Soils, Section 1: Soil organic matter dynamics and nutrient cycling

Research Article

Effects of Nitrogen Fertilizer Application Rates on Nitrate Nitrogen Distribution in Saline Soil in the Hai River Basin, China*

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Abstract

Background and Objectives. Soil nitrate nitrogen ($\text{NO}_3\text{-N}$) accumulation is related closely to $\text{NO}_3\text{-N}$ leaching, which is an important issue in groundwater pollution, especially in intensive agricultural areas with saline soils where volumes of water are used in irrigation to avoid salt accumulation in the root zone. However, in the saline environment in Hai River Basin, China, the importance of detailed research into $\text{NO}_3\text{-N}$ distribution in the root zone has not been adequately recognized. Considering the impacts of eco-environmental system N and crop production, the present study aimed at contributing to an understanding of the effects of N application rate on soil $\text{NO}_3\text{-N}$ distribution, $\text{NO}_3\text{-N}$ residue, N loss, and maize (*Zea mays L.*) yield in this region.

Methods. The experiment was a completely one-factorial, randomized layout with 4 N application rates. Plant samples and soil samples from 0 to 100 cm depth were collected 8 and 9 times during the growing season, respectively. Soil $\text{NO}_3\text{-N}$ concentration was determined using a Flow Solution IV Analyzer. Soil water content was monitored throughout the season via the soil auger method. Samples of irrigation water and rainfall were collected and analyzed for total nitrogen contents. Maize (*Zea mays L.*) above-ground, dry matter production, grain yield, and harvest index (HI) were measured. And nitrogen content in plant samples was determined by the Kjeldahl method.

Results. Under fertilizer treatment, larger quantities of $\text{NO}_3\text{-N}$ were present in the upper soil layer (0–40 cm) at 7 days after fertilization (DAF). From 7 to 37 DAF, $\text{NO}_3\text{-N}$ decreased, obviously because of the heavy rainfall together with the increase in the capacity of maize to accumulate N in this period, and a significant decrease in $\text{NO}_3\text{-N}$ stock was observed. There was a significant positive correlation between the quantity of $\text{NO}_3\text{-N}$ stock decrease and the nitrogen fertilizer application rates during this period. And there was more $\text{NO}_3\text{-N}$ accumulated in the lower layers under fertilization treatment at 76 DAF. N fertilizer application also had a great effect on maize yield and the highest yield occurred under the treatment of 70 kg N ha^{-1} .

Discussion. This study showed that the N application rate had a significant effect on maize yield, maybe because of the low initial $\text{NO}_3\text{-N}$ content. Higher N application rate increased N uptake, but it also increased $\text{NO}_3\text{-N}$ residue and N loss, therefore increasing the risk of $\text{NO}_3\text{-N}$ leaching. This study showed the present nitrate application rate (140–180 kg N ha^{-1}) during maize cropping season was excessive in the study area.

Conclusions. Nitrogen fertilizer application increased $\text{NO}_3\text{-N}$ concentration and stock in 0–100cm soil profile and changed $\text{NO}_3\text{-N}$ distribution during maize cropping season. And nitrogen fertilizer application promoted movement of $\text{NO}_3\text{-N}$ down the soil profile and increased N loss. But effects of nitrogen fertilization application rate on above-ground dry matter production and grain yield were non-linear.

Recommendations and Perspectives. A strictly controlled, site-specific, long-term fertilization study will be set up for the determination of biochemical processes of soil $\text{NO}_3\text{-N}$ and for the effective N fertilizer management of the saline soil areas.

Keywords: Maize; nitrate dynamics; nitrate residue; nitrogen application rate; nitrogen uptake; saline soil

Introduction

In order to produce food for the growing world population, increasing agriculture or innovative measures to enhance productivity are needed. To meet the nutrient requirements by crops, particularly N fertilizer, farmers normally apply excessive N fertilizer. However, the by-effect of the N fertilizer as a potential contaminant of groundwater is well known (Fried 1991, Rivers et al. 1996, Oenema et al. 1998, Sánchez-Pérez et al. 2003, Basso & Ritchie 2005). Following its application, the N fertilizer undergoes a series of transformations in the soil and forms NO_3^- , which is a major valuable nutrient (Hignett 1985), but is susceptible to leaching through the soil by infiltrating water, thereby posing a potential risk to the environment, particularly to water bodies (Pacheco & Cabrera 1997, Satorre & Slafer 1999, Zhu et al. 2003).

Many factors have effects on NO_3^- movement and potential leaching, which include N fertilizer management (Sánchez-Pérez et al. 2003), irrigation methods (Schepers et al. 1995, Diez et al. 1997, Rajput & Patel 2006), N uptake dynamics (Schmidtke et al. 2004) and transformation. The high rate of $\text{NO}_3\text{-N}$ accumulation and free drainage in the soil are conditions under which NO_3^- leach into the subsoil or groundwater (Ju et al. 2006).

Because of the limitation in fresh water resources, shallow groundwater including brackish water and semi-saline water has been used for irrigation for many decades in the saline area of Hai River basin of China. In order to reduce salinity accu-

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mulation in the root zone (especially the upper soil layer), flood irrigation (usually 90–130 mm of water at each irrigation event) is applied. With the intensive rainfall in the summer season (about 400 mm from June to August, the growing season of maize), the soil water condition is very prone to NO_3^- -N leaching.

Currently, the average rate of N application in this region reaches $400 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for the winter wheat-maize double cropping system, in which $140\text{--}180 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ is used during maize growing season. The trend of N application rate is still increasing. So it is quite important to examine NO_3^- -N distribution in the root zone in order to prevent its leaching and improve fertilizer use efficiency in this region. The objective of this present study were therefore (1) to compare N application rates on soil NO_3^- -N distribution in order to understand the impacts of different N management on soil environment, and (2) to compare N application on N uptake, maize yield and loss during the maize growing season.

1 Material and Methods

1.1 Site and soil

The field experiments were carried out in 2005 at the Nanpi agricultural experimental station ($38^\circ 05' \text{N}$, $116^\circ 42' \text{E}$) op-

erated by the Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, Chinese Academy of Sciences. The 30-year mean annual precipitation in this area is 550.0 mm, of which 74% occurs between June and August. The mean annual transpiration is 2138.6 mm, the mean annual air temperature is 12.3°C with the maximum and minimum mean monthly air temperature being 26.6°C (July) and -4.3°C (January), respectively, and with 184 frost-free days a year. The total salt content is over 0.8% at 0–10 cm and remained essentially constant at around 0.5% at depths below 40 cm in the saline soil of this region (Tóth et al. 1995, Mao et al. 2002). The depth of the groundwater table to surface is 5.6–6.0 m during the maize cropping season. The experimental site has been cultivated with the winter wheat (*Triticum aestivum* L.)-summer maize rotation for more than 10 years. The content of Olsen-P was 13.4, 15.8, 20.4 mg kg^{-1} and of exchangeable K was 175.4, 202.6, 179.5 mg kg^{-1} at 0–20, 20–60, and 60–100 cm in the soil profile, respectively. Just before sowing, the soil was sampled at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm to measure other soil properties, which have been shown in Table 1. The precipitation and soil water content during the study period are shown in Fig. 1.

Table 1: Soil physical and chemical properties of the study site

Depth (cm)	Soil texture	Particle size (%)			Bulk density (g cm^{-3})	Soil pH	Soil organic matter (%)	Total N (g kg^{-1})	NO_3^- -N ^a (mg kg^{-1})	NO_3^- -N ^b (mg kg^{-1})
		Sand	Silt	Clay						
0–10	Silt loam	54.0	45.1	0.9	1.39	8.53	1.71	0.64	3.3	8.6
10–20	Loam	54.3	44.8	0.9	1.33	8.76	1.45	0.64	3.4	4.4
20–40	Sandy loam	63.9	34.8	1.3	1.33	8.84	0.94	0.40	6.0	9.0
40–60	Sandy loam	62.7	36.7	0.6	1.43	9.07	0.74	0.30	9.8	16.4
60–80	Sandy loam	68.3	31.2	0.5	1.46	8.75	0.59	0.30	9.1	16.5
80–100	Sandy loam	64.4	35.0	0.6	1.40	8.61	0.61	0.30	4.7	7.8

^a Soil nitrate nitrogen content before seed sowing

^b Soil nitrate nitrogen content before applying nitrogen fertilizer

Fig. 1: Precipitation and soil water content during study period

1.2 Experimental set-up

The experimental plots (15 m × 8 m) were designed with a completely one-factorial, randomized layout with N application rates of 0, 70, 140, and 210 kg N ha⁻¹ (as urea), with 4 replicates. The treatments were expressed as N0, N70, N140, and N210, respectively. The designed fertilizer rates were side dressed in the plots on July 14. After harvesting winter-wheat, the experimental field was irrigated at a rate of 100 mm on June 8 and was not watered again during the rest of the experiment. Maize cv. Liyu No. 16 was sown on June 13 in rows spaced at 0.6 m apart (row direction: south-north), at a density of 6.67 plants m⁻² and was harvested on September 28 at the maturing grain stage.

1.3 Sampling and sample analysis

Soil samples were taken at 100 cm in six successive soil depths: 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm, using an auger with a diameter of 3.6 cm for 9 times during the season, i.e. before seed sowing (June 12); before fertilizing (July 11), as well as 7, 17, 27, 37, 47, 57 days after fertilization (DAF), and 76 DAF (at the time of harvesting). From each plot, 4 soil cores (2 samples in, and 2 samples between rows) were sampled and then mixed thoroughly and quickly. All soil samples were stored in plastic bags under a frozen condition achieved immediately until they were analyzed to determine the NO₃⁻-N concentration, which was determined using a Flow Solution IV Analyzer (FSIV, O.I. Analytical, U.S.A.) after extraction (with a 1:5 ratio) (w/w) soil:1 mol L⁻¹ KCl solution. The soil samples were weighed and dried to a constant weight at 105°C to determine gravimetric soil moisture content. At harvesting, soil samples were also analyzed to determine the soil total nitrogen content using the Kjeldahl method (Bao 2000).

Eight water samples were collected with a 10-min interval during irrigation. Rainwater samples (8 samples each time) were collected during the rain over the experiment period. All the water samples were stored in 100 ml polyethylene bottles under frozen conditions for the analysis of ammonia and nitrate nitrogen concentration using a Flow Solution IV Analyzer (FSIV, O.I. Analytical, U.S.A.).

The plant samples were collected simultaneously with soil samples, except before sowing. Three coterminous plants were cut from every plot each time. The plant samples were dried at 70°C to a constant weight to determine the total, above-ground dry matter. And then the samples were milled to a fine powder with a particle size <0.2 mm to determine the total nitrogen content in plant and calculate total plant N uptake. On September 28, when maize was matured, the plants were harvested at an area of 4 m × 3.6 m in the middle of each plot to determine grain yield and harvest index (HI). All the plant samples were cut near the soil surface and the plant underground fractions were preserved in field. The total nitrogen in plant samples was determined by the Kjeldahl method (Bao 2000).

1.4 Calculations and statistical analysis

The amount of NO₃⁻-N (kg N ha⁻¹) reserved in every soil layer (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm)

was calculated according to the equation modified by Emteryd (1989):

$$Y_i = T_i \times BD_i / (1 - RWC_i) \times [NO_3^-]_i \times 0.1 \quad (1)$$

where

T_i is the thickness of soil layer in cm;

BD_i is the bulk density in g cm⁻³;

RWC_i is soil relative water content in %;

$[NO_3^-]_i$ is the soil NO₃⁻-N concentration in mg kg⁻¹, and 0.1 is the conversion coefficient.

The total amount of NO₃⁻-N presented in 0–100 cm soil profile was the sum of those in all soil layers. N losses were calculated according to the equation:

$$N_L = TN_S + N_F + N_R + N_I - N_U - TN_H \quad (2)$$

where

N_L is the loss of N from 0–100 cm soil profile (including leaching, denitrification, and ammonium volatilization from 0–100 cm soil profile);

TN_S and TN_H are the total nitrogen at the sowing and harvest, respectively;

N_F , N_R , and N_I are the mineral N inputs into the plots from fertilizer, rain, and irrigation, respectively, and

N_U is the N uptake by the maize above-ground mass.

The unit of all parameters in Eq. (2) is kg N ha⁻¹. The HI was calculated as the ratio of dry matter grain yield to above-ground dry matter at the harvest. Statistical significance of the difference between treatments was analyzed using ANOVA (analysis of variance) and LSD (least significant deviation) multiple comparison (SPSS for Windows, Version 11.0.0, 2001).

2 Results and Discussion

2.1 N uptake, dry matter production and grain yield

There was a significant positive correlation between N uptake and N fertilizer application rate ($R=0.928^{**}$, Fig. 2). Nitrogen uptake rate behaved slow-fast-slow during the growing season. Before 7 DAF, N uptake rates were slow for all four treatments because of the lower N requirement during the earlier growing stages of maize. From 7 to 37 DAF, with the fast growing of the maize, N uptake rate reached 2.53, 2.58, 3.09, and 3.77 kg N ha⁻¹ d⁻¹ under N0, N70, N140, and N210, respectively, and the total N uptake quantity reached 77.8–113.0 kg N ha⁻¹ during this period. This showed that higher nitrogen fertilizer application increased maize N uptake significantly ($P<0.001$). From 37 to 76 DAF, the N uptake rate was slow again, because the N requirement of maize decreased during the later growing stages.

The effect of N fertilizer application rates on the total above-ground dry matter production, however, was not obvious until 27 DAF. When N application was lower than 140 kg N ha⁻¹, the increase in N fertilizer application rate increased above-ground, dry matter production. Afterwards, more N

Fig. 2: Temporal changes of above-ground dry matter production (ADMP) and nitrogen accumulation in maize (NAcc) under various nitrogen application rates. Bars signed by different letters in same sampling date were significant at $P < 0.05$. $n=4$

fertilizer decreased above-ground dry matter production (see Fig. 2). At 76 DAF, compared with N0, the above-ground dry matter production was increased by 5.2%, 21.9%, and 14.5% under N70, N140 and N210, respectively.

The N application had a great effect on maize HI, and the N fertilizer application rate over 70 kg N ha⁻¹ decreased HI significantly. The effect of N application rates on grain yield was also significant (Table 2). It was interesting to note that the lowest grain yield, 7% less than N0, occurred under N210, which was the highest N application rate in the experiment. The highest grain yield achieved under N70. And the reasons of the decrease in grain yield for different treatments were various. For N0, it might be its lower above-ground DM production. For N140, it might be its significantly lower HI. And for N210, the reasons might be both. Some studies showed that the yield had little response to N fertilization (Basso & Ritchie 2005, Li et al. 2005). The difference may be a result of the disparity of initial soil NO₃⁻-N contents in different studies. In this experiment, the initial NO₃⁻-N content was 92.93 kg N ha⁻¹. Abad et al. (2004) reported from Spain that if the initial soil NO₃⁻-N contents were below 157 kg N ha⁻¹, the grain yield would increase clearly with N fertilization up to 100 kg N ha⁻¹ and high initial soil NO₃⁻-N contents reduced the response of yield to N fertilization.

2.2 NO₃⁻-N distribution and stock in the profile

In the plots under N0, the NO₃⁻-N accumulated mainly in the lower soil layer (40–100 cm). NO₃⁻-N concentration in the upper soil layers (0–40 cm) was low and steady during the whole maize growing season. But in the lower layers, the NO₃⁻-N changed extensively over time (Fig. 3).

The mean NO₃⁻-N concentrations of lower layers increased steadily from 7.9 mg kg⁻¹ before sowing (see Table 1) to 22.5 mg kg⁻¹ at 7 DAF (see Fig. 3). Therefore, the NO₃⁻-N stock in 0–100cm soil profile had an increase during this period. This NO₃⁻-N increase under no nitrogen fertilizer application, commonly referred to as the 'N flush' (Wild 1972, Weber et al. 1995), showed that soil NO₃⁻-N input was higher than its requirement. Net nitrogen mineralization heavily governed by rainfall, soil moisture, and temperature (Maithani et al. 1998). And the warm and moist conditions in summer of the monsoon climate are advantageous to the mineralization of soil nitrogen (Adhikari et al. 1999). On the other hand, the slow growth of maize during early development resulted in a lower N uptake.

Applying N fertilizer, on the whole, increased NO₃⁻-N concentrations in all layers and, therefore, the NO₃⁻-N stock in 0–100 cm soil profile (see Fig. 3 and Fig. 4). At 7 DAF, the increase of NO₃⁻-N stock in soil profile under fertilized treat-

Table 2: Nitrogen balance, grain yield and HI under different nitrogen application rates

Treatment	TN _s (Mg N ha ⁻¹)	N _F (kg N ha ⁻¹)	N _R (kg N ha ⁻¹)	N _I (kg N ha ⁻¹)	N _U (kg N ha ⁻¹)	TN _H (Mg N ha ⁻¹)	N _L (kg N ha ⁻¹)	Grain yield (Mg ha ⁻¹)	HI
N0	5.4(0.2)	0	6.5(0.4)	1.8(0.04)	131.8(4.0) ^c	5.2(0.23)	20.9(7.59) ^c	7.75(0.08) ^b	0.41(0.02) ^a
N70	5.4(0.2)	70	6.5(0.4)	1.8(0.04)	134.7(3.0) ^c	5.3(0.26)	29.8(9.71) ^c	8.19(0.13) ^a	0.41(0.01) ^a
N140	5.4(0.2)	140	6.5(0.4)	1.8(0.04)	148.8(0.8) ^b	5.3(0.11)	57.0(6.34) ^b	7.73(0.18) ^b	0.33(0.01) ^b
N210	5.4(0.2)	210	6.5(0.4)	1.8(0.04)	162.6(1.7) ^a	5.3(0.17)	102.7(21.22) ^a	7.21(0.10) ^c	0.33(0.00) ^b

Standard errors of mean are in parentheses. Means followed by different letters in the same column were significantly different at $P < 0.05$. $n=8$ for TN_s, N_F, N_R, and N_I; $n=4$ for others

Fig. 3: Changes of nitrate distribution under various application rates after applying nitrogen fertilizer. $n=4$

ments was the result of the significant increase in NO_3^- -N concentrations in the upper soil layers. Especially in the 0–10 cm soil layer, NO_3^- -N concentration was increased significantly with the increased N application rate ($R=0.887^{**}$). This also showed that nitrogen fertilizer application increased the lower layers' NO_3^- -N concentration initially, in agreement with the study of Oikeh et al (2003). From 7 to 37 DAF, NO_3^- -N stocks under the four treatments all decreased quickly. At least two reasons contributed to this result. On the one hand, there were three heavy rainfall events during this period: 66 mm, 44 mm, and 60 mm 10, 25, and 33 DAF, respectively. and the fact that heavy rainfall leads to NO_3^- -N leaching has been shown in research performed by various groups (Delin and Landon 2002, Sánchez-Pérez et al. 2003). On the other hand, maize grew faster and had a greater capacity to accumulate N during this period (see Fig. 2). There was a significant positive correlation between the quantity of NO_3^- -N stock decrease and the nitrogen fertilizer application rates ($R=0.920^{**}$). It was because the higher application rate enriched the soil NO_3^- -N concentration.

And higher soil NO_3^- -N concentration could promote N uptake and was thus prone to leaching during the rainy season (Lee and Jose 2005). Under N0, the decrease of NO_3^- -N stock was mainly reflected by the decrease of NO_3^- -N concentration in lower layers. Under fertilized treatments, however, it was mainly reflected by the decrease of NO_3^- -N concentration in upper soil layers. During this period, for example, there was a mean decrease of 0.4 and 39.7 mg kg^{-1} in upper soil layers and a decrease of 17.4 and 1.6 mg kg^{-1} in lower layers under N0 and N210, respectively. Meanwhile, under fertilized treatments, NO_3^- -N concentrations in upper soil layers decreased quickly, whereas those in lower soil layers decreased more moderately and even increased appreciably. This showed the movement of nitrate down the soil profile. And the heavy rainfall might contribute to this downward movement.

From 37 to 57 DAF, there was a small increase in NO_3^- -N stock, which was reflected under each treatment by the increase of NO_3^- -N concentration in lower soil layers. However, the quantity of NO_3^- -N stock increase varied with the

Fig. 4: Temporal changes of soil nitrate along maize growth proceedings under various nitrogen application rates. Bars assigned by different letters on the same sampling date were significant at $P < 0.05$. $n = 4$

nitrogen fertilizer application rate. In detail, NO_3^- -N stock under N0, N70, N140, and N210 had an increase of 32, 59, 47, and 57 kg N ha^{-1} , respectively. This showed that fertilized treatments promoted NO_3^- -N stock during this period. From 7 to 37 DAF, fertilized treatment caused more NO_3^- -N leaching from 0–100 cm soil profile and maybe caused a higher NO_3^- -N concentration in soil water below 100 cm soil layer. The up movement of soil water that contained a higher NO_3^- -N concentration might be the reason for a higher NO_3^- -N stock increase in 0–100 cm profile under fertilized treatments.

At 76 DAF, comparing with N0, there was more NO_3^- -N accumulated in the lower layers under the fertilized treatments. Compared with NO_3^- -N stock at sowing, there was a decrease of 24.0 kg N ha^{-1} in the soil profile under N0, while there was a definite increase under the fertilized treatments. This showed that nitrogen fertilizer application increased NO_3^- -N residue in the profile, as reported by others (Bhogal et al. 2000, Abad et al. 2004, Li et al. 2005). And in this study, the NO_3^- -N contents under fertilized treatments after crop harvest exceeded the environmental safety standards of 100 kg N ha^{-1} as suggested by Hofman (1999).

2.3 N balance

Although applying N fertilizer increased total nitrogen reservation in 0–100 cm soil profile and there was a positive correlation between N fertilizer application rate and total nitrogen residue, the difference of total nitrogen residues between four treatments was not significant ($P = 0.697$). But applying N fertilizer significantly increased N losses (including the leaching, denitrification, and ammonium volatilization from 0–100 cm soil profile) from 0–100 cm soil profile (see Table 2). And in the plots under N140 and N210, N losses were significantly higher than those under N0 and N70.

The nitrogen balance in this experiment was a rough estimate of N losses of 100 cm soil profile, because our estimates of N losses did not take into account the N contents of the roots. Murwira and Kirchmann (1993) found N content of root of a well-fertilized maize crop was 8–12% of the shoot N content at 10 weeks after planting. Therefore, the N loss from 0 to 100 cm soil profile would have been reduced slightly. The maximum maize rooting depth was about 120 cm and 99% of its roots were at the depth above 100 cm (Mekonnen et al. 1997), so that the N lost from the 0–100 cm soil profile had a very low biological availability and was a potential source to groundwater contamination.

3 Conclusions

Nitrogen fertilizer application increased NO_3^- -N concentration and stock in the 0–100 cm soil profile and changed NO_3^- -N distribution during maize growth proceedings. And nitrogen fertilizer application promoted the movement of NO_3^- -N down the profile and increased N loss. There was a positive correlation between nitrogen fertilization application rate and maize nitrogen uptake. But the effects of nitrogen fertilization application rate on above-ground DM production and grain yield were non-linear. The maximum values of above-ground DM production and grain yield appeared under treatment of N140 and N70, respectively. By manipulating the impacts of N application rates on soil nitrate and maize production, the present nitrate application rate (140–180 kg N ha^{-1}) during maize cropping season was excessive in the study area.

4 Recommendations and Perspectives

The following step will be to study the impacts of N fertilizer managements on biochemical processes of soil NO_3^- -N under other cropping systems. The site-specific, long-term fertilization study is needed.

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