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Alternative cropping systems for sustainable water and nitrogen use in the North China Plain

Qingfeng Meng[a], Qinping Sun[b], Xinping Chen[a], Zhenling Cui[a,*], Shanchao Yue[a], Fusuo Zhang[a], Volker Römheld[c]

[a] Department of Plant Nutrition, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[b] Institute of Plant Nutrition and Resources, Beijing Academy of Agriculture and Forestry Science, Beijing 100097, China
[c] Institute of Crop Science, University Höhenheim, 70593 Stuttgart, Germany

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ABSTRACT

Serious water deficits and excessive nitrogen (N) applications are threatening the sustainability of intensive agriculture in the North China Plain (NCP). This study examined the possibility of replacing the conventional system (Con.W/M) of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.), with an optimized double cropping system (Opt.W/M), a 2-year system (winter wheat/summer maize–spring maize, W/M–M), and a monoculture system (spring maize, M) based on optimal water and N management strategies. From 2004 to 2010, a long-term field experiment conducted in the NCP showed that although >70 mm of irrigation water can be saved with Opt.W/M compared with Con.W/M, annual net groundwater use under Opt.W/M was still 250 mm, 65–90% of which was consumed during the winter wheat season. When wheat production was decreased, 35% and 61% of irrigation water could be reduced in W/M–M and M compared to Con.W/M, respectively. As a result, annual groundwater use was decreased to 190 mm in W/M–M and 94 mm in M. Meanwhile, the N fertilizer rate was reduced 59% and 72% in W/M–M and M compared to Con.W/M, respectively. There were no significant differences in net economic returns between Con.W/M and W/M–M across the 6-year period. In the 6 years, no significant economic loss was observed between Con.W/M and M except in the 2008–2010 rotation. The W/M–M and M systems showed great potential to reduce water and N application and achieve groundwater use balance, and thus should be considered for economic and sustainable agricultural development in the NCP.

1. Introduction

The North China Plain (NCP) is one of the major agricultural regions in China, and provides more than 75% of the nation's wheat and 35% of its maize (National Bureau of Statistics of China, 2009). Since the 1970s, the dominant cropping system in the NCP has changed from a single crop per year to double cropping to increase food production. The winter wheat/summer maize rotation with two harvests per year is the main cropping system used currently. In this system, winter wheat is seeded in early October and harvested the following June. Summer maize is then seeded in early June, immediately after the winter wheat harvest, and harvested at the beginning of October.

As a result of mechanization, irrigation, mineral fertilization, and crop-system change, the wheat and maize yield of the NCP increased from 0.6 to 0.7 Mg ha^{-1} in 1949 to 5.4 and 5.6 Mg ha^{-1} in 2009, respectively (China Agriculture-Database, 2011). However, side effects of such development include excessive fertilizer application and overuse of aquifers for irrigation water in the last two decades. For example, the typical nitrogen (N) rate applied in this area varies from 500 to 600 kg N ha^{-1} year^{-1}, exceeding the crop requirements of 200 to 300 kg N ha^{-1} year^{-1} (Chen, 2003; Cui et al., 2010). As a result, the partial factor productivity from applied N (PFP_N) decreased from 46 kg kg^{-1} in 1978 to 21 kg kg^{-1} in 1998 in the intensive double cropping system (Fang et al., 2006). Meanwhile, N overuse has resulted in many environmental problems in this region, including groundwater pollution by NO_3–N (Ju et al., 2006; Xing and Zhu, 2000; Zhang et al., 1996; Zhu and Chen, 2002), surface water quality degradation (Zhang et al., 2010), soil acidification (Guo et al., 2010), and air pollution (Liu et al., 2006).

More than excessive N application, water shortages and depletions have become the factors most restricting the sustainable development in agriculture in the NCP. The region has a typical warm temperate, sub-humid, continental monsoon climate, with hot, rainy summers and cold, dry winters. Annual precipitation is extremely variable ranging from 300 to 1000 mm with an average

* Corresponding author. Tel.: +86 10 62733454; fax: +86 10 62731016.
E-mail addresses: cuizl@cau.edu.cn, zhenlingcui@163.com (Z. Cui).

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of about 500 mm (Li et al., 2005). In comparison, annual water consumption is about 870 mm, including 420 mm for summer maize and 450 mm for winter wheat (Liu et al., 2002). Furthermore, the amount and distribution pattern of rainfall vary between crop seasons, and only 20–30% of total rainfall occurs during the winter wheat growing season (Liu et al., 2001; Sun et al., 2010; Wang et al., 2008). To achieve high grain yield of wheat, a total of >400 mm of supplementary irrigation is applied, splitted into three to four applications per season (Wang et al., 2003; Zhang et al., 2003).

The declining groundwater table in the NCP has attracted worldwide attention in recent decades (Brown, 1995; Foster et al., 2004; Kendy et al., 2003, 2004; Zhang et al., 2003). Groundwater levels have been persistently declining from about 10 m below the soil surface in the 1970s to about 32 m currently, with an average rate of about 1 m $year^{-1}$ in the northern NCP (Wang et al., 2002). Along a line from Cangzhou to Guantao counties in the NCP, the groundwater table has declined more than 40 m since the 1960s (Foster et al., 2004). As a result, a 50,000 km^2 cone of depression in the groundwater table, the largest recorded worldwide, has formed in this area (Hu et al., 2005). Meanwhile, a series of related environmental problems have been caused. For example, land subsidence due to the withdrawal of groundwater has affected an area of 60,000 km^2, with the maximum subsidence of 3.9 m at Tianjin city (Xu et al., 2008).

The need to reduce agricultural water use in the NCP has resulted in extensive studies evaluating approaches and strategies to improve crop water use efficiency (WUE). For example, studies have shown that controlled alternative partial root-zone irrigation (Kang and Zhang, 2004; Li et al., 2007), regulated deficit irrigation (Kang et al., 2000; Zhang et al., 1998), and limited irrigation for winter wheat and summer maize can reduce irrigation by 15–35% and increase WUE by 10–30%. However, because of the more than 200 mm gap between the available rainfall and water demand of the double cropping system, 200–450 mm of irrigation water was still applied in most studies to maintain grain yields for the double cropping systems, even under optimal irrigation water management. Any attempt or strategy to meet the crop water shortage by irrigation from groundwater will result in further groundwater table decline (Kendy et al., 2004).

According to some studies, the annual water consumption of spring maize monoculture only ranges from 350 to 551 mm (Gao et al., 2009; Gardiol et al., 2003; Meng and Zhang, 1996). Considering the 500 mm of mean precipitation in the NCP, a spring maize monoculture may potentially meet the positive groundwater balance. However, because wheat is the main grain ration in the NCP, it would be impossible to greatly decrease the intensity of wheat production. Three harvests in 2 years (first year: winter wheat/summer maize, second year: spring maize, W/M–M) would be an alternative solution, decreasing wheat production only partly. The specific objectives of this study were to (1) evaluate the irrigation and fertilizer N saving potentials of optimized water and N management strategies among different cropping systems; (2) compare the effects of different rotation systems on the groundwater use balance; and (3) compare the final economic returns of different cropping systems to determine optimal cropping systems.

2. Materials and methods

2.1. Experimental design

A long-term field experiment was conducted from 2004 to 2010 at the Quzhou Experimental Station, China Agricultural University (QZ, 115.0°E, 36.5°N, 40 m above sea level), located in Quzhou County, Heibei Province (Fig. 1). Quzhou County, as typical of the NCP, is an area of intensive agriculture, where more than 80% of agricultural fields are used for winter wheat and summer maize in annual rotations. The annual mean temperature is 13.2 °C. The annual precipitation ranges from 213 to 840 mm with a mean of 494 mm since 1980, and 68% of the precipitation falls from June to September. The rainfall distribution at the experimental site from 2004 to 2010 is shown in Table 1.

The soil texture was silt with a field capacity at 0–30, 30–60, and 60–90 cm soil depths of 25%, 24%, and 26% (volume) and corresponding wilting point of 9%, 7%, and 5% (volume), respectively. Other chemical parameters of the 0–30 cm soil layer before planting in 2004 were as follow: total N 0.67 g kg^{-1}; Olsen-P 5 mg kg^{-1}; exchangeable-K 74 mg kg^{-1}; organic matter content 10.3 g kg^{-1}; and soil pH (1:2.5, soil:water) 8.5.

A randomized complete block design was employed with four treatments and four replications. The treatments included conventional winter wheat and summer maize based on current farmer practice (Con.W/M); optimized winter wheat and summer maize with optimal water and N management (Opt.W/M); three harvests in 2 years (first year: winter wheat and summer maize; second year: spring maize, W/M–M), and one harvest in 1 year (spring maize, M). Plots of 60 (6 × 10) m^2 were separated by a 20-cm-wide zone managed to minimize the effects of the two adjacent plots.

The Con.W/M system was considered to be fully irrigated following current farmer practice. Depending on rainfall, the Con.W/M plots were irrigated three to five times for wheat and one or two times for maize. The amount of irrigation water ranged from 60 to 100 mm based on soil moisture and farmer practice. Irrigation water was applied via a 15-cm plastic hose. A flow meter recorded the amount of irrigation water used.

The rate and timing of irrigation in the Opt.W/M, W/M–M, and M systems were determined according to soil water content tests at the beginning of critical growing seasons. The wheat growth season was divided into four periods: planting to re-greening, re-greening to shooting, shooting to flowering, and flowering to harvest. Optimized irrigation was used to keep the soil water content between 45% and 80% plant available water content. In all systems, the irrigation of maize occurred only under dry weather conditions during germination or fertilizer application. Table 2 summarizes the irrigation events for wheat and maize from 2004 to 2010 for the four cropping systems.

Nitrogen management for Con.W/M followed current farmer practice in the NCP. Nitrogen input was 550 kg ha^{-1} $year^{-1}$, of which 300 kg ha^{-1} $year^{-1}$ was for winter wheat and 250 kg ha^{-1} $year^{-1}$ was for summer maize (Chen, 2003; Cui et al., 2010). For other systems, N management of wheat and maize followed the in-season root zone N management (IRNM) for the NCP reported elsewhere (Chen, 2003; Chen et al., 2006; Cui et al., 2008; Zhao et al., 2006). The rate and timing of N fertilization for wheat and maize in the Opt.W/M, W/M–M, and M systems were determined following this IRNM system. The wheat growing season was divided into two periods: from planting to shooting, and from shooting to maturity. The maize growing season was divided into three periods, from planting to the six-leaf stage, from the six-leaf to ten-leaf stage, and from the ten-leaf stage to harvest. The amount of N fertilizer applied at the beginning of each growing period was determined by deducting the amount of soil N_{min} (NH_4–N + NO_3–N) in the root zone from the target N value, which was estimated based on yield target and crop N uptake. The total chemical N input of the different systems from 2004 to 2010 is listed in Table 2. Phosphorus (P) and potassium (K) were applied as needed according to soil available P and K testing.

2.2. Crop management

Winter wheat was generally sown in early October using a seeder with a row spacing of 0.15 m and harvested in early June.

Table 1
Distribution of month rainfall in Quzhou experimental station from 2004 to 2010 (mm).

Growth seasons	Month												Total
	October	November	December	January	February	March	April	May	June	July	August	September	
2004–2005	2.3	18.3	10.6	1.0	28.0	1.1	8.0	53.9	125.1	45.1	56.3	116.0	465.7
2005–2006	10.1	7.7	0	1.7	2.3	0	19.6	68.9	61.4	57.8	131.3	17.5	378.3
2006–2007	8.2	19.1	0	0	0	0	0	53.8	37.4	56.6	101.0	82.4	358.5
2007–2008	21.3	1.0	0	0	0	0	42.8	92.1	33.3	146.2	72.6	25.2	434.5
2008–2009	16.9	1.6	0	0	0	0	26.1	50.2	28.3	92.4	79.9	104.2	399.6
2009–2010	10.8	36.0	0.5	0.6	12.1	7.5	12.2	28.4	41.2	112.9	113.7	58.7	434.6

Table 2
Annual irrigation and chemical N fertilizer input for wheat and maize from 2004 to 2010 in four cropping systems: conventional and optimized winter wheat and summer maize (Con.W/M and Opt.W/M), three harvests in 2 years (first year: winter wheat and summer maize; second year: spring maize, W/M–M), and one harvest in 1 year (spring maize, M).

		Wheat			Maize				Total			
		Con.W/M	Opt.W/M	W/M–M	Con.W/M	Opt.W/M	W/M–M	M	Con.W/M	Opt.W/M	W/M–M	M
Irrigation (mm)	2004–2005	240	180	180	75	75	75	80	315	255	255	80
	2005–2006	315	240	–	115	115	243	243	430	355	243	243
	2006–2007	255	225	225	150	120	120	105	405	345	345	105
	2007–2008	280	255	–	90	75	210	210	370	330	210	210
	2008–2009	350	245	245	110	110	110	165	460	355	355	165
	2009–2010	300	195	–	60	60	105	120	360	255	105	120
Chemical N fertilizer ($kg\ ha^{-1}$)	2004–2005	300	120	120	250	75	75	80	550	195	195	80
	2005–2006	300	145	–	250	80	130	130	550	225	130	130
	2006–2007	300	120	110	250	120	120	120	550	240	230	120
	2007–2008	300	102	–	250	185	231	231	550	287	231	231
	2008–2009	300	235	235	250	185	185	171	550	420	420	171
	2009–2010	300	176	–	250	185	155	195	550	361	155	195

Summer maize was planted immediately after the wheat harvest. The final density of maize was 6.5–7 plants m^{-2}, with a row spacing of 0.6–0.7 m. The cultivars used in this study were Shijiazhuang 8 and Zhengdan 958 for winter wheat and summer maize, respectively. Both cultivars were commonly used in this region. From 2005 to 2007, spring maize was sown at the end of April or the beginning of May at a density of 7 plants m^{-2}. The cultivar CF1505 was employed for spring maize in the first 3 years. Beginning in 2008, the M system was adjusted, with the hybrid maize DH3719, which has a high yield potential of >15 Mg ha^{-1} (Jiang et al., 2008; Wang et al., 2006), being introduced at a density of 8.5 plants m^{-2}, and the sowing date being delayed to the end of May. No obvious water, weed, pest, or disease stress was observed during either wheat or maize growing seasons.

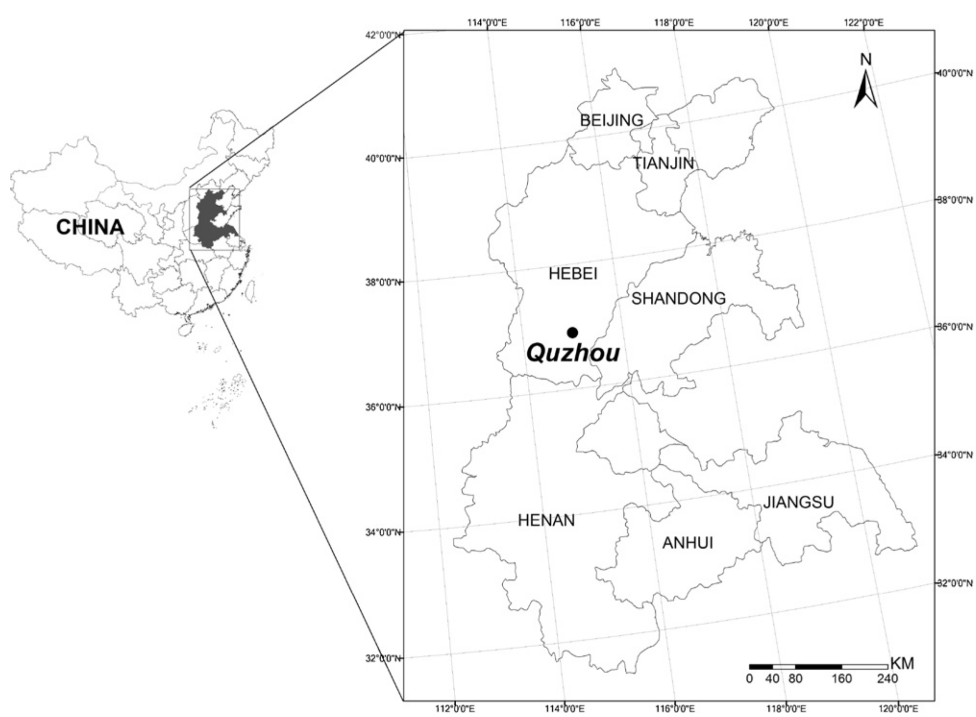

Fig. 1. The locations of North China Plain in China and Quzhou experimental station in Hebei province.

2.3. Sampling and data analysis

Three to five soil samples were taken in each plot at 30-cm increments to a depth of 90 cm and then mixed. Soil water content was determined after oven-drying at 105 °C to a constant weight. For wheat, soil samples were collected before planting, at the beginning of regreening, shooting, and flowering, and after harvest. For maize, samples were collected before planting, at the six- and ten-leaf stages, and after harvest. Soil mineral N ($NH_4 + NO_3$) was analyzed in all samples except the after-harvest samples to determine fertilization.

At the harvest stage, three 1-m^2 subplots randomly located in each wheat plot were harvested manually to determine dry matter and grain yields. A 12–14 m^2 area in the middle of each maize plot was harvested to determine maize yields. The grain samples were oven-dried at 60 °C for determination of dry grain yield. The grain yield was adjusted to 15.5% moisture.

Total evapotranspiration (ET) was determined using the soil water balance equation for the whole growing season and individual growth periods as follows (Zhang et al., 1999):

$$ET = P + I + SWD - R - D + W_g \quad (1)$$

where ET is total evapotranspiration for the growing period of each crop (mm); P is precipitation (mm); I is irrigation (mm); SWD is the change in soil water storage at the measured soil depth (mm); R is runoff (mm); D is drainage below the root zone (mm); and W_g is water used by the crop through capillary rise of groundwater to the root zone (mm). Because no runoff was observed in the plots in this study, R was ignored. Capillary rise was considered negligible because the groundwater table was more than 20 m below the soil surface and soil water extraction did not occur below 4 m (Liu and Wei, 1989). Drainage was estimated using a recharge coefficient (α) multiplied by the amount of irrigation or the effective rainfall (mm) as follows:

$$D = \alpha I \quad (2)$$

The recharge coefficient (α) depends on soil texture and the amount of irrigation or effective rainfall. The coefficient, which ranges from 0.1 for clay soil to 0.3 for sandy soil, was determined by monitoring changes in the groundwater table after irrigation was applied to a large area (Ministry of Geology and Mineral Resources, 1986). Under the experimental conditions, α was given a value of 0.1 for irrigation or rainfall amounts <90 mm and 0.15 for irrigation or rainfall between 90 and 120 mm.

Net groundwater use (mm), the difference between the amount of groundwater used for irrigation and the recharge by deep drainage, was calculated as

$$G_{use} = I - D \quad (3)$$

Water use efficiency WUE (kg m^{-3}) for the grain yield (kg ha^{-1}) was calculated as follows (Hussain et al., 1995):

$$WUE = \frac{GY}{ET} \quad (4)$$

where GY is the grain yield (kg ha^{-1}) and ET (mm) was calculated as in Eq. (1). Irrigation water use efficiency (WUE_{irri}) was calculated as

$$WUE_{irri} = \frac{GY}{I} \quad (5)$$

The partial factor productivity from applied N (PFP_N) is the ratio of grain yield to applied N rate, and integrates the use efficiency of both indigenous and applied N resources (Cassman et al., 1996). It is calculated as follows:

$$PFP_N = \frac{GY}{F} \quad (6)$$

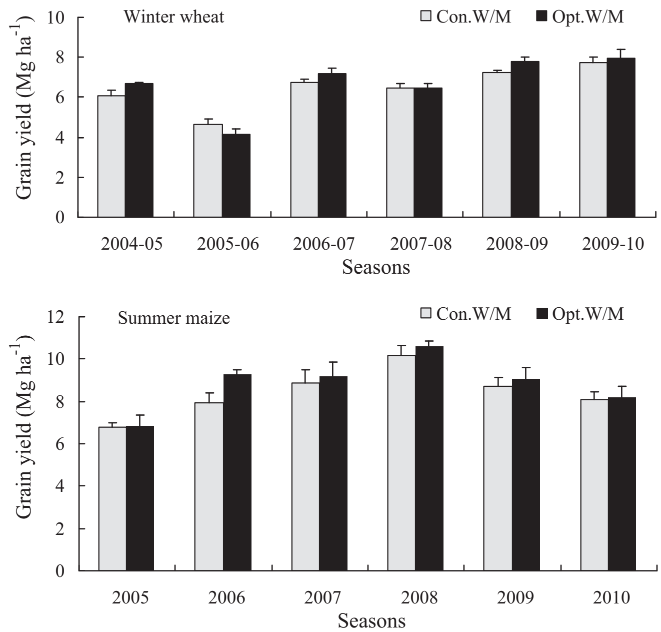

Fig. 2. Grain yield of winter wheat and summer maize under conventional and optimized double cropping systems (Con.W/M and Opt.W/M), from 2004 to 2010, respectively (grain yield difference between Con.W/M and Opt.W/M for wheat or maize was not significant at $P < 0.05$ for six seasons; bars represent standard error).

where F is the N rate (kg ha^{-1}) in N application treatments.

The economic performance of the four cropping systems was evaluated under free water and not-free water scenarios. If water was free, the costs included costs of land preparation and sowing, seeds, fertilization, insect and weed control, labor, and electricity or diesel and equipment for pumping water. These costs were based on the average local market prices from 2004 to 2010. The net economic return was also calculated if water was assumed to have a price of \$0.08 m^{-3} (Huang et al., 2010). The net economic return was calculated as follows:

$$\text{Net economic return} = \text{Gross revenue from grain yields} - \text{Costs} \quad (7)$$

Within the Con.W/M and Opt.W/M double cropping systems, mean grain yield, ET, and WUE for wheat and maize in each year were subjected to analysis of variance (ANOVA) using a one-way ANOVA in SAS (SAS Institute, 1998). A mixed ANOVA model with two treatments (degrees of freedom [d.f.] = 1) and 6 years (d.f. = 5) was used to assess the overall variability of ET and WUE.

For the four cropping systems, mean grain yield, equivalent grain yield, ET, WUE, WUE_{irri}, PFP_N, and estimated economic return every 2 years were analyzed using one-way ANOVA in SAS. A mixed ANOVA model with four treatments (d.f. = 3) and rotations every 2 years (d.f. = 2) was used to assess the overall variability of grain yield, equivalent grain yield, ET, WUE, WUE_{irri}, and PFP_N.

3. Results

3.1. Grain yields

The differences in grain yield between Con.W/M and Opt.W/M for winter wheat and summer maize were not significant from 2004 to 2010 (Fig. 2). Under Opt.W/M, the annual wheat yield averaged 6.7 Mg ha^{-1}, ranging from 4.1 to 8.0 Mg ha^{-1}, and the maize yield averaged 8.9 Mg ha^{-1} with a range of 6.9 to 10.6 Mg ha^{-1}. For comparison with the 2-year system (W/M–M), grain yields in the four systems were calculated every 2 years as one rotation from 2004 to 2010 (Table 3). On average, over the three rotations, the yield

Table 3
Grain yield, equivalent grain yield, evapotranspiration (ET), water use efficiency (WUE), irrigation water use efficiency (WUE_{irri}), N partial productivity from applied N (PFP_N), and estimated groundwater use in each rotation from 2004 to 2010 of four cropping systems: conventional and optimized winter wheat and summer maize (Con.W/M and Opt.W/M), three harvests in 2 years (first year: winter wheat and summer maize; second year: spring maize, W/M–M), and one harvest in 1 year (spring maize, M).

Year	Treatment	Grain yield (Mg ha^{-1})	Equivalent yield (Mg ha^{-1})[a]	ET (mm)	WUE (kg m^{-3})	WUE_{irri} (kg ha^{-1} mm^{-1})	PFP_N (kg kg^{-1})	Net groundwater use (mm)
2004–2006	Con.W/M	25.4a[b]	26.1a	1430a	1.50b	29c	20c	593
	Opt.W/M	26.9a	27.6a	1297b	1.76a	37b	54b	476
	W/M–M	20.8b	21.2b	1195c	1.47b	35b	54b	375
	M	17.8c	17.8c	845d	1.78a	47a	72a	183
2006–2008	Con.W/M	32.3a	33.1a	1461a	1.87b	35c	25d	613
	Opt.W/M	33.3a	34.2a	1394b	2.02b	42b	53b	545
	W/M–M	26.9b	27.3b	1119c	2.03b	41b	49c	423
	M	24.6b	24.6b	813d	2.56a	66a	59a	208
2008–2010	Con.W/M	31.8a	32.7a	1472a	1.82b	33c	24d	636
	Opt.W/M	33.0a	34.0a	1309b	2.13a	46b	36c	477
	W/M–M	27.1b	27.6b	1074c	2.13a	50b	40b	342
	M	19.5c	19.5c	794d	2.07a	58a	45a	170
Mean (2 years)	Con.W/M	29.8	30.6	1455	1.73	32	23	614
	Opt.W/M	31.1	31.9	1333	1.97	42	48	500
	W/M–M	24.9	25.4	1130	1.88	42	48	380
	M	20.6	20.6	818	2.14	57	59	187
Source of variation								
Treatment		***	***	***	***	***	***	–
Year		***	***	*	***	***	***	–
Treatment × year		NS	NS	***	**	***	***	–

[a] All wheat yields were transferred to maize yields using the average price ratio of wheat/maize (1.06:1) according to the average local market price from 2004 to 2010.
[b] Within one rotation four means followed by the same letter are not significantly different at $P < 0.05$ according LSD. NS indicates no significant difference and *, ** and *** indicates significance at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively.

for W/M–M averaged 24.9 Mg ha^{-1} 2 year^{-1}, which was 16% lower than that of Con.W/M (29.8 Mg ha^{-1} 2 year^{-1}). Grain yield in the M system was the lowest among the four cropping systems, at only 69% of the yield in Con.W/M. However, in comparison with W/M–M, no significant yield loss was observed in M when annual spring maize yields exceeded 12.3 Mg ha^{-1} in the 2006 to 2008 rotation because of the high maize grain yield in 2008.

For further comparison, equivalent grain yields of the different cropping systems were also calculated in terms of crop market price. All wheat yields were transferred to maize yields using the average price ratio of wheat/maize (1.06:1) according to the average local market price from 2004 to 2010. During the 6-year period, the equivalent yields in all systems performed similarly to grain yields (Table 3). Overall, the average grain yield or equivalent grain yield was the highest in the Opt.W/M system, followed by Con.W/M, and then W/M–M and M.

3.2. Irrigation water and chemical N fertilizer input

Over the 6-year period in Con.W/M, annual irrigation averaged 390 mm with a range from 315 to 460 mm, in which nearly 75% of irrigation occurred in the winter wheat growing season (Table 2). Irrigation in Opt.W/M averaged 316 mm, which saved 19% of water use compared with Con.W/M and resulted in no significant grain yield losses (Fig. 2, Table 2). However, even under Opt.W/M, 180–255 mm of irrigation was applied annually in the winter wheat season, which ranged from 65–77% (mean, 71%) of total annual irrigation (Table 2). This is mainly because of the large gap between the water demand of wheat and the water supply from available precipitation. Maize irrigation averaged 90–100 mm, with most applied to ensure maize emergence after planting under Con.W/M and Opt.W/M. The highest level of maize irrigation in Con.W/M and Opt.W/M (150 and 120 mm, respectively) among the 2005 to 2010 maize seasons occurred mainly because of the relative dry weather conditions during June and July 2006–2007 (94 mm precipitation).

With optimal irrigation water management, irrigation averaged 252 mm year^{-1} for W/M–M and 154 mm year^{-1} for M, saving 35% and 61% of irrigation water compared with Con.W/M, respectively (Table 2). For M, there were no considerable irrigation changes among the 2-year periods from 2004 to 2010. On average, 162, 158, and 143 mm of irrigation were applied in the 2004 to 2006, 2006 to 2008, and 2008 to 2010 seasons, respectively. However, the maize yields increased 38% and 26% in the 2006 to 2008 seasons in comparison with the 2004 to 2006 and 2008 to 2010 seasons, respectively, because of better crop management (Table 3).

Over the 6-year study period, the N application rate based on optimized N management averaged 288 kg ha^{-1} annually in Opt.W/M, which saved nearly half of the chemical N applied in Con.W/M (550 kg ha^{-1}). In the W/M–M and M systems, the annual N rates averaged 227 and 155 kg ha^{-1}, respectively, which were only 41% and 28% of the rate used in Con.W/M, respectively. These results clearly indicate that optimized water and N management can successfully decrease irrigation and N rates while maintaining grain yield. The W/M–M and M systems showed great potential for decreasing irrigation water and N application.

3.3. Evapotranspiration, water use efficiency, water balance, and N use efficiency

Evapotranspiration reflects water requirements due to crop transpiration and soil evaporation during crop seasons. Across the 6 years among the four systems, Con.W/M had the highest ET, with a mean of 1455 mm 2 year^{-1} (Table 3). The ET was significantly lower (by 8%) under Opt.W/M (1333 mm 2 year^{-1}) than under Con.W/M without yield losses. Under Opt.W/M, annual ET averaged 667 mm year^{-1} with 380 mm year^{-1} for wheat and 287 mm year^{-1} for maize (Tables 3 and 4). Meanwhile, annual precipitation averaged 412 mm, with 112 mm falling in the wheat season and 300 mm in the maize season on average during the 6 study years (Table 1). Accordingly, the nearly 270 mm gap between wheat demand and available precipitation required the use of more than 220 mm of irrigation during wheat seasons, even under optimized water management (Table 2). Because of the reduced wheat production, ET decreased to 1130 mm 2 year^{-1} in W/M–M and 818 mm 2 year^{-1} in M.

Water use efficiency (WUE) is the ratio between grain yield and crop ET. Over the 6-year period, the mean WUE of 1.73 kg m^{-3} in Con.W/M was the lowest among the four treatments (Table 3). Opt.W/M and W/M–M had WUE values of 1.97 and 1.88 kg m^{-3}, respectively. Furthermore, the WUE values of wheat averaged 1.29 kg m^{-3} in Con.W/M and 1.52 kg m^{-3} in Opt.W/M, which were only 53% and 57% of that for maize, respectively (Table 4).The highest WUE was 2.14 kg m^{-3} in M systems, which represented a 24% increase compared with Con.W/M.

Irrigation water use efficiency (WUE_{irri}) was determined based on total grain yield and applied water. Results similar to those for WUE were found for WUE_{irri}. The lowest WUE_{irri} was in Con.W/M, with an average value of 32 kg ha^{-1} mm^{-1}. In both Opt.W/M and W/M–M, WUE_{irri} was 42 kg ha^{-1} mm^{-1}, which was 31% higher than in Con.W/M. Meanwhile, the mean WUE_{irri} in M was 57 kg ha^{-1} mm^{-1}, which was 178% higher than that in Con.W/M.

Over the 6-year study period, annual groundwater use averaged 307, 250, 190, and 94 mm for Con.W/M, Opt.W/M, W/M–M, and M, respectively (Table 3). For Opt.W/M, the highest groundwater use among the three rotations was 270 mm in 2006 to 2008, the years with the lowest average precipitation. Meanwhile, optimized water management significantly reduced groundwater use from 245 mm to 191 mm for wheat and slightly decreased groundwater use for maize (Table 4). However, in both Con.W/M and Opt.W/M, nearly 65–90% of groundwater was consumed in the wheat season. Obviously, the current dominant double cropping system cannot maintain the groundwater balance because of the large gap between available rainfall and water demand by crops even under optimized water management. By decreasing wheat production and increasing the fallow time, W/M–M significantly decreased annual groundwater use by 38% compared with Con.W/M (Table 3). Furthermore, M significantly decreased groundwater use by 70% compared with Con.W/M by eliminating wheat production completely.

Partial factor productivity from applied N (PFP_N) was calculated using the ratio of grain yield to the applied N rate. Con.W/M always had the lowest PFP_N, with a mean of 23 kg kg^{-1} over the 6 years (Table 3). On average, PFP_N in both Opt.W/M and W/M–M based on optimized N management was 48 kg kg^{-1}, which doubled the N use efficiency of Con.W/M. The highest PFP_N, 257% higher than that in Con.W/M, was achieved in M (59 kg kg^{-1}).

3.4. Economic analysis

In the NCP, farmers currently only pay the electric or diesel and equipment costs associated with pumping groundwater, but the water itself is free. All economical costs for four cropping systems from 2004 to 2010 are shown in Table 5. When water was free, irrigation cost in four cropping systems varied from 16% in M to 26% in Con.W/M of the total input from 2004 to 2010. After marginal water pricing was introduced and set at \$0.08 m^{-3} (Huang et al., 2010), the percentage of irrigation input to others increased to 37% in Opt.W/M and 23% in M system.

Table 4
Annual evapotranspiration (ET), water use efficiency (WUE) and net groundwater use within double cropping systems from 2004 to 2010: conventional and optimized winter wheat and summer maize (Con.W/M and Opt.W/M).

Seasons	Winter wheat						Summer maize					
	ET		WUE		Net groundwater use		ET		WUE		Net groundwater use	
	Con.W/M (mm)	Opt.W/M (mm)	Con.W/M (kg m^{-3})	Opt.W/M (kg m^{-3})	Con.W/M (mm)	Opt.W/M (mm)	Con.W/M (mm)	Opt.W/M (mm)	Con.W/M (kg m^{-3})	Opt.W/M (kg m^{-3})	Con.W/M (mm)	Opt.W/M (mm)
2004–2005	415a[a]	360b	1.24a	1.57b	206	152	294a	286a	1.95a	2.04a	38	38
2005–2006	469a	412b	0.83a	0.85a	271	208	252a	239a	2.70a	3.33a	79	79
2006–2007	380a	368a	1.51a	1.66a	222	195	338a	296a	2.23a	2.70a	118	91
2007–2008	434a	417a	1.27a	1.31a	234	217	310a	314a	2.77a	2.85a	39	43
2008–2009	477a	401b	1.29a	1.64b	290	211	294a	300a	2.51a	2.56a	73	73
2009–2010	408a	324b	1.60a	2.10b	244	165	294a	285a	2.36a	2.45a	28	28
Mean	430	380	1.29	1.52	245	191	297	287	2.42	2.65	62	58
Source of variation												
Treatment	***		***		-		NS		*		-	
Year	***		***		-		***		**		-	
Treatment × year	*		*		-		NS		NS		-	

[a] Within two treatments means followed by the same letter are not significantly difference at $P < 0.05$ according LSD. NS indicates no significant difference and *, ** and *** indicates significance at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively.

Table 5
Economic costs from 2004 to 2010 in four cropping systems: conventional and optimized winter wheat and summer maize (Con.W/M and Opt.W/M), three harvests in 2 years (first year: winter wheat and summer maize; second year: spring maize, W/M–M), and one harvest in 1 year (spring maize, M).

Input category[a]	2004–2006				2006–2008				2008–2010			
	Con.W/M (US$ ha^{-1} 2 year^{-1})	Opt.W/M (US$ ha^{-1} 2 year^{-1})	W/M–M (US$ ha^{-1} 2 year^{-1})	M (US$ ha^{-1} 2 year^{-1})	Con.W/M (US$ ha^{-1} 2 year^{-1})	Opt.W/M (US$ ha^{-1} 2 year^{-1})	W/M–M (US$ ha^{-1} 2 year^{-1})	M (US$ ha^{-1} 2 year^{-1})	Con.W/M (US$ ha^{-1} 2 year^{-1})	Opt.W/M (US$ ha^{-1} 2 year^{-1})	W/M–M (US$ ha^{-1} 2 year^{-1})	M (US$ ha^{-1} 2 year^{-1})
Land preparation and sowing	350	350	316	282	350	350	316	282	350	350	316	282
Fertilizers	1022	620	564	496	1210	871	813	748	1398	1210	1068	925
Seeds	552	552	397	242	552	552	397	242	552	552	397	242
Herbicides and pesticides	150	150	136	121	150	150	136	121	150	150	136	121
Labors	909	909	682	455	909	909	682	455	909	909	682	455
Irrigation(free water)[b]	1038	955	694	450	1080	941	774	439	1143	850	641	397
Irrigation(not-free water)[c]	1625	1495	1087	705	1691	1473	1211	687	1789	1331	1004	622
Total input												
Irrigation (free water)	4021	3536	2788	2046	4251	3773	3118	2287	4502	4021	3240	2422
Irrigation (not-free water)	4608	4076	3182	2301	4862	4305	3555	2535	5148	4502	3603	2647

[a] US$ 1 = 6.6 Chinese Yuan. The prices for land preparing and sowing were: plough ($68 ha^{-1}), rotary ($45 ha^{-1}), sowing wheat ($27 ha^{-1}), and sowing maize ($34 ha^{-1}). Fertilizer prices: N ($0.59 kg^{-1}), P_2O_5 ($0.91 kg^{-1}), and K_2O ($1.55 kg^{-1}). Seeds prices: wheat ($0.52 kg^{-1}), summer maize ($1.15 kg^{-1}), and spring maize ($1.52 kg^{-1}). Herbicides and pesticides prices: wheat season ($23 ha^{-1}), summer maize season ($52 ha^{-1}), and spring maize season ($61 ha^{-1}). Labor price: $6 day^{-1}.

[b] Water was free.

[c] Water price = $0.08 m^{-3}.

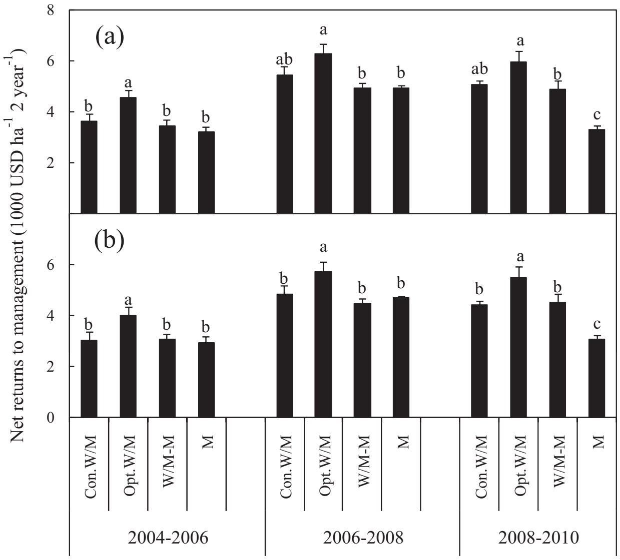

Fig. 3. The economic performance under free water (a) and not-free water (b) scenarios from 2004 to 2010 in four cropping systems: conventional and optimized winter wheat and summer maize (Con.W/M and Opt.W/M), three harvests in 2 years (first year: winter wheat and summer maize; second year: spring maize, W/M–M), and one harvest in 1 year (spring maize, M). (Within one rotation (every two years) four treatments means followed by the same letter are not significantly different at $P < 0.05$ according LSD; bars represent standard error).

When the price of water was not considered, net returns in Opt.W/M averaged $4561 ha^{-1} 2 year^{-1}, which were 26% greater than those in Con.W/M in the 2004 to 2006 rotations ($3627 ha^{-1} 2 year^{-1}) (Fig. 3a). Over the 6-year period, economic return in W/M–M was equivalent to that in Con.W/M. The net returns in M did not differ significantly from those in Con.W/M and W/M–M in the 2004 to 2006 and 2006 to 2008 rotation seasons. The 35% economic loss in M during the 2008 to 2010 rotation seasons was mainly due to the relatively lower grain yield compared with Con.W/M (Fig. 3a, Table 3).

After marginal water pricing was introduced, economic profits in Opt.W/M were consistently higher than in Con.W/M across the 6 years (Fig. 3b). There was no significant difference in net returns between W/M–M and Con.W/M during the 6 years. In the 2008 to 2010 rotations, M averaged net returns of $3079 ha^{-1} 2 year^{-1}, which were 31% lower than those for Con.W/M ($4441 ha^{-1} 2 year^{-1}).

4. Discussion

4.1. The groundwater balance

In this study, although Opt.W/M reduced irrigation by 19% compared with Con.W/M, >250 mm groundwater was still consumed annually. Thus, the double cropping system was unsustainable even under optimized water management. Annual irrigation was decreased by more than 35% in W/M–M and 61% in M compared with Con.W/M. As result, annual groundwater use decreased to 190 mm in W/M–M and 94 mm in M system. Using a statistical model, Chen et al. (2003) found that a reasonable exploitation rate to avoid groundwater table decline was 150 mm year^{-1}. Clearly, the M system was within this range, and annual groundwater use in W/M–M was close to this rate.

The W/M–M and M systems, as alternatives to double cropping (Con.W/M), can nearly meet the groundwater balance. This is mainly attributable to two factors. First, winter wheat production was significantly reduced in W/M–M and M. In the NCP, more than 65% of groundwater consumption is for wheat irrigation because of the large gap between available rainfall and water demand during the wheat growing season, even under optimized water management (Table 4). These results agree with other field-scale trials and model results for the NCP, which detected a similar trend in optimal irrigation for double cropping systems (Chen et al., 2010; Fang et al., 2010; Sun et al., 2006). Because of the large gap between rainfall and water demand of the double cropping system, any attempts to meet the crop water deficit by irrigation with groundwater will perpetuate the continuous decline of the groundwater table (Evans and Han, 1999; Hu et al., 2005; Kendy et al., 2004).

Second, the synchronization between water supply from precipitation and irrigation and water demand by crops during the maize season was effective. In this study, from 2004 to 2010, annual precipitation in Quzhou ranged from 359 to 466 mm with a mean of 412 mm, while 299 mm of precipitation, or 73% of total annual rainfall, fell from June to September, during the spring maize growing season. In this study, the annual water requirement for spring maize was 409 mm on average. The gap between water supply from precipitation and water demand by spring maize was 110 mm. Therefore, the annual groundwater consumption in the M system was 94 mm across all 6 years.

However, when water management was improved in M during the fallow season and early in the maize growing season by, for example, applying surface straw and plastic mulch, more water could be stored in the soil profile and therefore used for maize growth. According to a long-term field study conducted in the NCP using microlysimeters, applying straw mulch to maize fields may reduce soil evaporation loss by 40–50 mm year^{-1} (Zhang et al., 2005).

On the other hand, mean precipitation during this study from 2004 to 2010 was 412 mm year^{-1}, which was 82 mm lower than the 31-year average of 494 mm (1980–2010). If we consider this value for long-term average precipitation, then even less irrigation would be required in the M system.

Precipitation was concentrated from June to September, when maize is in fast growth stages and is most sensitive to water. For example, from June to September, 53% of precipitation concentrated in August and September in this study (Table 1), when maize was at the seedling to tasselling and tasselling to filling stages. Other studies have also shown that maize responds differently to water stress at different growth stages and is most sensitive to water availability from the tasselling to silking stages (Calviño et al., 2003; Otegui et al., 1995).

4.2. The high yield potential of spring maize

Grain yield in M increased 38% in the 2006 to 2008 rotation and 10% in the 2008–2010 rotation in comparison with the 2004–2006 rotation, even though irrigation levels remained constant at around 300 mm in each 2-year period (Tables 2 and 3). This result may have important implications; it suggests considerable potential for increasing yield and improving WUE in the NCP without increasing groundwater consumption. The potential yield of spring maize in Quzhou, as simulated by the Hybrid-Maize model (Yang et al., 2004, 2006), is 16.4 Mg ha^{-1}, indicating that current average yields are only at 63% of their potential. Further study is needed to determine how to substantially increase maize yields without significantly increasing irrigation water and N application. In this study, the highest grain yield in M of 13.5 Mg ha^{-1} was observed in 2008, although groundwater use was similar to that in other years. A recent study showed that a model-driven integrated soil-crop management system achieved mean maize yields of 13.0 Mg ha^{-1} in 66 on-farm experimental plots, nearly twice the yield of current farmers' practices (6.8 Mg ha^{-1}), without a significant increase in N application (Chen et al., 2011). Such integrated soil–crop system management systems should be considered for sustainable agriculture development in the NCP, especially in areas experiencing severe water crises and N overuse.

5. Conclusions

Water scarcity and environmental pollution due to excessive water use and N inputs are important environmental concerns in the NCP. Intensive irrigation in this region has rapidly depleted aquifers, threatening agricultural sustainability. Development of innovative cropping systems that minimize groundwater consumption and improve WUE is crucial. Field results showed that irrigation water and N fertilizer use could be decreased substantially by applying optimized water and N management (the Opt.W/M system) in comparison with conventional methods (Con.W/M) while maintaining similar grain yields. However, >250 mm groundwater were still consumed in the double cropping system even under optimized water management. By reducing the frequency of wheat cultivation, the W/M–M system reduced groundwater use by nearly 40% and N fertilizer use by 59% with no economic loss compared with Con.W/M, and thus showed great potential for groundwater sustainability. This lower water and N-consumption cropping system may be a suitable alternative to the double cropping system, particularly in areas with serious water deficit.

In the M system, 31% of grain yields were sacrificed but water and N application decreased considerably in comparison with those in Con.W/M. Further study is needed to increase spring maize grain yields to meet the yield potential. The use of rainfed cropping systems in the NCP should also be investigated as a strategy to cope with the water crisis, especially if farmers cannot afford future water prices set to reflect the declining groundwater table.

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