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RESEARCH ARTICLE

# Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat–maize double cropping system in the North China Plain

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**Abstract** There is a growing concern about excessive nitrogen (N) and water use in agricultural systems in North China due to the reduced resource use efficiency and increased groundwater pollution. A two-year experiment with two soil moisture by four N treatments was conducted to investigate the effects of N application rates and soil moisture on soil N dynamics, crop yield, N uptake and use efficiency in an intensive wheat–maize double cropping system (wheat–maize rotation) in the North China Plain. Under the experimental conditions, crop yield of both wheat and maize did not increase significantly at N rates above 200 kg N ha$^{-1}$. Nitrogen application rates affected little on ammonium-N ($NH_4$-N) content in the 0–100 cm soil profiles. Excess nitrate-N ($NO_3$-N), ranging from 221 kg N ha$^{-1}$ to 620 kg N ha$^{-1}$, accumulated in the 0–100 cm soil profile at the end of second rotation in the treatments with N rates of 200 kg N ha$^{-1}$ and 300 kg N ha$^{-1}$. In general, maize crop has higher N use efficiency than wheat crop. Higher $NO_3$-N leaching occurred in maize season than in wheat season due to more water leakage caused by the concentrated summer rainfall. The results of this study indicate that the optimum N rate may be much lower than that used in many areas in the North China Plain given the high level of N already in the soil, and there is great potential for reducing N inputs to increase N use efficiency and to mitigate N leaching into the groundwater. Avoiding excess water leakage through controlled irrigation and matching N application to crop N demand is the key to reduce $NO_3$-N leaching and maintain crop yield. Such management requires knowledge of crop water and N demand and soil N dynamics as they change with variable climate temporally and spatially. Simulation modeling can capture those interactions and is considered as a powerful tool to assist in the future optimization of N and irrigation managements.

**Keywords** Nitrate-N accumulation and leaching · Wheat–maize double cropping system · Crop nitrogen use · Ground water · North China Plain

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**Abbreviations**

BM Above ground biomass
GY Grain yield
IEN Internal N use efficiency
$P_E$ Physiological efficiency
PFP Partial factor productivity of applied N
$R_F$ Apparent recovery fraction

## Introduction

In China, application of chemical N fertilizers increased from $5.9\times10^7$ kg yr$^{-1}$ in 1952 to $1396.4\times10^7$ kg yr$^{-1}$ in 1987. The associated N losses increased from $3.0\times10^7$ kg yr$^{-1}$ to $698.2\times10^7$ kg yr$^{-1}$ (Zhu and Wen 1992), accounting for 0.6% and 34.7% of the total N application in those 2 years, respectively. The overuse of chemical N fertilizers has led to reduced N use efficiency and considerable N leaching into groundwater nationwide (Zhang et al. 1996). This is particularly the case in the North China Plain, where about 48% of the wheat and 39% of the maize yield in China (Liu and Mu 1993) were produced through intensive cropping (double or triple cropping), high rates of N fertilizer application and irrigation (Zhu and Wen 1992), leading to over-consumption of fresh water resources and increase in N leaching (Zhang et al. 1996; Ju et al. 2004). In the period from 1987 to 2000, the total N application in the North China Plain increased steadily from $546.04\times10^7$ kg yr$^{-1}$ to $1135.27\times10^7$ kg yr$^{-1}$, but the wheat and maize yield was not increased proportionally due to the declines of both N use efficiency and crop planting area (Anonymous 2001).

Elevated $NO_3$-N concentration in groundwater associated with excess N fertilizer application has raised growing concern about soil $NO_3$-N leaching from arable lands (Xing and Zhu 2000; Follett and Delgado 2002). In northern China, a positive correlation between $NO_3$-N concentrations in well water and N application rates has been reported by Zhang et al. (1996). High $NO_3$-N leaching ranged from 15% to 55% of applied N fertilizer in the North China Plain were reported by Zhu and Wen (1992).

Optimization of N application (amount and time) to meet crop N requirement is the key to increase crop yield, N use efficiency, and to minimize $NO_3$-N leaching. This requires knowledge of crop N demand and the amount of available N released from soil through mineralization process, the difference between the two vary considerably with crop species, season and soil types. In China, an average application rate of 150–180 kg N ha$^{-1}$ was recommended for a single crop when considering both grain production and environmental impacts (Zhu 1998). However, the annual N fertilizer application in many areas in the North China Plain exceeded 500 kg N ha$^{-1}$ in the wheat–maize double cropping system, which has caused reduced N use efficiency and increased risk of $NO_3$-N leaching to groundwater (Zhu 1998; Ju et al. 2004). Many studies have been carried out to investigate the effects of N application rates on grain yield of single crops and overall N balance in the soil (Zhang et al. 1992; Zhao et al. 1997; Liu et al. 2001, 2003; Ju et al. 2002), few efforts have been made to assess soil N dynamics and $NO_3$-N leaching, crop N uptake and use efficiency of a continuous wheat–maize double cropping system under different N and soil moisture conditions in the North China Plain. Such studies can provide insight into the dynamic interactions between soil–plant systems, climate and management options and assist in the optimization of N application and irrigation managements.

In this paper, we report on the $NO_3$-N dynamics (accumulation and leaching) in an intensive wheat–maize double cropping rotation under different N and irrigation regimes in the North China Plain. We first analyze the N balance in the root zone soil and N movement into deeper soil layers and groundwater, and then we evaluate the impact of N rates on crop yield and N use efficiency under different soil moisture conditions. Finally we discuss ways of improving crop production, N use efficiency, and reducing $NO_3$-N leaching in the intensive cropping system.

## Materials and methods

### Site description

Two years of field experiments were conducted from 2000 to 2002 on silt loam soil at Yucheng Ecological Station (36°50′ N, 116°34′ E, 20 m above sea level) in Shandong Province, North China Plain. It is one of 34 agricultural ecosystem stations of Chinese Ecological Research Network. The soil is formed from the sediments of the Yellow River and is calcareous, alkaline, and rich in phosphorus and potassium. Agriculture in the area is intensified by a double cropping system (two crops a year) with high-yielding cultivar and high fertilizer and water inputs. The physicochemical properties of the soil profile were determined in June 2000 (Table 1). The site is characterized by summer monsoon climate (Fig. 1) with mean annual rainfall of 515 mm (1990–2000). 70–80% of the rain falls in the maize growing season from July to late September and only 20–30% in wheat growing season from October to early June. In the 2000–2001 and 2001–2002 rotations, the rainfall in maize seasons accounts for 70% (385 mm) and 55% (161 mm) of annual rainfall, respectively. The solar radiation was slight lower in 2000–2001 than in 2001–2002 (Fig. 1). The groundwater table is generally about 3.5–4.0 m below the soil surface during wheat or maize seasons.

### Crop rotation

A typical winter wheat–summer maize double cropping rotation was chosen, representative of the common farming practices in the area, where winter wheat is usually planted in October and maize in June. Maize cultivar Nongda108 was planted in 65 cm rows at a density of 65,000 plant $ha^{-1}$ on 12 June 2000, 12 June 2001 and 8 June 2002 with no tillage. After maize harvest, soil was ploughed before planting winter wheat. Winter wheat cultivar Lankao 906 was planted in 25 cm rows at a rate of 180 kg $ha^{-1}$ on 10 October 2000 and 5 October 2001. The main growth stages of wheat and maize were listed in Table 2. The selected crop varieties and planting densities are representative of that used by local farmers.

### Nitrogen and irrigation treatments

Four N application rates (0, 100, 200, and 300 kg N $ha^{-1}$ for each crop noted as $N_0$, $N_1$, $N_2$, $N_3$) and two soil moisture levels (85±15% and 70±15% of field capacity in 0–50 cm soil noted as high (H) and low (L)) were arranged as split plots in a randomized complete block design with three replications. Soil moisture treatments were the main plots and N rates were the subplots (12.5 m×4 m), thus eight treatments in total are noted as $HN_0$, $HN_1$, $HN_2$, $HN_3$, $LN_0$, $LN_1$, $LN_2$, $LN_3$. Subplots were separated by PVC tiles down to 100 cm depth in soil and a 50 cm border area with ditch and PVC tiles down to 100 cm depth to prevent the movement of water and N between them.

Urea (46% N) was used as N fertilizer and applied by hand before irrigation or rainfall. For winter wheat, 50% of total applied N was incorporated into the surface soil (0–10 cm) shortly before sowing (7 Oct. in 2000 and 3 Oct. in 2001) and the rest at heading stage (25 Apr. in 2001 and 20 Apr. in 2002). For maize, half of the N was applied between V6 (sixth leaf) and V7 (seventh leaf) stages (22 July in 2000, 19 July in 2001 and 11 July in 2002) and the other half at tasseling stages (15 Aug. in 2000, 10 Aug. in 2001 and 5 Aug. in 2002). Phosphorus (as triple superphosphate) and potassium (as potassium sulphate) were applied at the rates of 300 kg $P_2O_5$ -$ha^{-1}$ and 225 kg $K_2O$ $ha^{-1}$, respectively only before planting winter wheat in the two rotations from 2000 to 2002. The fertilizers application schemes were chosen based on commonly practices used by local farmers.

**Table 1** Soil physicochemical properties in the experimental site at Yucheng ecological station

| Soil depth (cm) | Clay (%) | Silt (%) | Sand (%) | Bulk density (g $cm^{-3}$) | Total nitrogen (g $kg^{-1}$) | Organic matter (g $kg^{-1}$) | LL[a] ($cm^{-3}$) | DUL[b] ($cm^{-3}$) | pH |
|---|---|---|---|---|---|---|---|---|---|
| 0–20 | 22.1 | 65.1 | 12.8 | 1.28 | 0.64 | 9.56 | 0.147 | 0.362 | 8.16 |
| 20–65 | 21.7 | 67.0 | 11.3 | 1.39 | 0.36 | 5.30 | 0.135 | 0.350 | 8.20 |
| 65–97 | 13.7 | 58.0 | 28.3 | 1.40 | 0.21 | 2.66 | 0.110 | 0.296 | 8.22 |
| 97–104 | 25.1 | 71.5 | 3.4 | 1.42 | 0.18 | 2.33 | 0.165 | 0.384 | 8.23 |
| 104–150 | 12.5 | 63.0 | 24.5 | 1.39 | 0.18 | 1.86 | 0.130 | 0.361 | 8.25 |

[a] Lower limit of plant available water

[b] Drained upper limit

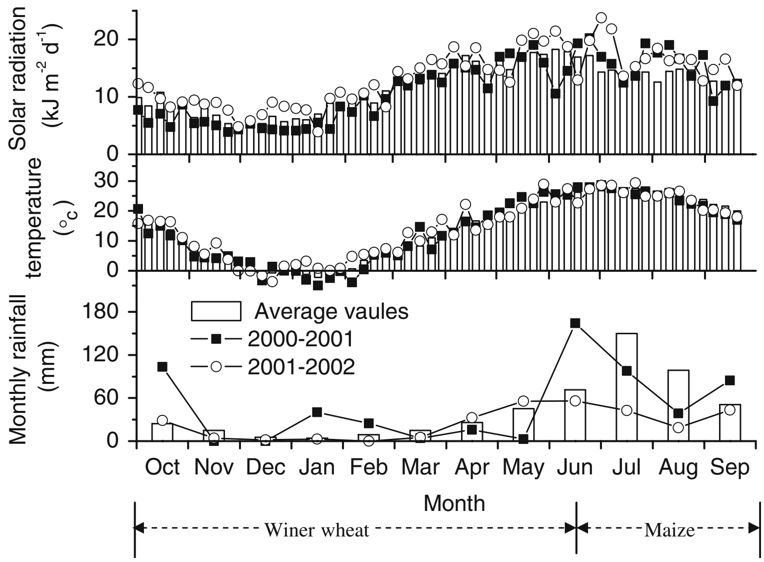



**Fig. 1** Seven-day moving averages of solar radiation and temperature, and monthly rainfall at Yucheng ecological station. Vertical bars are average values for a longer period from 1997 to 2004 for solar radiation and from 1980 to 2000 for monthly rainfall

**Table 2** Crop growth stages of wheat and maize in the double cropping system at Yucheng ecological station from 2000 to 2002

| Years | Crops | Growth stages | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sowing | Emergence | Tillering | Stem extension | Heading | Flowering | Physiological maturity | Harvest |
| 2000–2001 | Winter wheat | 10/10/2000* | 18/10/2000 | 02/11/2000 | 05/04/2001 | 24/04/2001 | 05/05/2001 | 05/06/2001 | 08/06/2001 |
| | Maize | 12/06/2001 | 18/06/2001 | – | – | – | 10/08/2001 | 23/09/2001 | 25/09/2001 |
| 2001–2002 | Winter wheat | 05/10/2001 | 11/10/2001 | 25/10/2001 | 02/04/2002 | 21/04/2002 | 01/05/2002 | 03/06/2002 | 05/06/2002 |
| | Maize | 08/06/2002 | 13/06/2002 | – | – | – | 08/08/2002 | 25/09/2002 | 28/09/2002 |

* All dates are in the format of DD/MM/YYYY

The two soil moisture levels were maintained at 85±15% (high moisture treatment) and 70±15% (low moisture treatment) of field capacity in the 0–50 cm soil layer by supplemental irrigation. Irrigation water was supplied to field capacity for high moisture treatments and 85% of filed capacity for low moisture treatments when the moisture in the soil profiles was below 70% and 55% of field capacity, respectively. Irrigation water amount was controlled by water meter. The amount of supplemental irrigation was calculated by comparing the soil moisture content in the 0–50 cm soil profiles with the target upper limits (100% field capacity for high moisture treatment and 85% field capacity for low moisture treatment). The total irrigation amounts during the growing seasons were listed in Table 3. The differences in added irrigation water between the low and high moisture levels or between N treatments were greater in the second rotation than in the first rotation mainly due to the lower seasonal rainfall in the second rotation. In the second rotation (2001–2002), higher irrigations were applied in the high N treatments, and in the first rotation (2000–2001) similar irrigation water was applied among these treatments mainly due to the high seasonal rainfall (Fig. 2).

Data collection and measurements

Daily rainfall, temperature and solar radiation were recorded at the meteorological station about 300 m away from the experimental site.

In the middle of each plot of the second field replication, aluminum access tubes were installed in the soil profile. Soil moisture was measured every 10 cm to the depth of 150 cm at five-day intervals using a neutron moisture meter (CNC503D2 developed by the Institute

**Table 3** Total irrigation amounts (mm of water) in different crop seasons during the two rotations (wheat and maize double cropping rotation) from 2000 to 2002

| Years | Crops | Treatments | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $HN_0$ | $HN_1$ | $HN_2$ | $HN_3$ | Average | $LN_0$ | $LN_1$ | $LN_2$ | $LN_3$ | Average |
| 2000–2001 | Winter wheat | 248 | 248 | 248 | 248 | 248 | 218 | 218 | 218 | 218 | 218 |
| | Maize | 200 | 212 | 214 | 202 | 207 | 198 | 206 | 182 | 190 | 194 |
| 2001–2002 | Winter wheat | 233 | 291 | 325 | 347 | 299 | 274 | 248 | 292 | 252 | 267 |
| | Maize | 196 | 258 | 276 | 324 | 264 | 250 | 224 | 258 | 232 | 241 |
| Total irrigation amounts | | 877 | 1009 | 1063 | 1121 | 1018 | 940 | 896 | 950 | 892 | 920 |

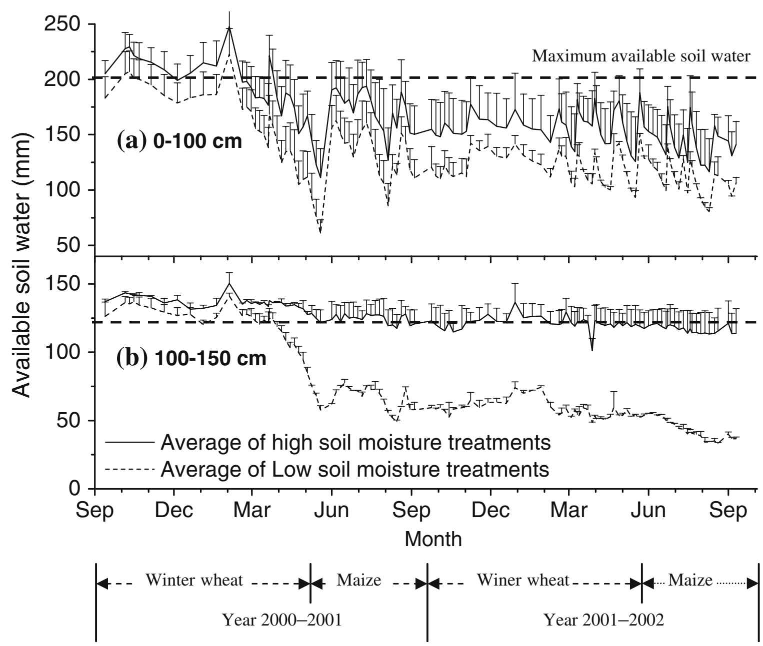



**Fig. 2** Changes in available soil water (differences between actual soil water content and lower limit of plant available water) in the 0–100 cm (**a**) and 100–150 cm (**b**) soil profiles under two soil moisture levels (neutron probe measurements in replication 2) in the wheat–maize rotation from 2000 to 2002. Vertical bar is standard error, i.e., SE based on the four N fertilizer application rates. The horizontal lines indicate the maximum available soil water calculated as the difference between soil moisture at drained upper limit (DUL) and lower limit (LL)

of Modern Physics, Chinese Academy of Sciences, CAS). Such measurements were taken only in the second field replication and additional measurements were taken after irrigation or rainfall. Other data such as soil $NO_3$-N, soil $NH_4$ and soil $NO_3$-N in solution and groundwater were also measured in this replication. In addition, moisture in the top 30 cm soil layer was measured by oven method in all replications before planting to calibrate the neutron moisture meter, to compare the differences in top soil moisture between replications, and to estimate the amount of water required for irrigation.

For soil N measurements, a ceramic candle extraction system with tubes (inside diameter 50 mm) was installed in each treatment in the second field replication at 100, 150, 250 cm soil depths. Samples of the soil water solution were taken at an interval of about 2 weeks from September 2000 to September 2002. In all field replications, soil samples were taken 1–2 d after each harvest or before each planting by sampling three cores per plot with an auger (3 cm inside diameter tube) to 100 cm depth in 20 cm increments. Subsequent soil samples were taken only in the second field replication with an interval of about 30 d from 2000 to 2002. Ammonium-N and nitrate-N contents were determined by UV spectrophotometer and indigotic colorimetric method after the soil samples or soil water extracts from the ceramic candle were extracted by 2 M KCl (Markus et al. 1985). Bulk density of the soils was measured from 0 cm to 150 cm depth with soil cores (3 cm inside diameter by 20 cm long) (Table 1). The $NH_4$-N and $NO_3$-N contents in soil (mg $kg^{-1}$ soil) were converted to kg N $ha^{-1}$ based on the bulk density of different soil layers.

A well was drilled in the middle of the field between the treatments $HN_2$ and $LN_3$ to measure the groundwater table, and the $NO_3$-N content in groundwater was measured by the same method as $NO_3$-N content in soil solution with an interval of 2–3 weeks from 2001 to 2002.

Soil organic matter was determined by oxidation with potassium dichromate in a sulphuric medium and excess dichromate evaluated using Mohr's salt (Yeomans and Bremner 1988).

The lower limit of plant available soil water (LL) and drained upper limit (DUL) were estimated as the volumetric soil water content at 1500 kPa and 33 kPa respectively using pressure plate method (Madsen et al. 1986). The maximum crop available water was calculated as the difference between DUL and LL.

Wheat and maize plants were sampled from a 4-$m^2$ area in each plot at harvest for the measurements of grain yields and above ground biomass. Subsamples of grain and straw were oven-dried at 65°C for 3 d to calculate the moisture contents and dry matter. The N content in grain and straw of the subsamples of both wheat and maize were determined by the micro-Kjeldahl method by digesting the sample in $H_2SO_4$–$H_2O_2$ solution (Bremner 1996). Nitrogen uptake by plants was estimated by multiplying the grain and straw dry matter weight by their N concentrations.

### Nitrogen balance in the soil and nitrogen use efficiency

Items in the N balance were estimated in each plot for the four crop growing seasons from September 2000 to September 2002. $NO_3$-N below 100 cm soil depth and $NH_4$-N throughout the soil profile will not be included in the N balance calculations because most of the crop roots were mainly distributed in the 0–100 cm depth (Liu et al. 2003) and relatively low changes in $NH_4$-N content between seasons were found in the experiment. For each period, the N balance can be written as:

$$N_{initial} + N_{input} + N_{min} - N_{uptake} - N_{residual} = N_{loss} \quad (\text{unit: kg N ha}^{-1})$$

where $N_{initial}$ is initial soil $NO_3$-N in the 0–100 cm soil profiles; $N_{input}$ is N application rate (100, 200, or 300 kg N ha$^{-1}$); $N_{min}$ is N mineralization; $N_{uptake}$ is N uptake by plant; $N_{residual}$ is residual $NO_3$-N in 0–100 cm soil profiles and $N_{loss}$ is N loss. $N_{loss}$ is considered as mainly $NO_3$-N leaching since other N losses via denitrification, volatilization and erosion are relatively low under such environmental conditions as reported by Xing and Zhu (2000) and Liu et al. (2003).

Seasonal N mineralization ($N_{min}$), was estimated by the balance of N inputs and outputs in the control ($HN_0$ or $LN_0$, where $HN_0$ was considered as the control in the high moisture level and $LN_0$ was considered as the control in the low moisture level) as follows (Liu et al. 2003):

$$N_{min} = N_{uptake,0} + N_{residual,0} - N_{initial,0}$$

where $N_{uptake,\,0}$, $N_{residual,\,0}$ and $N_{initial,\,0}$ are crop N uptake, residual and initial soil $NO_3$-N in the 0–100 cm soil profile of the controls, respectively.

Nitrogen use efficiency and N fertilizer recovery was analyzed using the following:

Partial factor productivity (PFP)
$$= GY_i/N_i = (GY_0 + \Delta GY_i)/N_i = GY_0/N_i + \Delta GY_i/N_i$$
Internal N use efficiency (IEN)
$$= GY_i/NUP_i$$
Apparent N recovery fraction (NF)
$$= (NUP_i - NUP_0)/N_i = \Delta NUP_i/N_i$$
Physiological efficiency (PE)
$$= (GY_i - GY_0)/(NUP_i - NUP_0) = \Delta GY_i/\Delta N_{up}$$

where $N_i$ is the N fertilizer rate (100, 200, or 300 kg N ha$^{-1}$); $\Delta GY_i$ is the difference between the grain yield at $N_i$ ($GY_i$) and the control ($GY_0$); $NUP_i$ is N uptake by crop at $N_i$ inputs and $\Delta NUP_i$ is the difference in N uptake between $N_i$ and the control.

### Statistical analyses

A mixed-model analysis of variance (ANOVA) was used to calculate effects of N rates and soil moisture on grain yields, N uptake, $NO_3$-N leaching during the four growth seasons. Pairs of mean values were compared by the least significant difference (LSD) at the 5% and 1% level using the SAS software package (SAS Institute 1996). Relationships between grain yield, nitrogen uptake and nitrogen application rates were evaluated by linear and curvilinear regressions.

## Results

### Soil water status

Available soil water (ASW), the difference between the actual soil moisture and the lower limit of plant available water in the 0–100 cm profile, was high with little fluctuations in the two soil moisture levels until April in 2001, and then it fluctuated greatly in response to rainfall, evapotranspiration and supplemental irrigation (Fig. 2a). At 100–150 cm soil depth (Fig. 2b), the average ASW of high moisture treatments showed stable high values during the two rotations, while that of the low moisture treatments declined quickly after early June in 2001 to a relatively low ASW. This is mainly due to lack of downward water movement from the upper layers (0–100 cm) in the low moisture treatments where ASW was maintained at about 55–75% field capacity (Fig. 2a). The soil moisture in 0–150 cm layer was generally higher in the first rotation than the second rotation. The higher ASW in the 100–150 cm soil layers of the high moisture treatments, where soil moisture generally reached or exceeded drained upper limit, implies that more water drained below 100 cm compared with that in the low moisture treatments.

### Changes in $NH_4$-N in the soil profiles

Soil $NH_4$-N in the 0–100 cm profiles ranged from 2 kg ha$^{-1}$ to 45 kg ha$^{-1}$ during the two rotations (data not shown) and was similar between the treatments. It peaked between late May and early June during both years mainly due to the mineralization caused by high soil temperature (Parker and Larson 1962). In the current experiments, N inputs did not clearly increase $NH_4$-N content in 0–100 soil layer and no significant difference in $NH_4$-N between treatments was found during the two rotations (this may also due to the nitrification process). The levels of $NH_4$-N were generally low in comparison to the $NO_3$-N level in the experiment. Therefore, the changes in $NH_4$-N were disregarded for calculation of N balance as suggested by Liu et al. (2001, 2003) in the Beijing area in the North China Plain.

### Changes in $NO_3$-N in the soil profiles

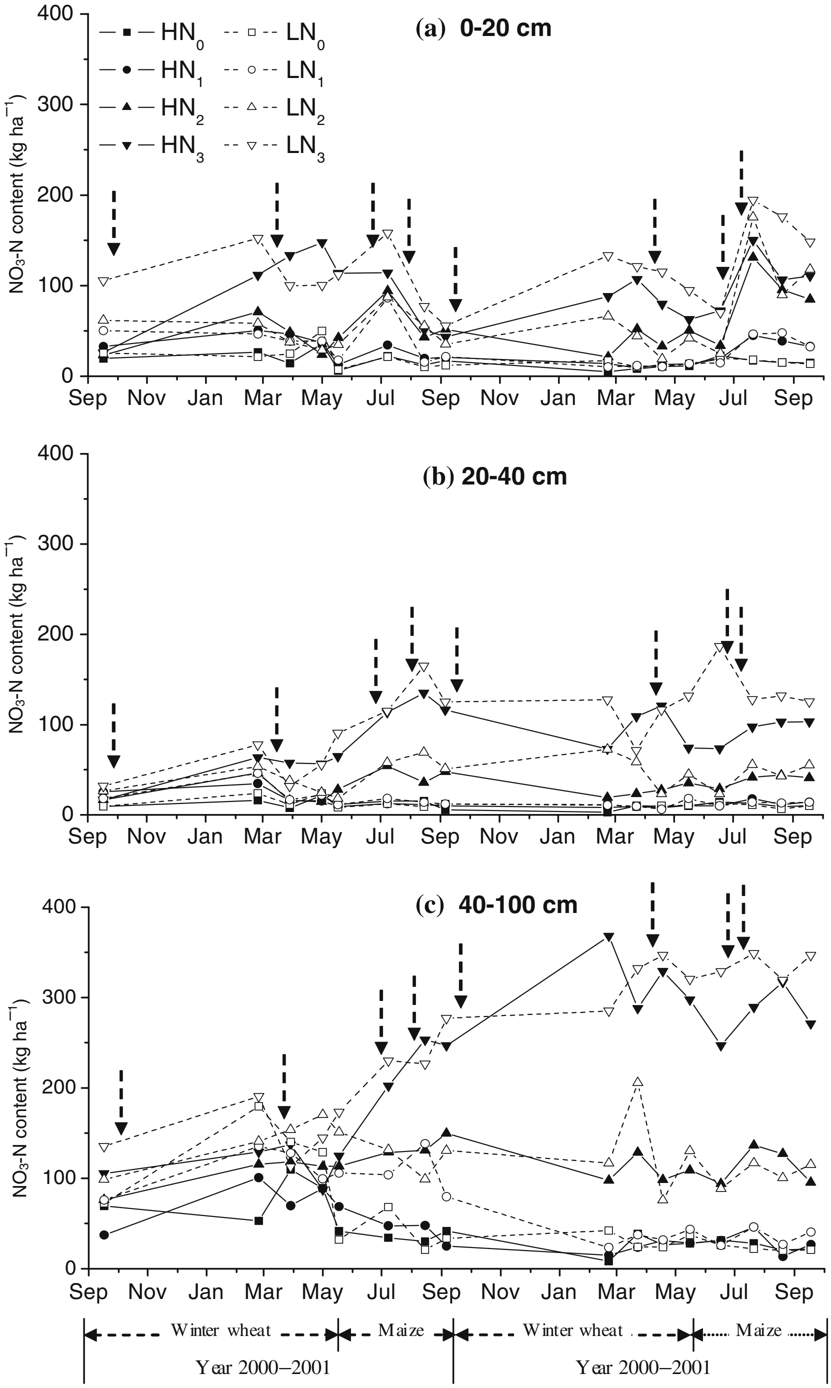
The initial soil $NO_3$-N in the 0–20 cm soil layer in the first rotation (6 October in 2000) varied from 20 kg ha$^{-1}$ in the control to 105 kg ha$^{-1}$ in $LN_3$ (Fig. 3a) as a result of the different N application rates in the previous maize season in 2000. At the beginning of the second rotation (25 September in 2001), in treatments with zero and 100 kg N ha$^{-1}$, $NO_3$-N level was lower than the initial soil $NO_3$-N before the first rotation, indicating soil N depletion especially in the 40–100 cm soil layer; treatments with 200 kg N ha$^{-1}$ kept the N level roughly unchanged, implying the right N balance; while treatments with 300 kg N ha$^{-1}$ significantly increased $NO_3$-N content in the soil profile below 20 cm, showing N accumulation in those layers (Fig. 3). After the second rotation, soil $NO_3$-N was generally increased in treatments with 300 kg N ha$^{-1}$, and treatments with 200 kg N ha$^{-1}$ also increased soil N in the top layers slightly. This result suggested that N application rate at or above 200 kg N ha$^{-1}$ exceeded N uptake by crops and contributed to $NO_3$-N accumulation in the 40–100 cm soil layer in the two experimental years. Such accumulation of $NO_3$-N in the 40–100 cm soil profile poses high risk of N leaching into deeper soil layers, particularly in the maize season when rainfall is high (Fig. 1).

Soil moisture had a significant influence on $NO_3$-N movement in the 0–100 soil profiles. At application rates of 200 kg N ha$^{-1}$ or 300 kg N ha$^{-1}$, $NO_3$-N accumulation in the topsoil (0–20 cm, Fig. 3a and 20–40 cm, Fig. 3b) was generally lower under high soil moisture compared that under low soil moisture levels due to more downwards water leakage into soil layers below 40 cm depth at high moisture level (Fig. 2), leading to more N leaching. In the first rotation with rainfall 576 mm, high $NO_3$-N level accumulated in the 40–100 cm soil layer when 300 kg N ha$^{-1}$ was applied (Fig. 3c). In the second rotation, the lower rainfall (292 mm) resulted in less drainage into deeper layers and more $NO_3$-N accumulation in the top 0–20 cm soil layer (Fig. 3a). Nitrate-N in the 20–40 cm and 40–100 cm soil layers was only slightly increased in the treatments of 200 kg N ha$^{-1}$ and 300 kg N ha$^{-1}$ (Fig. 3b, c).

### Soil $NO_3$-N leaching below 100 cm depth

The $NO_3$-N leached below the 100 cm soil depth varied with treatments and crop/season types, ranging from 0 kg ha$^{-1}$ to 80 kg ha$^{-1}$ for wheat and from 0 kg ha$^{-1}$ to 165 kg ha$^{-1}$ for maize (Table 4). There

**Fig. 3** Soil $NO_3$-N dynamics in the 0–20 cm (**a**), 20–40 cm (**b**) and 40–100 cm (**c**) soil layers under different N and water treatments in the wheat–maize rotation from 2000 to 2002. Vertical arrows denote N fertilizer applications




was a general increase in $NO_3$-N leaching with N application rate irrespective of the soil moisture levels. Soil $NO_3$-N leaching in the maize seasons was generally higher than in wheat seasons due to higher downwards water flow as a result of the concentrated summer rainfall.

Seasonal rainfall coupled with supplemental irrigation and starting soil $NO_3$-N had substantial influences on $NO_3$-N leaching in the wheat–maize double cropping system. Higher $NO_3$-N leaching below 100 cm soil depth occurred in the first maize season (94–165 kg N $ha^{-1}$) than the second maize season

(0–132 kg N $ha^{-1}$) irrespective of the soil moisture levels mainly due to the great different rainfall amounts between the two seasons. Significant higher $NO_3$-N leaching occurred at the low soil moisture level than the high soil moisture level in the first maize season, probably due to the high starting soil $NO_3$-N in the low soil moisture treatments (Table 4). While for the second wheat seasons, significant higher $NO_3$-N was leached at the high moisture level than at the low soil moisture level, probably due to the high water drainages at the high moisture level. Higher $NO_3$-N leaching below 100 cm depth occurred in the second wheat season than the first wheat season at high soil moisture level mainly due to the high starting soil $NO_3$-N level in the second wheat season (Table 4).

### Nitrate-N concentration in soil solution and groundwater

Nitrogen application rates of more than 200 kg N $ha^{-1}$ N resulted in much higher $NO_3$-N concentration at the 150 cm and 250 cm depth compared with other low N application rates, indicating significant $NO_3$-N leaching below the 100 cm depth in those treatments (Fig. 4). At the 150 cm depth, $NO_3$-N concentration was lower in $HN_3$ than in $LN_3$ (Fig. 4a), while at 250 cm depth the order reversed (Fig. 4b), suggesting more $NO_3$-N leached to deeper soil layers in the high moisture treatment. At N rate of below 200 kg N $ha^{-1}$, $NO_3$-N concentration differed little at the 150 cm depth between the two soil moisture treatments (Fig. 4a). At the 250 cm soil depth (Fig. 4b), $NO_3$-N concentration in treatments $LN_0$, $HN_0$, $LN_1$, $LN_2$ and $HN_1$ remained stable. An increase in $NO_3$-N concentration at the 250 cm soil depth in other treatments ($HN_3$, $HN_2$ and $LN_3$) occurred from September 2000 to March 2002, implying continuous $NO_3$-N leaching to this soil layer. Higher $NO_3$-N concentration at the 250 cm depth in $HN_1$ than in $LN_1$ and $LN_2$, or in $HN_2$ than in $LN_2$ and $LN_3$ suggested that more $NO_3$-N was leached to this soil depth under higher moisture level than under low moisture level. Very low $NO_3$-N concentration in soil solution at both 150 and 250 depths in $LN_1$ confirmed that little $NO_3$-N was leached to depth below the 150 cm under low soil moisture conditions when 100 kg N $ha^{-1}$ was applied. By comparing with the $NO_3$-N concentration in the soil solution at the 150 cm and 250 cm soil depths, it can be seen that N leached to depth below the 100 cm did not reach the 250 cm depth under lower soil moisture condition, unless the N fertilizer inputs was as high as 300 kg N $ha^{-1}$. Under high soil moisture condition, more N was leached to 250 cm even at 100 kg N $ha^{-1}$ application rate.

The $NO_3$-N content in groundwater ranged from 0 mg $l^{-1}$ to 2 mg $l^{-1}$ during the two rotations, and was low compared with the safety level for drinking waters (less than 10 mg $l^{-1}$) (Fig. 5). In general, there was an increase in $NO_3$-N content in groundwater during the maize growing seasons, indicating increased $NO_3$-N leaching into groundwater due to the concentrated summer rainfall. Optimizing N fertilizer application in the maize season appears to be essential for reducing $NO_3$-N leaching into the ground water in the wheat–maize rotation in the area.

### Grain yield and nitrogen uptake by crops

As expected, both above-ground biomass (BM) and grain yield (GY) of crops increased with N fertilizer inputs (Table 5). No significant effect of soil moisture on BM or GY was found in the two rotations though maize GY was lower in $LN_1$ and $LN_2$ compared to $HN_1$ and $HN_2$ in 2002. In the first wheat season (2000–2001), BM and GY of wheat increased by 21.4% and 16.3%, respectively from 0 kg N $ha^{-1}$ to 100 kg N $ha^{-1}$ treatment and no significant increase at N rates above 100 kg N $ha^{-1}$. In the second wheat season (2001–2002), BM and GY increased by 189.1% and 238.5%, respectively from 0 kg N $ha^{-1}$ to 200 kg N $ha^{-1}$ treatment. In the two maize seasons, BM and GY showed similar response to N application rates. The lower BM and GY of both wheat and maize in the second rotation (compared with that in the first rotation) in treatments with 100 kg N $ha^{-1}$ or less indicate N deficit stress in the second year in these treatments. This was caused mainly by the lower starting soil N with 60±12 kg N $ha^{-1}$ in the second rotation compared with 111±23 kg N $ha^{-1}$ in the first rotation in these treatments (Table 4).

Crop N uptake increased from 39.3 kg N $ha^{-1}$ to 258.5 kg N $ha^{-1}$ for wheat and from 53.2 kg N $ha^{-1}$ to 175.5 kg N $ha^{-1}$ for maize with N application rates changing from 0 kg N $ha^{-1}$ to 300 kg N $ha^{-1}$ (Table 5). Significant difference in crop N uptake

**Table 4** Soil starting Nitrogen (N), N mineralization ($N_{min}$) in the 0–100 cm profiles and Nitrate leaching below 100 cm depth as affected by soil moisture and fertilizer N rate in the wheat–maize double cropping system from 2000 to 2002 (kg $ha^{-1}$)

| Treatments | | Wheat 2000/2001 | | | Maize 2001 | | | Wheat 2001/2002 | | | Maize 2002 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Moisture | N rate | Starting N | $N_{min}$ | N leaching | Starting N | $N_{min}$ | N leaching | Starting N | $N_{min}$ | N leaching | Starting N | $N_{min}$ | N leaching |
| High | 0 | 98±13[a] | 82±10 | | 59±5 | 108±19 | | 64±12 | 37±3 | | 49±6 | 51±7 | |
| High | 100 | 95±15 | | 23±12 | 91±9 | | 94±32 | 85±15 | | −24±21 | 52±8 | | −7±22 |
| High | 200 | 116±20 | | 6±28 | 184±22 | | 96±33 | 249±43 | | 70±30 | 195±31 | | 66±9 |
| High | 300 | 148±26 | | 7±10 | 303±43 | | 142±31 | 407±76 | | 80±32 | 434±85 | | 132±4 |
| Low | 0 | 108±12 | 90±17 | | 47±5 | 106±13 | | 57±6 | 44±4 | | 62±7 | 48±15 | |
| Low | 100 | 145±19 | | −8±14 | 135±18 | | 100±13 | 123±21 | | 19±7 | 75±11 | | 25±5 |
| Low | 200 | 187±22 | | 38±17 | 204±27 | | 140±9 | 217±28 | | 26±13 | 237±38 | | 59±28 |
| Low | 300 | 273±47 | | 28±28 | 376±51 | | 165±14 | 458±67 | | 16±21 | 547±102 | | 99±24 |
| *Treatment means*[b] | | | | | | | | | | | | | |
| High | | 114±24 a | 82±17 a | 12±19 a | 159±110 b | 108±19 a | 111±35 b | 201±160 a | 37±3 | 62±42 a | 182±181 b | 51±7 | 64±61 a |
| Low | | 178±71 b | 90±17 a | 20±30 a | 191±139 a | 106±13 a | 132±35 a | 214±175 a | 44±4 | 20±15 b | 230±226 a | 48±15 | 58±34 a |
| 0 | | 103±7 c | | | 53±8 d | | | 61±5 d | | | 56±9 c | | |
| 100 | | 120±35 bc | | 8±23 a | 113±31 c | | 96±19 b | 104±27 c | | −3±19 b | 64±17 c | | 9±23 c |
| 200 | | 152±50 ab | | 22±24 a | 194±15 b | | 118±25 b | 233±23 b | | 48±32 a | 216±30 b | | 58±10 b |
| 300 | | 210±88 a | | 18±28 a | 340±51 a | | 153±16 a | 432±36 a | | 48±43 a | 490±80 a | | 115±20 a |
| *Interactions*[c] | | | | | | | | | | | | | |
| *F* value (Moisture×N) | | NS | | NS | * | | NS | NS | | ** | * | | ** |

[a] Standard error

[b] Means within main plot (soil moisture) or subplots (N fertilizer rate) levels followed by the same letter in each column are not significantly different at $P<0.05$ (LSD-test)

[c] NS indicates no significance and *, **, indicate significance at $P<0.05$, 0.01 and 0.001, respectively

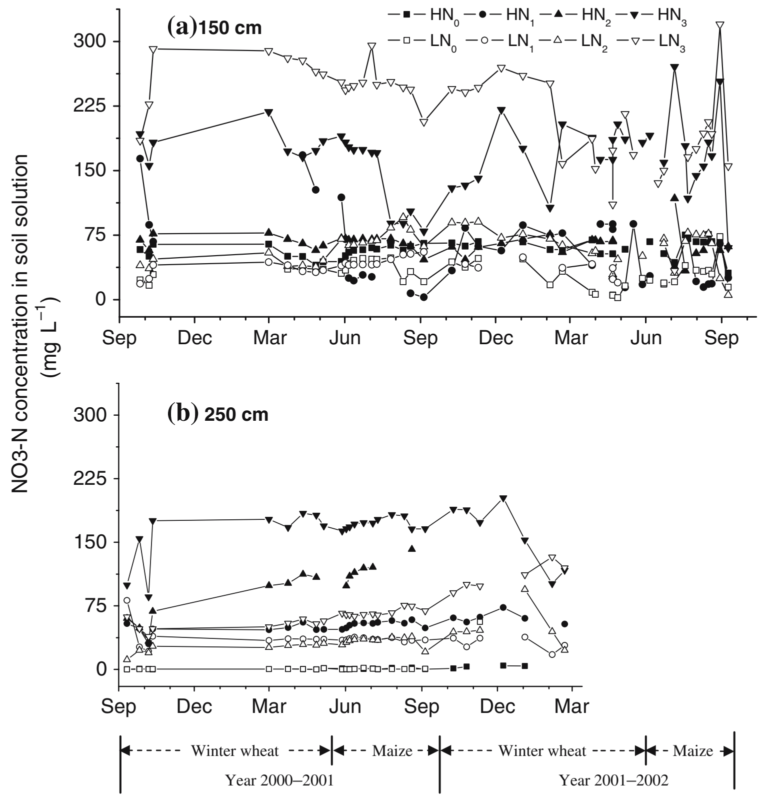



**Fig. 4** Nitrate concentration in soil solution at the 150 cm (**a**) and 250 cm (**b**) soil depths under different N application rates and soil moisture levels in the wheat–maize rotation from 2000 to 2002

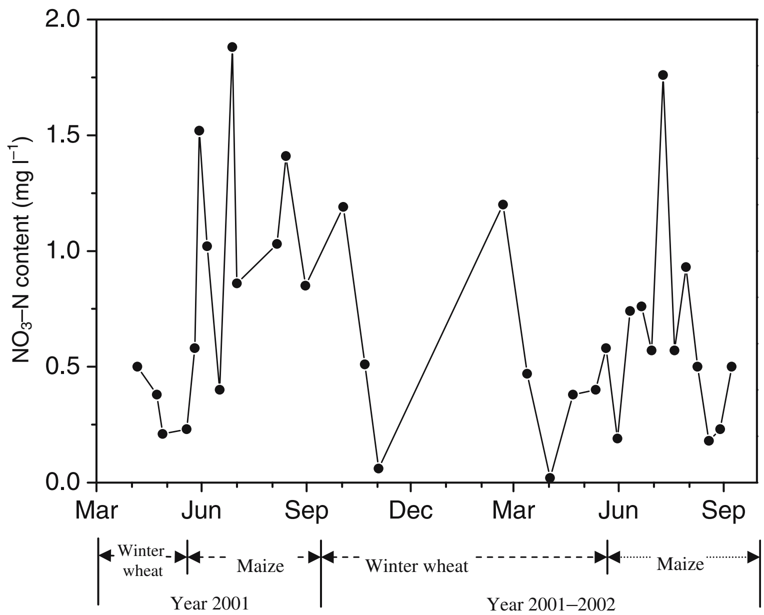



**Fig. 5** Changes of $NO_3$-N concentration in the groundwater at the field experiment from 2001 to 2002

between high and low moisture levels was only found in the first wheat season, where high N uptake was mainly due to high N concentration in plant since no significant different BM and GY was found between the two soil moisture levels. The high initial soil $NO_3$-N at the low moisture level in the first wheat season provided more available $NO_3$-N to wheat in the first season.

**Table 5** Grain yield (GY), above-ground dry-matter (DM), harvest index (HI), plant N in above-ground dry-matter, apparent recovery fraction of applied fertilizer N (NF), Physiological efficiency (PE) and internal N use efficiency (IEN) as affected by soil moisture and fertilizer N rate in wheat–maize rotation from 2000 to 2002

| Treatments | | Wheat 2000/2001 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Moisture | N rate ($kg\ ha^{-1}$) | GY ($mg\ ha^{-1}$) | DM ($mg\ ha^{-1}$) | HI ($kg\ kg^{-1}$) | Plant N ($kg\ ha^{-1}$) | NF (%) | $P_E$ ($kg\ kg^{-1}$) | IEN ($kg\ kg^{-1}$) |
| High | 0 | 4.8±0.5[a] | 11.0±1.0 | 0.44±0.06 | 121.1±11.0 | | | 39.9±5.4 |
| High | 100 | 6.0±0.1 | 14.8±2.1 | 0.40±0.06 | 164.3±22.7 | 43.2±12.0 | 26.9±18.1 | 36.8±5.6 |
| High | 200 | 5.9±0.3 | 14.1±1.7 | 0.42±0.03 | 208.8±21.0 | 43.9±13.8 | 12.8±5.4 | 28.2±1.9 |
| High | 300 | 6.1±0.2 | 15.4±1.2 | 0.35±0.01 | 220.1±2.5 | 33.0±3.4 | 12.0±3.7 | 27.8±0.5 |
| Low | 0 | 5.0±0.5 | 11.5±1.8 | 0.44±0.03 | 150.1±15.9 | | | 33.7±2.3 |
| Low | 100 | 5.5±0.3 | 12.4±0.7 | 0.44±0.01 | 207.3±12.2 | 57.2±14.1 | 9.2±1.4 | 26.6±0.7 |
| Low | 200 | 5.9±0.1 | 14.6±0.5 | 0.41±0.02 | 233.9±8.4 | 41.9±8.4 | 11.1±4.6 | 25.4±1.4 |
| Low | 300 | 5.7±0.5 | 14.2±2.2 | 0.40±0.04 | 258.5±19.7 | 36.1±9.2 | 6.7±1.8 | 22.3±2.2 |
| *Treatment means*[b] | | | | | | | | |
| High | | 5.7±0.6 a | 14.3±2.7 a | 0.40±0.05 a | 178.6±14.3 b | 40.0±9.7 a | 17.2±9.0 a | 33.2±2.2 a |
| Low | | 5.5±0.5 a | 13.2±1.8 a | 0.42±0.03 a | 212.4±14.1 a | 45.1±10.6 a | 9.0±2.6 a | 27.0±1.0 b |
| $N_0$ | | 4.9±0.5 b | 11.2±1.4 c | 0.44±0.04 b | 135.6±13.4 c | | | 36.8±2.8 a |
| $N_1$ | | 5.7±0.3 a | 13.6±1.9 b | 0.43±0.04 ab | 185.8±17.5 b | 50.2±13.0 a | 18.1±9.7 a | 31.7±2.5 b |
| $N_2$ | | 5.9±0.2 a | 14.3±1.2 ab | 0.41±0.02 a | 221.4±14.7 a | 42.8±10.1 ab | 11.9±4.9 a | 26.8±1.6 c |
| $N_3$ | | 5.9±0.4 a | 15.8±2.3 a | 0.38±0.04 a | 239.3±11.1 a | 34.5±6.3 b | 9.3±2.7 a | 25.0±0.9 c |
| *Interactions*[c] | | | | | | | | |
| *F* value (Moisture×N) | | NS | * | NS | NS | NS | NS | NS |
| Treatments | | Maize 2001 | | | | | | |
| Moisture | N rate ($kg\ ha^{-1}$) | GY ($mg\ ha^{-1}$) | DM ($mg\ ha^{-1}$) | HI ($kg\ kg^{-1}$) | Plant N ($kg\ ha^{-1}$) | NF (%) | $P_E$ ($kg\ kg^{-1}$) | IEN ($kg\ kg^{-1}$) |
| High | $N_0$ | 5.8±0.3 | 13.9±3.3 | 0.42±0.07 | 102.6±24.2 | | | 62.1±3.6 |
| High | $N_1$ | 8.6±0.3 | 19.1±1.3 | 0.45±0.02 | 148.7±11.1 | 46.1±31.4 | 101.2±40.3 | 58.0±3.2 |
| High | $N_2$ | 9.5±0.5 | 20.6±1.3 | 0.46±0.03 | 146.3±9.2 | 21.9±16.3 | 206.0±87.2 | 65.1±4.5 |
| High | $N_3$ | 8.8±0.9 | 21.3±0.9 | 0.41±0.03 | 162.8±7.0 | 20.1±10.4 | 57.0±20.4 | 53.8±3.6 |
| Low | $N_0$ | 5.3±1.1 | 16.3±2.2 | 0.32±0.07 | 96.1±13.7 | | | 53.9±13.9 |
| Low | $N_1$ | 8.4±0.6 | 19.7±2.5 | 0.43±0.03 | 127.7±16.4 | 25.3±13.3 | 139.9±54.4 | 66.2±5.0 |
| Low | $N_2$ | 9.1±0.7 | 21.2±1.1 | 0.43±0.01 | 153.6±7.7 | 25.6±4.4 | 79.8±33.5 | 59.3±2.0 |
| Low | $N_3$ | 8.4±0.8 | 21.0±1.6 | 0.40±0.03 | 159.3±12.2 | 19.0±4.6 | 56.1±18.5 | 52.6±3.4 |
| *Treatment means* | | | | | | | | |
| High | | 8.2±1.6 a | 18.7±3.4 a | 0.44±0.04 a | 140.1±12.9 a | 29.3±19.3 a | 121.4±49.3 a | 59.8±2.2 a |
| Low | | 7.8±1.7 a | 19.6±2.6 a | 0.40±0.06 a | 134.2±12.5 a | 23.3±7.4 a | 91.9±35.5 a | 58.0±4.9 a |
| $N_0$ | | 5.5±0.8 c | 15.1±2.8 b | 0.38±0.09 b | 99.4±19.0 c | | | 58.0±5.1 ab |
| $N_1$ | | 8.5±0.4 b | 19.4±1.8 a | 0.44±0.03 a | 138.2±13.7 b | 42.1±19.0 a | 120.6±47.3 a | 62.1±4.0 a |
| $N_2$ | | 9.3±0.6 a | 20.9±1.1 a | 0.45±0.03 a | 150.0±8.4 a | 27.0±6.2 b | 142.9±60.3 a | 62.2±3.2 a |
| $N_3$ | | 8.6±0.8 ab | 21.1±1.2 a | 0.41±0.03 ab | 161.1±9.6 a | 21.7±4.0 b | 56.6±19.5 b | 53.2±2.6 b |
| *Interactions* | | | | | | | | |
| *F* value (Moisture×N) | | NS | NS | NS | NS | * | ** | NS |
| Treatments | | Wheat 2001/2002 | | | | | | |
| Moisture | N rate ($kg\ ha^{-1}$) | GY ($mg\ ha^{-1}$) | DM ($mg\ ha^{-1}$) | HI ($kg\ kg^{-1}$) | Plant N ($kg\ ha^{-1}$) | NF (%) | $P_E$ ($kg\ kg^{-1}$) | IEN ($kg\ kg^{-1}$) |
| High | $N_0$ | 1.2±0.3 | 4.7±0.1 | 0.21±0.06 | 51.9±0.6 | | | 22.7±5.3 |
| High | $N_1$ | 4.6±0.4 | 14.1±1.2 | 0.35±0.04 | 164.0±20.5 | 112.1±20.7 | 31.0±6.9 | 28.3±3.8 |
| High | $N_2$ | 5.4±0.2 | 14.7±1.4 | 0.37±0.05 | 221.3±20.8 | 84.7±15.0 | 26.4±4.0 | 24.7±3.9 |
| High | $N_3$ | 6.1±0.3 | 18.7±1.9 | 0.36±0.05 | 229.8±21.9 | 59.3±10.8 | 28.7±7.4 | 27.0±4.4 |
| Low | $N_0$ | 1.4±0.3 | 4.5±0.2 | 0.24±0.07 | 39.3±2.1 | | | 35.9±7.0 |
| Low | $N_1$ | 4.2±0.6 | 12.9±0.5 | 0.33±0.04 | 162.2±7.8 | 122.9±7.1 | 23.1±5.2 | 26.1±3.9 |
| Low | $N_2$ | 6.1±0.1 | 16.3±0.9 | 0.38±0.01 | 197.8±14.2 | 79.3±6.6 | 30.9±3.4 | 31.2±2.5 |
| Low | $N_3$ | 6.2±0.6 | 18.1±3.2 | 0.34±0.02 | 238.7±16.9 | 66.5±7.0 | 23.7±3.4 | 26.0±2.4 |
| *Treatments means* | | | | | | | | |
| High | | 4.3±2.0 a | 13.3±4.8 a | 0.32±0.05 a | 166.8±15.9 a | 85.4±15.5 a | 28.7±6.4 a | 25.6±0.9 a |
| Low | | 4.5±2.1 a | 12.9±5.7 a | 0.32±0.02 a | 159.5±10.2 a | 89.5±6.9 a | 25.9±4.0 a | 29.8±2.2 a |
| $N_0$ | | 1.3±0.3 c | 4.6±0.2 c | 0.22±0.05 c | 45.6±1.4 d | | | 29.3±6.0 a |
| $N_1$ | | 4.4±0.5 b | 13.3±0.9 b | 0.34±0.02 b | 163.1±14.2 c | 117.5±13.8 a | 27.1±6.0 a | 27.2±3.8 a |

**Table 5** continued

| Treatments | | Wheat 2000/2001 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Moisture | N rate ($kg\ ha^{-1}$) | GY ($mg\ ha^{-1}$) | DM ($mg\ ha^{-1}$) | HI ($kg\ kg^{-1}$) | Plant N ($kg\ ha^{-1}$) | NF (%) | $P_E$ ($kg\ kg^{-1}$) | IEN ($kg\ kg^{-1}$) |
| $N_2$ | | 5.8±0.4 a | 15.0±1.6 b | 0.37±0.03 b | 209.6±17.5 b | 82.0±10.8 b | 28.7±4.1 a | 27.9±3.2 a |
| $N_3$ | | 6.1±0.4 a | 18.1±1.4 a | 0.35±0.05 b | 234.3±19.4 d | 62.8±8.9 c | 26.2±5.3 a | 26.5±1.2 a |
| *Interactions* | | | | | | | | |
| *F* value (Moisture×N) | | NS | NS | NS | NS | NS | | * |
| Treatments | | Maize 2002 | | | | | | |
| Moisture | N rate ($kg\ ha^{-1}$) | Gyn ($mg\ ha^{-1}$) | DM ($mg\ ha^{-1}$) | HI ($kg\ kg^{-1}$) | Plant N ($kg\ ha^{-1}$) | NF (%) | $P_E$ ($kg\ kg^{-1}$) | IEN ($kg\ kg^{-1}$) |
| High | $N_0$ | 4.3±0.2 | 8.9±1.2 | 0.48±0.05 | 53.2±7.4 | | | 81.5±8.3 |
| High | $N_1$ | 7.8±1.2 | 14.3±1.6 | 0.55±0.07 | 135.8±15.1 | 82.6±22.5 | 51.0±8.8 | 57.7±7.2 |
| High | $N_2$ | 8.9±0.7 | 16.0±0.3 | 0.56±0.04 | 158.2±3.6 | 52.5±4.5 | 46.2±1.8 | 56.2±3.9 |
| High | $N_3$ | 8.8±0.6 | 19.5±1.1 | 0.45±0.06 | 168.3±9.5 | 38.4±1.2 | 41.0±6.9 | 52.7±6.9 |
| Low | $N_0$ | 3.7±0.5 | 8.2±2.7 | 0.45±0.07 | 65.1±13.3 | | | 58.8±9.5 |
| Low | $N_1$ | 6.1±0.8 | 13.3±2.1 | 0.46±0.07 | 111.4±17.6 | 46.2±5.2 | 61.0±20.4 | 56.1±15.9 |
| Low | $N_2$ | 7.7±0.5 | 16.8±0.9 | 0.46±0.02 | 127.5±6.8 | 31.2±14.0 | 83.0±41.8 | 56.2±1.8 |
| Low | $N_3$ | 7.8±0.9 | 19.2±1.0 | 0.41±0.04 | 165.5±8.8 | 36.8±7.9 | 38.0±9.6 | 44.3±4.2 |
| *Treatement means* | | | | | | | | |
| High | | 7.5±2.1 a | 14.7±4.1 a | 0.51±0.06 a | 128.9±8.9 a | 57.8±9.4 a | 46.0±5.8 a | 62.0±4.9 a |
| Low | | 6.3±1.8 a | 14.4±4.6 a | 0.45±0.07 b | 117.4±11.6 a | 38.1±9.0 b | 60.6±23.9 a | 53.9±5.0 b |
| $N_0$ | | 4.0±0.5 c | 8.6±1.9 d | 0.48±0.06 a | 59.2±10.3 d | | | 70.1±8.1 a |
| $N_1$ | | 7.0±1.4 b | 13.8±1.8 c | 0.51±0.10 a | 123.6±16.4 c | 64.4±13.8 a | 55.9±14.5 a | 56.9±9.3 b |
| $N_2$ | | 8.3±0.8 a | 16.4±0.7 b | 0.51±0.06 a | 142.9±5.2 b | 41.8±9.2 b | 64.6±21.8 a | 56.2±2.2 b |
| $N_3$ | | 8.3±0.9 a | 19.3±0.9 a | 0.43±0.05 a | 166.9±9.2 a | 37.6±4.5 b | 39.5±7.6 a | 48.5±2.3 b |
| *Interactions* | | | | | | | | |
| *F* value (Moisture×N) | | NS | NS | NS | NS | * | NS | NS |

[a] Standard error

[b] Means within main plot (soil moisture) or sub-plots (N fertilizer rate) levels followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD-test)

[c] NS indicates no significance and *, **, indicate significance at $P < 0.05$, 0.01 and 0.001, respectively

There was an obvious increase in GY with N uptake until up to about 150 kg N $ha^{-1}$ for maize or 200 kg N $ha^{-1}$ for wheat and a decrease in both NF and IEN with increasing N fertilizer inputs (Table 5). The higher IEN of maize than wheat indicates that maize has higher N use efficiency than wheat, and maize requires less N than wheat to achieve a given GY level. This result was consistent with the report from Cassman et al. (2002). Significant effects of soil moisture on IEN were found in the first wheat season mainly caused by the high N uptake at the low soil moisture level and in the second maize season mainly due to the reductions in GY at the low soil moisture level.

## Discussions and conclusion

Zhu and Chen (2002) concluded that accumulation of $NO_3$-N in 0–200 cm soil layer in many farmlands in China was a result of long period of continuous luxury use of N fertilizer. Under our experimental conditions, N application rate higher than 300 kg N $ha^{-1}$ increased $NO_3$-N accumulation in 0–100 cm soil profile in the following season (Fig. 4). Nitrate-N leaching below 100 cm depth varied greatly from 0 kg $ha^{-1}$ to 164.9 kg $ha^{-1}$ per crop growing season with N application rates, irrigation regimes and seasonal rainfall. In general, high risk of $NO_3$-N leaching occurred in maize growing season even with low N fertilizer inputs due to high summer rainfall in the area, consistent with other findings in the North China Plain (Liu et al. 2003; Ju et al. 2004). Reducing N fertilizer rates to about 100–200 kg N $ha^{-1}$ did not deplete $NO_3$-N content in 0–100 cm soil layer and maintained stable grain yield. With the starting soil N in our experiments (103 kg N $ha^{-1}$ and 61 kg N $ha^{-1}$ in the first and second rotation, respectively in the control), the optimum N fertilizer input for maximum GY of wheat and maize were about 100 kg N $ha^{-1}$ per crop in the first rotation and about 200 kg N $ha^{-1}$ in the second one for a wheat yield level of 5.5–6.0 mg $ha^{-1}$ and maize yield level of 8.0–8.5 mg $ha^{-1}$. These values are comparable with the values of 150–180 kg N $ha^{-1}$ recommended by Zhu and Wen (1992) in northern China. The actual N fertilizer application rate of 400–600 kg N $ha^{-1}$ per year in the North China Plain would exceed the N requirements of crops in the wheat–maize rotation and result in reduced N use efficiency, N accumulation in soil and leaching to deeper layers as reported by Zhu and Chen (2002) and Ju et al. (2004).

The PFP (grain yield per unit applied N) decreased significantly when N fertilizer input exceeded 200 kg N $ha^{-1}$ for both wheat and maize in the experiments. This is consistent with the changes in PFP of applied N calculated for wheat and maize double cropping system across the North China Plain (Fig. 6). The PFP in the North China Plain decreased from 46.3 kg grain $kg^{-1}$ N at 174.4 kg N $ha^{-1}$ $yr^{-1}$ application rate in 1978 to 21.2 kg grain $kg^{-1}$ N at 592.4 kg N $ha^{-1}$ $yr^{-1}$ application rate in 1998. N fertilizer inputs above 500 kg N $ha^{-1}$ $yr^{-1}$ have not increased crop productions but instead resulted in low PFP of applied N and high accumulation of residual N in soil (Zhang et al. 1996; Zhu and Chen 2002; Ju et al. 2004). Roelcke et al. (2002, 2004) also showed that reducing inorganic N fertilizer input by 10–25% did not decrease GY of rice or wheat in Taihu Region in eastern China. This shows a significant potential to better manage N applications to increase N use efficiency and to reduce $NO_3$-N leaching in the North China Plain.

Optimization of water and N management requires knowledge of crop water and N demand and the interaction between soil N dynamics and crop N uptake. Intra- and inter-seasonal variability of climate can have significant impact on crop growth and N demand as well as soil mineralization process. Determination of optimal N application rate and timing of application needs to take these changes and the amount of available N already in the soil into consideration. In addition, there are diminishing returns and increased risk of N leaching with increasing N application rate. This needs to be well balanced considering the environmental impact of agricultural production. The optimum N fertilizer rates for such balance may be lower than that for only production. This is particularly the case in the maize growing season in North China Plain. Real-time N management based on monitoring of plant and soil N status has shown some promise (Peng et al. 1996) to increase N fertilizer recovery and use efficiency and reduce N leaching. Agricultural systems models are playing an increasingly important role to assist N management under variable climate because they can

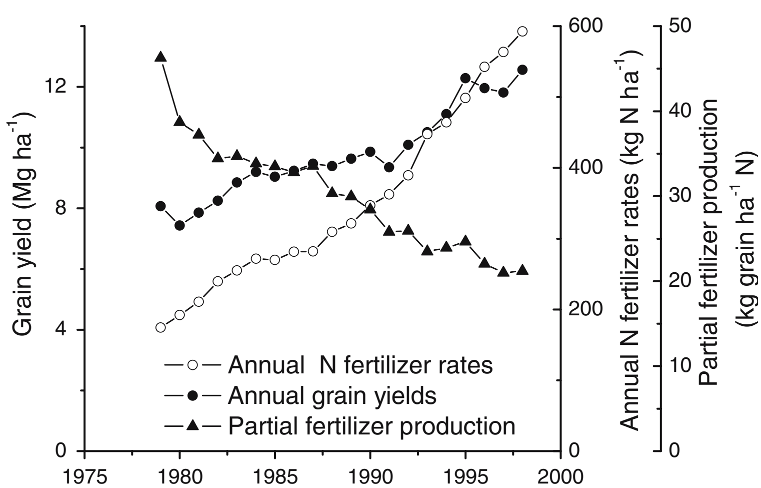



**Fig. 6** Changes in grain yields of wheat and maize, annual inorganic N fertilizer input and partial fertilizer production of applied N fertilizer (PFP) in the wheat–maize double cropping system in the North China Plain from 1979 to 1998. *Note*: The total annual N fertilizer inputs and the annual grain yield for winter wheat, maize, spring wheat and rice et al. were used to represent the wheat–maize double cropping system in the North China Plain because the planting areas of spring wheat and rice is very small in the North China Plain comparing with the planting areas of wheat and maize

capture the dynamic interactions between plant growth/nitrogen uptake, climate, soils and management practices. Long-term simulation modeling using historical climate data and soil information can provide the well estimates of crop N demands for a given location.

It can be concluded that in areas with similar conditions to the experimental site, N application rates above 200 kg N $ha^{-1}$ would not significantly increase crop yield, but lead to high risk of excess N accumulated in the 0–100 cm soil profile and increased risk of N leaching into the groundwater. This indicates that the optimum N rate may be much lower than that used in many areas in the North China Plain given the high level of N already in the soil, and there is great potential for reducing N inputs to increase N use efficiency and to mitigate N leaching. In the wheat–maize double cropping system in the North China Plain, careful N management practices in the maize season are required to balance the production and the impact of nitrate leaching on groundwater due to the higher risk of $NO_3$-N leaching in the maize growing season, especially at high N rates. Avoiding excess water leakage through controlled irrigation and matching N application to crop nitrogen demand both in time and space is the key to reduce $NO_3$-N leaching and maintain crop yield. Such management requires knowledge of crop water and nitrogen demand and soil N dynamics as they change with variable climate temporally and spatially. Simulation modeling can capture those interactions and is considered as a powerful tool to assist in the future optimization of nitrogen and irrigation managements.

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