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Interception of residual nitrate from a calcareous alluvial soil profile on the North China Plain by deep-rooted crops: A ^{15}N tracer study

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Deep-rooted crops have a greater capacity than shallow-rooted crops to intercept residual nitrate from the subsoil and restrict its movement down to the shallow groundwater.

Abstract

^{15}N -labeled nitrate was injected into different depths of an alluvial calcareous soil profile on the North China Plain. Subsequent movement of NO_3^- -N and its recovery by deep-rooted maize (*Zea mays* L.) and shallow-rooted eggplant (*Solanum melongena* L.) were studied. Under conventional water and nutrient management the mean recoveries of ^{15}N -labeled nitrate from K^{15}NO_3 injected at depths 15, 45, and 75 cm were 22.4, 13.8, and 7.8% by maize and 7.9, 4.9, and 2.7% by eggplant. The recovery rate by maize at each soil depth was significantly higher than by eggplant. The deeper the injection of nitrate the smaller the distance of its downward movement and this corresponded with the movement of soil water during crop growth. Deeper rooting crops with high root length density and high water consumption may therefore be grown to utilize high concentrations of residual nitrate in the subsoil from previous intensive cropping and to protect the environment.

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1. Introduction

Large amounts of mineral nitrogen (N), mostly in the form of nitrate, have been found to accumulate at various depths in the soil profile after crop harvest following excessive application of N fertilizers and manures in intensively managed crop production systems (Roth and Fox, 1990; Angle et al., 1993; Ju et al., 2004). Nitrate has a high potential either to leach downwards to the subsoil and eventually to groundwater or to denitrify to produce N_2O , a greenhouse gas that can be emitted to the atmosphere.

High intensity of cultivation (e.g. two cereal crops or up to four vegetable crops per year) and excessive application of N fertilizers or manures to each crop on the North China Plain mean that successive crops cannot efficiently utilize the residual nitrate that exists in the soil profile, leading to progressively increasing accumulation in the soil profile and subsequent leaching. According to our measurements of soil nitrate in 47 winter wheat fields after harvest, in 56 vegetable greenhouses after harvest, and in 34 apple orchards after harvest in Huimin county, Shandong province in 2003, nitrate accumulation in the top 90 cm of the soil profile was 52–609, 270–5038, and 32–2406 kg N ha^{-1} , respectively. The corresponding ranges of values at 90–180 cm depth were 224–3273, 68–1047, and 228–2430 kg N ha^{-1} . The amounts of nitrate in the 0–90 and

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90–180 cm depth zones in vegetable greenhouses were significantly higher than in the other two cropping systems (Ju et al., 2006).

Five pathways of residual nitrate in the soil profile have been identified. These are uptake by succeeding crops, leaching to the deep subsoil or shallow groundwater under intensive rainfall or irrigation (Ju et al., 2006), transfer to the upper soil horizons with upward soil water movement during periods of drought (Boswell and Anderson, 1964), denitrification to N_2 or N_2O under favorable conditions (Aulakh et al., 1992), and fixation by soil microorganism (Recous et al., 1990). The Nmin method for N fertilizer recommendations assumes that the availability to crops of residual NO_3^- -N in the root zone (to about 100 cm depth) is equal to that of applied N fertilizer (Chen, 2003). However, plant root systems must develop first in order to take up the residual nitrate located at different soil depths. This implies that crops can utilize NO_3^- -N from only certain soil layers at any particular growth stage. Numerous studies have shown crop recovery of residual ^{15}N applied to previous crops but have not identified the recovery rates at different depths in the soil profile (Strong et al., 1996; Zhu, 1997; Jensen et al., 1997; Glendinning et al., 2001). Rowe et al. (2001) developed ^{15}N depth placement procedures to test and calculate recovery of nitrate from deep subsoils by plants. Menezes et al. (1997) investigated the recovery of subsoil nitrate by injecting $K^{15}NO_3$ solution with 60% ^{15}N abundance at a rate of 50 kg N ha^{-1} into a Kandiuult soil in the southeastern USA at a depth of 100 cm. They found that the recovery of ^{15}N -labeled nitrate from that depth by pearl millet (*Pennisetum glaucum* (L.) R. Br.) was 14.7%. Huang et al. (1996) used this technique to investigate the relative recoveries of deep point-injected soil ^{15}N by switchgrass (*Panicum virgatum* L.), alfalfa (*Medicago sativa* L.) and maize, and found that the amounts of N taken up were 20, 8 and 1 kg ha^{-1} , respectively. The studies described above have shown the recovery of ^{15}N -labeled nitrate at different soil depths by crops growing in soils with low background concentrations of residual nitrate in the soil profile. However, the movement of ^{15}N -labeled nitrate injected at different depths of the soil profile, including the subsoil, and its recovery by crops under conditions characteristic of the North China Plain remain to be investigated.

Residual nitrate is transported with soil water movement in the soil profile and most is concentrated in the topsoil if the water supply is limited. However, residual nitrate may move to the deep subsoil and then leach outside the root zone if the water supply exceeds field capacity through either irrigation or rainfall (Sveda et al., 1992). Residual nitrate will leach to a depth of 60 cm if rainfall or irrigation exceeds 100 mm under the edaphic and climatic conditions of the North China Plain. Large amounts of residual nitrate in the topsoil may also leach to 120 cm (the subsoil) after heavy rainfall in late summer or early autumn in some years (Chen et al., 1996), resulting in a substantial change in the nitrate distribution pattern in the soil profile, with the nitrate concentration decreasing in the surface soil and simultaneously increasing in the deeper layers of the soil profile. Large amounts of residual nitrate have been observed to accumulate at various depths in the soil profile under the intensive crop production systems of the North China

Plain (Ju et al., 2004, 2006). We assume that residual nitrate in different layers has a different potential for downward movement according to the rainfall pattern. Nitrate may be transported over relatively long distances in the upper soil layers and over shorter distances in the deeper layers. This leads to a peak of nitrate accumulation at a particular depth in the soil profile under the prevailing sub-humid conditions, with long distance transport to the shallow groundwater occurring only after extremely high water inputs.

The recovery rate of residual nitrate at any particular soil depth by different crops is different owing to differences in root system morphology and root density. Cereal crops usually have deep root systems. For instance, wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) roots may reach a depth of 200 cm. Vegetable crops usually have shallow root systems, especially leafy vegetables such as spinach, the roots of which are distributed mainly in the top 30 cm of the soil profile. Under these conditions nitrate below a soil depth of 30 cm may be unavailable to the crop. Nitrate uptake by crops from a particular soil layer is closely related to the root length density in this layer (Schenk et al., 1991; Costa et al., 2000). A higher rooting density in the deep subsoil is therefore the key for full utilization of residual nitrate and prevention of nitrate pollution of the groundwater (Robinson et al., 1994; van Vuuren et al., 1996; Kage, 1997). The recovery rate of residual nitrate also depends on the water consumption of the crops. Crops with higher water consumption can also take up more residual nitrate because large amounts of nitrate can move towards the root systems together with the water (mass flow) under copiously watered crops (Marschner, 1997).

The objective of the present study was to examine the recovery of residual nitrate from different depths in the soil profile by two crops, maize and eggplant, with contrasting root systems and the transport behavior of the nitrate in the soil profile.

2. Materials and methods

2.1. Site description

The climate on the North China Plain is warm-temperate sub-humid continental monsoon with cold winters and hot summers. The annual precipitation is 500–700 mm, with 60–70% of the rain falling during summer (June–September). Residual nitrate in the soil profile is readily leached to the deep subsoil or shallow groundwater during the hot and wet summers (Zhang et al., 1996; Ju et al., 2003). In general, the light textured soils of the alluvial plains at the conjunction of the Yellow, Huai, and Hai rivers are also vulnerable to nitrate leaching. It would therefore be a useful technique to protect groundwater quality in this area by capturing residual nitrate, especially deep soil nitrate, using appropriate crop plants.

The field experiment was conducted from May to September 2002 at Dongbeiwang Experimental Station near Beijing. The research site is located at $39^\circ 5' \text{ N}$ and $116^\circ 3' \text{ E}$ at an altitude of 60 m and the groundwater table is 18–20 m deep. The experimental period was relatively dry with 445 mm of precipitation (Fig. 1), which is 80% of the average precipitation for the period 1952 to 1996. The experimental soil is a calcareous alluvial soil with a loamy and silty texture (FAO) typical of the region. Selected physicochemical properties of the soil are summarized in Tables 1 and 2. According to the local soil fertility classification in Beijing (Liu et al., 1999) the soil is highly fertile. Cumulative NO_3^- -N in the top 100 cm of the soil profile before sowing can be as high

as 215 kg N ha^{-1} , which represents moderate nitrate accumulation in the soil profile of local agricultural fields due to long-term high application rates of N fertilizers and manures (Ju et al., 2004).

2.2. ^{15}N microplots

The field experiment examined two factors, crop species (main treatment) and ^{15}N label position (sub-treatment). Maize and eggplant were selected as typical representatives of summer cereal and summer vegetable crops. The three ^{15}N label positions were soil depths of 15, 45 and 75 cm, giving 6 treatments in triplicate and a total of 18 plots arranged in randomized blocks. In addition, control (unlabeled) plots of the two crops were established to correct the ^{15}N -enrichments of labeled plant and soil samples. The area of each ^{15}N microplot was $1 \times 1 \text{ m} = 1 \text{ m}^2$. A microplot frame was inserted 35 cm into the soil with 5 cm extending aboveground, leaving a 1-m margin between adjacent plots to minimize edge effects.

A ^{15}N depth placement procedure was used to inject $100 \text{ kg } ^{15}\text{N}$ -labeled N ha^{-1} into the center of soil zones 0–30, 30–60 and 60–90 cm at the seedling stage. There were three points of injection for each depth of injection in each plot as shown in Fig. 2. The detailed procedure for labeling at each soil depth was as follows. Three vertical holes were made in the soil to the appropriate depth using a steel auger and a PVC tube was installed in each hole. A syringe was used to inject 24.4 g of $5.26 \text{ atom } \% \text{ K}^{15}\text{NO}_3$ (produced by the Institute of Chemical Industry, Shanghai, China) dissolved in 20 ml deionized water through the tubes. The syringes and tubes were then washed by rinsing with 40 ml deionized water. Each hole was backfilled with its original soil and the injection points were labeled at the surface.

Basal fertilizers were applied to each plot by mixing 50 kg N ha^{-1} as urea, $50 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ as double superphosphate, and $50 \text{ kg K}_2\text{O ha}^{-1}$ as potassium sulfate with the top 10 cm of surface soil before sowing. A further 100 kg N ha^{-1} as urea was applied to each plot before rainfall as a top dressing at the ten-leaf growth stage (June 23).

Maize variety NongDa 108 and eggplant variety ZhaoQie 1 were grown at a density of $60,000$ plants per hectare, i.e. six plants per plot (Fig. 2). Maize was sown on May 2 and eggplant was transplanted on May 5. The ^{15}N depth placement procedure was carried out on May 13. Irrigation water (24 mm) was applied on May 27. Eggplant fruits were collected on July 7, July 21, August 1, August 16 and August 29 and oven-dried. The final harvest of maize and eggplant was on September 16.

Time domain reflectometry (TDR) probes were installed in each block of each crop, i.e. three microplots with ^{15}N label at 15, 45 and 75 cm in each crop were selected to monitor soil water in the top 100 cm of the soil profile in every 7 days. The average soil water for each crop was calculated from three plots in the crop.

2.3. Collection of plant and soil samples and measurement

Six plants were partitioned into grain and straw (maize) or stems, leaves and fruit (eggplant) from each plot at maturity on September 16. All samples were chopped into small pieces, immediately dried for 30 min at 105°C , and then dried for 24 h at 65°C , weighed and the dry matter yield was calculated. Plant material (including eggplant fruits collected during the experiment) was mixed thoroughly before taking representative samples of each plant component using the quartering procedure, and then ground using a micro hammer

Fig. 1. Comparison between precipitation in the experimental period in 2002 and the average for the same part of the year from 1952 to 1996.

mill to pass a 0.25-mm sieve. All plant samples were analyzed for total N by the Kjeldahl method and ^{15}N abundance using a Finnigan Mat model 251 mass spectrometer (Germany) after evaporating the distillate.

Soil samples were collected 5, 10, and 15 cm from each labeled point (Fig. 2) after harvest to provide information on the possible vertical and horizontal movement of the labeled nitrate. Vertical sampling was done at 10-cm intervals up to 100 cm depth in the plots labeled at 15 and 45 cm depths and to 150 cm in the plots labeled at 75 cm depth using a steel auger 2 cm in diameter. Each sample was air-dried and finely ground. Soil total N was analyzed by the Kjeldahl method after reduction of $\text{NO}_3^- \text{N}$ with $5\% \text{ KMnO}_4$ and iron powder. ^{15}N abundance in soil was measured after evaporating the distillate using a Finnigan Mat model 251 mass spectrometer (Germany).

Root samples were taken at the midpoint between two plants at 15-cm depth intervals up to 105 cm (Fig. 2) with an 8-cm -diameter root auger after crop harvest. Roots were obtained after each soil core was carefully washed on a 0.25-mm sieve. Root length density was determined using the intercept counting techniques described by Tennant (1975).

2.4. Calculation methods and statistical analysis

The ^{15}N enrichment of all plant material was expressed as atom $\% ^{15}\text{N}$ excess. The proportion of the total applied labeled N recovered by plants was calculated using the formula:

Plant recovery of labeled N (%)

$$= \frac{\sum_i^n \text{Dry weight} \times \text{N content} \times \text{atom } \% ^{15}\text{N excess}_{\text{sample}}}{N_{\text{fertilizer}} \times \text{atom } \% ^{15}\text{N excess}_{\text{fertilizer}}} \times 100$$

Where i = plant component, $n = 2$ in maize (grain and straw) and $n = 3$ in eggplant (stem, leaf and fruit) in this study. All of the eggplant fruits collected

Table 1
Selected soil chemical properties at Dongbeiwang experimental station

Soil depth (cm)	pH (H_2O)	OM (g kg^{-1})	TN (g kg^{-1})	Olsen-P (mg kg^{-1})	$\text{NH}_4\text{OAc-K}$ (mg kg^{-1})	$\text{NH}_4^+\text{-N}$ (kg ha^{-1})	$\text{NO}_3^-\text{-N}$ (kg ha^{-1})
0–20	8.11	22.1	1.23	26.9	84.2	13.4	65.8
20–40	8.29	20.1	1.04	17.3	63.5	13.9	34.1
40–60	8.15	10.6	0.83	8.41	42.8	11.3	39.6
60–80	8.31	7.93	0.54	3.87	20.7	12.2	38.1
80–100	8.05	6.65	0.28	2.76	15.9	9.2	38.2

Fresh soil sample was extracted with $0.01 \text{ mol L}^{-1} \text{ CaCl}_2$ to determine the concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ using a continuous flow analyzer (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany). The other chemical properties were measured according to the book edited by Sparks (1996).

Table 2
Selected physical properties of the soil at Dongbeiwang experimental station

Soil depth (cm)	Soil texture (%)			Bulk density (g cm ⁻³)	Saturated soil water content (w/w %)	Field capacity (w/w %)	Wilting point (w/w %)
	Sand (%)	Silt (%)	Clay (%)				
0–15	27	57	16	1.34	40.3	25.4	7.46
15–30	27	57	16	1.35	31.8	20.7	5.92
30–60	22	60	18	1.52	25.0	19.7	6.58
60–90	31	55	14	1.49	24.2	19.5	4.03
90–120	20	63	17	1.58	28.5	20.9	6.96

The physical properties were measured according to the book edited by Klute (1996).

during the experiment together with those taken at final harvest were used to calculate the overall ¹⁵N uptake and recovery.

The significance of aboveground biomass, N uptake and recovery of labeled nitrate by different crops with different depths of soil ¹⁵N labeling was tested by analysis of variance and mean values were compared by least significant difference (LSD) at the 5% level using the SAS software package (Version 6.12). The distribution of atom % ¹⁵N excess of total N in the soil profile, root length density and soil water content of the two crops were compared by *t*-test using Microsoft Excel.

3. Results

3.1. Effects of labeled nitrate on shoot biomass and N uptake

Total aboveground biomass of neither crop varied significantly with depth of ¹⁵N-labeling with nitrate (Table 3). The biomass of maize was significantly higher than that of eggplant and total aboveground N uptake by both crops showed similar trends to total aboveground biomass (Table 3).

3.2. Crop recoveries of labeled nitrate at different soil depths

Mean recoveries of labeled nitrate at depths 15, 45 and 75 cm by maize were 22.4, 13.8 and 7.8%, respectively,

decreasing significantly with increasing depth of labeling. In the case of eggplant, mean recoveries at 15 and 45 cm were 7.9 and 4.9% and were not significantly different from each other but were both significantly higher than that of labeled nitrate at a depth of 75 cm (2.7%). Recoveries of labeled nitrate by maize were significantly higher than by eggplant. There were significant interaction effects between crop species and position of labeled nitrate.

3.3. Vertical movement of labeled nitrate in soil

¹⁵N abundance of total N at different soil depths 5 cm from the labeling positions was determined after crop harvest and the atom % ¹⁵N excess was calculated on the basis of ¹⁵N natural abundance in the soil of the control plot (Fig. 3). The highest atom % ¹⁵N excess occurred at 70–80 cm soil depth for both maize and eggplant when labeled nitrate was injected at 15 cm depth in the soil profile, indicating downward movement of NO₃⁻-N. Atom % ¹⁵N excess of total N at 20–50 cm soil depth was slightly lower in the maize than in the eggplant plots, corresponding to the higher recovery of labeled nitrate by maize. The maximum atom % ¹⁵N excess appeared at 75–85 cm soil depth for maize and 80–90 cm for eggplant when labeled nitrate was injected 45 cm into the soil. The maximum atom % ¹⁵N excess appeared at 80–90 cm soil depth for maize and 90–100 cm for eggplant when labeled nitrate was injected at 75 cm depth soil and most of the labeled nitrate remained in the soil because of low recovery by the crops from this depth. The amount of residual labeled nitrate was greater in the eggplant plots and moved deeper down the soil profile than in the maize plots.

The vertical movement of the labeled nitrate in maize and eggplant treatments was different when the same amount of water was supplied with 414 mm of total rainfall and irrigation during the crop growing season. Movement of labeled nitrate was lower in maize treatments compared to eggplant. We used the distance of the maximum atom % ¹⁵N excess away from the labeled position as an index of movement of labeled nitrate, and calculated the distance of labeled nitrate movement downward derived by 1 mm of water supply under local soil and climatic conditions (Table 4). However, it is clear that nitrate movement is not related only to total rainfall and irrigation during the crop growing season, but also to the distribution and intensity of rainfall and irrigation. As shown in Fig. 3

Fig. 2. Schematic diagram showing the structure of the microplots in the field, the positions of the plants, the points of ¹⁵N labeling, and the locations of soil and root sampling.

Table 3
Aboveground biomass, N uptake and recovery of labeled nitrate by different crops with different depths of soil ^{15}N labeling

Label depth (cm)	Aboveground biomass (g m^{-2})		Aboveground N uptake (g m^{-2})		Recovery of labeled nitrate (%)	
	Maize	Eggplant	Maize	Eggplant	Maize	Eggplant
15	2455.3a ^a	966.4a	29.7a	21.6a	22.4a	7.9a
45	2699.4a	1109.1a	32.6a	24.3a	13.8b	4.9a
75	2674.6a	1134.4a	32.4a	25.3a	7.8c	2.7b
Mean	2609.7	1069.9	31.6	23.7	14.6	5.2
Significance ^b						
Crop species	**		**		**	
Labeled depth	NS		NS		**	
Crop species $\times$ labeled depth	NS		NS		*	

^a Within each column, mean values with the same letter are not significantly different by LSD at the 5% level.

^b By analysis of variance; **, $P < 0.01$; *, $P < 0.05$; NS, not significant.

and Table 4, in both crops the deeper the placement of labeled nitrate, the shorter was the distance of vertical movement.

3.4. Horizontal movement of labeled nitrate in soil

The ^{15}N abundance of total N at different soil depths 10 and 15 cm away from the labeling position were also determined to investigate horizontal movement of labeled nitrate in the soil. The atom % ^{15}N excess in soil 10 and 15 cm away from the labeling position around the peak layers (i.e. layers of maximum atom % ^{15}N excess 5 cm away from the labeling position, Fig. 3) in both crops exceeded 0 at all three labeled positions, indicating that labeled nitrate moved horizontally more than 15 cm from the labeled position (data not shown).

3.5. Relationship between root distribution and recovery of labeled nitrate

Fig. 4 shows that root length densities of maize were 0.47–1.76 cm cm^{-3} and were significantly higher than those of eggplant (0.10–0.70 cm cm^{-3}) throughout the soil profile to a depth of 105 cm. This trend corresponded to the higher N uptake and higher recovery of labeled nitrate by maize compared with eggplant. Root length density decreased with increasing soil depth,

leading to a decrease in the recovery of labeled nitrate from the subsoil. Root length density (x) in soil layers where the ^{15}N was injected was significantly and positively correlated with the % recovery of the injected ^{15}N (y) in both crops (maize: $y = 19.12x - 8.07$, $r = 0.920$, $P < 0.01$; eggplant: $y = 14.00x - 1.09$, $r = 0.899$, $P < 0.01$). The steeper slope of the regression line for maize reflected the stronger increase in % recovery with increasing root length density compared to eggplant.

3.6. Dynamics of soil water at different soil depths over the crop growing season

Two clear increases in soil water were detected at different soil depths down to 100 cm during the crop growing season under the same rainfall and irrigation inputs to both crop species. The first increase appeared 40–55 days after sowing and the second after 70–110 days (Fig. 5). The water content throughout the soil profile remained below field capacity during most of the growing season (Table 2), indicating that any soil water movement occurred under non-saturated conditions or through soil interstitial spaces. The highly soluble labeled nitrate is likely to have moved with this flow of water. The water content in the surface 20 cm of the soil profile showed no significant difference between the two crops throughout the

Fig. 3. Distribution of atom % ^{15}N excess of total N in the soil profile 5 cm from different labeling points after harvest of the two crops (*, significant difference at the 5% level; **, significant difference at the 1% level (both by t -test)).

Table 4
Transport of labeled nitrate in the soil profile

Labeled depth (cm)	Atom % ^{15}N excess total N (cm)		Distance of downward movement of labeled N (cm)		Distance of downward movement of labeled N from 1 mm precipitation or irrigation (cm)	
	Maize	Eggplant	Maize	Eggplant	Maize	Eggplant
15	70–80	70–80	60a ^a	60a	0.145a	0.145a
45	75–85	80–90	35a	40a	0.084a	0.100a
75	80–90	90–100	10b	20a	0.024b	0.048a

^a Within each row, mean values with the same letter between two crops are not significantly different by *t*-test at the 5% level.

growing season. The water content at 20–40 cm depth showed no differences at other times except for around 85 days after sowing when it was significantly higher in eggplant than in maize plots. The water content in the 40–100 cm depth zone did not vary significantly over the first 85 days and was significantly higher in eggplant than in maize plots after 85 days. Maize had a higher water requirement and absorbed subsoil water 85 days after sowing, and this prevented the downward movement of subsoil water and resulted in shorter distance movement of labeled nitrate in the maize plots compared to the eggplant plots.

4. Discussion

Edaphic and climatic conditions on the North China Plain are generally favorable for mineralization and nitrification (Richter and Roelcke, 2000; Liu et al., 2003; Ju et al., 2004). These conditions, combined with the high N surpluses arising from excessive fertilizer applications, lead to accumulation of nitrate at various soil depths. The amount of residual nitrate in the top 100 cm of the soil profile in the experimental field before sowing was 215 kg N ha^{-1} . This, together with 100 kg N ha^{-1} of labeled nitrate, gives a total of 315 kg N ha^{-1} nitrate-N, which represents high nitrate accumulation in the soil profile typical of local wheat-maize rotation fields (Ju et al., 2004, 2006). The recoveries of labeled nitrate by the two crops (2.7–22.4%, depending on crop species and depth of labeled nitrate

placement) in our experiment were likely to be representative of local farming conditions using typical fertilizer application rates (150 kg N ha^{-1} applied to the top soil). Labeled nitrate placed at different soil depths was taken up by the crops or transported down the soil profile in a similar fashion to indigenous residual nitrate at different soil depths as indicated by the distribution of nitrate measured after crop harvest (data not shown). Our results indicate that the recovery of labeled nitrate from deep down the soil profile was quite low, emphasizing the very high potential for large losses of residual nitrate to the subsoil in intensive crop production systems in the region. Due to the uneven horizontal distribution of labeled ^{15}N in the soil after harvest, we only investigated the trends of changes in labeled ^{15}N by taking soil samples 5 cm away from the labeling positions and we cannot calculate the percentage recovery of the labeled ^{15}N in the soil. Because the crop recoveries of labeled nitrate placed at shallow depths was much higher than of labeled nitrate placed at greater depths, recoveries of labeled nitrate in the soil would be expected to show the opposite trend.

Crop species significantly affected the recovery of residual nitrate at different soil depths. Nitrate leaching can be substantially reduced by crops with high N uptake ability (Steenvoorden, 1989). Residual nitrate in the soil profile showed a significant negative relationship with the amount of N uptake by different maize varieties (Wiesler and Horst, 1992, 1993). Maize has a large fibrous root system that can usually extend to a soil depth of 140–150 cm and sometimes to 200 cm, but over 80% of the roots are distributed in the top 30 cm (Anonymous, 1983). In contrast, eggplant has a root system in which the main and lateral roots are more clearly defined and can extend to 130–170 cm depth, but most of the roots are distributed within the top 25 cm of the cultivated layer and they display early lignification (Zhou and Li, 2002). The root length density of maize is usually higher than that of eggplant because of its strong fibrous roots. Wiesler and Horst (1994) showed that the degree of exhaustion of nitrate in the subsoil increased with increasing crop rooting density in the deeper horizons. The results of our experiment indicate that the root length density of maize was significantly higher than that of eggplant in the top 105 cm of the soil profile (Fig. 4), leading to higher uptake of N and recovery of labeled nitrate at different soil depths by maize than by eggplant.

The higher water consumption of maize may also have contributed to the higher uptake and recovery of labeled nitrate at any given soil depth by maize compared to eggplant. Due to differences in albedo, crop height, aerodynamic properties,

Fig. 4. Root distributions of maize and eggplant at different soil depths after harvest (*, significant difference at the 5% level by *t*-test).

Fig. 5. Dynamics of soil water content at different soil depths during the growing season of maize and eggplant (*, significant difference at the 5% level by *t*-test).

and leaf and stomatal properties, the crop coefficient (K_c) of maize is much higher than that of eggplant, leading to higher evapotranspiration from fully grown, copiously watered maize compare with eggplant (Allen et al., 1998). The higher water consumption by maize than by eggplant was also reflected by the lower soil water content at 40–100 cm depth 85 days after sowing (Fig. 5). The labeled nitrate was presumably taken up during transpiration and the higher water consumption by maize may thus help to account for the large recovery of labeled nitrate in maize.

Within each crop, the question arises why the peak of the labeled nitrate appeared at similar soil depth after harvest although the labeled nitrate was originally injected at different depths and why the deeper the ^{15}N -labeled nitrate placement, the smaller the distance of downward movement of the ^{15}N -labeled nitrate. This may be explained by soil water movement derived from rainfall during the crop growing season (Fig. 5). Water flow from rainfall may only have penetrated to a certain depth of soil. Labeled nitrate may have moved downward with the soil water instead of moving to greater depths. This would also explain the high cumulative nitrate peak that usually appears deep in the soil profile after

excessive application of N fertilizer under the prevailing sub-humid climatic conditions with the onset of precipitation of 500–700 cm (Guo et al., 2003a; Yang et al., 2001; Ju et al., 2004). This cumulative nitrate usually resides in the soil for a long time (Richter and Roelcke, 2000; Guo et al., 2003b) unless there is an extremely high water supply when it may leach to the shallow groundwater. This extremely high rainfall has been observed to occur in some years on the North China Plain. For example, 103 mm of rain fell on June 30 1998 and 76 mm on July 29 2004 in the Beijing area.

The horizontal movement of labeled nitrate in the soil in excess of 15 cm in our field experiment agrees with results obtained from a clay soil in Kenya (Gathumbi et al., 2003) in which labeled nitrate diffused to the whole layer of the soil from the labeling point and the crop took up labeled nitrate from whole labeled soil layer.

5. Conclusions

Crops with deep rooting systems and high water consumption may have higher recoveries of residual nitrate than crops with shallow rooting systems and low water consumption. The

low recoveries of residual nitrate located in the deep subsoil by both crops illustrate the great potential losses of nitrate to pollute the shallow groundwater under current farming practices on the North China Plain. To mitigate this environmental risk, techniques such as the Nmin method for N fertilizer recommendation should be adopted by extension workers to prevent progressive accumulation of nitrate in the soil profile, especially in the deep subsoil after harvest. A trend of nitrate movement in which the deeper the nitrate is located in the soil profile the shorter the distance it will move downward may explain how the peak of residual nitrate was clearly discernible in the prevailing sub-humid soil and climatic conditions. This residual nitrate may reside in the soil for extended periods until extremely large rainfall events occur or large amounts of water are supplied by excessive irrigation, resulting in the leaching of nitrate to the shallow groundwater. Crops with deeper root systems and high water consumption may therefore be grown to utilize the high residual nitrate in the soil. Careful management of the water supply for field crops is also required to minimize or control the downward movement of residual nitrate in the soil profile.

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