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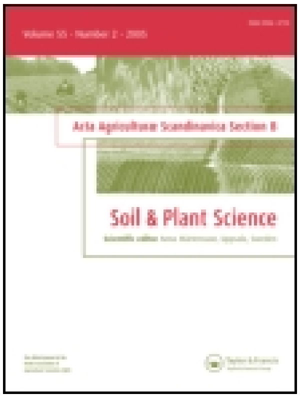

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Nitrate leaching on loess soils in north-west China: Appropriate fertilizer rates for winter wheat

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ORIGINAL ARTICLE

Nitrate leaching on loess soils in north-west China: Appropriate fertilizer rates for winter wheat

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Abstract

Nitrate leaching is an important factor affecting N fertilizer consumption in the agroecosystem of the Loess Plateau of China. Therefore, the movement and residual amounts of nitrate within the soil profile under different fertilizer application rates were studied to determine the most appropriate rates of fertilizer application. Soil samples were collected from a long-term experimental site to determine the concentration of nitrate in mid-September 1999 and 2007. The results showed that NO_3^--N had moved more than 100 cm down the soil profile from 1999 to 2007, and two peaks of NO_3^--N were present at different depths after 23 years of high rates of N application. NO_3^--N had leached to depths exceeding 300 cm in plots where >90 kg ha^{-1} N had been applied alone. At the fertilization rate of 180 kg N ha^{-1}, up to 1500 kg ha^{-1} residual NO_3^--N was detected, equivalent to 34.8% of the total input of N fertilizer during the experiment. The total amount of residual nitrate increased with increases in the N application rate, but decreased with increases in P_2O_5 application when the N application was up to 90 kg ha^{-1} or more. The results indicate that fertilization using a 1:1 mixture of N:P_2O_5 at 90 kg ha^{-1} p.a. could prevent NO_3^--N from leaching in soil used to grow continuous winter wheat (*Triticum aestivum* L.) crops in the rain-fed agricultural areas of China, while providing optimum yields.

Keywords: *Continuous wheat, fertilizer application rate, nitrate leaching, nitrogen, phosphorus, rain-fed agriculture area.*

Introduction

Nitrate nitrogen (NO_3^--N) is apt to leach into groundwater after the overuse of fertilizer in farmland ecosystems (Spalding & Exner, 1993; Mcmahon et al., 1994; Aparicio et al., 2008). Groundwater is an essential drinking water resource for many communities in developing cities (Umezawa et al., 2008) and NO_3^--N could threaten human health (Fewtrell, 2004; Lundberg et al., 2004). Since the water table is very deep in the rain-fed agricultural region of China, NO_3^--N is unlikely to reach groundwater. However, it can be leached by rainwater into the subsoil and accumulate in deep layers. For instance, we previously found accumulations at 140 cm depth following 15 years of high rates of N application (Fan et al., 2003). Ju et al. (2007) found that N recovery by crops decreased with soil depth, so leached NO_3^--N in the deep soil layer was not utilized by the crops. Many studies have also shown that the depth to which NO_3^--N leaches in the soil profile is correlated with rates of applied fertilizer (Jolley & Pierre, 1977; Hooker et al., 1983; Benbi et al., 1991; Halvorson & Reule, 1994; Westerman et al., 1994; Yang et al., 2001). Furthermore, the amount of residual NO_3^--N in soil is affected by the rate of N fertilizer applied (Powlson et al., 1986; Addiscott & Powlson, 1992) and NO_3^--N is leached when N fertilizer is applied excessively (Bergström & Brink, 1986). Thus, unabsorbed NO_3^--N in deep fertilized soil represents wasted fertilizer.

However, applying phosphorus (P) fertilizer may reduce the residual amount of NO_3^--N in agricultural soil (Yuan et al., 2000), which may be highly relevant in the context of Chinese agriculture since

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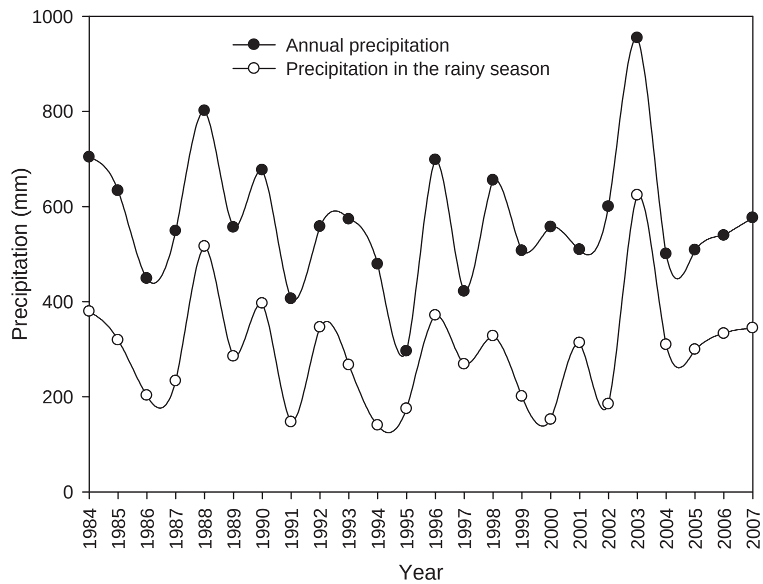

Figure 1. Precipitation in the rainy season and annual precipitation are shown from 1984 to 2007. The rainy season period is from July to September.

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N and P fertilizer are frequently used in combination by Chinese farmers to ensure high yields of crops. Thus, to minimize NO_3^--N leaching and residual amounts of NO_3^--N in deep soil layers it is important to determine the optimum application rates of N and P_2O_5 for crops grown in the region.

The objectives of the study presented here were: (1) to quantify the movement of NO_3^--N in the vertical soil profile under different fertilization conditions, by comparing data acquired in 1999 and 2007 from the long-term experimental site used in our previous study, (2) to investigate the amounts of residual NO_3^--N under different fertilizer treatments, and (3) to identify a suitable application rate of fertilizer to minimize NO_3^--N leaching.

Materials and methods

Site description

The research site is located near the city of Changwu (35°12′–35°16′ N; 107°40′–107°42′ E) in north-west China. The ongoing long-term field experiment, on which this paper is based, was started in 1984. The altitude of the site is 1000–1200 m above sea level, and the average groundwater table is very deep, below 60 m (Hao et al., 2003). The climate is of monsoonal continental type, typical for the semi-arid in warm temperate zone of the study area. Crop growth on the dark loess soils at the experimental site, which are typical for the area, is mainly dependent on rainfall. The annual average precipitation was 571 mm from 1984 to 2007, about 64% of which fell in the rainy season (July–September). Precipitation data for the period of 1984 to 2007 are shown in Figure 1. The annual cumulative temperature above 10 °C was 3029 °C, and annual average temperature was 9.1 °C with 171 frost-free days (Hao et al., 2007).

Table I. Fertilizer treatments and annual application rates (kg ha^{-1} p.a.) in a 23-year fertilization experiment. CK is the control in the treatments. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P mean that how much fertilizers were applied yearly.

	Fertilizer application rates (kg ha^{-1} p.a.)	
Treatments	N	P_2O_5
CK	0	0
P90	0	90
P180	0	180
N45P45	45	45
N45P90	45	90
N45P135	45	135
N90	90	0
N90P45	90	45
N90P90	90	90
N90P135	90	135
N90P180	90	180
N135P45	135	45
N135P90	135	90
N135P135	135	135
N180	180	0
N180P90	180	90
N180P180	180	180

The soil at the site was classified as a medium loam soil with a pH of 8.3. In 1984, at the start of the experiment, the organic matter, total N, alkaline dissolved N, total P, available P and available K contents in the topsoil were 10.5 g, 0.80 g, 37.0 mg, 0.66 g, 3.0 mg and 129.3 mg per kg, respectively (Hao et al., 2007).

Experiment design

The experiment was arranged as an incomplete randomized block designed with three replications and 17 treatments per block, applied to 22.2 m^2 (5.5 m $\times$ 4 m) plots. The treatments consisted of applications of N and P_2O_5 (urea and calcium super-phosphate, respectively) at rates varying between 0 and 180 kg ha^{-1} since 1984 (Table I), before winter wheat was sown (cvs. Qinmai-4 from 1984 to 1985, Changwu-131 from 1986 to 1995 and Changwu-134 from 1996 to 2007) at a rate of 180 kg ha^{-1} in 15 rows per plot in late September of each year. Plots were bare fallowed from late June to late September after harvesting the crop each year.

Soil sampling and chemical analysis

In mid-September 1999, soil samples were collected before the crop was sown, from the soil horizon in ten 20 cm layers from the surface to a depth of 200 cm (0–20, 20–40 cm etc.) and then in four 30 cm layers from 200 cm to 320 cm deep and then in two 40 cm layers from 320 cm to 400 cm deep. In mid-September 2007, samples were collected from fifteen 20 cm soil layers from the surface to a depth of 300 cm (0–20, 20–40 cm etc.), again prior

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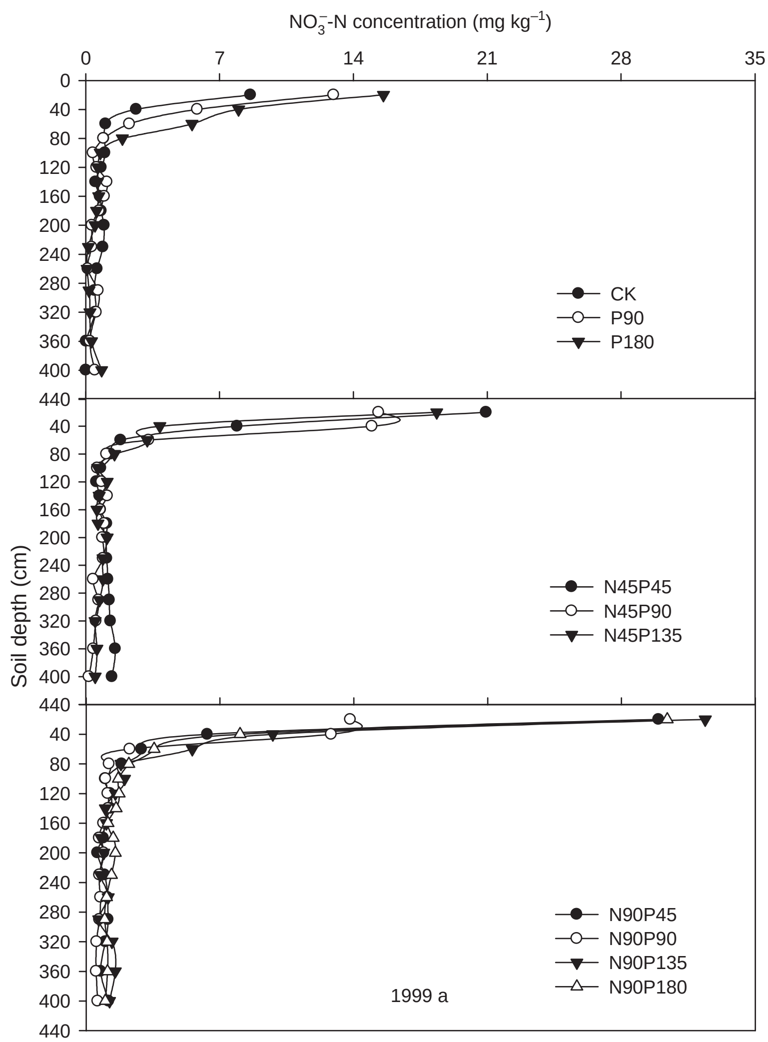

Figure 2. NO_3^--N distribution in the vertical soil profiles at the plots in 1999 where NO_3^--N was not accumulated in deep soil (after Fan et al., 2003). CK (control) is a treatment without fertilizer in the figure. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

to crop sowing. NO_3^--N was extracted from these samples using 1 mol L^{-1} KCl in the ratio 1:10 soil:KCl solution, and NO_3^--N concentrations were determined using an AA3 automated Flow Injection Auto Analyzer (Bran+Luebbe Corporation, Germany).

Data calculation and statistics

Residual NO_3^--N rate at different soil layers in the vertical soil profile are calculated as:

$$TRN = H*C*B/10 \quad (1)$$

Where TRN is total amount of residual NO_3^--N in soil (kg ha^{-1}); H, soil depth (cm); C, the concentration of NO_3^--N (mg kg^{-1}); and B, the bulk density of soil layer (g cm^{-3}).

$$TNI = F*n \quad (2)$$

$$RNP = TRN/TNI*100 \quad (3)$$

$$ARN = (TRN_{2007} - TRN_{1999})/8 \quad (4)$$

Where TNI is total N fertilizer input prior to sampling since the start of the experiment in 1984 (kg ha^{-1}); F, fertilizer application rated (kg ha^{-1} p.a.); n, years of fertilizer application (a); RNP, residual NO_3^--N as a percentage of TNI (%); ARN, annual rate of residual NO_3^--N accumulation in soil (kg ha^{-1} p.a.); TRN_{1999}, TRN in the 0–300 cm soil layer in 1999 (kg ha^{-1}); and TRN_{2007}, TRN in the 0–300 cm soil layer in 2007 (kg ha^{-1}).

All figures were constructed using Sigmaplot 10.0 software. The variances of residual NO_3^--N measurements under different fertilization conditions were compared using least significant difference

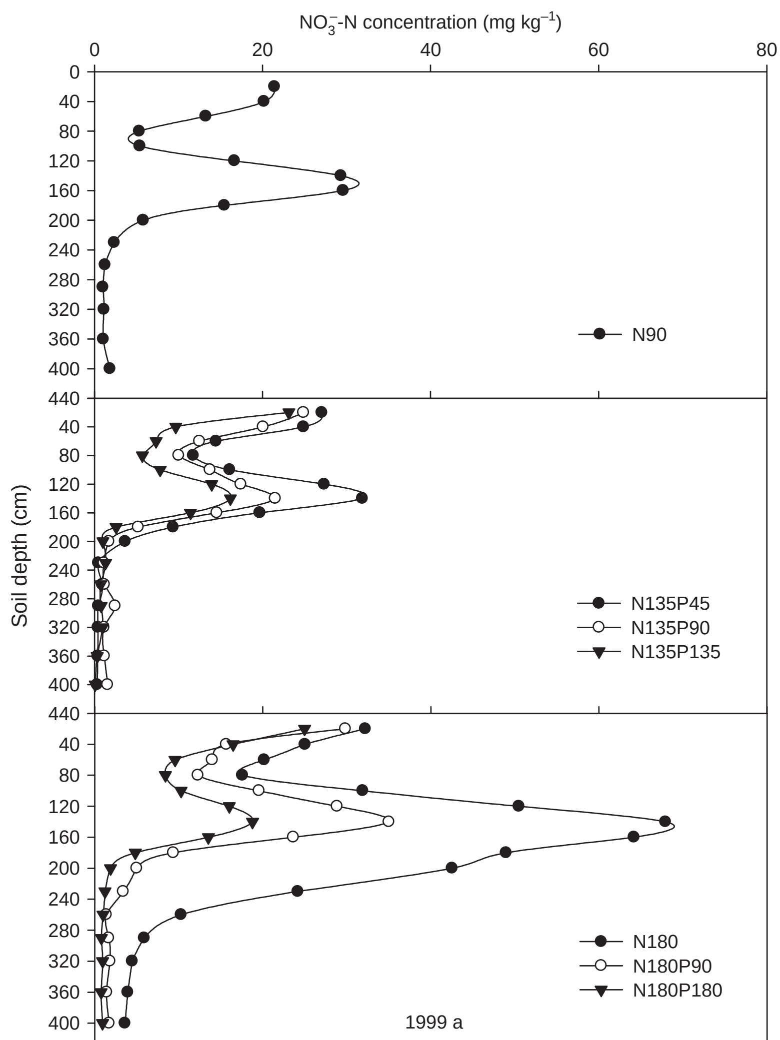

Figure 3. NO_3^--N distribution in the vertical soil profiles at the plots in 1999 where lots of NO_3^--N was accumulated near 140-cm deep soil (after Fan et al., 2003). N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

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(LSD) tests, implemented in SPSS statistical software deeming differences to be significant if $p < 0.05$.

Results

NO_3^--N distribution in the vertical soil profile in 1999 and 2007

Analyses of the samples collected in 1999 (Figures 2 and 3) showed that the NO_3^--N concentration in the soil decreased with increasing soil depth in plots where less than 90 kg ha^{-1} N had been applied annually. NO_3^--N was mainly present at depths <60 cm, and the concentration was highest in the 0–20 cm soil layer. It had not accumulated at depth in the soil (Figure 2). At plots where more than 90 kg ha^{-1} N had been applied, even combined with P fertilizer, NO_3^--N concentrations peaked in the deeper soil layers, showing accumulation near the 140 cm soil layer (Figure 3). In addition, in plots where 90 kg ha^{-1} N had been applied NO_3^--N accumulated at 140 cm depth only when N was applied alone, without P (Fan et al., 2003).

Analyses of the samples collected in 2007 (Figures 4 and 5) showed that no NO_3^--N had accumulated in the deep soil in plots where the CK, P90, P180, N45P45, N45P90, N45P135, N90P90, N90P135 and N90P180 treatments were applied, which showed similar distribution patterns to those observed in 1999. However, NO_3^--N was mainly located in the 0–160 cm soil layer (Figure 4), and a new accumulation peak was observed near 100 cm depth in plots subjected to the N90P45 treatment (Figure 5), indicating that NO_3^--N moved from the topsoil to the deeper subsoil from 1999 to 2007 in these plots. In addition, two NO_3^--N accumulation peaks were found in plots where >90 kg N ha^{-1} had been applied, one at 100–120 cm and another

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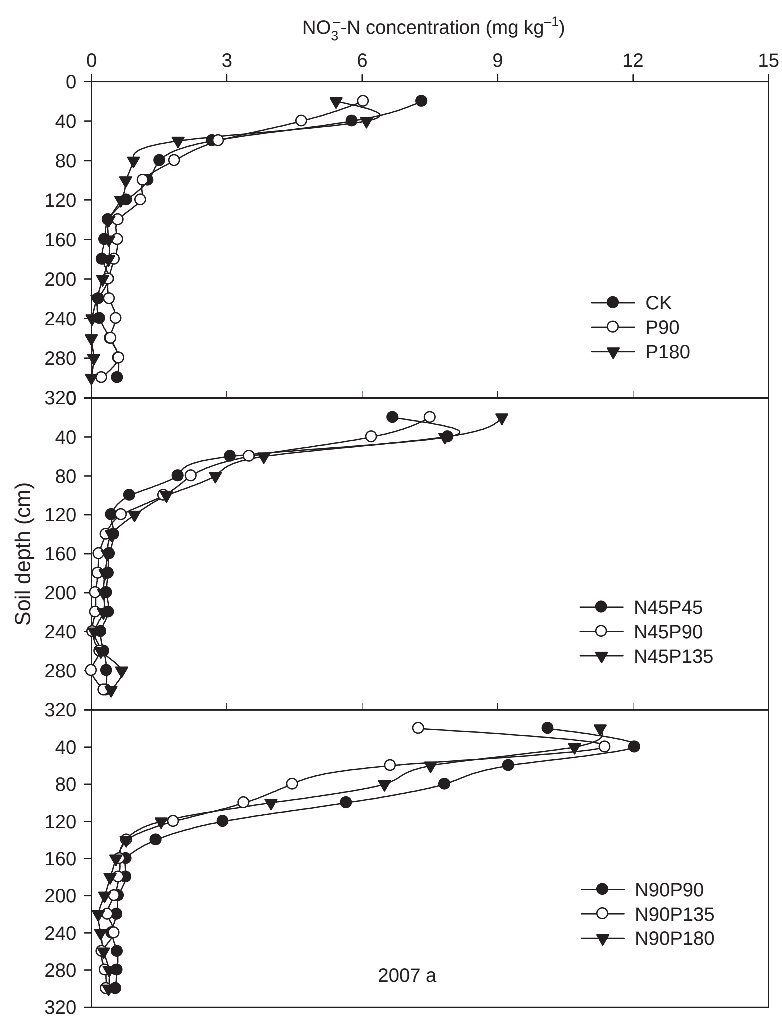

Figure 4. NO_3^--N distribution in the vertical soil profiles at the plots in 2007 where NO_3^--N was not accumulated in deep soil (after Xue & Hao, 2009). CK (control) is a treatment without fertilizer in the figure. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

at 240–260 cm (Figure 5), whereas in 1999 a single accumulation peak had been observed at around 140 cm (Figure 3). The second accumulation layer in 2007 was about 100 cm deeper in the vertical soil profile than the 1999 peak. In plots where N was applied alone at rates of 90 or 180 kg ha^{-1} concentrations of NO_3^--N were 19.9 and 69.2 mg kg^{-1} in the 280–300 cm soil layer, respectively. These were so high that NO_3^--N would be leached to depths >300 cm in the soil (Xue & Hao, 2009).

N application rate and residual NO_3^--N amount

The total amount of residual NO_3^--N (TRN) increased significantly with increases in the application rate of N, when N was applied alone (Table II). The lowest TRN values observed in 1999 and 2007 were 56.1 and 45.7 kg ha^{-1}, for CK and P180 plots, respectively. The TRN values were highest for plots where N fertilizer was applied alone at the highest rate (180 kg ha^{-1} p.a.) in both 1999 and 2007 (1240 and 1500 kg ha^{-1}, equivalent to 43.8% and 34.8% of the total N input of fertilizer, TNI, respectively). TRN values in 2007 for plots receiving N fertilizer at rates from 0 to 90 kg ha^{-1} with P fertilizer were not significantly different from each other, averaging 94.9 kg ha^{-1}. However, the difference of TRN value increased with increasing N application rates, especially at N rate of 180 kg ha^{-1}. In addition, the annual residual rates of NO_3^--N accumulation (ARN) under the tested fertilizer treatments ranged from −12.0 to 48.5 kg ha^{-1} p.a.

In order to quantify NO_3^--N leaching more thoroughly, the soil profile was divided into 0–60, 60–160 and 160–300 cm layers and changes in

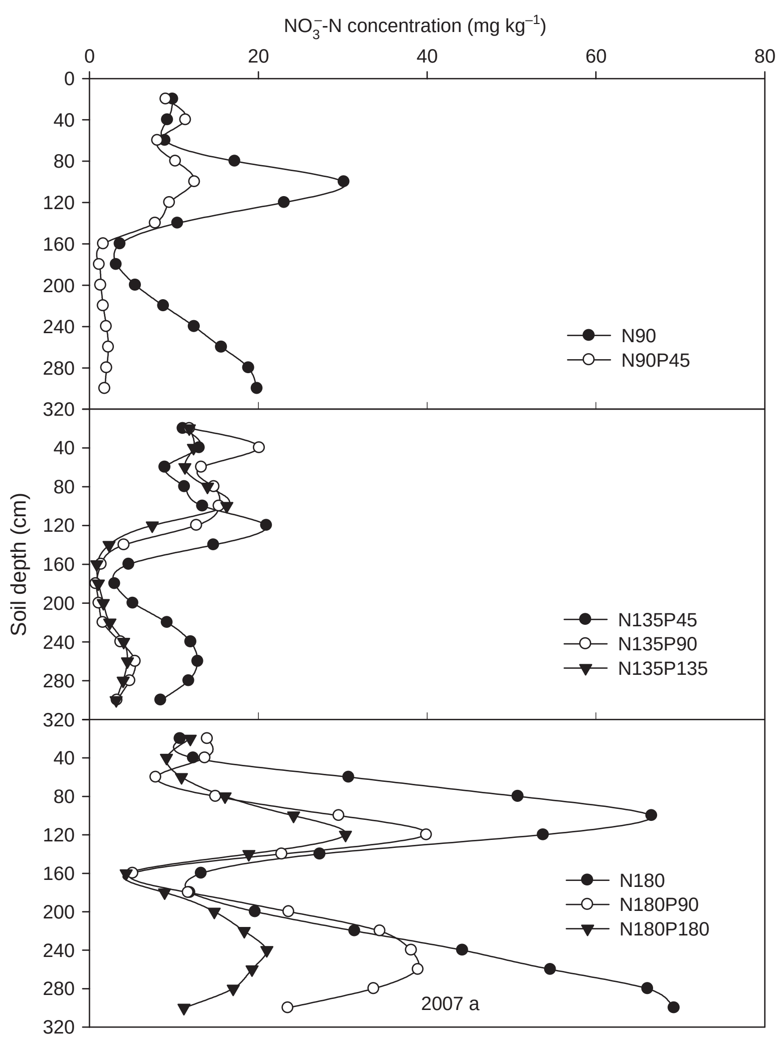

Figure 5. NO_3^--N distribution in the vertical soil profiles at the plots in 2007 where lots of NO_3^--N were accumulated in deep soil (after Xue & Hao, 2009). N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

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Table II. TNI, TRN, RNP and ARN in the 0–300 cm soil layer in 1999 and 2007. CK is the control in the treatments. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizers were applied yearly.

	TNI† ($kg\ ha^{-1}$)		TRN ($kg\ ha^{-1}$)		RNP (%)		
Treatments	1999(a)	2007(a)	1999(a)	2007(a)	1999(a)	2007(a)	ARN ($kg\ ha^{-1}$ p.a.)
CK	0	0	56.1	59.3fg‡	–	–	0.40
P90	0	0	73.5	57.7fg	–	–	−1.98
P180	0	0	93.0	45.7g	–	–	−5.91
N45P45	675	1035	112	63.1fg	8.28	0.37	−6.11
N45P90	675	1035	113	60.6fg	8.40	0.13	−6.53
N45P135	675	1035	94.0	76.7fg	5.61	1.68	−2.16
N90	1350	2070	455	526c	29.5	22.5	8.88
N90P45	1350	2070	137	220efg	5.99	7.76	10.4
N90P90	1350	2070	104	143efg	3.55	4.04	4.88
N90P135	1350	2070	161	104efg	7.77	2.16	−7.13
N90P180	1350	2070	155	119efg	7.33	2.88	−4.50
N135P45	2025	3105	509	428cd	22.3	11.9	−10.0
N135P90	2025	3105	400	304de	17.0	7.88	−12.0
N135P135	2025	3105	278	259def	11.0	6.43	−2.38
N180	2700	4140	1240	1500a	43.8	34.8	32.5
N180P90	2700	4140	548	936b	18.2	21.2	48.5
N180P180	2700	4140	348	631c	10.8	13.8	35.4

†TNI: total N fertilizer input prior to sampling since 1984; TRN: total amount of residual NO_3^--N in soil; RNP: residual NO_3^--N as a percentage of TNI; ARN: annual rate of residual NO_3^--N accumulation in soil.

‡Within a column, means followed by the same letter are not significantly different according to LSD-tests at a 0.05 probability level.

residual NO_3^--N between 1999 and 2007 were characterized. The results showed that the difference of residual NO_3^--N increased slightly or decreased in the 0–60 cm and 60–160 cm soil layers (Figures 6 and 7), but it increased sharply in the 160–300 cm soil layer in N90, N90P45, N135P45, N135P90, N135P135, N180, N180P90 and N180P180 plots (Figure 8), These findings indicate that substantial amounts of NO_3^--N were leached to depths exceeding 160 cm from 1999 to 2007. The

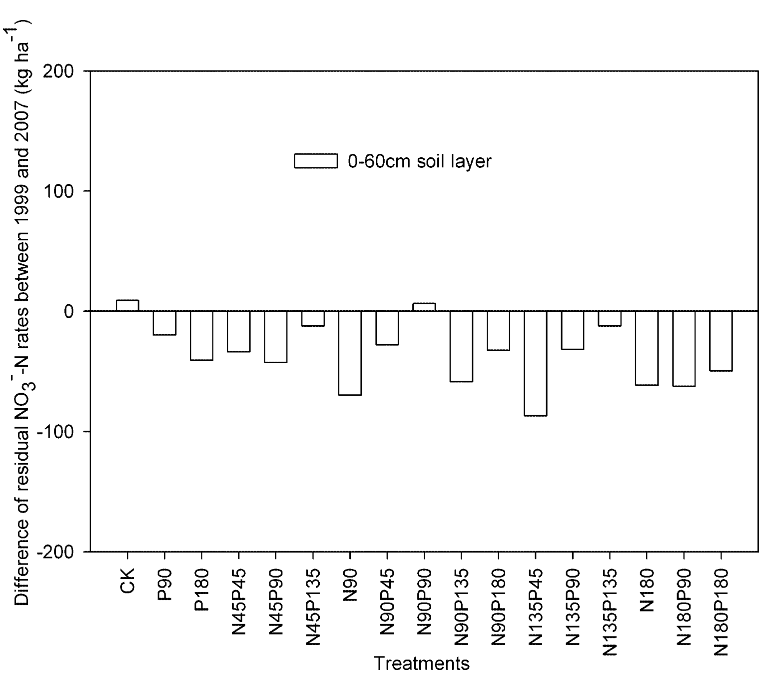

Figure 6. Differences of residual NO_3^--N between 1999 and 2007 under different fertilization conditions in the 0–60 soil layer. CK (control) is a treatment without fertilizer. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

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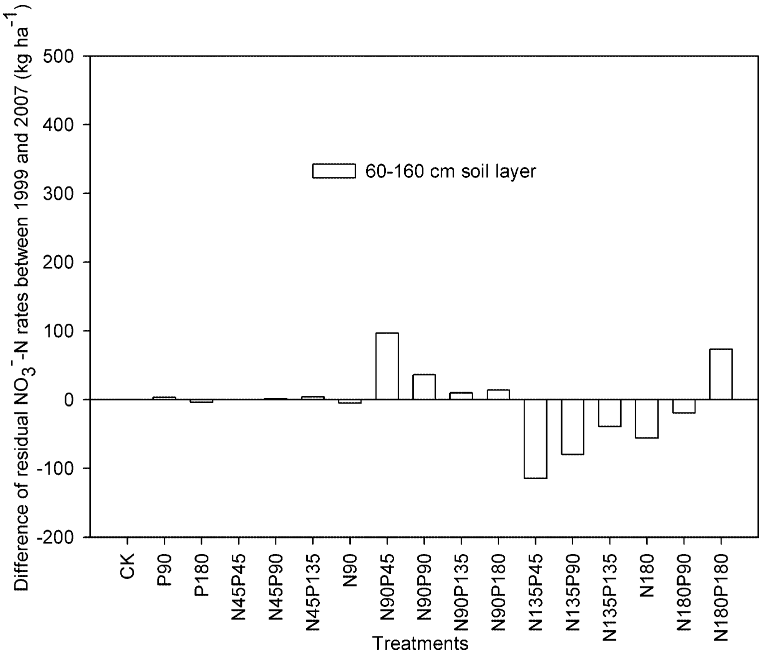

Figure 7. Differences of residual NO_3^--N between 1999 and 2007 under different fertilization conditions in the 60–160 soil layer. CK (control) is a treatment without fertilizer. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

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difference of residual NO_3^--N was highest in the 160–300 cm layer in the N180P90 plot, not in the N180 plot because NO_3^--N had already leached to greater depths when N was applied alone.

P fertilizer and residual NO_3^--N amount

TRN values were not significant ($p = 0.05$) for N fertilizer treatments applied together with P at annual rates of 0 or 45 kg ha^{-1} in 2007 (Table II). However, TRN values declined significantly with increasing P_2O_5 rates when N fertilizer rates were 90 kg ha^{-1} p.a. or more. For example, TRN was 1500 kg ha^{-1} in 2007 (RNP = 34.8%) when N had been applied with 180 kg ha^{-1} for 23 years. But, when N was applied at 180 kg ha^{-1} p.a. together with P_2O_5 at the same rate, TRN was much lower (631 kg ha^{-1}) in the 0–300 cm soil layer.

Optimal application rates of fertilizer

The optimal fertilizer rate would be one that minimized NO_3^--N leaching to the subsoil while providing near-maximal crop yields. After fertilizer treatments for 23 years, NO_3^--N did not accumulate at depth in the CK, P90, P180, N45P45, N45P90, N45P135, N90P90, N90P135 and N90P180 plots under continuous winter wheat cropping (Figure 4). The yields of winter wheat were highest (without NO_3^--N accumulation in deep soil) when N and P_2O_5 were both applied at a rate of 90 kg ha^{-1} p.a., which gave yields of 3500 kg ha^{-1}, 87% of the highest yield found with the N180P180 treatment (Figure 9). Therefore, the most appropriate fertilizer application rate was 90 kg ha^{-1} p.a. of both N and P_2O_5 which would minimize NO_3^--N leaching and ensure adequate yields.

Discussion

Although NO_3^--N leaching may not threaten groundwater in the rain-fed agricultural areas in the north-west of China, there could be significant waste of N fertilizer if NO_3^--N is leached into deep subsoil layers. Knowledge of the patterns of NO_3^--N movement in soil is important to identify effective fertilization regimes that ensure efficient N utilization by the crop from the vertical soil profile. When fertilizers had been applied for 15 years in 1999, NO_3^--N was concentrated mainly in the 0–60 cm soil layer in plots where application rates of N were less than 90 kg ha^{-1} a^{-1}. After the fertilizer experiment for 23 years, NO_3^--N had been leached to 160 cm depth in the vertical soil profile, but total residual amounts of NO_3^--N changed slightly in soil. This reflected the lack of N in the topsoil, and the high recovery of N fertilizer by the crop when small amounts of N fertilizer were applied (Dang & Hao, 2000).

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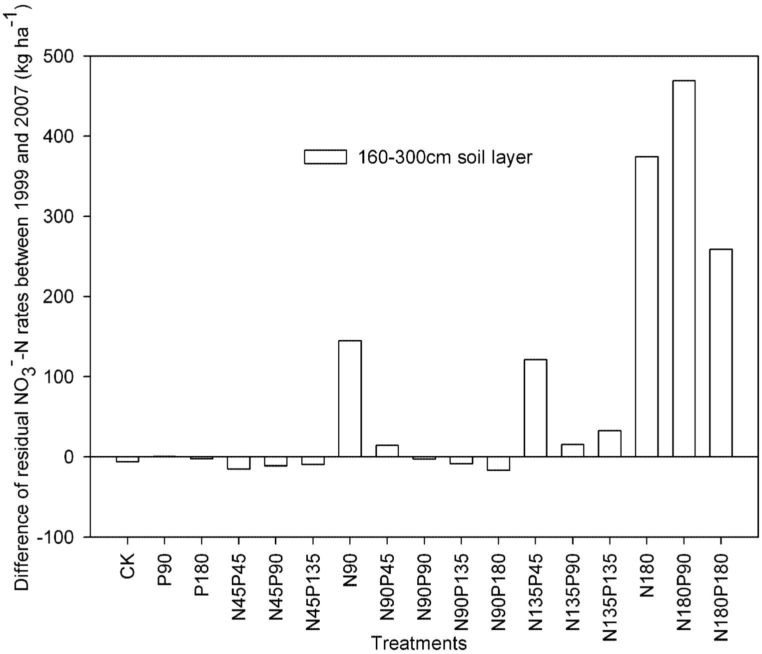

Figure 8. Differences of residual NO_3^--N between 1999 and 2007 under different fertilization conditions in the 160–300 cm soil layer. CK (control) is a treatment without fertilizer. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

Since winter wheat can only recover nitrate from up to 2.0 m depths in soil (Zhou et al., 2008), NO_3^--N at greater depths is likely to be lost from the system. N applied at more than 90 kg ha^{-1} a^{-1} to plots supporting continuous winter wheat from 1984 formed an accumulation peak in 1999 at a depth of 140 cm, while in 2007 two accumulation peaks were observed, at 100–120 cm and 240–260 cm depths. Thus, by 2007 substantial amounts of NO_3^--N had moved 1 m or more down the vertical soil profile and beyond the reach of winter wheat roots. A likely explanation for much of the large losses of nitrate by leaching was exceptional rainfall (Addiscott & Powlson, 1992). Annual average precipitation and

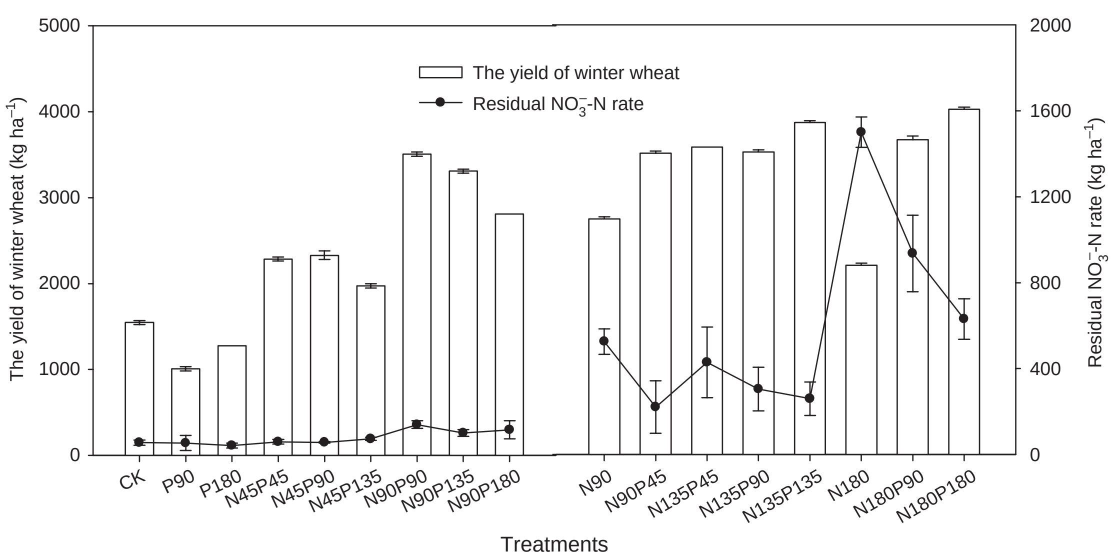

Figure 9. Winter wheat yields and residual NO_3^--N rates in the 0–300 cm soil layer at different fertilization treatments. CK (control) is a treatment without fertilizer. N and P mean nitrogen and phosphorus pentoxide in the applied fertilizer, respectively. Different numbers after N or P indicate how much fertilizer was applied yearly.

average precipitation during the rainy season were higher from 2000 to 2007 than from 1984 to 1999, and were particularly high in 2003 (Figure 1), when annual precipitation reached 954 mm, and 624 mm rain fell in the rainy season, the highest amount since 1984. Furthermore, Li (1983) considered that rainwater can infiltrate to depths of 250 cm in the rainy season in the south of Shaanxi Provence, China.

TRN increased markedly with increasing rates of N fertilizer application. Using N fertilizer alone (without P) resulted in more NO_3^--N in deeper soil layers than N and P fertilizer application in combination. Following continuous application of N for 23 years at a rate of 90 kg ha^{-1} or more, NO_3^--N moved to below 300 cm. The effect of P fertilizer was not significant on NO_3^--N leaching at the low N application rates. TRN only decreased when N fertilizer rate exceeded 90 kg ha^{-1}, and then TRN decreased with increasing rate of P_2O_5. The addition of P fertilizer may reduce NO_3^--N leaching because it accelerates the root growth of winter wheat in the soil (Yuan et al., 2000), and NO_3^--N recovery rate by plants is closely related to their root length density (Schenk et al., 1991; Costa et al., 2000). Hence, higher rooting density in soil is the key for utilization of NO_3^--N (Robinson et al., 1994; Van Vuuren et al., 1996). The results indicate that an N fertilizer rate of 90 kg ha^{-1}, applied in a 1:1 ratio with N: P_2O_5, was optimal since it resulted in low levels of NO_3^--N leaching, and a crop yield that was 87% of the maximum recorded in the experiment.

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