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Nitrogen dynamics and budgets in a winter wheat–maize cropping system in the North China Plain

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Abstract

Nitrogen dynamics and budgets in a clay loam soil (Meadow Aqualf) in the North China Plain were investigated in a winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) cropping system comparing the effects of four N rates (0, 120, 240 and 360 kg N ha⁻¹ as urea) applied twice to each crop over 2 years. Ammonium nitrogen (NH₄-N) in the soil profile remained at a low and constant level (except in the surface 20 cm layer) following application of fertilizer N. In contrast, nitrate nitrogen (NO₃-N) levels were significantly altered by the rate of applied N. A strong tendency of NO₃-N to move from the surface layer to the lower layers (20–100 cm) was observed during the wheat and maize growth seasons in treatments of 240 and 360 kg N ha⁻¹ per crop (N240 and N360). The amounts of NO₃-N accumulated in the soil profile were significantly higher in N240 and N360 than those in N0 and N120 (treatments receiving 0 and 120 kg N ha⁻¹ per crop). After 2 years, soil NO₃-N levels at 0–300 cm depth in N120, N240 and N360 amounted to 336, 815 and 1141 kg ha⁻¹, respectively, with more than half of these amounts distributed in the 100–300 cm layer. The calculated total N balance indicates that most fertilizer N was available as NO₃-N in the top 300 cm of the soil profile using traditional fertilization and irrigation practices. Over the subsequent 2 years, N losses were calculated to be relatively low in N120 but significantly higher in N240 and N360. Measured gaseous N losses showed that NH₃ volatilization and denitrification comprised only a small fraction of total N losses during the 2-year rotation, while NO₃-N leaching from the top 100 cm of the soil profile accounted for most N losses across all N rates and experimental years. The N budget showed that accumulation and/or leaching of NO₃-N below 100 cm depth (beyond the reach of most roots) was the main pathway for N losses in the winter wheat–maize cropping system. The recommended N application rate of 120 kg N ha⁻¹ minimized soil NO₃-N accumulation and leaching losses while maintaining high yields and N utilization by winter wheat and maize.

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Keywords: Winter wheat–maize cropping; NO₃-N accumulation and leaching; Gaseous N losses; N budgets; China

1. Introduction

Nitrogen cycles in intensively managed agricultural ecosystems have received more attention than those in

natural ecosystems because fertilizer N inputs are much higher in the former (Richter and Roelcke, 2000). Increasing fertilizer N inputs to arable land beyond crop needs results in gaseous and leaching loss and/or an enhanced N input by runoff to surface water (Spalding and Exner, 1993; Xing and Zhu, 2000). As the nation with the largest agricultural production, China consumed 23 million t of fertilizer N in 2000

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(Anonymous, 2001), accounting for about 28% of total world N consumption (Fixen and West, 2002). Thus the N budget and the fate of fertilizer N in Chinese agricultural systems are becoming important issues and are receiving much attention from both agricultural and environmental scientists (Zhu, 1997; Zheng et al., 2002). The N budget or balance is often evaluated by comparing various N inputs and outputs in soil–crop systems by considering changes of soil mineral N (Sogbedji et al., 2000) or not (Sapek, 1997; Zhu, 1997). Research on N balances that takes into account mineralization and inorganic N in soils can provide more detailed information on the N cycles and losses by integrating soil N process into the total N budgets (R. Schulz, personal communication). There are limitations to the calculation of N balances, however, because it is difficult to measure accurately each component of N budgets in relation to soil processes (Jarvis, 1996; Sogbedji et al., 2000).

Winter wheat–maize double cropping is an important rotation system mainly practiced in an area of >14 million ha in the North China Plain (Anonymous, 2001; Zhu et al., 1994) and contributes 48 and 39% of the total winter wheat and maize production in China, respectively (Liu and Mu, 1993). Excessive use of fertilizer N is very common in the winter wheat–maize cropping system, particularly in regions with high population densities. In the Beijing area, for example, the average N application rates are 309 kg N ha⁻¹ for winter wheat and 256 kg N ha⁻¹ for maize (Zhao et al., 1997). An investigation by Ma (1999) in Shandong province also found average N application rates of >500 kg N ha⁻¹ in wheat–maize cropping systems. Clearly, such high N rates greatly exceed the N requirements of both crop species at local yield levels and will inevitably lead to large losses of N. Gaseous N losses, particularly NH₃ volatilization, are often considered as the main pathway for fertilizer N loss on calcareous soils, particularly when urea and ammoniacal fertilizers are applied to the surface of soils (Sommer and Jensen, 1994; Weier, 1994; Zhu and Chen, 2002). However, this loss can be lowered substantially by incorporating the fertilizer N into the soil or applying just prior to irrigation (Zhang et al., 1989, 1992). In most cases, denitrification is also regarded as an important N loss process in spite of the great uncertainty associated with its measurement (Mosier et al., 1986). Nitrogen loss by NO₃-N leaching from

agricultural fields is a growing concern as elevated NO₃-N levels are found in groundwater in many countries (Spalding and Exner, 1993; van der Ploeg et al., 1997; Diez et al., 2000). Zhang et al. (1996) used to find that at over half of 69 locations investigated, NO₃-N concentrations in well water exceeded the allowable limit (11.3 mg N l⁻¹) by WHO and were positively correlated with fertilizer N rates across the Beijing–Tianjin–Tangshan region. NO₃-N accumulation in the soil profile and its downward movement below 1–2 m depths have been shown for winter wheat (Westerman et al., 1994) and maize (MacGregor et al., 1974; Sogbedji et al., 2000) at higher N application rates. NO₃-N leaching may thus occur under appropriate environmental conditions. In the UK, for example, increasing fertilizer N use has led to an increase of 36 kg N ha⁻¹ per year in leachable nitrate on intensive wheat fields over the past 50 years (Davies and Sylvester-Bradley, 1995). In arable systems in Germany, the annual N leaching loss was 45 kg N ha⁻¹ while the gaseous loss was <20 kg N ha⁻¹, although N immobilization in the lower topsoil has governed N balances since about the 1960s (Richter and Roelcke, 2000; Nieder et al., 1995).

However, there is a lack of in situ integrated studies on N dynamics, N budgets and N loss pathways under high fertilizer N inputs in winter wheat–maize cropping systems. Integrated research is essential to understand N behavior and balance in specific soil–crop systems. An in situ field study with irrigated winter wheat–maize rotation in the North China Plain was undertaken to investigate (1) the yield response to different N fertilizer rates under traditional irrigation and management systems; (2) dynamics and accumulation of inorganic N in the soil profile; (3) the N budget and pathways for N losses as related to the N application rate.

2. Materials and methods

2.1. Experimental site

A field experiment was conducted for 2 consecutive years (October 1998–September 2000) on a typical agricultural soil of the North China Plain (Meadow Aqualf) at the Campus Experimental Farm of China Agricultural University in Beijing. Before the

Table 1
Precipitation (mm) measured at the campus experimental station of CAU, Beijing, China

	1998	1999	2000	30-year average
January	1	0	15	3
February	26	0	0	7
March	4	3	7	9
April	35	44	9	19
May	54	41	32	33
June	183	18	22	78
July	248	79	134	192
August	114	66	197	212
September	5	38	31	57
October	62	23	38	24
November	11	6	5	7
December	1	0	0	3
Sum	744	318	490	644

experiment commenced, a winter wheat–maize rotation was grown from 1997 to 1998 without any NPK fertilizer inputs to make the soil at the field site homogeneous. The site is located at 39°57'N and 119°30'E, and is 38 m above mean sea level at the north edge of the North China Plain. During the experiment, total and monthly precipitation values were clearly different from the 30-year average (Table 1). Selected soil profile characteristics are presented in Table 2. According to the local soil fertility classification in Beijing (Liu et al., 1999), the experimental soil is highly fertile. Prior to the experiment, continuous winter wheat–maize rotation was practiced using traditional tillage conditions for more than 10 years. The average grain yields were between 5 and 7 t ha⁻¹ with rates of 210–320 kg N, 90–120 kg P₂O₅ and 120–180 kg K₂O ha⁻¹ (including both chemical fertilizers and organic manures) applied to each wheat or maize crop. Winter wheat usually requires three

irrigation episodes (each of 75 mm water) while maize only requires supplemental irrigation especially during periods of dry weather. Crop management including inputs of pesticides and herbicides was conducted according to conventional agricultural practice.

2.2. Fertilizer N treatments

Rates of N fertilizer as urea were 0, 120, 240, and 360 kg N ha⁻¹ per crop, representing the unfertilized control (N0), the current recommended N rate (N120), the traditional N rate (N240) and 1.5 times the traditional N rate (N360). The plots, each 6 m × 21 m in size, were arranged in a randomized complete block experimental design with three replicates. Fertilizer N was applied in two equal dressings for both winter wheat and maize. For winter wheat, half of the N was incorporated into the surface soil (0–10 cm) in early October prior to planting, and the other half broadcasted before sprinkler irrigation at shooting stage (mid-April). In the case of maize, half of the N was bandspread at the three-extended-leaf stage (early July) and the remainder was top-dressed prior to rainfall or sprinkler irrigation at the 10-extended-leaf stage (early August). The same amounts of P and K were applied to all plots as concentrated superphosphate and potassium sulfate. 60 kg P₂O₅ ha⁻¹ was applied for winter wheat prior to planting and 60 kg P₂O₅ ha⁻¹ and 60 kg K₂O ha⁻¹ were applied for maize at the three-extended-leaf stage.

2.3. Crop and soil management

Winter wheat cultivar 'Nongda101' was planted in 25 cm rows at a rate of 180 kg seeds ha⁻¹ between 5 and 9 October each year. After the harvest of winter wheat, a hybrid maize cultivar 'Nongda108' was

Table 2
Selected initial soil physicochemical characteristics at the experimental site

Soil depth (cm)	pH (H ₂ O)	Organic C (g kg ⁻¹)	Total N (g kg ⁻¹)	Olsen P (mg kg ⁻¹)	NH ₄ OAc K (mg kg ⁻¹)	Sand (%)	Silt (%)	Clay (%)
0–20	7.9	15.5	1.43	41.9	95.5	43	40	17
20–40	8.2	9.2	0.79	27.2	90.3	37	49	14
40–60	8.1	5.6	0.39	10.9	88.8	34	43	23
60–80	8.2	4.4	0.42	9.6	85.2	27	42	31
80–100	8.1	4.6	0.41	8.5	79.0	28	40	32

planted with zero-tillage in 60 cm rows with 30 cm distance between every pair of adjacent plants with a density of 55 000 seedlings ha^{-1} in the same permanent plots between 18 and 24 June. The selected varieties and the planting densities are popular in the local wheat–maize rotations. Water management was as follows. Winter wheat was irrigated prior to planting and at shooting stage with 75 mm water on each occasion (1998–1999 season), and at seedling, tillering, shooting and ear emergence stages with 75 mm water on each occasion (1999–2000 season). Maize was irrigated at seedling (40 mm) and 10-leaf stages (60 mm) in the 1999 season and irrigated at seedling stage only (60 mm) in 2000. A sprinkler irrigation system with a water meter was used to ensure the uniform distribution and accurate control of irrigation water rate on each plot. The plants of each plot were harvested manually and aboveground crop residues except stubbles of both crops were removed from the plot during the 2-year period. The plant samples, comprising separate grain and straw from 1 m^2 sampling area of wheat and five plants in the case of maize, were oven-dried at 65 °C for 3 days. Grain and straw yields were recorded and grain data were adjusted to 14% moisture content. Concentrations of N in grain and straw samples of both wheat and maize were digested $\text{H}_2\text{SO}_4\text{--H}_2\text{O}_2$ solution and determined by the micro-Kjeldahl method (Bremner, 1996). N uptake (kg ha^{-1}) by winter wheat and maize was estimated from the grain and straw dry matter yields multiplied by their N concentrations.

Dynamics of inorganic N as $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the soil profile were monitored by sampling three cores per plot with a 3 cm i.d. tube auger, and separating them into 20 cm depth increments. Sampling was done separately at 10 soil depths (0–200 cm) before planting and after harvest of winter wheat, and for 15 soil depths (0–300 cm) after harvest of maize in all N treatments during the 2-year study. Following the same protocol, soil samples were periodically taken from the upper five soil depths (0–100 cm) before and/or after important field operations during the first cycle of the winter wheat–maize rotation to monitor the dynamics of inorganic N during and after each crop.

Field moist soil samples were thoroughly mixed, and representative sub-samples were extracted immediately by shaking with 0.01 M CaCl_2 solution

(1:10 soil:solution ratio) for 1 h on a rotary shaker (180 rev min^{-1}) followed by filtration. The extracts were directly analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ by an automated continuous flow analyzer (TRAACS 2000, Germany) or were stored at -19°C in a refrigerator until they were analyzed by the same method within 3 months. Bulk density (D_b) of the soils was determined to 200 (winter wheat) or 300 cm depth (maize) with 3 cm i.d. by 20 cm long steel corers with open ends following the soil sampling protocol described above for N dynamics. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations (mg kg^{-1} soil) were converted to units of kg ha^{-1} according to the mean D_b values of the different soil layers.

2.4. Nitrogen budget

A N budget was estimated for each plot for four growing periods of winter wheat and maize from October 1998 to September 2000. Soil $\text{NH}_4\text{-N}$ was not used in the N budget due to its relative stability throughout the crop rotation. Only the 0–100 cm soil profile was used for $\text{NO}_3\text{-N}$ in the N budget calculation as most of the crop roots were distributed in the 0–90 cm depth under the experimental conditions (Cao, 2002). For each period, the inputs to the budget consisted of initial soil $\text{NO}_3\text{-N}$ before planting, N mineralization and the applied fertilizer N. N mineralization was estimated by the balance of inputs and outputs in the control (N0) treatment according to the following formula:

$$\begin{aligned} N_{\text{mineralization}} &= \text{N uptake from the control} \\ &+ \text{initial 0–100 cm soil } \text{NO}_3 \\ &- \text{N in the control} - \text{residual 0–100 cm soil } \text{NO}_3 \\ &- \text{N in the control (units : } \text{kg ha}^{-1}) \end{aligned}$$

Outputs consisted of plant N uptake, residual soil profile $\text{NO}_3\text{-N}$ and apparent N loss. The latter was attributed to the sum of $\text{NO}_3\text{-N}$ leaching, gaseous N emission as NH_3 volatilization and denitrification, and the N unaccounted for (other N losses not determined). The increment of $\text{NO}_3\text{-N}$ accumulation below 100 cm soil depth in fertilizer N treatments for each growing season compared with the control was regarded as leaching loss in this budget calculation considering the distribution of roots and water movement in the soil

profile. A semi open-static system (Nommik, 1973) was adapted to monitor NH_3 volatilization loss from the plots as described by Beyrouthy et al. (1988). However, the ammonia-trapping chamber used in this study was constructed from PVC pipe with inner dimensions measuring 15 cm $\times$ 10 cm (diameter $\times$ height). Sheet PVC tabs, welded to each of the inner walls of the chambers at two levels, supported a lower sponge for NH_3 volatilizing from fertilizer treatments and the upper sponge to prevent contamination from atmospheric NH_3 using phosphoric acid/glycerine solution. The NH_3 absorbed by the inner sponge was analyzed by TRAACS 2000 and 99.5% recovery was achieved in a preliminary trial (Wang et al., 2002). Ammonia volatilization in each N treatment was monitored only in the first cycle of winter wheat–maize rotation. Field denitrification in selected treatments (N0, N120 and N360) was monitored by a soil core incubation system using the C_2H_2 -inhibition method (Ryden et al., 1987) during the 2-year study. Three soil cores (0–15 cm) were sampled and incubated for 24 h under 10% C_2H_2 concentration and the N_2O concentration was analyzed by a GC system (HP 5890II; Zou, 2001).

Statistical analysis of the data was accomplished by standard analysis of variance (ANOVA) and pairs of mean values compared by least significant difference (LSD) at the 5% level using the SAS software package (SAS Institute, 1996).

3. Results and discussion

3.1. Grain yields of winter wheat and maize

The response of crops to fertilizer N mainly depends on soil N fertility, crop yield level and climatic conditions. In the first cycle of the rotation (1998–1999), grain yields of winter wheat (6.2–6.4 t ha⁻¹) did not respond to applied N rate but significantly increased with increasing N rate in maize. The sole exception was grain yield in the N240 treatment, probably because soil N supply (e.g. initial $\text{NO}_3\text{-N}$, N mineralization and other N inputs from atmosphere and irrigation) sufficed for adequate growth of the first crop (Table 3). From the second rotation (1999–2000), however, grain yields of both crops (4.6–7.2 t ha⁻¹ for wheat and 6.0–7.5 t ha⁻¹ for maize) significantly increased with increasing

Table 3

Mean grain yields (t ha⁻¹, adjusted to 14% moisture content) of winter wheat and maize under each N treatment in a 2-year winter wheat–maize cropping system^a

	N0	N120	N240	N360
1998–1999 winter wheat	6.19 a	6.38 a	6.36 a	6.38 a
1999 maize	4.15 a	4.88 b	4.33 ab	4.81 b
1999–2000 winter wheat	4.65 a	7.16 b	6.40 b	6.69 b
2000 maize	6.04 a	7.07 b	7.44 b	7.48 b

^a Values within the same crop followed by the same letter are not significantly different at 5% level (method of LSD).

fertilizer N application as N became growth limiting (Table 3). Severe drought in 1999 particularly from July to September (as shown in Table 1) led to a significant decline in maize yields and a reduced N response in 1999 compared with those in 2000 under normal rainfall conditions (Table 3). Water stress was almost certainly the main reason for the lack of response of maize to applied N. Winter wheat and maize yields were not significantly different among the three N application rates (N120, N240, N360) in 2 years of the rotation, suggesting that N application exceeding 120 kg N ha⁻¹ did not further increase crop yields. In addition, the levels 240 and 360 kg N ha⁻¹ were beyond the N requirements of the two crop species at these grain yield levels. Considering the high available P and K levels in our experimental soil, these two nutrients would be very unlikely to limit grain yields of wheat and maize particularly under high N levels. No Zn or other micronutrient deficiency symptoms in maize or wheat were observed during the 2-year study. Thus, the availability of micronutrients in the soil is unlikely to be the yield-limiting factor as well.

Many other studies in China have also confirmed that both winter wheat and maize seldom respond to N rates higher than 120–180 kg N ha⁻¹ in spite of different crop varieties (Chen et al., 2000; Zhou et al., 2001; Zhu, 1998). In Germany, similar yield response to N supply was observed by Blankenau and Kuhlmann (2000), who found a small decline in grain yields of winter wheat and barley when 0–90 cm N_{min} + fertilizer N > 190–220 kg N ha⁻¹. Therefore, the very high N application rate used in the area could not produce greater grain yields but probably led to substantially more N loss compared with the recommended N rate as discussed later.

Fig. 1. Dynamics of $\text{NH}_4\text{-N}$ in the topsoil (0–20 cm) as affected by N application rate in the first cycle of a winter wheat–maize cropping system (1998–1999). Solid arrows denote fertilizer N application and dotted arrows denote irrigation. Bars = S.E.M (standard error of mean).

3.2. Dynamics of soil inorganic N

After application of fertilizer N as urea, soil $\text{NH}_4\text{-N}$ increased drastically due to the rapid hydrolysis of the urea, then declined to its original level as nitrification occurred. In winter wheat, $\text{NH}_4\text{-N}$ in the topsoil (0–20 cm layer) peaked at 6 days after the basal application was incorporated into the soil, and then it dropped to the level of the control within the next 14–21 days, depending on the rate of fertilizer N (Fig. 1). The change in $\text{NH}_4\text{-N}$ in the same layer was less pronounced when urea was applied as topdressing (with irrigation) at the shooting stage (Fig. 1), presumably due to higher soil temperature and moisture (Parker and Larson, 1962). This was quite similar to our previous results (Liu et al., 2001). During the maize season, $\text{NH}_4\text{-N}$ in the topsoil changed more rapidly by N applications (Fig. 1) mainly due to the high nitrification rate in the summer season. Little change was observed in the lower soil layers (20–100 cm) throughout the whole cropping year (data not shown). It appears that the dynamics of $\text{NH}_4\text{-N}$ in the profile of these upland soils can therefore be disregarded for calculation of N recommendations and N budgets.

In contrast, $\text{NO}_3\text{-N}$ in the soil profile was greatly altered by the N application rate (Fig. 2). $\text{NO}_3\text{-N}$ levels in all soil layers (0–100 cm profile) remained at a very low level in the control during the entire rotation with the exception of a slight increase in $\text{NO}_3\text{-N}$ in the topsoil in mid-October 1998, presumably due to tillage (ploughing) enhancing mineralization of organic

N in this soil layer. In the N120 treatment, only the topsoil $\text{NO}_3\text{-N}$ significantly increased after fertilizer application over the control showing that the amount of $\text{NO}_3\text{-N}$ entering into 20–100 cm profile at this relatively low N level did not exceed crop uptake. In the N240 and N360 treatments, $\text{NO}_3\text{-N}$ in all soil layers increased after application of fertilizer N. Topsoil $\text{NO}_3\text{-N}$ in the two N treatments remained at very high levels (60–120 kg ha^{-1}) during the whole winter wheat–maize cropping season (Fig. 2A). $\text{NO}_3\text{-N}$ in other subsoil layers increased significantly after the second N application in the winter wheat season compared to the control and N120, suggesting a large amount of $\text{NO}_3\text{-N}$ moving into deeper soil layers after the shooting stage of winter wheat (Fig. 2B and C). The change in $\text{NO}_3\text{-N}$ at a soil depth of 0–100 cm was much greater during the maize crop than winter wheat, indicating a relatively pronounced movement of $\text{NO}_3\text{-N}$ in the soil profile during the summer when rainfall peaked (Fig. 2).

3.3. Accumulation and leaching of $\text{NO}_3\text{-N}$

The amounts of $\text{NO}_3\text{-N}$ in the soil profile varied greatly among experimental years and crops (Table 4). $\text{NO}_3\text{-N}$ in 0–200 (wheat) or 0–300 cm (maize) of the soil profile increased with increasing N rate and over time. After the winter wheat harvest (1998–1999), the amounts of $\text{NO}_3\text{-N}$ in 0–100 and 100–200 cm layers in N240 and N360 increased markedly compared with the control and even the original $\text{NO}_3\text{-N}$ before the

Fig. 2. Dynamics of $\text{NO}_3\text{-N}$ in different soil depths (0–20, 20–60 and 60–100 cm) as affected by N application rate in the first cycle of a winter wheat–maize cropping system (1998–1999). Solid arrows denote fertilizer N application and dotted arrows denote irrigation. Bars = S.E.M.

trial, while the amounts of $\text{NO}_3\text{-N}$ in corresponding layers in N120 were not significantly different from the original $\text{NO}_3\text{-N}$ level. In the first rotation cycle (1998–1999), $\text{NO}_3\text{-N}$ accumulated mainly in the top 200 cm of the soil profile and the accumulation of $\text{NO}_3\text{-N}$ below this layer was not significantly different

among four N levels, indicating that negligible amounts of $\text{NO}_3\text{-N}$ were leached out of the top 200 cm of the profile in the first rotation cycle (Fig. 3). In the second rotation cycle (1999–2000), the accumulation of $\text{NO}_3\text{-N}$ in the soil profile increased continuously, especially in the N240 and N360 treatments (Fig. 3).

Table 4

NO₃-N leaching losses (kg ha⁻¹) in a 2-year winter wheat–maize cropping system^a

	N0	N120	N240	N360
After harvest of 1998–1999 wheat				
NO ₃ -N accumulation below 100 cm	18 a	40 a	135 b	184 c
Accumulated leaching as fertilizer N	–	22 a	117 b	166 b
Leaching in 1998–1999 wheat season	–	22 a	117 b	166 b
After harvest of 1999 maize				
NO ₃ -N accumulation below 100 cm	72 a	115 a	227 b	254 b
Accumulated leaching as fertilizer N	–	43 a	155 b	182 b
Leaching in 1999 maize season	–	21 a	38 a	16 a
After harvest of 1999–2000 wheat				
NO ₃ -N accumulation below 100 cm	32 a	82 a	249 b	345 c
Accumulated leaching as fertilizer N	–	50 a	217 b	313 b
Leaching in 1999–2000 wheat season	–	7 a	62 ab	131 b
After harvest of 2000 maize				
NO ₃ -N accumulation below 100 cm	64 a	194 b	385 c	574 d
Accumulated leaching as fertilizer N	–	120 a	321 b	510 c
Leaching in 2000 maize season	–	70 a	104 a	197 b

^a Values within the same row with the same letters are not significantly different at the 5% level.

After the winter wheat harvest (1999–2000), the total amount of NO₃-N in the 0–200 cm soil layers were 499 and 675 kg ha⁻¹ in N240 and N360, respectively, significantly higher than those of the control and N120 (Fig. 3). After the maize harvest in 2000, NO₃-N accumulation amounted to 657 and 865 kg ha⁻¹ at 0–200 cm and to 158 and 276 kg ha⁻¹ in the 200–300 cm layer at the high N levels (Fig. 3). This indicates that much larger amounts of NO₃-N in N240 and N360 were leached out of the top 200 cm of soil compared to the control and N120.

Both cumulative NO₃-N leaching and NO₃-N leaching per crop are shown in Table 4. The NO₃-N leaching in N120, which ranged from 7 to 70 kg ha⁻¹, was relatively small during the four crop seasons (Table 4). The amounts of NO₃-N leaching increased markedly under high N levels (N240 and N360). Much greater NO₃-N leaching was observed in N240 and N360 treatments in all crop seasons with the exception of the 1999 maize season when dry weather conditions probably limited the movement of water and nitrate in the soil profile (as seen in Table 1). In this study, irrigation promoted the downward movement of NO₃-N in the soil profile. As seen in Fig. 2, each irrigation event caused a rapid decline in NO₃-N in the topsoil and an increase in the subsoil. However, NO₃-N leaching below 200 cm soil depth was mainly driven

by the rainfall, particularly in the 2000 summer season (Table 1). Significant leaching of NO₃-N from the root zone (100 cm depth) under winter wheat occurred only under high N levels (Table 4), and would have been considered to be very unlikely at lower application rates (Yuan et al., 1995). Large NO₃-N accumulations below 2 m soil layers have been reported frequently under high N rates in the same winter wheat–maize cropping systems (Lu et al., 1998) and in vegetable cropping systems (Yuan, 1999) in northern China. These observations clearly indicate that the accumulation in the subsoil and leaching of NO₃-N to the groundwater may be a serious environmental issue in the high N input regions of China. Further studies would be needed to trace the fate of the NO₃-N that has accumulated in the subsoil.

3.4. Gaseous N losses by NH₃ volatilization and denitrification

Gaseous N losses by NH₃ volatilization and denitrification are illustrated in Table 5. NH₃ volatilization as fertilizer N ranged from 3 to 34 kg ha⁻¹ in winter wheat and 7–19 kg ha⁻¹ in maize, and the total volatilization losses were 10, 21 and 53 kg ha⁻¹ (equivalent to 4–7% of total fertilizer N) in N120, N240 and N360, respectively, in the first rotation cycle (Table 5).

Fig. 3. Accumulation of $\text{NO}_3\text{-N}$ in the 0–200 cm and/or 0–300 cm soil profile at the beginning of the trial and after the harvest of winter wheat and maize during the two cycles of rotation (1998–2000). Values within the same column with same letters are not significantly different at the 5% level.

We assume that similar volatilization losses occurred at the same N application rates in both the 1999 and 2000 growth seasons of wheat and maize but NH_3 volatilization was not measured in the second rotation cycle. The volatilization losses measured were somewhat lower than the average losses estimated on calcareous upland soils in China (9%) estimated by Xing and Zhu (2000). However, the volatilization losses in this study may have reflected the actual losses more closely because the urea used was incorporated in top 10 cm of the soil or top-dressed with irrigation or rainfall, thus lowering NH_3 volatilization compared with surface application (Cai, 1997; Zhu and Chen, 2002).

Denitrification losses were negligible in winter wheat and were small and variable in maize (6–8 kg ha^{-1} in 1999 and 12–19 kg ha^{-1} in 2000) under different N

rates (Table 5). This variation is thought to be mainly due to the change in rainfall between experimental years (Table 1). Similarly, Sanchez et al. (2001) reported that 10% of N applied as urea (40.7 kg ha^{-1}) was lost by denitrification mainly during the maize cropping period in central Spain. It should be pointed out that the denitrification losses determined using the direct method are often lower than those estimated using the indirect method (the difference method). New direct methods are required that account for the rapid spatial and temporal variability of denitrification in the field (Ryden and Rolston, 1983).

3.5. Nitrogen budgets

For sustainable land use, nutrient budgets have to be balanced to avoid negative impacts on the environment,

Table 5

Gaseous N losses (kg ha⁻¹) by NH₃ volatilization and denitrification in a 2-year winter wheat–maize cropping system

	N120	N240	N360
NH₃ volatilization			
1998–1999 wheat	3 a ^a	9 a	34 b
1999 maize	7 a	12 ab	19 b
Sum	10 a	21 a	53 b
Denitrification			
1998–1999 wheat	tr.	n.d. ^b	tr.
1999 maize	6 a	n.d.	8 a
Sum	6 a	n.d.	8 a
1999–2000 wheat	tr.	n.d.	tr.
2000 maize	12 a	n.d.	19 b
Sum	12 a	n.d.	19 b

^a Values within the same row with the same letters are not significantly different at the 5% level.

^b Not determined.

especially in high-yielding systems. We therefore calculated the N budget for each growing season and both crops from the top 100 cm soil layer during the experimental period (October 1998–September 2000) and the results are presented in Table 6 together with measured N losses by NO₃-N leaching and gaseous N emissions. The results show that N mineralization (91–153 kg ha⁻¹ per crop) was a significant input from the highly fertile soil particularly in the wet summer season. This source of N often determines crop response to N fertilizer. Under similar

Table 6

Nitrogen budget (kg ha⁻¹) showing N inputs (initial soil NO₃-N, applied N and N mineralization) and N outputs (N uptake, residual NO₃-N, and apparent N loss) together with measured N losses in a 2-year winter wheat–maize cropping system

	N0	N120	N240	N360
1998–1999 wheat season				
Initial soil NO ₃ -N	57	57	57	57
Applied N	0	120	240	360
N mineralization	91	91	91	91
Plant N uptake	124 a ^b	149 b	155 b	163 b
Residual soil NO ₃ -N	24 a	85 ab	106 b	186 c
Apparent N loss (= 1 + 2 + 3 – 4 – 5)	0	34	127	159
NO ₃ -N leaching	–	22	117	166
Gaseous N emission	–	3	9	34
Unaccounted for ^a	–	9	1	–41

Table 6 (Continued)

	N0	N120	N240	N360
1999 maize season				
Initial soil NO ₃ -N	24 a	85 ab	106 b	186 c
Applied N	0	120	240	360
N mineralization	95	95	95	95
Plant N uptake	106 a	138 b	141 b	147 b
Residual soil NO ₃ -N	13 a	82 ab	149 b	256 c
Apparent N loss (= 1 + 2 + 3 – 4 – 5)	0	80	151	238
NO ₃ -N leaching	–	21	38	16
Gaseous N emission	–	13	12	27
Unaccounted for	–	46	101	195
1999–2000 wheat season				
Initial soil NO ₃ -N	13 a	82 ab	149 b	256 c
Applied N	0	120	240	360
N mineralization	91	91	91	91
Plant N uptake	98 a	175 b	179 b	177 b
Residual soil NO ₃ -N	6 a	44 a	250 b	330 b
Apparent N loss (= 1 + 2 + 3 – 4 – 5)	0	74	51	200
NO ₃ -N leaching	–	7	62	131
Gaseous N emission ^c	–	tr.	n.d. ^d	tr.
Unaccounted for	–	67	–9	69
2000 maize season				
Initial soil NO ₃ -N	6 a	44 a	250 b	330 b
Applied N	0	120	240	360
N mineralization	153	153	153	153
Plant N uptake	136 a	173 b	182 b	182 b
Residual soil NO ₃ -N	23 a	152 b	430 c	567 d
Apparent N loss (= 1 + 2 + 3 – 4 – 5)	0	–8	31	94
NO ₃ -N leaching	–	70	104	197
Gaseous N emission	–	12	n.d.	19
Unaccounted for	–	–90	–73	–122
Two cycles of wheat–maize rotation (1998–2000)				
Initial soil NO ₃ -N	57	57	57	57
Applied N	0	480	960	1440
N mineralization	430	430	430	430
Plant N uptake	464 a	635 b	657 b	669 b
Residual soil NO ₃ -N	23 a	152 b	430 c	567 d
Apparent N loss (= 1 + 2 + 3 – 4 – 5)	0	180	360	691
NO ₃ -N leaching	–	120	321	510
Gaseous N emission	–	28	21	79
Unaccounted for	–	32	18	102

^a The rest N loss could not be included in NO₃-N leaching and gaseous N emissions.

^b Values within the same soil layer with the same letters are not significantly different at the 5% level.

^c NH₃ volatilization in the second rotation cycle was not measured.

^d Denitrification was not measured during the two cycles of wheat–maize rotation in the treatment (N240).

maize–wheat–maize sequences, Diez et al. (1997) also reported high rates of N mineralization, particularly when soil temperature and moisture were favorable. It should be pointed out that the N mineralization in our study included the N from environment (e.g. N deposition and biological N fixation) as well.

Most of the N uptake by winter wheat and maize exceeded the low N application rate (N120) but was less than the traditional N rate (N240), typically ranging from 100 to 180 kg ha⁻¹ (Table 5). Crop N uptake significantly increased with increasing N rate, but further fertilizer N inputs beyond 120 kg N ha⁻¹ did not lead to significant increases in N uptake (Table 6). The lack of response of plant N uptake to higher application rates indicates that the extra N from the two highest N rates studied is very poorly utilized by winter wheat and maize, as crop yields did not differ between these N treatments (Table 3). In both crops, the lower rate of N applied by the N120 treatment prevented waste of N fertilizer by matching crop N requirements better than the N240 and N360 treatments at local yield levels. This conclusion is supported by the results of NO₃-N accumulation in the soil profile (Fig. 3) and the apparent N losses (Table 6).

Estimates of inputs and outputs of the N budget (Table 5) indicate that the variation in NO₃-N was related mainly to the applied N rates in the cropping system. In October 1998 (at start of the trial), 57 kg ha⁻¹ soil NO₃-N was present in the 0–100 cm depth for all N levels, while the residual soil NO₃-N after the maize harvest in 2000 was 23, 152, 430 and 567 kg ha⁻¹ for the control, N120, N240 and N360 treatments, respectively. Apparent N losses drastically increased with increasing N rate, particularly when the N rate exceeded 120 kg N ha⁻¹ (Table 6), indicating that fertilizer N losses occurred mainly under high inputs of fertilizer N.

During the 1998–1999 winter wheat growing season, the apparent N losses amounted to only 34 kg ha⁻¹ in N120, but increased to 127 and 159 kg ha⁻¹ at the two higher N rates (Table 6). The data indicate that a large fraction of the apparent N losses was due to NO₃-N leaching below 100 cm depth (accumulated in 100–200 cm soil layer) while gaseous N losses (as NH₃ volatilization and denitrification) and the N unaccounted for contributed only marginally to the total N losses (Table 6).

In the 1999 maize growth season, the apparent N losses in all three N treatments (N120, N240 and N360) were much greater than in the previous winter wheat season (Table 6). However, the NO₃-N leaching (16–38 kg ha⁻¹) and gaseous N losses (12–27 kg ha⁻¹) in all N treatments were relatively small and comparable in the maize season. The large amounts of N unaccounted for (Table 6) suggest that a considerable amount of fertilizer N was immobilized, lost through plant shoots or denitrified in the subsoil in the 1999 maize season.

During the 1999–2000 winter wheat growing season, this large apparent N loss was observed only in the N360 treatment, indicating that N leaching losses as NO₃-N were much higher than in the other treatments (Table 6). Among the total N losses, NO₃-N leaching accounted for the main part in the N240 and N360 treatments. Lower N level (N120) led to much lower N leaching but relatively high N unaccounted for compared with the higher N levels.

During the 2000 maize growing season, a gain in N was measured under all N treatments. This was because the September 2000 soil NO₃-N levels were higher than the June 2000 levels due to a large amount of N mineralized during the summer season. Elevated residual soil NO₃-N levels were measured down to 300 cm (Fig. 3 and Table 4) with rates of 240 and 360 kg ha⁻¹ after harvest of maize in 2000, suggesting that the accumulation of NO₃-N in the 100–300 cm layer from NO₃-N leaching below 100 cm soil depth was the main pathway for N losses during this period.

After two cycles of the rotation, the total apparent N losses were 180, 360 and 691 kg ha⁻¹ in N120, N240 and N360 treatments while the accumulated NO₃-N leaching were 120, 321 and 510 kg ha⁻¹ in above three N treatments, respectively. In contrast, gaseous N losses were much lower than N leaching in the corresponding N treatments especially at the higher N levels. The close relationship between total apparent N loss and NO₃-N leaching further supports the conclusion that NO₃-N leaching was the main loss pathway in the winter wheat–maize cropping system.

Weier (1994) reviewed the nitrogen loss in agriculture in subtropical Australia. He found that the leaching of added or mineralized N was the major pathway of N removal from that used for sorghum production.

In a 5-year field lysimeter study, Rasse et al. (1999) showed that about 23% of fertilizer N as $\text{NO}_3\text{-N}$ could be leached out of 1.83 m soil depth when the N rates were 202 kg N ha^{-1} per year while the leaching loss dropped to 17% at N rate of 101 kg N ha^{-1} per year in the inbred maize systems. These results agreed with our findings on the N loss pathway in the winter wheat–maize rotation.

4. Conclusions

Traditional tillage improved N mineralization and total N supply and thus masked the effects of N fertilizer on yields in the first crop of the study. In the subsequent crops, N levels significantly affected crop yields, N utilization, soil $\text{NO}_3\text{-N}$ accumulation and N losses. Nitrogen use efficiency rapidly decreased with increasing over-fertilization. The recommended N rate (120 kg N ha^{-1}) was effective in reducing gaseous and leaching losses of N, minimizing over-fertilization, and maintaining good crop yields compared to the traditional and high N rates (240 and 360 kg N ha^{-1}). Soil $\text{NO}_3\text{-N}$ levels increased substantially when N application rate exceeded crop requirements during the four growing seasons of winter wheat and maize. The dynamics of $\text{NO}_3\text{-N}$ in the soil profile showed that high nitrate leaching losses occurred at conventional and high N application rates. The N budgets indicated that N losses via NH_3 volatilization and denitrification were comparatively small while $\text{NO}_3\text{-N}$ leaching with movement below 100 cm soil depth was the major pathway for N losses in the winter wheat–maize cropping system.

In general, minimizing N leaching losses requires precise estimation of N fertilizer needs, particularly in high-yielding production systems. The traditional N rates practiced by farmers on the North China Plain exceeded the crop N requirement regardless of soil N supply. A 50% reduction in fertilizer N on the basis of conventional N application (240 kg ha^{-1}) still maintained high grain yields, improved N utilization and prevented $\text{NO}_3\text{-N}$ accumulation in the soil profile, showing the large potential for saving N on highly fertile soils. The soil $\text{N}_{\min}$ test (mainly for $\text{NO}_3\text{-N}$) is likely to be an effective N recommendation tool for the purpose of precise N management (Wehrmann and Scharf, 1986). Our previous results (Liu et al., 2003a,b)

identified the possibility of the $\text{N}_{\min}$ method for N management in winter wheat and maize crops in a neighboring site in Beijing. According to those studies, the optimized N supply (fertilizer N plus soil $\text{N}_{\min}$) was 180 kg N ha^{-1} for both winter wheat and maize crops. The actual N supply in N120 treatment was even higher than the optimized N supply by the $\text{N}_{\min}$ method in the present study if both $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ contents were also included, suggesting that the recommended fixed-N rate be further optimized in high-yielding winter wheat–maize cropping systems.

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