

Yu SHI, Zhenwen YU

Effects of nitrogen fertilizer rates and ratios of base and topdressing on wheat yield, soil nitrate content and nitrogen balance

© Higher Education Press and Springer-Verlag 2008

Abstract Application of nitrogen (N) fertilizer is one of the most important measures that increases grain yield and improves grain quality in winter wheat (*Triticum aestivum* L.) production. Presently, there is a large number of investigations (experiments) in the field on different nitrogen fertilizer application regimes. However, there still exists a serious problem of low nitrogen use efficiency, especially in winter wheat high yield conditions: unsuitable nitrogen fertilizer, which often leads to lower yield and large accumulation of nitrate in the soil, bringing a potential risk to the environment. In order to explore the optimal regime of nitrogen fertilizer application suitable for environment and economy, a field experiment on the different rate and ratio of base and topdressing of nitrogen fertilizer at the different growth periods of winter wheat was conducted. The field experiment was undertaken from the fall of 2003 to the summer of 2004 in the village of Zhongcun in Longkou city, in the Shandong Province of China. The field experiment with three repeats for each treatment was designed in a split-plot. The major plot was applied with urea at a nitrogen fertilizer rate of three levels, namely, $0 \text{ kg}\cdot\text{hm}^{-2}$ (CK), $168 \text{ kg}\cdot\text{hm}^{-2}$ (A), and $240 \text{ kg}\cdot\text{hm}^{-2}$ (B). In the sub-plot, the ratios of base and topdressing nitrogen fertilizer at the different development periods of wheat were 1/2:1/2 (A1 and B1), 1/3:2/3 (A2 and B2) and 0:1 (A3 and B3). Treatment B1 was under a regime used now in the local region. It was found that the amount of N accumulation in plants had no significant difference between treatments applied with nitrogen fertilizer. The grain yield and grain protein

content were all elevated remarkably by applying nitrogen fertilizer compared with those of treatment CK. There was no significant difference in the grain yield and grain protein content between A2 and B2 and B3. However, when compared with those of B2 and B3, in A2 there was an increase in nitrogen use efficiency and residual soil NO_3^- -N and N losses were reduced. Under the condition of the same rate of nitrogen fertilizer, increasing topdressing nitrogen rate clearly elevated the grain yield, grain protein content and nitrogen use efficiency. The results indicated that the residual soil NO_3^- -N in A1 and B1 accumulated higher than that of CK in 80–160 cm soil layers at the jointing stage, but that of A2 had no significant difference compared with that of CK in 0–200 cm soil layers. At the maturity stage, more residual soil NO_3^- -N was detected in B2, B3 and A3 than that in CK in 120–180 cm soil layers, which could not be absorbed by the roots of wheat, but led to be eluviated easily. The amount of soil NO_3^- -N accumulation in treatment A2 had no significant difference compared with that of treatment CK in the 100–200 cm soil layer. In conclusion, A2, whose nitrogen fertilizer rate was $168 \text{ kg}\cdot\text{hm}^{-2}$ and the ratio of base and topdressing was 1/3:2/3, had a higher grain yield and grain protein content, and heightened N use efficiency and minimized the risk of NO_3^- -N leaching. This should be one of the most appropriate nitrogen fertilizer application regimes in wheat production in local regions in China.

Keywords nitrogen fertilizer rate, ratio of base and topdressing, wheat, yield, soil nitrate, nitrogen balance

Translated from *Acta Ecologica Sinica*, 2006, 26(11): 3661–3669 [译自: 生态学报]

Yu SHI, Zhenwen YU (✉)

Key Laboratory of Wheat Physiology and Genetics Improvement, Ministry of Agriculture, Shandong Agricultural University, Tai'an 271018, China

E-mail: yuzw@sdau.edu.cn; sdauno42@sdau.edu.cn

Yu SHI

Tai'an Agricultural Bureau, Tai'an 271000, China

1 Introduction

Application of nitrogen (N) fertilizer is very important in winter wheat (*Triticum aestivum* L.) production. However, unsuitable nitrogen fertilizer often leads to a low nitrogen use efficiency and serious nitrogen loss,

bringing a potential risk of pollution to the environment (Yang et al., 2003; Wu et al., 2003; Dana et al., 2002). Many recent studies have shown that the fertilizer N rate and ratio of base fertilizer and topdressing affect the wheat grain yield. Some researchers have reported that the optimum fertilizer N rate was 225–300 kg·hm⁻² and the optimum ratio of base fertilizer and topdressing was 2/3:1/3 (Kong et al., 1996). Other researchers believe that the N application regime in wheat fields to gain a higher grain yield was 240 kg·hm⁻² with a ratio of base fertilizer and topdressing at 5:5 (Han et al., 1998), but Yue et al. (1998) reported that the optimum nitrogen fertilizer application regime was 160 kg·hm⁻² and the optimum ratio of base fertilizer and topdressing was 5:5. In short, the former studies have emphasized particularly on the effects of nitrogen fertilizer rate and ratio of base and topdressing nitrogen fertilizer on the wheat grain yield rather than on reducing the residual soil NO₃⁻-N, increasing N use efficiency and keeping nitrogen in balance in the higher yield field at the same time, considering the grain yield and quality. Most notably, the distribution of base and topdressing nitrogen fertilizer and its effects on yield, N use efficiency and soil NO₃⁻-N content in higher yield fields have not been studied together. Considering wheat yields, qualities, benefits and ecosystems, the present study was conducted to examine the effects of nitrogen fertilizer rate and ratio of base and topdressing on the grain yield, protein content, nitrogen use efficiency, nitrogen balance and change of soil NO₃⁻-N content to determine an optimum N application regime and to offer a theoretical base for reasonably adjusting the nitrogen application in wheat fields.

2 Methods

2.1 Experimental design

The field experiment was conducted in the village of Zhongcun in Longkou city, in China's Shandong Province (120°3'E, 37°3'N, 10 m a.s.l.), which is located in a temperate and monsoon type zone. Mean annual precipitation in this area is 600 mm, with peaks in July and August. Mean annual air temperature is 12°C, with a frost-free period of 190 days. The rotation between winter wheat and summer maize is the main cropping system. Rainfall and air temperature during the winter wheat

growth period from October of 2003 to July of 2004 are shown in Table 1.

The field experiment was conducted from the fall of 2003 to the summer of 2004 in Zhongcun village. The brown soil nutrient components were: organic matter at 13.1 g·kg⁻¹, with total nitrogen at 1.14 g·kg⁻¹, and available nitrogen (N), phosphorus (P) and potassium (K) at 87.5 mg·kg⁻¹, 10.49 mg·kg⁻¹ and 84 mg·kg⁻¹, respectively. As a winter wheat variety, Jimai 20 which is a typical strong gluten cultivar currently used locally, was selected for this experiment.

Three replicates of each treatment in the field experiment were randomly arranged in a split-plot design. The major plot was provided with nitrogen fertilizer rate of urea at three levels: 0 kg·hm⁻² (CK), 168 kg·hm⁻² (A), and 240 kg·hm⁻² (B). The sub-plot was provided with the base and topdressing nitrogen fertilizer at the different development periods of wheat, at a ratio of 1/2:1/2 (A1 and B1), 1/3:2/3 (A2 and B2) and 0:1 (A3 and B3), respectively. B1 employed a regime used now in the local region. The basal N fertilizer with total P₂O₅ (135 kg·hm⁻²) and K₂O (105 kg·hm⁻²) was applied before sowing, and the topdressing N fertilizer was applied at the jointing stage. Each plot was 3 m × 8 m in size. At the three-leaf stage of seedling, plants in each plot were thinned to a density of 150 plant·m⁻². The date of sowing wheat seeds was on October 4, 2003 and the harvest date was on June 15, 2004. In total, irrigation was done three times (before the winter stage, at jointing stage and on 28 d after flowering) throughout the wheat life.

2.2 Measurements

Two soil sites at each plot were sampled randomly in 20 cm increments to a depth of 200 cm at five growth stages including sowing, before winter, at jointing stage (before fertilization), flowering and maturity with a soil auger and the sample was obtained by mixing the soils in the same layer, and were frozen immediately. The procedure for treating the sample was: 1) sifting after fully mixing the defrosted sample with a 2 mm-sieve; 2) 5 g each sample was weighed and extracted in 0.05 L of 0.01 mol·L⁻¹ CaCl₂ on a horizontal shaker for 30 min; 3) NO₃⁻-N and NH₄⁺-N were determined using an auto analyzer (AA3) after filtering (Zhou et al., 2001; Liu et al., 2002). The soil water content of each sample was measured as well.

Table 1 Rainfall and air temperature during different winter wheat growth period

item		sowing– before winter	before winter– jointing	jointing – anthesis	anthesis – maturity	sum
rainfall	AR/mm	82.9	33.3	28	84.3	228.5
	RPW/%	36.3	14.6	12.2	36.9	100.0
air temperature	AT(Σ _t ≥0°C)	649.8	578.7	359	837.6	2425.1
	TPW/%	26.8	23.9	14.8	34.5	100.0

Note: AR: amount of rainfall; AT: accumulated temperature; RPW: the rainfall amount proportion of each growth period to whole wheat growth stage; TPW: accumulated temperature proportion of each growth period to whole wheat growth stage.

At jointing and maturity, the colony was investigated and 30 culms randomly chosen from every plot in the main field experiment were cut at the ground level. All the plant samples were oven-dried at 70°C to a constant weight, weighed, ground in a Wiley Mill, and passed through a 1-mm sieve. Subsamples were taken for N analysis. The N concentration in plant tissues and grains was determined by the standard macro-Kjeldahl procedure (Nitrogen Analysis System, Büchi, Switzerland). At harvest, the wheat in the area of 6 m² was obtained and its yield was calculated.

Soil NO₃⁻-N accumulation amount = soil layer thickness (cm) × soil bulk density (g·cm⁻³) × soil NO₃⁻-N content (mg·kg⁻¹)/10.

Nitrogen mineralization amount was calculated based on the N uptake amount by the crop and the net mineralization amount of soil N min before sowing and after harvest (Ju et al., 2002). Disregarding the exploding domino effect of nitrogen fertilizer, it was assumed that the soil nitrogen mineralization amount in the plot treated with N fertilizer was the same as in the control plot treated with zero-N. This can be illustrated by the following equation:

Soil nitrogen net mineralization amount in one growth stage = Total aboveground plant N accumulation amount in the zero-N control + Soil residual Nmin amount in the zero-N control – Soil initial Nmin amount in the zero-N control.

Based on a nitrogen balance model, i.e., a nitrogen input and output balance theory (Liu et al., 2002), the calculation for nitrogen apparent losses was as follows:

Nitrogen apparent losses = Nitrogen input amount – Plant uptake amount – Soil residual Nmin amount.

Nitrogen input consisted of applying nitrogen, initial Nmin, and nitrogen mineralization, while nitrogen output consisted of plant uptake, residual Nmin, and apparent losses. So based on the nitrogen balance model, the calculation for nitrogen apparent losses rate was as follows:

Nitrogen apparent losses rate (%) = Nitrogen apparent losses amount/Nitrogen fertilizer rate × 100%;

Nitrogen harvest index = Nitrogen accumulation amount in grain/Nitrogen accumulation amount in plant (Liu et al., 2003a);

N fertilizer agronomic efficiency (kg grain·kg⁻¹) = (Grain yield in the plot received N fertilizer – Grain yield in the zero-N control)/Nitrogen fertilizer rate (Liu et al., 2003a);

Total aboveground plant nitrogen use efficiency (PRE) (%) = [Total aboveground plant N accumulation in the plot treated with N fertilizer – Total aboveground plant N accumulation in grain in the zero-N control]/Nitrogen fertilizer rate × 100% (Liu et al., 2003a);

Grain nitrogen use efficiency(GRE)(%) = [Total N accumulation in grain in the plot treated with N fertilizer – Total N accumulation in grain in the zero-N control]/Nitrogen fertilizer rate × 100%.

2.3 Data statistical analysis

Treatment mean differences were separated by the least significant difference (*LSD*_{0.05}) test when the *F*-tests were significant (*P* ≤ 0.05). Charts were made by Originpro. V7.0 software.

3 Results

3.1 Effect of nitrogen rate and ratio of base fertilizer to topdressing on soil NO₃⁻-N content and accumulation amount

As shown in Fig. 1, before the winter stage, the soil NO₃⁻-N content in 0–40 cm soil layers with treatments of nitrogen fertilizer was markedly higher than that without treatments of nitrogen fertilizer, and all treatments had no

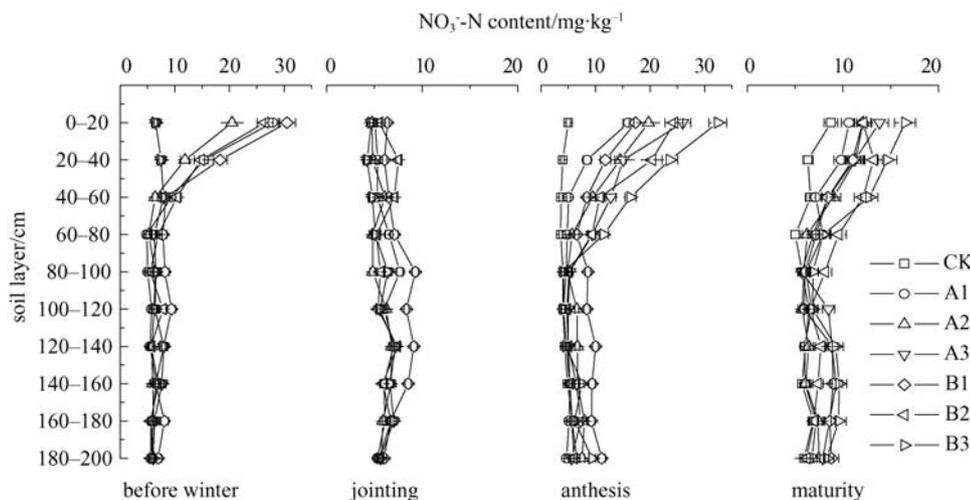


Fig. 1 The content of NO₃⁻-N in 0–200 cm soil layers at different growth stage of wheat

significant difference in 60–80 cm and 120–200 cm soil layers, but in 80–120 cm soil layers, soil NO_3^- -N content of B1 was markedly higher than that of any other treatment. This indicated that wheat plants were small at the initial development period, and needed a small amount of nitrogen fertilizer. Therefore, too much basal nitrogen rate could lead to eluviating of soil NO_3^- -N, but have no effect on the soil NO_3^- -N content in 120–200 cm soil layers.

At the jointing stage, the soil NO_3^- -N content in 0–60 cm soil layers of all treatments decreased compared with that prior to the winter stage, and the differences between treatments became smaller. In 80–100 cm soil layers, the soil NO_3^- -N contents of B1 and A1 were significantly higher than those of other treatments. In 100–160 cm soil layers, the soil NO_3^- -N content of B1 was significantly higher than that of any other treatment. This indicated that the soil NO_3^- -N of A1 was eluviated to 80–100 cm, and that of B1 was eluviated to 160 cm, forming a hidden danger of nitrogen losses.

At anthesis, because of the application of topdressing nitrogen fertilizer at the jointing stage, the soil NO_3^- -N content of treatments with nitrogen fertilizer was markedly higher than that of CK, and the soil NO_3^- -N content increased with an increase in the topdressing nitrogen fertilizer rate. Compared with the jointing stage (before fertilization), soil NO_3^- -N content of treatments with nitrogen fertilizer was eluviated to 80 cm soil layers, which on the one hand led the root to absorb more NO_3^- -N, while on the other hand increased the possibility of eluviation loss.

At maturity, compared with anthesis stage, the soil NO_3^- -N content in 0–60 cm soil layers decreased, and the differences between treatments became smaller, but that of treatments with topdressing nitrogen fertilizer application were markedly higher than CK, and soil NO_3^- -N content was increased with an increase in topdressing nitrogen fertilizer rate. In treatments B2, B3 and A3 more residual soil NO_3^- -N were detected compared with treatment CK in 120–180 cm soil layers. This indicated that the soil NO_3^- -N content of these treatments

that eluviated to 120–180 cm soil layers could not be absorbed by wheat roots, and eluviated easily.

Table 2 shows the soil NO_3^- -N accumulation amount in all treatments at the jointing stage and maturity stage. As shown in Table 2, B1, A1, and B2 possessed a markedly higher soil NO_3^- -N accumulation amount at the jointing stage than that of CK in 0–100 cm and 0–200 cm soil layers, of which B1 had a markedly higher soil NO_3^- -N accumulation amount than that of any other treatment in 100–200 cm soil layers, indicating that the soil NO_3^- -N accumulation amount markedly increased and tended to increase eluviation when the basal nitrogen fertilizer rate was higher than $80 \text{ kg}\cdot\text{hm}^{-2}$. At maturity, in 0–100 cm soil layers, the soil NO_3^- -N accumulation amount of those treated with nitrogen fertilizer was markedly higher than that of CK, of which B3 was the highest; in 100–200 cm soil layers, the soil NO_3^- -N accumulation amount of A3, B1, B2 and B3 was markedly higher than that of CK, A1 and A2; in 0–200 cm soil layers, with that of B3 being the highest, followed by B2, A3, and B1. So when the topdressing nitrogen fertilizer rate was more than $120 \text{ kg}\cdot\text{hm}^{-2}$, the soil NO_3^- -N accumulation amount increased in 0–200 cm soil layers, especially in 100–200 cm soil layers, and easily led to losses.

The above results show that at the jointing stage, A1, and B1 with $84 \text{ kg}\cdot\text{hm}^{-2}$ and $120 \text{ kg}\cdot\text{hm}^{-2}$ basal nitrogen fertilizer rate accumulated more soil NO_3^- -N in 80–100 cm and 100–160 cm soil layers respectively, but the soil NO_3^- -N content and the accumulation amount of A2 with $56 \text{ kg}\cdot\text{hm}^{-2}$ basal nitrogen fertilizer rate had no significant difference with those of CK in 0–200 cm soil layers, and could hardly lead to eluviation losses. At maturity, B3, A3, and B2 with topdressing nitrogen fertilizer rate at more than $160 \text{ kg}\cdot\text{hm}^{-2}$ accumulated more soil NO_3^- -N in 120–180 cm soil layers, and eluviation in 0–200 cm soil layers was easy. But the soil NO_3^- -N accumulation amount of A2 with $112 \text{ kg}\cdot\text{hm}^{-2}$ topdressing nitrogen fertilizer rate had no marked difference with that of CK in 100–200 cm soil layers, which indicated that the soil NO_3^- -N did not markedly accumulate in 100–200 cm soil layers, if the base and topdressing nitrogen fertilizer

Table 2 Effects of nitrogen fertilizer rate and ratio of base and topdressing nitrogen on soil NO_3^- -N accumulation at jointing and maturity ($\text{N kg}\cdot\text{hm}^{-2}$)

treatment	soil layer					
	jointing stage			maturity stage		
	0–100 cm	100–200 cm	0–200 cm	0–100 cm	100–200 cm	0–200 cm
CK	63.68c	83.30b	146.99c	81.00c	80.92b	161.92d
A1	81.74a	79.17b	160.91b	104.21b	85.13b	189.34c
A2	63.93c	81.53b	145.46c	111.28b	86.24b	197.53c
A3	63.68c	80.32b	144.00c	114.49b	112.30a	226.79b
B1	89.17a	100.67a	189.84a	111.68b	107.32a	219.00b
B2	78.31ab	80.22b	158.53b	128.48ab	100.71a	229.20b
B3	63.68c	81.73b	145.41c	146.18a	113.43a	259.62a

Note: Values without the same letters in the same column are significant at 5% level.

Table 3 Nitrogen balance during different wheat growth period ($\text{kg}\cdot\text{hm}^{-2}$)

item	treatment						
	CK	A1	A2	A3	B1	B2	B3
from sowing to jointing							
A) nitrogen input							
1) nitrogen fertilizer rate	0	84	56	0	120	80	0
2) initial Nmin	237	237	237	237	237	237	237
3) net mineralization	25	25	25	25	25	25	25
B) nitrogen output							
4) crop uptake	129b	152a	148a	128b	158a	153a	127b
5) residual Nmin	133a	139b	135b	133b	156a	144ab	135b
6) apparent losses	0d	55b	35c	1d	68a	45b	0d
from jointing to maturity							
A) nitrogen input							
1) nitrogen fertilizer rate	0	84	112	168	120	160	240
2) initial Nmin	133a	139a	135a	133a	156a	144a	135a
3) net mineralization	85	85	85	85	85	85	85
B) nitrogen output							
4) crop uptake	97c	117b	125b	142a	112b	125b	148a
5) residual Nmin	121e	167cd	178c	175c	189b	209a	211a
6) apparent losses	0d	24c	29c	69b	60b	55b	101a

Note: Values without the same letters in the same row are significant at 5% level.

rate were smaller than $56 \text{ kg}\cdot\text{hm}^{-2}$ and $120 \text{ kg}\cdot\text{hm}^{-2}$, respectively. Under the conditions in this experiment, soil $\text{NO}_3^- \text{-N}$ was not notably accumulated in 100–200 cm soil layers, and it was a little possible to cause the eluviating losses.

3.2 Effect of nitrogen rate and ratio of base fertilizer to topdressing on nitrogen balance in the soil-wheat system

Nitrogen balance of two wheat growth periods (from sowing to jointing and from jointing to maturity) was calculated using the nitrogen balance principle, which was based on the soil Nmin amount and nitrogen uptake trends of wheat (Table 3). The nitrogen input amount included the applied N rate, the total amount of the original Nmin, and the mineralized N rate, while the nitrogen output amount included the rate of uptake N by crops, the total amount of residual Nmin, and the rate of apparent loss. The rate of apparent loss was equal to the difference after the rate of both N uptaken by crops and residual Nmin was subtracted from the total amount of nitrogen input, and which was the N loss of those applied with nitrogen relative to CK. In the calculation of nitrogen balance, the soil layer of the valid soil inorganic nitrogen was defined as 0–100 cm, which is the main soil layer where wheat root absorbed nutrient.

As shown in Table 3, from sowing to jointing, the apparent loss rate increased with the increase in the base nitrogen fertilizer rate, but there was no marked difference between the plant nitrogen accumulation amounts in the treatments with applied nitrogen. So the N fertilizer use efficiency was decreased from 34% (A2) to 24% (B1). In this experiment, decreasing basal nitrogen fertilizer rate

could increase nitrogen apparent use efficiency and reduce nitrogen loss during this growth period. From jointing to maturity, when the nitrogen fertilizer amount was increased at the same ratio of base fertilizer to topdressing, the nitrogen apparent loss rate increased, and soil residual nitrogen amount increased markedly. With the same nitrogen amount applied, increasing topdressing N fertilizer rate significantly enhanced the nitrogen apparent use efficiency, and the appropriate topdressing N fertilizer rate could reduce the nitrogen loss rate. So reducing basal nitrogen amount and increasing topdressing nitrogen amount appropriately could encourage wheat plants to absorb more fertilizer nitrogen and increase the N use efficiency. In this experiment, A2 possessed the highest nitrogen apparent use efficiency, and the least apparent loss rate.

Table 4 shows the nitrogen balance of the soil-wheat system during the whole wheat growth stage. The nitrogen amount offered by soil was $347 \text{ kg}\cdot\text{hm}^{-2}$, which was the

Table 4 Nitrogen balance during the whole wheat growth stage ($\text{kg}\cdot\text{hm}^{-2}$)

item	treatment						
	CK	A1	A2	A3	B1	B2	B3
A) nitrogen input							
1) nitrogen fertilizer rate	0	168	168	168	240	240	240
2) initial Nmin	237	237	237	237	237	237	237
3) net mineralization	110	110	110	110	110	110	110
B) nitrogen output							
4) crop uptake	226b	269a	273a	270a	270a	278a	275a
5) residual Nmin	121d	167c	178c	175c	189b	209a	211a
6) apparent losses	0e	79c	64d	70cd	128a	100b	101b

Note: Values without the same letters in the same row are significant at 5% level. The same as below.

sum of the nitrogen mineralization amount and initial N_{min} before sowing, and it was higher than the nitrogen amount that wheat needed during the whole growth stage, indicating that decreasing nitrogen application rate was effective in this experiment. As far as the soil apparent loss was concerned at maturity, both loss amount and loss rate increased when the nitrogen application rate was increased. With the increase of the amount of topdressing nitrogen, both loss amount and loss rate had a trend of decrease-level off-increase. At maturity, the soil residual N_{min} (especially NO_3^- -N) was 167–211 $kg \cdot hm^{-2}$ in the treatments with applied nitrogen, especially in the treatments with 240 $kg \cdot hm^{-2}$ nitrogen fertilizer rate, whose soil residual N_{min} was markedly higher than that in the treatments with 168 $kg \cdot hm^{-2}$ nitrogen fertilizer rate. The higher residual N_{min} , especially the ease by which NO_3^- -N eluviated out in the soil-wheat system, could result in environmental pollution.

3.3 Effect of nitrogen rate and ratio of base fertilizer and topdressing on nitrogen uptake and use by wheat

When the nitrogen fertilizer amount was increased at the same ratio of base fertilizer to topdressing, the total N absorption amount in wheat plants and N harvest index had no significant difference, which indicated that N fertilizer rate with 168 $kg \cdot hm^{-2}$ could meet the need of crop growth. With the same nitrogen amount applied, increasing topdressing N fertilizer rate could significantly enhance the N harvest index, which indicated that more nitrogen absorbed by plant would be translocated into grains. On the other hand, increasing basal N fertilizer rate could significantly enhance the nitrogen proportion

in wheat stems, and led to the appearance of a nitrogen wasting phenomenon (Table 5).

As shown in Table 5, the agronomic efficiency of N fertilizer, total aboveground plant nitrogen use efficiency (PRE) and grain nitrogen use efficiency (GRE) all significantly decreased with the increase in the amount of nitrogen application. But with the same nitrogen amount applied, increasing topdressing N fertilizer rate could significantly enhance these indexes. The agronomic efficiency of N fertilizer and GRE could reflect the contribution of nitrogen to grain yield and grain N accumulation amount respectively. In this experiment, all indexes of A2 with a nitrogen fertilizer rate of 168 $kg \cdot hm^{-2}$ and a ratio of base fertilizer and topdressing of 1/3:2/3 were higher.

3.4 Effect of nitrogen rate and ratio of base fertilizer and topdressing on grain yield and protein content

As shown in Table 6, applying N fertilizer greatly increased grain yield, grain protein content and grain protein yield, compared with CK without applying N fertilizer, but there existed no difference among A2, B2 and B3, which indicated the N application rate of A2 could meet the need of wheat growth and higher grain yield with better quality. At the same N application rate, increasing the ratio of topdressing fertilizer appropriately could also enhance grain yield as follows: A2>A1>A3, and B2>B3>B1, and the protein content, protein yield and harvest index all markedly increased. It indicates that increasing topdressing N fertilizer rate at jointing stage could promote the translocation of more nitrogen from vegetative parts to grain, so that both the

Table 5 Effects of nitrogen fertilizer rate and ratio of base and topdressing nitrogen on nitrogen using efficiency

treatment	total N absorption/ $kg \cdot hm^{-2}$	N harvest index/%	agronomic efficiency of N fertilizer/ $kg \text{ grain} \cdot kg^{-1}$	PRE/%	GRE/%
CK	226.17b	76.43c	—	—	—
A1	268.67a	75.60c	4.36b	25.30ab	18.02b
A2	272.72a	80.97ab	4.92a	27.71a	28.54a
A3	270.38a	81.20a	4.27b	26.32a	27.80a
B1	270.11a	75.47c	2.43d	18.31d	12.91c
B2	278.15a	79.22b	3.55c	21.66c	19.79b
B3	274.82a	82.02a	3.49c	20.27c	21.12b

Table 6 Effects of nitrogen fertilizer rate and ratio of base and topdressing nitrogen on grain yield and protein content

treatment	kernel yield/ $kg \cdot hm^{-2}$	protein content/%	protein yield/ $kg \cdot hm^{-2}$	harvest index/%
CK	7325.57e	13.45d	985.29d	46.38ab
A1	8057.21c	14.37c	1157.82c	45.78bc
A2	8151.71ab	15.44ab	1258.62ab	46.55a
A3	8042.85c	15.56a	1251.47ab	46.13b
B1	7909.80d	14.69c	1161.95c	44.27d
B2	8177.21a	15.36b	1259.09ab	45.50c
B3	8162.54ab	15.61a	1274.17a	46.72a

grain protein content and the protein yield could be increased, under the conditions used in this experiment. As far as the grain yield, protein content, protein yield, fertilizer N use efficiency and nitrogen loss were concerned, A2, with a nitrogen fertilizer rate of $168 \text{ kg} \cdot \text{hm}^{-2}$ and a ratio of base fertilizer and topdressing of 1/3:2/3 was recommended as the most appropriate regime of applying the nitrogen fertilizer.

4 Discussion

4.1 Effect of nitrogen rate and ratio of base fertilizer and topdressing on soil NO_3^- -N content

Soil NO_3^- -N content varies with both nitrogen application rate and nitrogen application phase. Many studies have shown that a long-range mass nitrogen application rate could result in NO_3^- -N accumulation in soil, and the soil NO_3^- -N content may increase with the increase in the nitrogen application rate (Li et al., 2003; Guillard et al., 1995; Liu et al., 2003b; Malhi et al., 2002; Malhi et al., 2003). On the other hand, some believe that the nitrogen application rate has no effect on the soil NO_3^- -N content in clay soil and sandy soil (Ottman and Pope, 2000). When the nitrogen fertilizer rate is higher than the optimal nitrogen fertilizer rate, there exist no marked changes of the soil Nmin content at maturity (Raun and Johnson, 1995). As for topdressing nitrogen fertilizer, Jaime et al. (2001) believed that a lot of NO_3^- -N accumulation was not found at maturity when the topdressing nitrogen fertilizer rate was $200 \text{ kg} \cdot \text{hm}^{-2}$. So the earlier conclusions were different. On the other hand, fewer reports about the effects of base and topdressing fertilizer on soil NO_3^- -N have been published. In this experiment, when the base and topdressing nitrogen application rate was higher than $84 \text{ kg} \cdot \text{hm}^{-2}$ and $160 \text{ kg} \cdot \text{hm}^{-2}$ respectively, a peak of NO_3^- -N accumulation could be found during the whole wheat growth stage, especially in B1, B2, B3 and A3, where marked NO_3^- -N accumulation appeared in 120–180 cm soil layers at maturity. A2 with a nitrogen fertilizer rate of $168 \text{ kg} \cdot \text{hm}^{-2}$ and a ratio of base fertilizer to topdressing of 1:2 had the least NO_3^- -N accumulation amount in 0–100 cm soil layers, and there was no marked difference in 100–200 cm soil layers during the whole wheat growth stage. So, one-off application of mass nitrogen fertilizer should be avoided in wheat production. Applying nitrogen fertilizer by stages could promote wheat absorption of more nitrogen, and decrease the nitrogen loss. Once a reasonable nitrogen application rate is confirmed, the base and topdressing nitrogen application rate should be strictly controlled so as to reduce the NO_3^- -N accumulation amount in deep soil layers, avoid eluviation losses, and at the same time insure a higher wheat yield with better quality.

4.2 Effect of nitrogen rate and ratio of base fertilizer and topdressing on nitrogen fertilizer use efficiency and nitrogen balance

Many studies have reported that wheat N fertilizer use efficiency could be reduced by increasing the fertilizer N application rate, while the N fertilizer loss could be markedly increased (Liu et al., 2002; Huo et al., 2004; Ju et al., 2003). Another study has shown that residual nitrogen may increase with an increase in the fertilizer N application rate in the range of $75\text{--}150 \text{ kg} \cdot \text{hm}^{-2}$, with the loss rate having no marked change, but when applying $300 \text{ kg} \cdot \text{hm}^{-2}$ fertilizer N, the loss rate may markedly increase (Zhang et al., 1999). As for the effects of different ratios of base and topdressing of nitrogen fertilizer use efficiency, some studies believe that treatment with N fertilizer may increase the nitrogen accumulation and enhance nitrogen fertilizer use efficiency. The optimum ratio of base fertilizer and topdressing is 5:5, and the topdressing stage should be divided into jointing and anthesis (Zhao et al., 2000). This study suggests that there is no marked difference between treatments with the application of nitrogen fertilizer in the plant nitrogen accumulation amount. At the jointing stage, the nitrogen fertilizer apparent loss amount may markedly increase with increasing base nitrogen fertilizer rate. At maturity, when the same ratio of base fertilizer and topdressing is applied, a marked decrease of fertilizer nitrogen rate may markedly increase the nitrogen fertilizer use efficiency, and reduce the nitrogen fertilizer apparent loss and the soil residual amount. At the same N application rate, increasing the ratio of topdressing fertilizer appropriately could enhance nitrogen fertilizer use efficiency and decrease both soil residual and loss rate of N fertilizer. A2 with the highest nitrogen fertilizer use efficiency and less soil residual loss is propitious to keeping the nitrogen balance in the soil-wheat system. So in conditions with higher soil initial Nmin as in this experiment, a lesser basal nitrogen fertilizer rate could markedly reduce the nitrogen fertilizer apparent loss, and enhance the nitrogen fertilizer use efficiency from sowing to the jointing stage. Increasing the ratio of topdressing fertilizer appropriately may also promote the uptake and translocation of more nitrogen by wheat, and enhance the N fertilizer agronomic efficiency, GRE and N harvest index, so as to obtain a higher grain protein yield.

4.3 Effect of nitrogen rate and ratio of base fertilizer and topdressing on grain yield and protein content

Many studies have shown that increasing the fertilizer N rate properly can increase the grain yield, but the excessive fertilizer N rate may not increase the grain yield but even reduce it (Xu et al., 1998; Pan et al., 1999; Lin et al., 2004). Some studies suggest that the optimum nitrogen fertilizer application regime is $240 \text{ kg} \cdot \text{hm}^{-2}$ and the optimum ratio

of base fertilizer to topdressing is 5:5 (Han et al., 1998), but other studies report that the optimum nitrogen fertilizer application regime may be 160 kg·hm⁻², with the optimum ratio of base fertilizer and topdressing at 5:5. This may help obtain the highest grain yield and increase the grain protein content (Yue et al., 1998). This study has indicated that applying nitrogen fertilizer can markedly increase the grain yield, protein content and protein yield, but there exists no marked difference among A2, B2, and B3. At the same N application rate, increasing topdressing fertilizer rate can enhance the grain protein content. Based on the results from A2 in this study, as far as three grain yield inscapes (spike amount, kernel amount per spike, and kernel weight), grain yield and protein content are concerned, the most appropriate nitrogen fertilizer application regime is 168 kg·hm⁻² and the optimum ratio of base fertilizer and topdressing is 1/3:2/3. So on the condition of B1, whose nitrogen fertilizer application regime is 240 kg·hm⁻² and the optimum ratio of base fertilizer and topdressing is 1/2:1/2, a regime applied now in local regions in Longkou city, reducing the nitrogen fertilizer rate and decreasing the ratio of base and topdressing nitrogen can gain a high yield, good quality and high benefit. Under conditions used in this experiment, as far as grain yield, protein content, fertilizer N use efficiency, soil nitrogen balance and NO₃⁻-N accumulation in 0–200 cm soil layers are concerned, A2, whose nitrogen fertilizer rate is 168 kg·hm⁻² and the ratio of base fertilizer and topdressing is 1/3:2/3, is the most appropriate nitrogen fertilizer application regime, considering wheat yields, qualities, benefits and ecology.

The field experiment was conducted in the wheat field with high yield, with available nitrogen at 87.5 mg·kg⁻¹. But there is a vast area of farmland in the Huang (Yellow River)-Huai (Huai River) Plain and the Plain of North China where the available nitrogen content is lower than 80 mg·kg⁻¹. So further studies about how yields, qualities, soil NO₃⁻-N and nitrogen balance performances respond to both N fertilizer rate and ratio of base and topdressing, and the determination of the optimum N application regime in wheat fields with different fertilities is greatly needed.

References

- Dana L D, Douglas L K, Dan B J, Thomas C K, Jerry L H, Thomas S C, Cynthia A C (2002). Nitrogen management strategies to nitrate leaching in tile-drained Midwestern soils. *Agronomy Journal*, 94: 153–171
- Guillard K, Griffin G F, Allinson D W, Yamartino W R, Rafey M M, Pietrzyk S W (1995). Nitrogen utilization of selected cropping system in the U.S. northeast: soil profile nitrate distribution and accumulation. *Agronomy Journal*, 87: 199–207
- Han Y L, Jie X L, Tan J F, Guo T C, Zhu Y J, Wang C Y, Xia G J, Liu Z (1998). Studies on absorption distribution and translocation of N, P and K of super-high-yielding winter wheat. *Acta Agronomica Sinica*, 24(6): 908–915 (in Chinese)
- Huo Z Y, Ge X, Zhang H C, Dai Q G, Xu K, Gong Z K (2004). Effect of different nitrogen application types on N-absorption and N-utilization rate of specific use cultivars of wheat. *Acta Agronomica Sinica*, 30(5): 449–454 (in Chinese)
- Jaime L, Antonio L, Javier F, Sergi E, Joan S (2001). Bread-making wheat and soil nitrate are effected by nitrogen fertilization in irrigated Mediterranean condition. *Agronomy Journal*, 93: 1183–1190
- Ju X T, Liu X J, Zhang F S (2002). Studies on effects of nitrogen fertilizer and nitrogen balance in a winter wheat and summer maize rotation system. *Scientia Agricultura Sinica*, 35(11): 1361–1368 (in Chinese)
- Ju X T, Pan J R, Liu X J, Zhang F S (2003). Studies on the fate of nitrogen fertilizer in a winter wheat/summer maize rotation system in Beijing suburban. *Plant Nutrition and Fertilizer Science*, 9(3): 264–270 (in Chinese)
- Kong L C, Wang Z S, Cao C F (1996). Effects of applying nitrogen fertilizer on yield and quality in high quality wheat. *Journal of Anhui Agricultural Science*, 24 (3): 214–216 (in Chinese)
- Li X X, Hu Y S, Cheng Y S (2003). Effects of different fertilizers on crop yields and nitrate accumulation. *Agricultural Research in the Arid Areas*, 21(3): 38–42 (in Chinese)
- Lin Q, Hou L B, Han W (2004). Effects of nitrogen rates on grain yield and quality of wheat in different soil fertility. *Plant Nutrition and Fertilizer Science*, 10(6): 561–567 (in Chinese)
- Liu L J, Sang D Z, Yang J C, Wang Z Q, Yang J C, Zhu Q S (2003a). Effects of real-time and site-specific nitrogen managements on rice yield and nitrogen use efficiency. *Scientia Agricultura Sinica*, 36(12): 1456–1461 (in Chinese)
- Liu X J, Ju X T, Zhang F S, Pan J R, Christie P (2003b). Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain. *Field Crops Research*, 83: 111–124 (in Chinese)
- Liu X J, Zhao Z J, Ju X T, Zhang F S (2002). Effect of N application as a basal fertilizer on grain yield of winter wheat, fertilizer N recovery and N balance. *Acta Ecologica Sinica*, 33(7): 1122–1128 (in Chinese)
- Malhi S S, Brandt S A, Ulrich D, Kutcher R H (2002). Accumulation in the soil profile under a various alternative cropping system. *J Plant Nutr*, 25: 2499–2520
- Malhi S S, Gill K S, Harapiak J T, Nyborg M, Gregorich E G, Monreal C M (2003). Light fraction organic N, ammonium, nitrate and total N in a thin black chernozemic soil under brome grass after 27 annual applications of different N rates. *Nutrient Cycling in Agroecosystems*, 65(3): 201–210
- Ottman M J, Pope N V (2000). Nitrogen fertilizer movement in the soils influenced by nitrogen rate and timing in irrigated wheat. *Soil Sci Soc Am J*, 64: 1883–1892
- Pan Q M, Yu Z W, Wang Y F, Tain Q Z (1999). Studies on uptake and distribution of nitrogen in wheat at the level of 9000 kg per hectare. *Acta Agronomica Sinica*, 25(5): 541–547 (in Chinese)
- Raun W R, Johnson G V (1995). Soil-plant buffering of inorganic nitrogen in continuous winter wheat. *Agronomy Journal*, 87: 827–834
- Wu J S, Guo S L, Dang T H (2003). Mechanisms in the accumulation and movement of mineral N in soil profiles of farming land in a semi-arid region. *Acta Ecologica Sinica*, 23 (10): 2041–2049 (in Chinese)
- Xu Y C, Jiang T H, Zhang C L, Wang Y B, Cai D T (1998). Responses of grain yield and protein content of bread-making wheat cultivars to nitrogen application rate. *Acta Agronomica Sinica*, 24(6): 731–737 (in Chinese)
- Yang X Q, Feng F, Song C Q, Leng S Y (2003). Fate and efficient use of nitrogen fertilizer in main agroecosystems. *Plant Nutrition and Fertilizer Science*, 9(3): 373–376 (in Chinese)

- Yue S C, Yu Z W, Yu S L (1998). Effect of nitrogen application at different growth stages on nitrogen distribution and leaves metabolism in winter wheat. *Acta Agronomica Sinica*, 24(5): 1–4 (in Chinese)
- Zhang X, Zhu H X, Sun C H (1999). Studies on a nitrogen recommendation system on middle and low yield wheat fields by ^{15}N . *Chinese Journal of Soil Science*, 30(5): 224–226 (in Chinese)
- Zhao G C, Li C X, Zhang B M, Wang C Y (2000). Effects of different proportion and stage of nitrogen application on nitrogen utilization in winter wheat. *Acta Agriculturae Boreali-Sinica*, 15(3): 99–102 (in Chinese)
- Zhou S L, Zhang F S, Wang X R (2001). Studies on the spatio-temporal variations of soil $\text{NO}_3^- \text{N}$ and apparent budget of soil nitrogen I. Winter wheat. *Acta Ecologica Sinica*, 21(11): 1782–1789 (in Chinese)