food, and fibre (Bagheri *et al*., 2012; Frimpong *et al*., 2011; Hatfield, 2008; Zare *et al*., 2011). The rapid and steady increase in agricultural production in China in past decades is mainly attributable to improvements in irrigation technologies (Gong *et al*., 2011) and the increasing use of fertilizers, especially N fertilizers (Zhu and Chen, 2002). The consumption of N fertilizers increased continuously from 1980, reaching a peak in 1998, and China has become the world largest consumer of synthetic N fertilizers (Jiang *et al*., 2010). Maintaining high crop production under limited water resources and deteriorating environmental conditions is a current focus of significant research (Liu and Diamong, 2005, 2008).

The North China Plain (NCP), located between 32 and 40°N is one of the most important agricultural production areas in China. It includes Beijing, Tianjin, and most areas of Hebei, Shandong, Henan, Jiangsu, and Anhui province. Winter wheat and summer maize are the predominant crops, with the average cultivated area exceeding 70% of the region (Liu and Luo, 2010). The plain supports a population of over 300 mln and produces about 29.6% of China food, including half of its wheat and a third of its maize (Fang *et al*., 2010).

However, mean annual precipitation (600 mm) in the region falls short of the annual water demand for winter wheat and summer maize production (Liu and Luo, 2010). The lack of precipitation, especially in the winter wheat season (October to June), leads to frequent and severe water stress (Chen *et al*., 2010). The large evapotranspiration (ET) deficit is the most important factor limiting agricultural sustainability on the plain. Since surface water is largely limited, agricultural irrigation depends almost entirely on groundwater resources. Consequently, groundwater levels have steadily declined in the NCP region (Hu *et al*., 2005). As piezometric heads in production wells exceed 30 m deep

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in some areas, irrigation severely threatens the sustainability of groundwater resources and the agricultural systems that rely on them (Zhang *et al*., 2003). Over-irrigation also causes additional waste of the limited water resources (Devkota and Jha, 2011; Paltineanu *et al*., 2011). However, there is the potential to cut irrigation water use by 50% in the plain without any reductions in crop yield (Hu *et al*., 2005).

Nitrogen fertilizer on the NCP accounts for more than one quarter of the total N consumption in China (National Bureau of Statistics of China, 2008). In fact, the application of N fertilizer has drastically increased in recent years. Liu *et al*. (2003) has reported that the annual average application rate of N fertilizer across the whole country is 450 kg N ha^{-1}. For the NCP, Zhu and Chen (2002) noted annual rates of N fertilizer application as high as 400-900 kg N ha^{-1}. Despite these heavy application rates, nitrogen fertilizer use (*NUE*) efficiency in the region remains generally low. Field investigations show that the low *NUE* is not only financially wasteful, but also environmentally detrimental. This is because excess N can be lost through leaching and runoff, and may negatively affect the groundwater resources (Hu *et al*., 2005; Liu *et al*., 2003; Zhu and Chen, 2002). The development of water- and N-saving agricultural strategies is therefore essential to improve resource-use efficiency in the region. Such strategies could avert over-exploitation of groundwater and N fertilizer resources, which will in turn protect the environment and ensure sustainable agricultural production.

The focus of this study was therefore to develop an integrated water-N scheme for winter wheat/summer maize cropping system on the NCP using the DSSAT/CERES (Decision Support System for Agricultural Technology Transfer/Crop Environment Resource Synthesis) crop model (Jones *et al*., 2003). The simulation compares yields under the integrated and present schemes and offers a sound scientific basis for efficient crop production on the NCP.

MATERIAL AND METHODS

Three main production provinces on the NCP (Shandong, Henan, and Hebei) were selected as our study areas. The study area is largely flat, with deep alluvial soil profiles deposited by the Yellow River. Because of intensive irrigation, the soils are fairly moist and slightly saline. In the region, winter wheat is sown in mid-October and harvested in early June. This is followed by sowing summer maize in mid-June, which is harvested in early October. There are many geo-climatologically representative experimental stations located in the primary winter wheat/summer maize rotation regions to support model input. These include the three Experimental Station:

– Luancheng (LCS) (114°24'E, 37°53'N) Hebei province,
– Yucheng (YCS) (116°38'E, 36°56'N) Shandong province,
– Zhengzhou (ZZS) (113°42'E, 34°44'N) Henan province.

In total, 52 additional station points were used in the integrated water and nitrogen scheme simulation.

The latest process-based CERES-wheat and CERES-maize crop model of DSSAT-V4.0.2 (Jones, 2003) was adapted in this study to simulate the yield of winter wheat and summer maize in the study area. The ability of the CERES model in simulating crop yield, phenology, soil water, nitrogen of various crops under a variety of conditions has been evaluated in a wide range of environments (Lobell, 2006; Persson *et al*., 2010).

Model input data include: soil information, meteorological data, crop genetic parameters, and management data, which include planting depth, planting density, sowing date, station latitude and longitude, date of fertilization, irrigation date, the amount of fertilizer and irrigation, and irrigation mode information. The soil water balance routine of CERES includes the soil water quantity resulting from the input of precipitation and irrigation, the outputs of evaporation from plants and the soil, runoff and drainage. Nitrate movement associated with water movement in both an upward and downward direction is also simulated. The nitrogen dynamics routines of the CERES models were designed to simulate each of the major N loss processes and the contributions to the N balance made by mineralization. The routines also describe the uptake of N by the crop and the effects of N deficiency on crop growth processes. The effect of soil and plant water deficits on plant growth and yield reduction is calculated by the soil water balance (Jones and Kiniry, 1986; Jones *et al*., 2003). Daily or seasonal time step weather data can be selected as an input to simulate phenological development, dry matter accumulation and distribution, LAI, yield, and fertility of soil moisture balance. In this study, daily step weather data were used as an input. Daily climate data for precipitation, maximum and minimum temperature, and solar radiation were collected for 2003-2008 from the selected 52 station points. Solar radiation was computed from sunshine duration using the Angström-Prescott (A-P) equation (Angström,1956; Prescott, 1940). The soil profiles of the 52 points are from China Second Soil Survey Data. The yield, N use, and irrigation water use data for 2000-2007 from the statistics yearbook were also used to compare the results for the present and integrated schemes.

To achieve an integrated water and nitrogen scheme through model simulation, the field data from different water and nitrogen experiments from YCS were used to calibrate and validate the DSSAT/CERES model simulation results. For winter wheat, a water conservation irrigation experiment was used which included four water supply levels: no irrigation (W1), 40% of field capacity (FC, W2), 60% of FC (W3), and 80% of FC (W4). Once the soil water storage in the top 50 cm soil layer was depleted to 40, 60, or 80% of field capacity, irrigation was applied to fill the 50 cm soil layer to field capacity. As a large amount of precipitation falls during the summer maize growing season, most farmers did not use any additional irrigation. However, in some upstream areas that have plentiful water, farmers may irrigate one or two times. Therefore, we set two different water treatments for summer maize: no irrigation (M1) and irrigation (M2), with irrigation times and amounts as supplied by farmers. Except for different water use, fertilizer use and field management were the same in each water level treatment. In the nitrogen management experiment, four nitrogen supply levels were set for both winter wheat and summer maize: 70 kg N ha^{-1} (N1), 140 kg N ha^{-1} (N2), 210 kg N ha^{-1} (N3), and 280 kg N ha^{-1} (N4). This level was applied twice to winter wheat, before planting (early October) and at jointing (early April), but applied to summer maize only at jointing (middle of July). Urea (46% N content) was chosen as the nitrogen fertilizer. Similar to the water conservancy experiment, except for different nitrogen levels in the nitrogen management experiment, irrigation and field management were the same for each nitrogen level treatment. Field experimental data were collected on crop phenology, leaf area index (LAI), biomass, and yield.

In our simulation, the highest rates of irrigation and fertilizer application were set based on the experience of local farmers. The other scenarios setting in the simulation were decreased stepwise from the highest rates. The corresponding wheat and maize yields were collected from the three provinces from 2003 to 2008. The calculated *WUE* (water use efficiency, could be calculated as grain yield/applied water amount), *NUE* (nitrogen use efficiency, could be calculated as grain yield/applied N amount), and yield serve as indicators for the integrated treatment. On this basis, 64 water and N control treatments (with eight levels in each treatment) were simulated for winter wheat. Each treatment was designed to be irrigated three times during the whole growing period. The irrigation amount was the same each time and systematically increased by 20 mm from 0 mm to 140 mm. Similarly, each of the N fertilization treatments was replicated two times and systematically increased by 20 kg N ha^{-1} from 0 to 140 kg N ha^{-1}. The treatments are respectively denoted in an increasing order of rates of application by T1, T2, T3, …, T64. The full combinations of the treatments are depicted in Table 1.

Because rainfall is abundant during the summer maize season, only the N treatment was designed for summer maize. The mode of fertilization is the same as that described above for winter wheat (Table 2).

The *WUE* and *NUE* of winter wheat and summer maize were calculated for the present and integrated schemes as follows:

$$NUE = \frac{G_w}{N_s}, \quad (1)$$

where: *NUE* is N use efficiency (kg kg^{-1}), G_w is grain yield (kg ha^{-1}), and N_s is the applied N amount (kg N ha^{-1}). Then:

$$WUE = \frac{G_w}{I}, \quad (2)$$

where: *WUE* is water use efficiency (kg m^{-3}) and I is the amount of applied water. Based on the calibration and validation analysis, the simulated grain yield of winter wheat and summer maize at the LCS, YCS, and ZZS for 2003-2008 under the various treatments were used to calculate WUE and NUE. Statistical methods are also used to evaluate the performance of the CERES-wheat and CERES-maize models. These methods include model efficiency (ME), root mean square error (RMSE), and relative error (RE).

T a b l e 1. Water and nitrogen treatment scheme for winter wheat

Treatment	Water, N (mm, kg N ha^{-1})	Treatment	Water, N (mm, kg N ha^{-1})	Treatment	Water, N (mm, kg N ha^{-1})	Treatments	Water, N (mm, kg N ha^{-1})
T1	0, 00	T17	0, 8	T33	0, 16	T49	0, 24
T2	60, 00	T18	60, 80	T34	60, 16	T50	60, 24
T3	120, 00	T19	120, 80	T35	120, 16	T51	120, 24
T4	180, 00	T20	180, 80	T36	180, 16	T52	180, 24
T5	240, 00	T21	240, 80	T37	240, 16	T53	240, 24
T6	300, 00	T22	300, 80	T38	300, 16	T54	300, 24
T7	360, 00	T23	360, 80	T39	360, 16	T55	360, 24
T8	420, 00	T24	420, 80	T40	420, 16	T56	420, 24
T9	0, 40	T25	0, 12	T41	0, 20	T57	0, 28
T10	60, 40	T26	60, 12	T42	60, 20	T58	60, 28
T11	120, 40	T27	120, 12	T43	120, 20	T59	120, 28
T12	180, 40	T28	180, 12	T44	180, 20	T60	180, 28
T13	240, 40	T29	240, 12	T45	240, 20	T61	240, 28
T14	300, 40	T30	300, 12	T46	300, 20	T62	300, 28
T15	360, 40	T31	360, 12	T47	360, 20	T63	360, 28
T16	420, 40	T32	420, 12	T48	420, 20	T64	420, 28

T a b l e 2. Nitrogen treatment scheme for summer maize

Treatment	N (kg N ha^{-1})	Treatment	N (kg N ha^{-1})
Z1	0	Z5	160 (80×2)
Z2	40 (20×2)	Z6	200 (100×2)
Z3	80 (40×2)	Z7	240 (120×2)
Z4	120 (60×2)	Z8	280 (140×2)

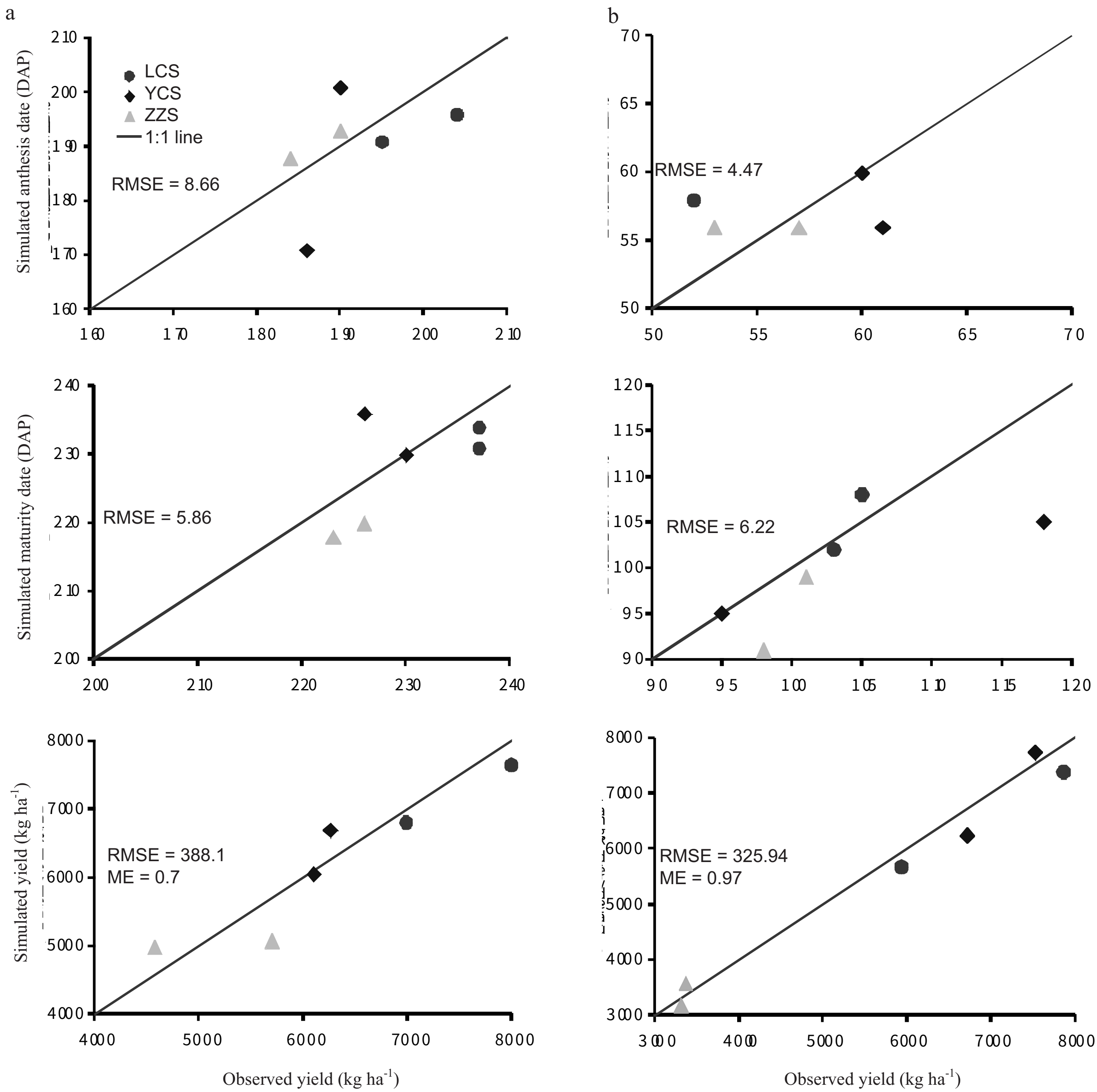

Fig. 1. Models CERES: a – wheat, b – maize calibration and validation for phenology and yield of winter wheat.

RESULTS AND DISCUSSION

Model calibration involves adjustment of parameters, so that simulated values compare well with measured values. For each treatment, we used experimental records from one season at the YCS for model parameter calibration, and the records of another year for model validation. There is good agreement between observed and simulated values of phenology and yield for both winter wheat and summer maize. The calculated RE is less than 20% with RMSE less than 12 d for anthesis and maturity. The simulated yields also match well with the observed values, with ME of 0.70 and 0.97 for winter wheat and summer maize, respectively (Fig. 1).

For winter wheat, *WUE* increases with water and the rate of N application (Fig. 2). Under the same N application rate, it is always highest for the 20×3 mm irrigation treatment. Irrespective of the water and N application rate, the variation trends in *WUE* remain similar. Precipitation is the only source of water for summer maize, which is assumed to be uniform across the treatments at any one station. Therefore, under this condition *WUE* is mainly driven by the N application rate. *WUE* for maize generally increases for all treatments less than the 60×2 kg N ha^{-1} N application rate (Fig. 3). No significant increases are noted in treatments with N application rates greater than 60×2 kg N ha^{-1}.

For the simulated winter wheat, *NUE* decreases with the increasing N application rate (Fig. 4). It is highest for the 20×2 kg N ha^{-1} N application rate. For summer maize, the variation trend in *NUE* is similar to that in *WUE* (Fig. 5). It is highest for the 40×2 kg N ha^{-1} application rate.

The winter wheat yield is very sensitive to the N application rate and generally increases with the increasing N application rate. Under the same N application rate, irrigation amounts have little effect on wheat yield (Fig. 6). At an

a

WUE (kg m^{-3})

b

WUE (kg m^{-3})

c

WUE (kg m^{-3})

Fig. 2. Water use efficiency in winter wheat for 2003-2008 at the: a – Luancheng (LCS), b – Yucheng (YCS), c – Zhengzhou (ZZS) Experimental Stations.

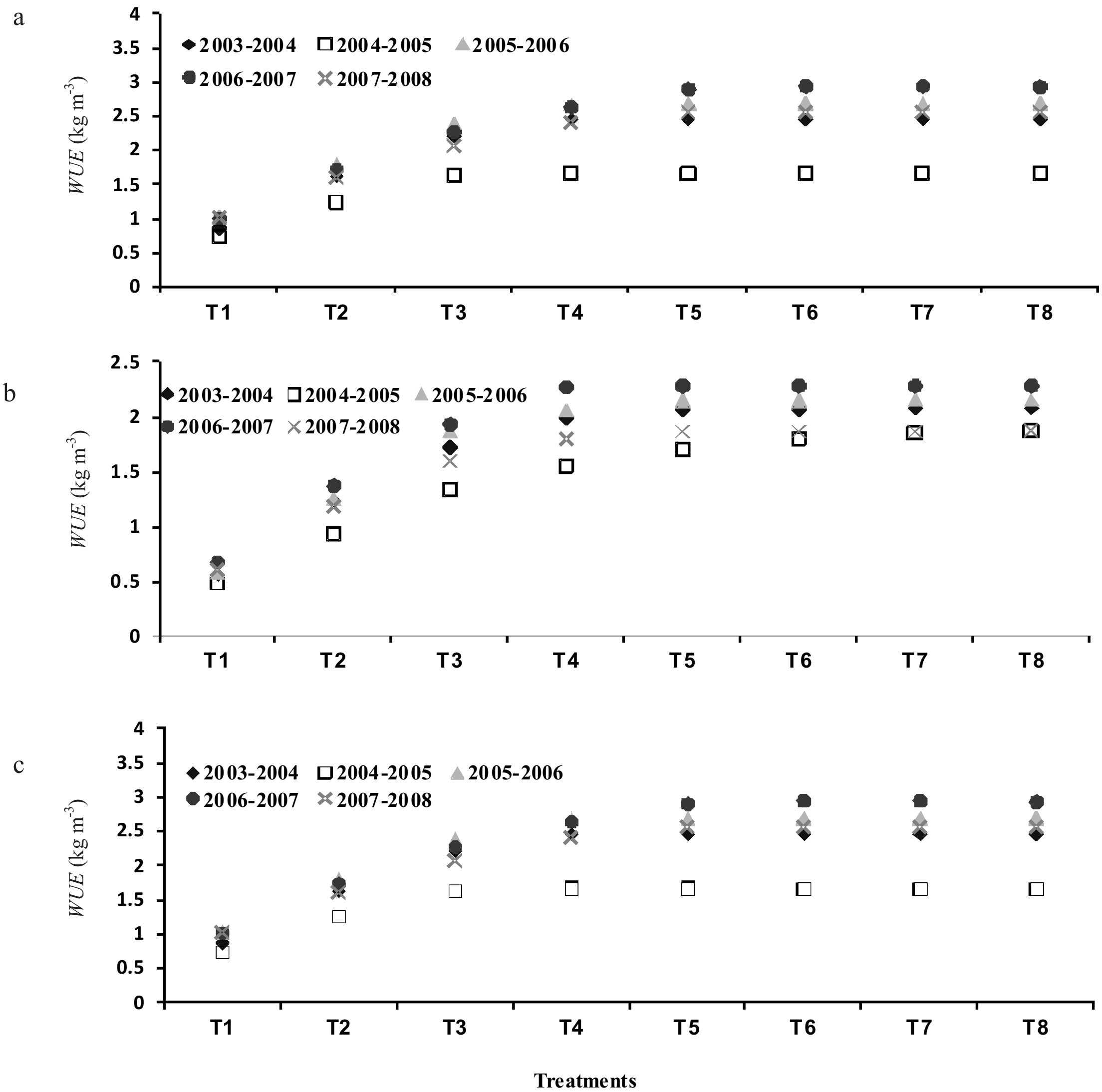

Fig. 3. Water use efficiency in summer maize for 2003-2008 at: a – LCS, b – YCS, c – ZZS.

N application rate of 40×2 kg N ha^{-1}, the yield of winter wheat at the LCS changes from 4 000 to 6 000 kg ha^{-1}. This is close to the present winter wheat production level in Hebei province. At an N application rate of 60×2 kg N ha^{-1}, winter wheat yields also approach the present production levels at the YCS and ZZS stations. Because precipitation is abundant in summer, summer maize yield is determined by the N application rate only (Fig. 7). The respective N application rates for Hebei under the integrated maize production practices are 20×2 kg N ha^{-1} and 40×2 kg N ha^{-1} for Shandong and Henan provinces. Additional N application rates beyond these levels have no significant impact on maize yield.

The above results suggest that not only are high *WUE* and *NUE* attainable, but that high yields are also ensured to meet consumption demand. The optimum conditions for winter wheat in 2000-2007 are obtained under the T19 (120 mm, 80 kg N ha^{-1}) for Hebei, and T27 (120 mm, 120 kg N ha^{-1}) for Shandong and Henan provinces, respectively. The corresponding optimum conditions (2003-2008) for summer maize production in the three provinces are obtained under the Z2 (40 kg N ha^{-1}) for Hebei, and Z3 (80 kg N ha^{-1}) for Shandong and Henan provinces, respectively. Under the optimized schemes, the 2003-2008 average *WUE*, *NUE*, and yield of winter wheat for Henan, Shandong, and Hebei provinces are 3.99, 3.62, and 4.03 kg m^{-3}; 119.56, 83.34, and 87.57 kg kg^{-1}; and 4782, 4346, and 4840 kg ha^{-1}, respectively. The corresponding average *WUE*, *NUE* and yield for summer maize in the three provinces are 1.61, 1.69, and 2.12 kg m^{-3}; 52.37, 51.90, and 112.07 kg kg^{-1}; and 4780, 6124, and 9577 kg ha^{-1}, respectively.

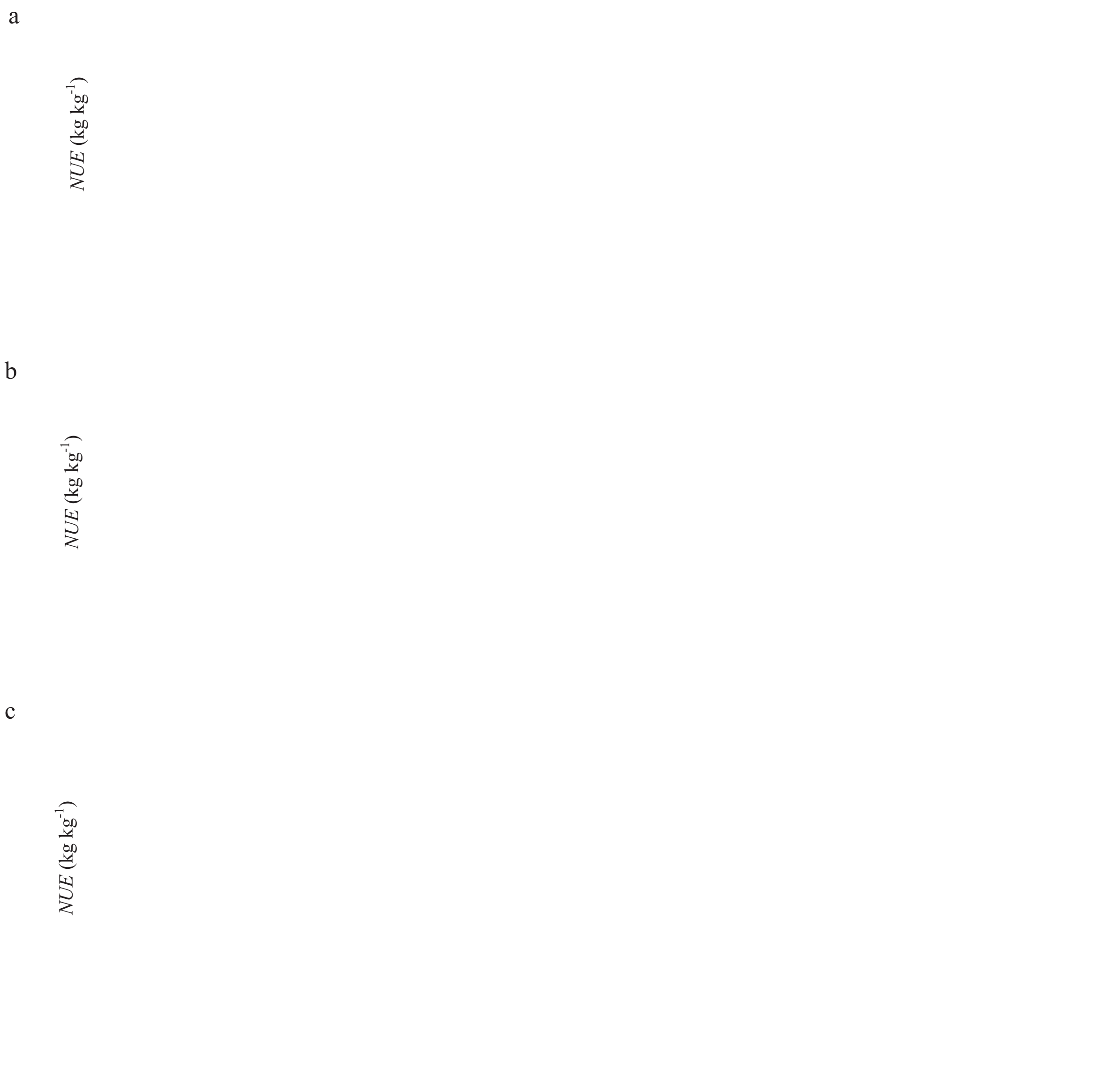

Fig. 4. Nitrogen use efficiency in winter wheat for 2003-2008 at: a – LCS, b – YCS, c – ZZS.

The interpolated maps of the differences between model-simulated yield and that registered in the statistical yearbook for the 50 field-sites averaged for 2000-2007 are depicted in Fig. 8. For winter wheat, the model-simulated average yields in the vast majority of Henan and Shandong provinces are lower than the statistical values. However, the model-simulated average yields are higher than the statistical values in most areas of Hebei province. The model-simulated yields for summer maize are lower than the statistical values in the middle areas of the three provinces. Basically, the model-simulated yields under the optimal scheme are slightly lower than those under the present scheme. The simulated average yield under the optimized scheme is 299 and 1613 kg ha^{-1} lower than the statistical value for the present winter wheat and summer maize management systems. The benefits of integrated water-saving irrigation and N-saving application rates are discussed in the next section.

DISCUSSION

The shortage of water resources is increasing with increasing demand for production on the NCP. Improving *WUE* is therefore critical not only to meet this demand, but also for the sustainability of agricultural production (Frank and Manuel, 2008). Under the normal irrigation systems, water use for winter wheat production is estimated at 300 mm year^{-1} (Guo *et al.*, 2004a), 370 mm year^{-1} (Zhang *et al.*,

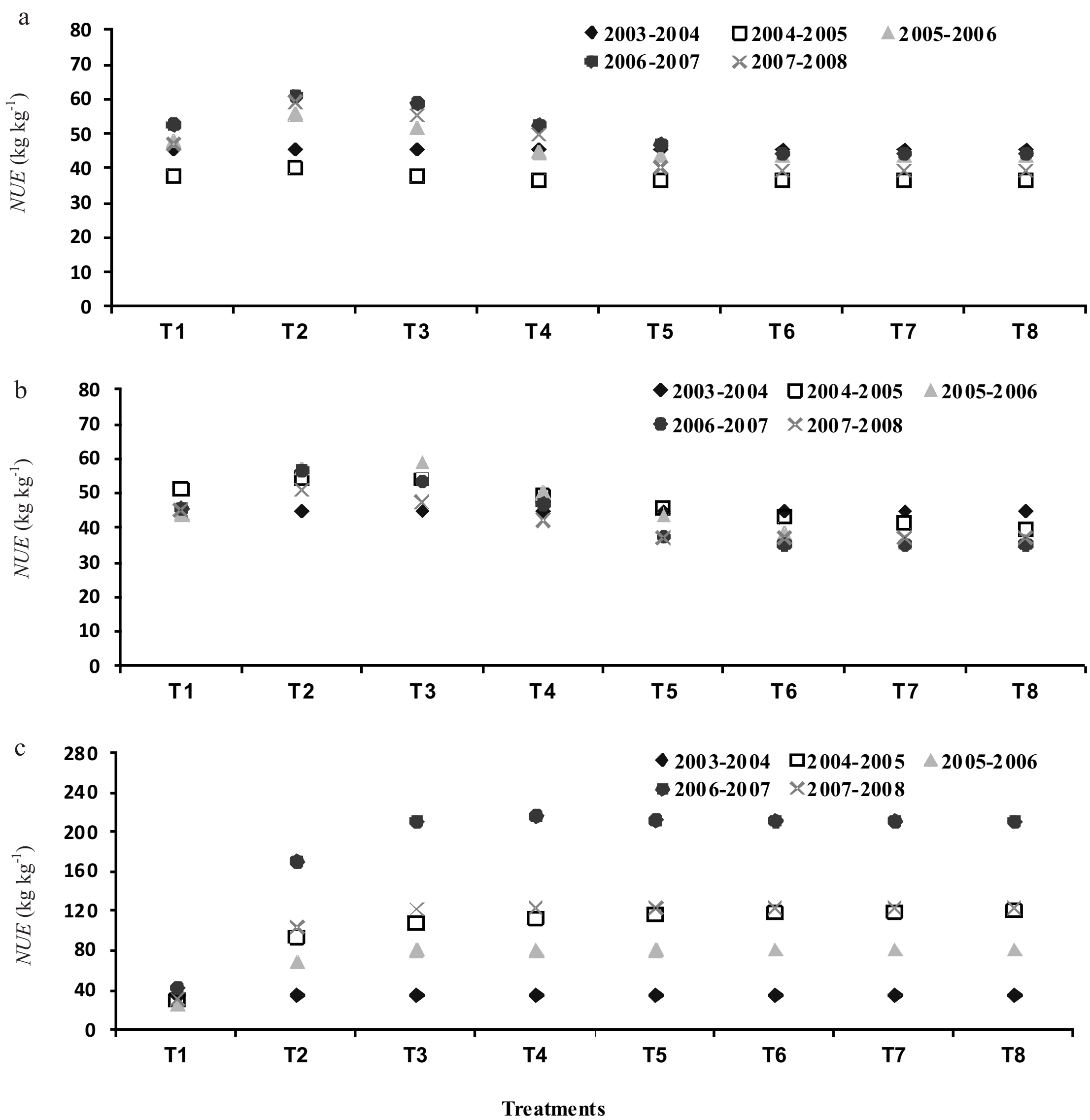

Fig. 5. Nitrogen use efficiency in summer maize for 2003-2008 at: a – LCS, b – YCS, c – ZZS experimental stations.

2007), and 340 mm year^{-1} (Ma *et al.*, 2010) in Hebei, Shandong, and Henan provinces, respectively . Based on the 2008 statistics yearbook, wheat planting areas in these three provinces are 2.63 10^6, 3.39 10^6, and 4.89 10^6 ha, respectively. This translates into total annual water use of 78.88 10^8, 125.52 10^8, and 166.16 10^8 m^3, respectively, in the three provinces. Under the integrated irrigation scheme, however, the annual irrigation water use by wheat in the three provinces is only 31.55 10^8, 40.71 10^8, and 58.64 10^8 m^3, respectively. Compared with the existing wheat irrigation systems, the integrated irrigation scheme saves a total of 47.33 10^8, 84.81 10^8, and 107.52 10^8 m^3, respectively in Hebei, Shandong, and Henan provinces. For the study area, a total of 239.65 10^8 m^3 of water is therefore saved per annum.

To ensure long-term and high-yield production of maize in some areas of Hebei, Shandong and Henan provinces, minimum irrigation is often applied. The average irrigation amount in the maize growing season is ≈135 mm year^{-1} (Zhang *et al.*, 2007). The present cultivated areas for maize in the three provinces are 2.51 10^6, 2.57 10^6, and 2.37 10^6 ha, respectively. The corresponding annual water use in the three provinces is therefore 33.90 10^8, 34.71 10^8, and 32.04 10^8 m^3, respectively. This then implies that an additional total of 100.65 10^8 m^3 of water can be saved in the study area. The details of these analyses are presented in Table 3.

Overall, a total of 341.74 10^8 m^3 of water would be saved annually under the optimized integrated wheat/maize irrigation scheme. This is close to the total amount of exploited groundwater (391.8 10^8 m^3 year^{-1}) in the three provinces (National Bureau of Statistics of China, 2008).

a

b

c

Fig. 6. Winter wheat yield (2003-2008) for the: a – LCS, b – YCS, c – ZZS.

The urea application rates under the conventional wheat fertilization system are 489 kg N ha^{-1} in Henan and Hebei provinces (Guo *et al*., 2004b; Wang *et al*., 2009) and 522 kg N ha^{-1} in Shandong province (Wang *et al*., 2007). Note that this calculation is based on the net N fertilizer application rate per hectare and assuming a urea N content of 46%. For the three provinces, this corresponds to annual urea application rates of 128.57 10^4 t, 177.09 10^4, and 238.98 10^4 Mg. However, under the optimized scheme, the fertilizer application rates during wheat production in the three provinces are 174, 261, and 261 kg N ha^{-1}, respectively, corresponding to annual consumption of urea application rates of only 45.7 10^4, 88.50 10^4 , and 127.49 10^4 Mg, respectively. Compared with the existing system therefore, the optimized scheme saves 82.85 10^4 , 88.59 10^4, and 111.49 10^4 Mg of urea per year in the Hebei, Shandong, and Henan provinces, respectively, which amounts to a total annual saving of 282.92 10^4 Mg of urea under winter wheat cultivation.

The conventional N fertilizer application rate under maize cultivation is 457 kg N ha^{-1} in Hebei (Wang *et al*., 2010), 489 kg N ha^{-1} in Shandong (Sun, 2010), and 675 kg N ha^{-1} in Henan provinces (Yan, 2010). The corresponding annual urea consumption in the three provinces is 114.75 10^4, 125.72 10^4, and 160.22 10^4 Mg, respectively. Based on the optimized scheme, however, the amount of fertilizer use drops to 87, 174, and 174 kg N ha^{-1} in Hebei, Shandong and Henan provinces, respectively, which corresponds to 21.83 10^4, 44.71 10^4, and 41.28 10^4 Mg of urea consumption in the three provinces. As such, the three provinces could save a total of 292.86 10^4 Mg of urea annually. Under the optimized fertilization scheme, the combined amount of N fertilizer saved annually under wheat and maize cultivation is 575.79 10^4 Mg (Table 4).

The integrated management of water and N fertilizer for optimal food security is fully discussed by Gong *et al*. (2011) and Chen *et al*. (2011). For instance, according to the

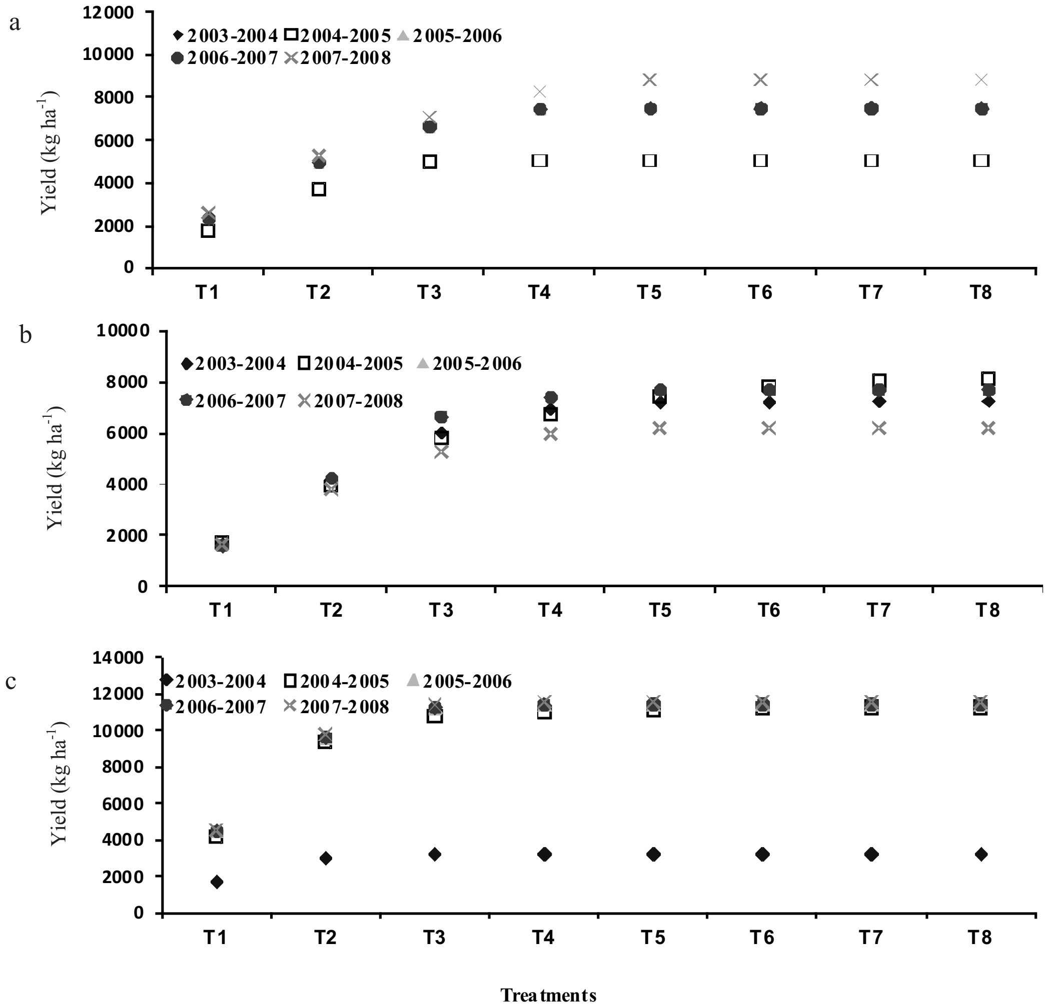

Fig. 7. Summer maize yield (2003-2008) for the: a – LCS, b – YCS, c – ZZS.

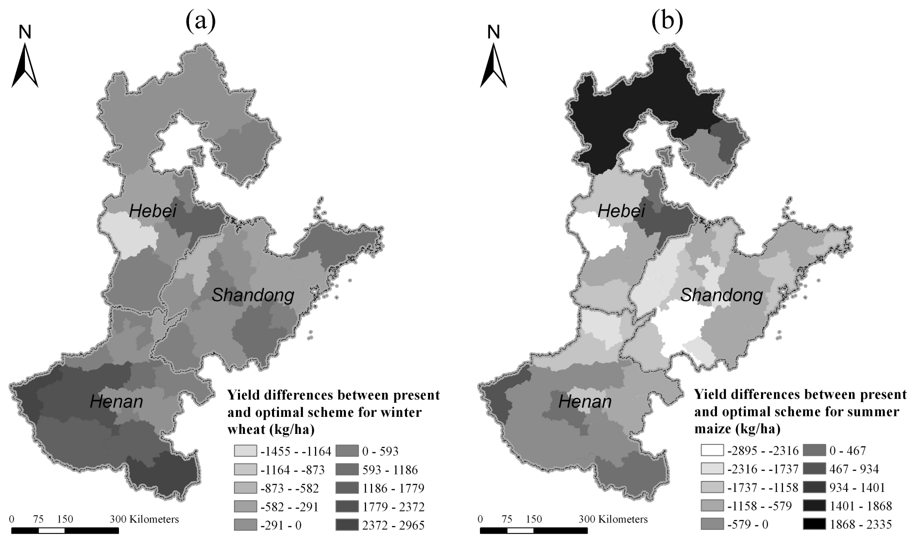

Fig. 8. Spatial distributions of the differences between the model-simulated yield and the estimate in the statistical year book for: a – winter wheat, and b – summer maize.

T a b l e 3. Analysis of water use under the present and optimal scheme

Crop	Province	Water consumption (mm, unit area)			Planting area (10^6 ha)	Water consumption (10^8 m^3)		
		Present scheme	Optimal scheme	Saving		Present scheme	Optimal scheme	Saving
Winter wheat	Hebei	340	120	220	2.63	78.88	31.55	47.33
	Shandong	300	120	180	3.39	125.52	40.71	84.81
	Henan	370	120	250	4.89	166.16	58.64	107.52
	Sub total	–	–	–	–	370.56	130.91	239.65
Summer mize	Hebei	135	0	135	2.51	33.90	0.00	33.90
	Shandong	135	0	135	2.57	34.71	0.00	34.71
	Henan	135	0	135	2.37	32.04	0.00	32.04
	Sub total	–	–	–	–	100.65	0.00	100.65
	Grand total	–	–	–	–	471.21	130.91	340.30

T a b l e 4. Analysis of fertilizer consumption under the present and optimal scheme

Crop	Province	Fertilizer consumption per unit area (kg ha^{-1})			Planting area (10^6 ha)	Fertilizer consumption per province (10^4 Mg)		
		Present scheme	Optimal scheme	Saving		Present scheme	Optimal scheme	Saving
Winter wheat	Hebei	489	174	315.09	2.63	128.57	45.73	82.85
	Shandong	522	261	261.14	3.39	177.09	88.50	88.59
	Henan	489	261	228.14	4.89	238.98	127.49	111.49
	Sub total	–	–	–	–	544.64	261.71	282.92
Summer mize	Hebei	457	87	370.04	2.51	114.75	21.83	92.92
	Shandong	489	174	315.09	2.57	125.72	44.71	81.01
	Henan	675	174	501.09	2.37	160.22	41.28	118.94
	Sub total	–	–	–	–	400.69	107.83	292.86
	Grand total	–	–	–	–	945.33	369.54	575.79

China National Statistics Bureau 1996-2005, China cereal grain yield increased by 10% between 1996 and 2005 along with a 51% increase in chemical fertilizer use. The imbalance between increased fertilizer input and grain yield not only leads to decreases in the input/grain ratio, but also induces nutrient imbalances and environmental pollution (Chen *et al*., 2011; Jiang *et al*., 2010).

Appropriate countermeasures are needed to minimize waste of the limited natural resources and environmental deterioration in the study area. The integrated scheme has a negative economic impact in the short-run, but could save substantial amounts of water and fertilizer. Water is not only an indispensable element in agricultural production, but also a critical environmental requirement. China should therefore move to unify the price of water across the country. A unified water price could force farmers to save water and reduce fertilizer use. For instance, a high water price would be also good for a certain environment possessing many water resources. Local governments should find, however, effective alternative ways to increase farmers incomes.

CONCLUSIONS

1. Based on this study, optimal regulation of water and N does not essentially affect yield of the wheat/maize rotation system on the NCP. Under the optimized scheme, 341.74 10^8 m^3 of water and 575.79 10^4 Mg of N fertilizer could be saved per year under the wheat/maize rotation system. Simulated average yields under the optimized scheme are 299 kg ha^{-1} lower than that under the present winter wheat management system. Similarly, simulated average yields under the optimized scheme are 1 613 kg ha^{-1} lower than that under the present summer maize management system.

2. The annual savings in water could induce groundwater recovery, a critical environmental factor on the NCP. N fertilizer saving could also improve soil conditions and reduce environmental risk. This research attempts to provide a scientific basis for sustainable agricultural production management for the NCP and other semi-arid regions.

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