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The effects of irrigation and nitrogen application rates on yield of spring wheat (longfu-920), and water use efficiency and nitrate nitrogen accumulation in soil

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Abstract

In the middle reaches of Heihe River Basin, the environmental deterioration caused by excessive nitrogen (N) and irrigation application in agricultural ecosystems has received much attention in recent years. A combination of careful irrigation and N management is needed to improve N uptake efficiency and to minimize potential nitrate (NO_3^--N) leaching. A field experiment was designed to investigate the effects of different irrigation and N application rates on grain yield, water use efficiency (WUE) and soil nitrate-N (NO_3^--N) accumulation on a recently reclaimed sandy farmland at the margin of the Gobi Desert in 2006 and 2007. The experiment followed a completely randomized split-plot design, taking the various irrigation treatments (0.6, 0.8 and 1.0 of the estimated evapotranspiration-ET) in the main-plots and N supply treatments as split-plot (with five levels of 0, 79, 140, 221 and 300 kg N ha^{-1}). The results indicated a wide annual variability in grain yield, kernel numbers and straw yield, mainly due to greater rainfall and irrigation rates in the second year. A significant irrigation effect was observed on grain yield, kernel numbers and straw yield. The highest levels were achieved with a high irrigation supply, although WUE generally decreased linearly with increasing seasonal irrigation rates in 2 years. The low irrigation treatment (0.6 ET) produced significantly lower grain yield (20.7 %), kernels number (9.3 %) and straw yield (12.2 %) than high irrigation treatment (1.0 ET). The low irrigation treatment had a higher WUE (4.25 kg ha^{-1} mm^{-1}) than that of 3.25 kg ha^{-1} mm^{-1} with high irrigation over the 2 years. On contrary to the irrigation, the N application rate of 221 kg ha^{-1} had the highest values of grain yield, kernel numbers, straw yield and WUE under the 3 irrigation regimes. The average grain yield of 221 kg N ha^{-1} were found to be 99.1, 45.1, 20.0 and 7.4 % higher than those of 0, 79, 140 and 300 kg N ha^{-1}, respectively over the 2 years. The 221 kg N ha^{-1} had the highest WUE (4.75 kg ha^{-1} mm^{-}) among all N treatments. No more NO_3^--N accumulation was found in the 200 cm soil profiles under the medium (0.8 ET) and low irrigation, when the N application was below 221 kg ha^{-1}, at harvesting stage and there was a little potential for NO_3^--N leaching. High irrigation led to a high NO_3^--N leaching and a high plant N-uptake, resulting in lower NO_3^--N accumulation at the harvest stage compare to the sowing or soil preparation stage. This was within the 200 cm soil profiles and over the 2 wheat growing seasons. The N application rate of 221 kg N ha^{-1} produced a high grain yield of spring wheat, but the N application rate was lower than that of 221 kg N ha^{-1} as concerned NO_3^--N accumulation at harvesting stage under deficit irrigation. The optimum economic N rates ranged from 174 to 226 kg ha^{-1}.

Keywords: Irrigation; Nitrogen; Grain yield; Water use efficiency; Nitrate nitrogen accumulation.
Abbreviations: ANOVA -analysis of variance, LSD-least significance difference, SD-standard deviation, GY-Grain yield, KN-kernel numbers, SY-straw yield, ET-evapotranspiration, $I_{0.6}$, $I_{0.8}$ and $I_{1.0}$ -irrigation treatment, N-nitrogen, N_0, N_{79}, N_{140}, N_{221} and N_{300}-nitrogen application treatment, WUE- water-use efficiency.

Introduction

Heihe River Basin is the second largest inland river basin in the arid regions of Northwest China, and one of the main areas for grain-production in China. Maize (*Zea mays* L.) and wheat (*Triticum aestivum* L) are produced on 85 % of the total cultivated area in the region (Su et al., 2002; 2006). This region is dependent mainly on snow melt-water from mountains and underground water for irrigation. In order to increase the grain yield and to get high economic returns, farmers normally reclaim sandy lands using high fertilizers and irrigation rates. In Northwest China the current average rate of N application and irrigation reaches 250-350 kg N ha^{-1} yr^{-1} and 64-94 cm, respectively, in single-cropping systems (Su et al., 2007b). However, a high rate of nitrogen (N) fertilizer and irrigation application has led to an over-use of fresh water resources and an increase in soil nitrate nitrogen (NO_3^--N) accumulation and leaching (Ju et al., 2004). Nitrate nitrogen leaching ranges from 15 to 55 % of applied N fertilizer in North China Plain (Zhu and Chen, 2002). This has resulted in groundwater contamination (Zhang et al., 1996). Nitrate-nitrogen pollution of ground and drinking water due to high N fertilizer and irrigation rates has become a serious issue in this arid zone of Heihe River Basin, China (Yang et al., 2008). The investigations showed that nearly 50 % of groundwater has NO_3^--N content, exceeding 50 mg L^{-1}, the allowable limit for drinking water. In some areas of Northwest China, the NO_3^--N content in groundwater and drinking water reaches 300 mg L^{-1} (Zhang et al., 1995; 1996). Spring wheat is usually grown from March to July in warm temperatures and high evapotranspiration, especially in June and July, when the average precipitation is only 52.5 mm during the wheat growing season. The adverse effect of this stress can be partially mitigated by adequate water and N supply (Pandey et al., 2001). Heihe River is the only surface water resource for irrigation and the increased demand of this limited water sources presents a constraint in crop production with deteriorating quality as result of increased consumption (Ma et al., 2005; 2009). Zhang et al. (1996) found that fertilizers are applied at double or even triple the rates required for agricultural production. The trend of N application and irrigation is still on the rise, and this causes a reduced N use efficiency and increased risk of NO_3^--N leaching into the groundwater (Ma et al., 2005; Chen et al., 2007). The soils are relatively poor in plant nutrients and they have a loose sandy structure on recently reclaimed sandy farmlands. Water shortage has become the major obstacle to the plant production which relies thoroughly on irrigation (Zhang et al., 1996; Kang et al., 2004; Yang et al., 2008). Many factors affect wheat yield and NO_3^--N accumulation in soil. These include crop N uptake dynamics, N fertilizer management, rainfall, irrigation, soil texture, and N transformation in the soil. However, N fertilizer and irrigation are two major factors influencing wheat yield and NO_3^--N accumulation but these can be controlled by the grower (Ottman and Pope, 2000; Yin et al., 2007). Irrigation effectively increases crop yield although water-use efficiency (WUE) decreases as the irrigation rate increases (Al-Kaisi et al., 2003). N fertilization also increases crop yield when the soil N supply is low (Fredrick et al., 1995a: 1995b; Sexton et al., 1996). N fertilizer applied at rates higher than the optimum requirement for crop production may cause an increase in NO_3^--N accumulation below the root zone and pose a risk of NO_3^--N leaching (Zhu et al., 2003; Fang et al., 2006). N application rate was found to be the main factor causing NO_3^--N leaching. No NO_3^--N leaching was found when the N application was below 150 kg ha^{-1}, but NO_3^--N leaching increased at a rate of 225 - 300 kg N ha^{-1} (Campbell et al., 1993; Fan et al., 1998). In general, increased soil water content enhances crop yield response to N fertilization, especially when high N rates are applied (Norwood, 2000). Interest in the relationship between wheat production and water-use is being increased because of the increasing scarcity and cost of irrigation water in this dry region. Profits and risks inherent in irrigation management decisions depend directly on crop-water production function (Pandey et al., 2001; Zhu et al., 2002). Preferred management practices for N fertilization recommend that N fertilizer is applied in split applications or timely according to crop needs. NO_3^--N uptake efficiency has been shown to be the greatest with split N applications to wheat (Alcoz et al., 1993; Sowers et al., 1994; Ayoub et al., 1995). Many studies have been carried out to investigate the effects of N application rates on grain yield and overall N balance in the soil (Liu et al., 2001, 2003; Ju et al., 2003). Few efforts have been made to assess yield of spring wheat, WUE and NO_3^--N accumulation in soil under different irrigation and N fertilizer application rates, specifically on recently reclaimed sandy farmland. This study can provide insights on how deficit irrigation and N rates can be manipulated for maximization of grain yield of spring wheat and the minimization of NO_3^--N leaching below root depth in the soils. The object of this study was to find the optimum N application rate on a recently reclaimed sandy farmland in Heihe River Basin, Northwest China.

Results

Soil water storage

The high irrigation treatments were 735 mm in 2006 and 895 mm in 2007. The amounts of water supplied to these sandy lands were higher than those applied to old farmlands mainly due to the loose structure and high evaporation rate. Soil water storage, differences between N application rates at a given irrigation rate, and between irrigation treatments at a given N application rate in the 0 - 200 cm profile are given in Fig. 1. Soil water storage fluctuated greatly in response to supplemental irrigation. This increased with supplemental irrigation and afterwards decreased with ET, and showed small fluctuations with rainfall in 2006 and 2007. Soil water storage declined quickly from the heading stage to the flowering stage in this area of high evaporation and high crop-water-requirements. The total rainfalls, during the spring wheat growing seasons, were 43.9 mm (2006) and 61.0 mm (2007). These were much less than the amounts of irrigation supplied during the periods. The ET rate is very high in the study area. The maximum rainfalls of 10.2 mm (2006) and 14.4 mm (2007) (seen as a considerable rainfall in this region) can only moisten the top of the dry soil layer (2.5-5 cm in a flat field). However, the evaporation capacity can reach 10 mm per day in warm periods. So, after only 1-2 days the rain-water retained in the soil evaporates completely. Thus, rainfall has little effect on the soil water storage in this area. After analyzing the differences in soil water storage between different irrigation rates, and between different N application rates, the differences between treatments were not significant. This indicated that irrigation treatments and N application rates have little effect on soil water in the 0-200 cm soil layer. This is mainly due to the fact that the soil water content was higher than the field capacity, and permeated from the measured layer 24 h after irrigation in the well- drained sandy farmland.

Analysis of variance

Irrigation and N treatments had significant effects on grain yield, kernel numbers, straw yield and WUE at $P < 0.05$. An exception was the effect of irrigation treatment on straw yield in 2007. However, their interactions were not significant, except for the interaction on WUE in 2006 and on grain yield in 2007 (Table 1). The results of Table 1 indicated that, in most cases, N had more effect on grain yield, kernel numbers and WUE than irrigation. The amount of irrigation in 2007 was greater than that in 2006. This suggested that the interaction of irrigation and N treatment on WUE in 2006 and on grain yield in 2007 were significant.

Grain yield

Grain yield response varied by year and is presented separately. Yields were generally greater in 2007 than that in 2006. The

Table 1. Analysis of variance for each wheat variable measured in 2006 and 2007 (F value). (** and * indicate significance at 0.01 and 0.05 P level).

Variable	Treatment					
	2006			2007		
	I	N	I × N	I	N	I × N
Grain yield	193.2**	820.2**	1.9	48.8**	109.1**	2.5*
Kernel number	135.4**	621.2**	1.3	7.0**	141.4**	0.4
Straw yield	3.9*	8.3**	0.0	0.8	21.6**	0.1
WUE	164.6**	612.6**	11.8**	66.8**	76.6**	0.8

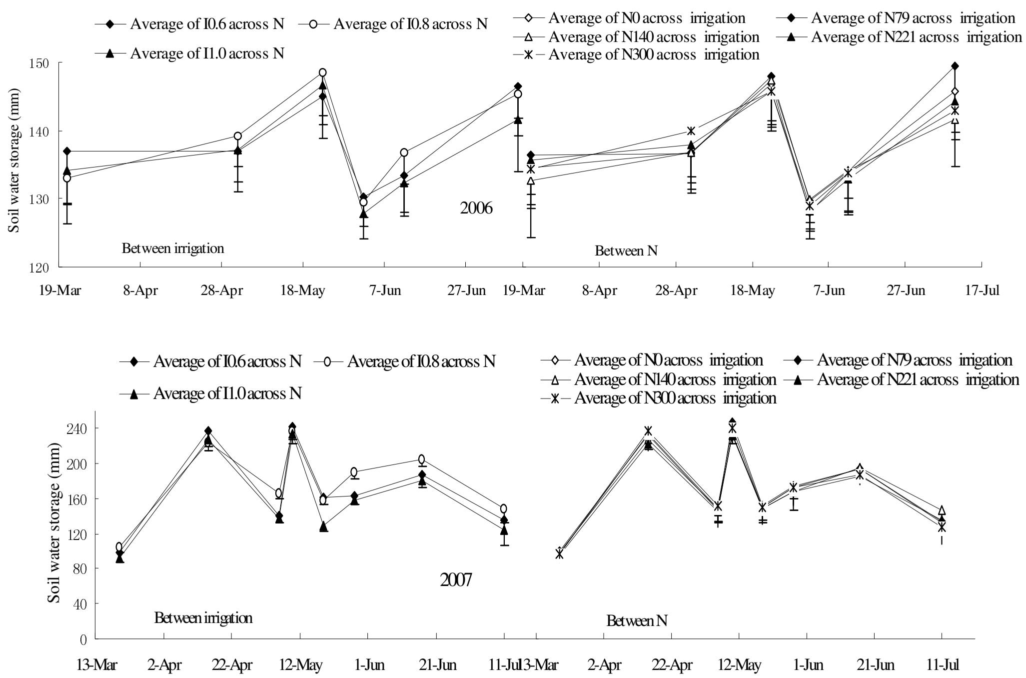

Fig 1. Influences of nitrogen application rates and irrigation regimes on soil water storage in 0 - 200 cm soil profiles (mean ± SD). Between irrigation: influences of different irrigation treatments on soil water storage at a given N application rate; Between N: influences of different N application rates on soil water storage at a given irrigation level. Vertical bars indicate standard deviation (SD).

average grain yield were 1589 kg ha^{-1} in 2006 vs. 2803 kg ha^{-1} in 2007 (Table 2). The greater grain and straw yield in 2007 is mainly explained by a higher amount of irrigation and coincidental rainfall. This rainfall was 16.4 mm and occurred from 14 to 17 June during the filling stage (the crucial stage for forming grain yield), while no rainfall occurred from 21 May to 22 June (flowering stage to the filling stage) in 2006 (Fig. 2). The grain yield increased with the irrigation application. The high irrigation treatment ($I_{1.0}$-1.0ET) had a significantly higher grain yield than the low irrigation treatment ($I_{0.6}$-0.6ET). The differences in grain yield between the high and the medium irrigations ($I_{0.8}$-0.8ET), and between the low and the medium irrigations were not significant (Table 2). Grain yield was decreased by withholding irrigation at various growth stages at all N rates, the reduction rates were 21.7 % (2006) and 19.8 % (2006) at low irrigation, compared with high irrigation. The grain yield response to N was quadratic for all irrigation regimes. The grain yield significantly increased with increasing N, up to 221 kg N ha^{-1}, under 3 irrigation regimes in the 2 years (Fig. 3). The highest grain yield obtained with application of 221 kg N ha^{-1} treatments were 2089 kg ha^{-1} (2006) and 3462 kg ha^{-1} (2007). Treatment N_{221} (221 kg N ha^{-1}) had significantly higher grain yield response than those in the N_0 (0 kg N ha^{-1}), N_{79} (79 kg N ha^{-1}) and N_{140} (140 kg N ha^{-1}) treatments. The difference in grain yield between N_{221} and N_{300} (300 kg N ha^{-1}) was not significant in the 2 years. Obviously, the amount of supplied water influenced the response to N. The N_{221} treatment gave grain yield increases of 156.2, 56.4, 17.7 and 8.2 % compared to N_0, N_{79}, N_{140} and N_{300} at all irrigation rates in 2006, while there were increases of 75.5, 39.0, 21.4 and 6.9 % in 2007.

Kernel numbers

The differences in kernel numbers between irrigations treatments were not significant in the 2 years (Table 2). Similar to grain yield, kernel numbers significantly increased with increasing N up to 221 kg N ha^{-1} under the 3 irrigation regimes in 2 years. The highest value of kernel numbers obtained with N_{221} treatment were 4469 (2006) and 10864 (m^{-2}) (2007).

Straw yield

Like grain yield, straw yield data showed that the individual

Table 2. Grain yield (GY), kernel numbers (KN), straw yield (SY) and water use efficiency (WUE) as affected by different irrigation and nitrogen supply levels during the spring wheat growing seasons in 2006 and 2007.

N rate kg ha^{-1}	Irrigation mm	2006					2007			
		GY kg ha^{-1}	KN plant m^{-2}	SY kg ha^{-1}	WUE kg ha^{-1} mm^{-1}	Irrigation mm	GY kg ha^{-1}	KN plant m^{-2}	SY kg ha^{-1}	WUE kg ha^{-1} mm^{-1}
0		643±27d	2656±44e	1157±39b	1.6±0.1d		1843±87c	4492±64d	1080±162c	3.7±0.2c
79		1109±79c	3519±20d	1573±272ab	2.9±0.2c		2289±246b	8620±284c	2404±235b	4.7±0.6b
140	485	1563±40b	3755±64c	1736±90a	4.0±0.1b	580	2564±116ab	9458±329b	2817±255b	5.2±0.2ab
221		1814±82a	4273±43a	1888±147a	4.6±0.2a		2918±279a	10489±581a	2966±391a	5.8±0.6a
300		1762±112a	3882±31b	1942±585a	4.5±0.2a		2790±157a	9753±58b	2806±681a	5.6±0.3a
0		845±39e	2964±68e	1365±109b	1.6±0.1e		1950±97e	5250±102c	1255±91c	3.3±0.2d
79		1390±70d	3627±42d	1730±236ab	2.6±0.1d		2488±92 d	8813±146b	2520±96b	3.7±0.1c
140	611	1784±42c	3957±82c	1851±515ab	3.4±0.1c	738	2797±32c	9596±163ab	2929±673a	4.3±0.1b
221		2159±27a	4448±123a	2017±143a	4.1±0.1a		3623±113a	10764±194a	3042±572a	5.3±0.1a
300		1976±37b	4151±108b	2035±177a	3.7±0.1b		3317±179b	9973±7ab	2961±108a	5.1±0.2a
0		959±59e	3108±45d	1543±108b	1.5±0.1d		2126±112d	5849±302d	1165±65c	2.7±0.1d
79		1510±39d	3850±47c	1858±117ab	2.3±0.1c		2695±146c	9298±329c	2740±80b	3.3±0.2c
140	737	1978±23c	4252±6b	1990±703ab	3.0±0.0a	898	3194±215b	9849±171b	3106±655a	4.0±0.3b
221		2295±4a	4684±93a	2175±108ab	3.6±0.1a		3846±197a	11340±113a	3119±223a	4.7±0.4a
300		2054±12b	4323±117b	2273±99a	3.1±0.0a		3609±143a	10236±44b	3079±163a	4.3±0.2ab
Treatment means		2006					2007			
Irrigation	485	1378±464b	3617±559a	1659±386b	3.5±1.2a	580	2481±430b	8562±2213a	2414±937a	5.0±0.8a
	611	1631±486ab	3830±531a	1800±345ab	3.1±0.9b	738	2835±621ab	8879±2121a	2542±771a	4.6±0.8b
	737	1759±492a	4044±560a	1968±384a	2.7±0.8c	898	3094±665a	9314±1932a	2642±824a	3.8±0.8c
N rate kg ha^{-1}	0	815±144d	2909±205d	1355±185c	1.6±0.1e	0	1973±151d	5197±611d	1167±124c	3.4±0.6d
	79	1336±187c	3666±150c	1720±226b	2.6±0.3d	79	2491±231c	8910±380c	2554±199b	3.9±0.7c
	140	1775±182b	3988±222b	1859±452ab	3.5±0.4c	140	2851±302b	9634±266b	2951±503ab	4.5±0.5b
	221	2090±219a	4469±196a	2026±170a	4.1±0.5a	221	3462±470a	10864±108a	3042±763a	5.4±0.6a
	300	1930±144ab	4119±209b	2083±343a	3.70.6±b	300	3239±385a	9987±212b	2948±374ab	5.0±0.6a

Means within N fertilizer rates under same irrigation level, treatment means (irrigation or N rate) followed by the different letters in each column are significantly different at $p<0.05$ according to Duncan's multiple comparison test.

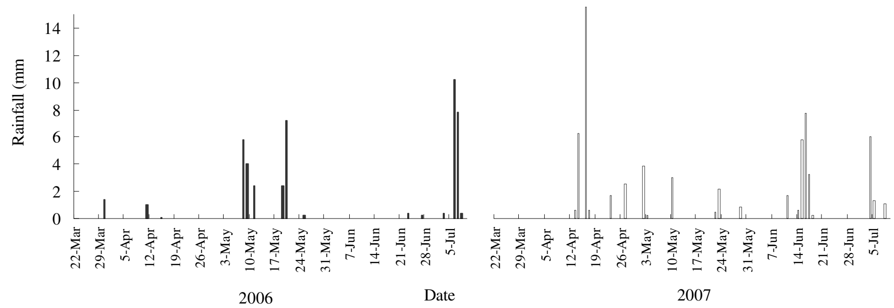

Fig 2. Rainfall at the experiment site during wheat growing seasons in 2006 and 2007.

effects of irrigation and N were greater than their interactive effects. Aboveground, the straw yield was lower in 2006 (1809 kg ha^{-1}) than in 2007 (2533 kg ha^{-1}) (Table 2). Irrigation treatments had significant effects on the straw yield in 2006, but not in 2007. Straw yield decreased with decreasing irrigation rates, the reductions of $I_{0.6}$ and $I_{0.8}$ were 15.7 % and 8.5 % compared with $I_{1.0}$ in 2006, while the reductions were 8.6 % and 3.8 % in 2007. Straw yield significantly increased with N rate increasing. Applications of 221 kg N ha^{-1} in 2006 and 300 kg N ha^{-1} in 2007 proved sufficient to reach maximum straw yield.

Economic nitrogen rates

Predicted maximum grain yield and N rates required for maximum grain yield and profitable N rates for the 3 irrigation regimes were calculated from regression equations (Fig. 3) for each season (Table 3). The most profitable N rates were less than the maximum N rates (required for maximum yield) in the all irrigation regimes. The predicted N rates to achieve maximum grain yield were 44.3% (2006) and 55.0 % greater (2007) than the optimum economic N rates for the $I_{0.6}$ treatment. For the $I_{0.8}$ treatment, the N rates were 37.9 % (2006) and 37.0 % greater (2007). For $I_{1.0}$ treatment, the N rates were 33.8 % (2006) and 31.3 % greater (2007), respectively. The predicted N rates to achieve the maximum yield ranged from 237 to 310 kg ha^{-1}, while the optimum economic N rates ranged from 174 to 226 kg ha^{-1}. This information is useful to farmers farming with limited irrigation in these arid regions.

Water-use efficiency

In both years, crop water use was linearly related to the amount of irrigation (the regression equations between crop water use and the amount of irrigation were not showed in this paper). The low crop water-use, related to high irrigation treatments, was most likely due to high permeation over the root layer and high ET. In 2007, WUE was higher than that observed in 2006 due to the better climatic conditions which were favorable to the formation of grain yield (Table 2). The WUE decreased with increasing irrigation application rates. The low irrigation treatment had higher WUE (3.5 and 5.0 kg ha^{-1} mm^{-1} in 2006 and in 2007, respectively) than that of high irrigation treatment (2.7 and 3.8 kg ha^{-1} mm^{-1} in 2006 and in 2007, respectively). The medium irrigation treatment had a medium WUE (3.1 and 4.4 kg ha^{-1} mm^{-1} in 2006 and in 2007, respectively). In both years, the WUE increased significantly with N application rates up to rate of 221 kg ha^{-1}. The N_{221} treatment had the highest WUE value (4.1 and 5.3 kg ha^{-1} mm^{-1} in 2006 and in 2007, respectively) among the various N treatments. There was a tendency for low irrigation treatments to have the highest WUE over the 2 wheat-growing seasons. This may indicate that deficit irrigation reduces grain yield, but increases WUE.

Nitrate nitrogen accumulation

As the NO_3^--N accumulation of N_{79} was between N_0 and N_{140} in the 3 irrigation regimes over the 2 years, the NO_3^--N accumulation of N_{79} is not discussed here. Before the sowing stage, the differences of NO_3^--N accumulation within 200 cm depth, ranging from 57.3 to 62.7 kg ha^{-1} in 2006 and from 16.3 to 22.4 kg ha^{-1} in 2007, between treatments were not notable. At low irrigation level, the NO_3^--N accumulation of N_{221} at harvesting (67.4 kg ha^{-1}in 2006 and 26.6 kg ha^{-1} in 2007) was higher than the average value before sowing (60.1 kg ha^{-1} in 2006 and 20.0 kg ha^{-1} in 2007) in the 200 cm depth soil. Similar to the N_{221}, the N_{300} had a higher NO_3^--N accumulation at harvesting (120.1 kg ha^{-1} in 2006 and 33.6 kg ha^{-1} in 2007). At medium irrigation level, only N_{300} had higher NO_3^--N accumulation at harvesting stage (139.9 kg ha^{-1} in 2006 and 27.7 kg ha^{-1} in 2007) than the average value before sowing. Comparisons of the NO_3^--N accumulations before sowing and at harvesting under deficit irrigation (Fig. 4) indicates a significant NO_3^--N accumulation increase with N application rates, especially when the application rate is over 221 kg N ha^{-1}. At high irrigation level, the NO_3^--N accumulation at harvesting (the average values were 32.9 kg ha^{-1} in 2006 and 14.6 kg ha^{-1} in 2007) was lower than that accumulated before sowing within 200 cm over the 2 years. This suggests that more NO_3^--N leached to deeper soil layers and more N was absorbed by plants under high irrigation treatment. This confirmed that there would be little NO_3^--N leaching to a depth below the 200 cm at a N rate of below 221 kg N ha^{-1} under deficit irrigations. By comparing the average values over the 4 nitrogen rates, it was found that the medium and the low irrigations had more NO_3^--N accumulation than the high irrigation in 200 cm soil depth. The NO_3^--N accumulation (the average value was 50.0 kg ha^{-1}) at harvesting in 2006 was higher than that accumulated (the average value was 18.3 kg ha^{-1}) before sowing in 2007 in the 0-200 cm soil profiles. There was no plant growth and no N absorbed, and this indicated that NO_3^--N was leached with the winter irrigation water applied on 15 November 2006.

Discussion

Effects of irrigation on grain yield

In this 2 year study, grain yield significantly increased with

Table 3. Predicted N rate for the production of maximum yield (from quadratic equations for two seasons at 3 irrigation regimes, and optimum N rates for maximum economic yield) kg ha^{-1*}.

Irrigation regime	Predicted N rate		Maximum yield		Optimum N for economic yield	
	2006	2007	2006	2007	2006	2007
$I_{0.6}$	270	269	1804	2851	187	174
$I_{0.8}$	254	310	2066	3444	184	226
$I_{1.0}$	237	290	2206	3712	177	221
Mean	254	290	2025	3335	183	207

* N price was 0.6 US $ per kg and grain price was 0.2 US $ per kg.

Table 4. Physical properties of soil profiles in the experimental plots.

Depth cm	Sand (%) 2-0.05mm	Silt (%) 0.05-0.02 mm	Clay (%) < 0.02 mm	Bulk density g cm^{-3}	Field capacity %	Saturated water capacity %
0-20	90.5	7.9	1.6	1.46	19.10	22.38
20-40	92.2	5.3	2.5	1.60	15.67	23.32
40-60	93.8	4.2	2.0	1.68	16.68	22.29
60-80	94.4	4.1	1.5	1.70	15.06	21.48
80-100	92.3	4.4	3.3	1.68	16.46	21.20

irrigation rates. This agreed with the results of Pandey et al. (2001). Conversely, water lack at any growth stage reduced grain yield, kernel numbers and straw yield. In both years, during the growing season, the rainfall was low, and the high temperature and high ET demand had adverse effects on wheat growth, especially from the flowering to the filling stages of wheat. The adverse effects of this stress can be partially mitigated by an adequate supply of water (Pandey et al., 2001). Medium irrigation ($I_{0.8}$) and low irrigation ($I_{0.6}$) consistently resulted in lower grain yield (20 % and 8%), kernel numbers (9 % and 5 %) and straw yield (12 % and 6 %) than high irrigation ($I_{1.0}$) over the 2 years period. These results are similar to Al-kaisi et al. (2003) who observed significant and positive impacts of irrigation levels on corn grain yield response to N rates, and they agreed with Hergert et al. (1993) and O'Neill et al. (2004) that grain yield under high irrigation were significantly greater than that under deficit irrigation. As a result of the present high ET and limited irrigation, crops will not grow reliably under water-stressed conditions in the studied area. This indicates that it is difficult to obtain satisfactory grain yield without irrigation, suggesting that supplemental irrigation is necessary.

Effects of nitrogen on grain yield

Paolo and Rinaldi (2008) showed that applied N had a marked influence on grain yield and kernel numbers, but had little influence on kernel weights. The results of our experiment agreed partly with the above finding. In general, the 2-year results showed that 221 kg N ha^{-1}, which is the low N fertilizer rate currently used on farmland in the area, had the highest values of grain yield, kernel numbers and straw yield. An exception was the highest straw yield obtained with 300 kg N ha^{-1} supply under the 3 irrigation regimes in 2006. Compared to N_0, N_{79}, N_{140} and N_{300} over the 2 years, The N_{221} treatment showed grain yield increases of 99.1, 45.1, 20.0 and 7.4 %. This, in some degrees, agreed with Mandal et al. (2005), where crops maintained higher biomass with increased water supply in combination with N optimum, causing an ascribed to overall improvement in plant vigor in term of development of leaves, stems and grains. Li et al. (2001) found that treatment with N rate of 225 kg ha^{-1} resulted in the highest yield and yield components. Paolo and Rinaldi (2008) reported that the N was the most limiting factor for grain yield, and water stress had only a slight effect under lower N rates. Conversely, with adequate or excessive N rates, water became the more limiting factor. Optimizing inputs of both water and N simultaneously minimize the adverse effects of high temperatures and compensate for loss in crop productivity (Gajri et al., 1993). Irrigation and N treatment had significant impacts on wheat grain yield, kernel numbers and straw yield, but the interaction of "I× N " was insignificant in most cases.

The economic nitrogen rates and the maximum nitrogen rates

The most profitable N rate ranged from 174 to 226 kg ha^{-1}. These were less than the maximum N rates required for maximum grain yield, which ranged from 237 to 310 kg ha^{-1} in the all irrigation regimes. This result agreed with the findings of Pandey et al. (2001) who also concluded that the most profitable N rates and the maximum N rates were markedly higher with high irrigation than with deficit irrigation. These results agreed, to a degree, with Russelle et al. (1981) that the maximum N rate for maximum yield was the same under different irrigation conditions. Grain yield of winter wheat and N utilization efficiency reached the highest at an application rate of 225 kg N ha^{-1}, while the economic yield was a maximum at a rate of 150-225 kg N ha^{-1} (Li et al., 2001).

Effects of irrigation and nitrogen on WUE

The results of the current experiment showed that the WUE was decreased directly with irrigation rates, but increased significantly with N fertilizer applications, when the N application rate reached 221 kg ha^{-1} in the both years. The low irrigation had the highest WUE (4.25 kg ha^{-1} mm^{-1}) among the irrigation treatments, and the 221 kg N ha^{-1} had the highest value (4.75 kg ha^{-1} mm^{-}) among the N application treatments over the 2 years. Crop water use increased significantly with the increase in water supply in every N level. This is because of the relative decrease in WUE at higher levels of irrigation compared with WUE at deficit irrigation (Zhang and Oweis, 1999). Several studies have reported WUE values that were higher under water deficit than high irrigation condition, especially when irrigation is applied in the critical stages of plant development (Mandal et al., 2005). However, in contrary to the irrigation influence, the N rate positively influenced the WUE of wheat (Howell, 2001). Hussain and Al-Jaloud (1995) concluded that the application of 150-225 kg N ha^{-1} for high irrigation and 75-150 kg N ha^{-1} for deficit irrigation would be sufficient to obtain optimum grain yield and higher WUE of wheat. The WUE of winter wheat was reduced markedly by

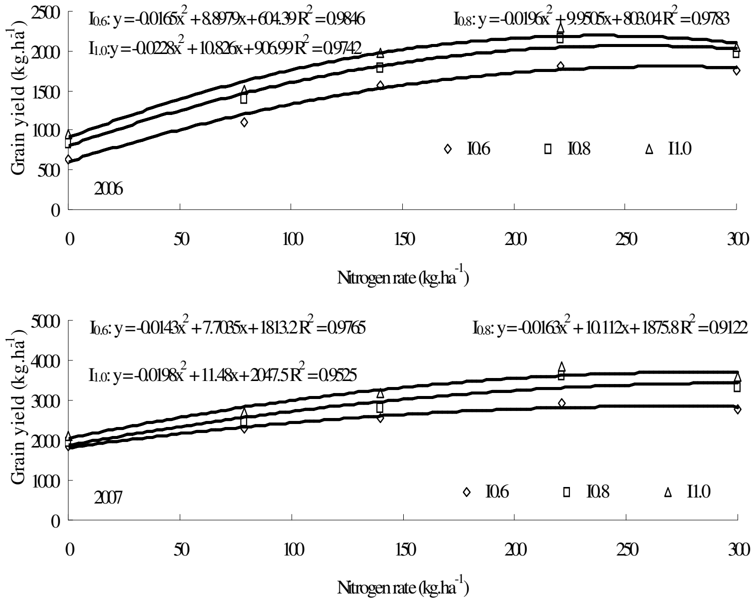

Fig 3. Grain yield of wheat as affected by nitrogen rates under 3 irrigation regimes in the 2006 and 2007 growing seasons.

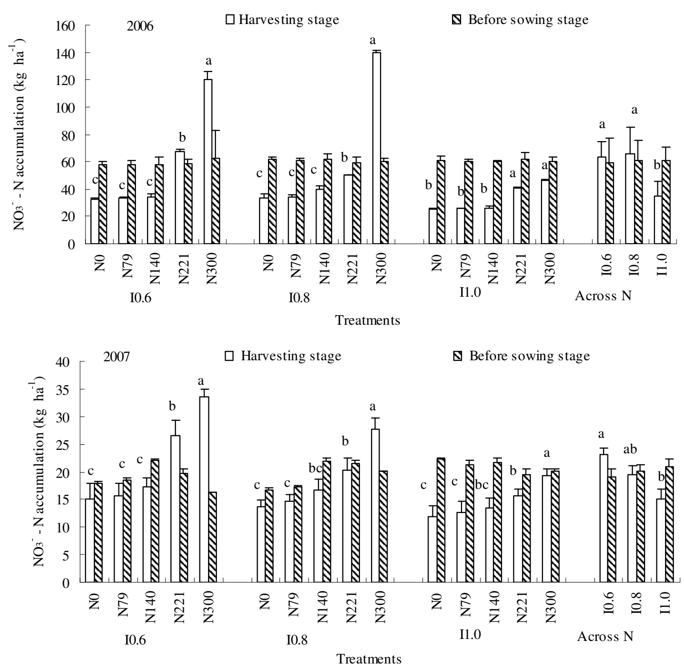

Fig 4. Accumulation of NO_3^--N in the 0-200 cm soil profile under different irrigation and N treatments (Across N: the average over the 4 nitrogen rates. Means with the same letters within each soil layer are not significantly different among treatments at harvesting at *P* < 0.05).

either a deficiency or an excess of N supply. The results of the current experiment showed that the highest WUE was obtained at a 221 kg ha^{-1} N application rate combined with low irrigation each season.

Effects of irrigation and nitrogen on nitrate nitrogen accumulation

Zhu and Chen (2002) concluded that the accumulation of NO_3^--N, in many farmlands within 200 cm depth of soil, was a result of a long period of excessive use of N fertilizer. In our experiment, the N application at rate of 221 kg N ha^{-1} or above showed more NO_3^--N accumulation at harvesting than before sowing, under irrigation deficit conditions,. These values are comparable with the values of 150-180 kg N ha^{-1} recommended by Zhu and Wen (1992) in Northwest China.

Table5. Chemical properties of soil profiles in the experimental plots

Depth cm	Total N g kg^{-1}	Total P g kg^{-1}	Total K g kg^{-1}	Available N mg kg^{-1}	Olsen P mg kg^{-1}	Available K mg kg^{-1}	Organic matter %	pH
0-20	0.05	0.05	2.37	11.73	0.75	51.09	0.56	8.55
20-40	0.03	0.04	2.30	5.24	0.48	36.96	0.21	8.71
40-60	0.01	0.03	1.7	2.04	0.15	35.00	0.16	8.94
60-80	0.01	0.03	1.7	1.83	0.16	35.00	0.13	9.00
80-100	0.01	0.03	1.7	1.74	0.19	41.50	0.10	8.96

Table 6. Rate and date of nitrogen fertilizer application (kg ha^{-1})

2006	2007	Growth stage	N_0	N_{79}	N_{140}	N_{221}	N_{300}
04-14	04-12	Two leaves	0	79	79	79	79
05-04	05-09	Stem elongation	0	0	61	61	61
05-16	05-20	Heading	0	0	0	81	81
06-03	05-31	Flowering	0	0	0	0	79

Table 7. Rate and date of irrigation (mm)

	2006							
Date	03-22	04-14	05-04	05-16	06-03	06-13	06-24	Total
Growth stage	Seeding	Two leaves	Stem elongation	Heading	Flowering	Filling	Mature	irrigation
$I_{0.6}$	107	50	65	65	65	65	65	482
$I_{0.8}$	107	66	87	87	87	87	87	608
$I_{1.0}$	107	83	109	109	109	109	109	735
	2007							
Date	03-22	04-12	05-09	05-20	05-31	06-10	06-25	Total
Growth stage	Seeding	Two leaves	Stem elongation	Heading	Flowering	Filling	Mature	irrigation
$I_{0.6}$	107	59	82	82	82	82	82	576
$I_{0.8}$	107	79	110	110	110	110	110	736
$I_{1.0}$	107	98	138	138	138	138	138	895

Expectations

Considering the high WUE, deficit irrigation may still be acceptable for wheat production although it resulted in low grain yield in Heihe River Basin. Due to limited water resources, many irrigation systems have to adopt deficit irrigation practices to cover greater areas and benefit more farmers. In order to minimize NO_3^--N accumulation in soil at harvesting stage, the N application rate should be lower than that of 221 kg N ha^{-1} for spring wheat production in a recently reclaimed sandy farmland. The optimum N rate is lower than the current average N rate (250-350 kg N ha^{-1}) in these areas.

Materials and methods

Climate

Field experiments were conducted at Linze Inland River Basin Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (39°21′ N, 100°07′ E, 1367 m above Mean Sea Level), during two consecutive spring wheat growing seasons in 2006 and 2007. The station was located at the southern edge of Badain Jaran Desert. The experimental fields were reclaimed in 2000, from the Gobi Desert (by which they were surrounded), and had been planted continuously with irrigated maize for the past 5 years. The natural vegetation before reclaimation included *Nitraria sphaerocarpa* (Maxim.), *Reaumria soongorica* (Pall. Maxim.), *Suaeda glauca* (Bge.) *and Sillium mongolicum* (Rgl.). The region has a typical temperate desert climate: dry and hot in summer, cold in winter, ample sunshine, very little precipitation, strong winds, and frequent drifting sands. The annual mean air temperature is about 7.6 °C, with an absolute maximum and absolute minimum of 39.1 °C in July, and -27 °C in January. The normal annual precipitation is 117 mm (1965-2005) and about 60 % of the total precipitation occurs from July to September (Su et al., 2007b) and groundwater level ranges from 4 to 10 m.

Soil characteristics

The soils all formed from diluvial-alluvial materials and are classified as Calci-Orthic Aridosols, and Calciothids according to Chinese Soil Taxonomy. The dominant texture is loamy sand with a very low nutrient concentration and a loose structure (Su et al., 2006; 2007a). Just before sowing in 2006, the soil was sampled at depths of 0 - 100 cm. The physical and chemical properties of the soil are presented in Tables 4 and 5. The total rainfalls during the spring wheat growing seasons were 43.9 mm in 2006 and 61.0 mm in 2007.

Experimental design

Estimated evapotranspiration

The experiment was conducted with 3 replications in a split-plot on a randomized complete block design, with irrigation rates as the main plots and N rates as the sub-plots. The 3 irrigation rates were 0.6, 0.8, and 1.0 of the estimated evapotranspiration (ET_c). This was based on a model simulating the actual process of soil evaporation, plant transpiration and the total ET from irrigated farmlands in the oasis of Heihe River Basin during spring wheat-growing seasons. ET_c, ET_0 and K_c were calculated using following formulae (Allen et al., 1998; Ji et al., 2004; Zhao et al., 2009).

$$ET_c = K_c \times ET_0 \quad (1)$$

$$K_c = K_{c(Tab)} + [\,0.04\,(\mu_2 - 2) - 0.004\,(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (2)$$

$$ET_0 = \frac{0.408\Delta(R_n - G)\gamma\left(\frac{900}{T+273}\right)\mu_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (3)$$

where, ET_c is the crop evapotranspiration (mm d^{-1}), K_c the crop coefficient and ET_0 reference evapotranspiration (mm d^{-1}). $K_{c(Tab)}$ is the value of K_c taken from Table 17 of FAO-56 (Allen et al., 1998), RH_{min} the mean value for daily minimum relative humidity, h the mean plant height, R_n the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux (MJ m^{-2} day^{-1}), T the air temperature at 2 m height (°C), μ_2 the wind speed at 2 m height (m s^{-1}); $e_s - e_a$ the saturation vapor pressure deficit (kPa), Δ the slope vapor pressure curve (kPa °C^{-1}) and γ the psychrometric constant (kPa °C^{-1}).

Irrigation and nitrogen treatments

The irrigation treatments were 482, 608, 735 mm in 2006 and 576, 736, 895 mm in 2007, respectively. These treatments represented 0.6 ET_c ($I_{0.6}$), 0.8 ET_c ($I_{0.8}$), and 1.0 ET_c ($I_{1.0}$). The N rates of 0, 79, 140, 221 and 300 kg ha^{-1} in the form of urea were applied within each irrigation treatment and were denoted by N_0, N_{79}, N_{140}, N_{221}, and N_{300}, respectively. The rates and dates of N fertilizer supply during the wheat-growing seasons over the 2 years were represented in Table 6. The $I_{0.6}$ irrigation treatment and N_0 treatment were used as controls for the respective irrigation and N treatments. Between all main plots and all subplots, a 2 m alley and a 1.5 m alley were kept to eliminate the influence of lateral water and N movement. Calibrated siphons were used to deliver the required amount of water from the irrigation channel into the hose. In order to measure the delivered amount of water accurately, a water flow meter was placed at the head of the hose for each plot of 9 m ×4.5 m. To contain irrigation water, the plots were surrounded by 25 cm-high banks. The amount of irrigation water was greater in 2007 than in 2006. This was mainly being due to a high net radiation in 2007. The rates and dates of irrigation during the wheat growing-season over the 2 years of this experiment are listed in Table 7. Irrigation was stopped at the dough-growth stage of spring wheat.

Field management

Prior to 2005, the experimental fields had been under irrigated maize cultivation for 5 years. After the harvest of maize in 2005, the land was plowed once and harrowed. The plot was laid out in September 2005, and uniform winter irrigations of 100 mm were applied on 20 November (2005) and again on 15 November of 2006 to pulverize the soil. A local wheat cultivar (Longfu-920) was used to seed 15 cm rows at 337.5 kg ha^{-1} in the dry seedbed. This was followed by a uniform 107 mm post-sowing irrigation to all plots, regardless of treatments, to ensure proper germination and establishment of the seeds. During cultivation 41 kg P ha^{-1} and 39 kg K ha^{-1} were applied along with the wheat seeds. Seeding was done on 22 March, 2006 and 21 March, 2007. Urea (46 % N) was used as a N fertilizer and applied manually before irrigation. The crop varieties, fertilizer dozes, irrigation interval and planting densities were based on common practices used by local farmers. Manual weeding was used to control the weeds. The crop was harvested manually on 9 July in both years.

Sampling and sample analysis

The soil samples were taken at increments of 20 cm within 200 cm depth using an auger with a diameter of 3.6 cm during the wheat-growing seasons, before each sowing, at harvesting and 24 h after irrigation, This was performed 6 times in 2006 and 8 times in 2007. The soil samples were weighed then dried to a constant weight at 105°C to determine the gravimetric soil moisture content. Before sowing and at harvesting, three soil cores were sampled from each plot, thoroughly mixed, quickly stored in plastic bags and analyzed immediately to determine the NO_3^--N concentration. This was determined by using a Flow Solution IV Analyzer (FSIV, O.I. Analytical, U.S.A.) after extraction (with a 1:5 ratio) (w/w) soil:1 mol L^{-1} KCl solution (Bao 2000). The amount of NO_3^--N (kg N ha^{-1}) reserved in 0-200 cm soil profiles was calculated according to the equation modified by Emteryd (1989):

$$Y_i = T_i \times BD_i \times [NO_3^-]_i \times 0.1 \quad (4)$$

where, T_i is the thickness of soil layer in cm; BD_i the bulk density in g cm^{-3}; $[NO_3^-]_i$ the soil NO_3^--N concentration in mg kg^{-1}, and 0.1 the conversion coefficient. Crop water use was calculated by the water balance equation: $ET_{actual} = P + I - Dp - R - \Delta S$, where ET_{actual} is the actual evapotranspiration, P the precipitation; I the depth of irrigation water applied; Dp the drainage beyond the measured depth; R the runoff and ΔS the variation of soil water storage between sowing and harvesting dates within 200 cm, and all measurements were expressed in mm. As Dp and R were negligible, ET_{actual} was calculated as $ET_{actual} = P + I - \Delta S$. WUE was calculated as grain yield divided by seasonal ET_{actual} (Pandey et al., 2001, Mandal et al., 2005).

At harvest, plants were sampled, from 60 cm in the middle row of each replication, for plant dry weight and yield components. All the plant samples were cut near the soil surface and the below-ground fractions were left in the field. Dry matter of grain and straw was determined by drying the sub-samples in a convection oven at 65 °C to a constant weight. Kernels numbers per spike and kernels numbers per m^2 were calculated from the head number and 1000-kernel weight. Grain yield was hand-harvested from the 16 m^2 plot and adjusted to 14 % moisture weight.

Statistical analysis

The treatment at which the maximum yield occurred was determined by differentiating the resulting equations with respect to the fertilizer N and the N rate at which the first derivative equaled zero. The most profitable N rate was calculated as the N rate at which the ratio of fertilizer N price to grain price equaled the first derivative of grain yield with respect to fertilizer N (Sticker et al., 1995).

Grain yield, kernel numbers, straw yield and WUE were analyzed using an analysis of variance (ANOVA) appropriate for a randomized complete block split-plot design, with irrigation treatment as the main-plot factor and N rate as the split-plot factor. To determine the significant differences of the means between the irrigation treatments and between the N treatments, a One-Way ANOVA was used. Pairs of mean values were compared by the least significant difference (LSD) at the 5% and 1% level using SPSS software (for Windows, Version 11.0), and Duncan's multiple range test was used for comparisons. Regression analysis was performed on the relationships between the crop parameters and the irrigation and N rates. Best fit regression models were calculated.

Conclusions

It can be concluded that in areas with similar conditions to the experimental site, optimization of N and irrigation application can improve wheat grain yield and minimize potential NO_3^--N leaching. In Heihe River Basin, deficit irrigation results in reduced grain yield, kernel numbers and straw yield, but increased WUE. In general, the 2-year results showed that, under 3 irrigation regimes, the N application rate of 221 kg ha^{-1} had the highest values of grain yield, kernel numbers, straw yield and WUE, and this application rate can be used as an alternative to that of 300 kg N ha^{-1}. Differential strategies of N application rates were concluded when considering different sectors of farming. The N application rate of 221 kg N ha^{-1} could lead to high risk of excess soil NO_3^--N accumulation within 200 cm soil profile at harvesting under deficit irrigation over 2 years. This indicates that the optimum N rate is below 221 kg ha^{-1}, which is much lower than that used in many places in the middle reaches of these areas. There is little potential for soil NO_3^--N accumulation and leaching. Full irrigation leads to NO_3^--N leaching and plant N-uptake, resulting in lower NO_3^--N accumulation at harvest than prior to sowing. The most profitable N rates range from 174 to 226 kg ha^{-1} and these would enhance economic returns to farmers.

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