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Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation District, China

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Abstract

Soil water and salinity are crucial factors influencing crop production in arid regions. An autumn irrigation system employing the application of a large volume of water (2200–2600 m^3 ha^{-1}) is being developed in the Hetao Irrigation District of China, since the 1980s with the goal to reduce salinity levels in the root zone and increase the water availability for the following spring crops. However, the autumn irrigation can cause significant quantities of NO_3^- to leach from the plant root zone into the groundwater. In this study, we investigated the changes in soil water content, NO_3–N and salinity within a 150 cm deep soil profile in four different types of farmlands: spring wheat (F_W), maize (F_M), spring wheat–maize inter-planting ($F_{W–M}$) and sunflower (F_S). Our results showed that (1) salt losses mainly occurred in the upper 60 cm of the soil and in the upper 40 cm for NO_3–N; (2) the highest losses of salt and NO_3–N could be observed in F_W, whereas the lowest losses were found in $F_{W–M}$.

NO_3–N concentration, pH and electrical conductivity (EC) in the groundwater were also monitored before and after the autumn irrigation. We found that the autumn irrigation caused the groundwater concentration of NO_3–N to increase from 1.73 to 21.6 mg L^{-1}, thereby, exceeding the standards of the World Health Organization (WHO). Our results suggest that extensive development

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of inter-planting tillage might be a viable measure to reduce groundwater pollution, and that the application of optimized minimum amounts of water and nitrogen to meet realistic yield goals, as well as the timely application of N fertilizers and the use of slow release fertilizers can be viable measures to minimize nitrate leaching.

Keywords: Autumn irrigation; Farmlands; Hetao Irrigation District; N leaching; NO_3–N; Salinity

1. Introduction

The leaching of nitrogen from farmland has become an important environmental issue because high nitrate concentrations in the groundwater can cause methemoglobinemia, or blue baby syndrome (Ritter, 1989). In rural area of China, most residents usually drink untreated groundwater. In areas with intensive agricultural production, the NO_3–N concentration in the groundwater can sometimes exceed 200 mg L^{-1} (Zhang et al., 1987). The increased incidence of nitrate contamination of the groundwater has been related to the increased use of N fertilizers and irrigation (Ersahin, 2001; Goulding, 2000; Keeney and DeLuca, 1993). In China, the area under irrigation has increased from 44.89×10^6 ha in 1980 to 53.82×10^6 ha in 2000 (Rural Statistical Yearbook of China, 2001).

Nitrate leaching in irrigated agriculture is assumed to be an inevitable result of the relatively high N fertilizer rates applied and the need to periodically leach salts from surface soil horizons (Ottman et al., 2000; Ritter, 1989). For annual crops, the N uptake efficiency is <50%, even when following good management practices (Ju and Zhang, 2003; Gillian et al., 1985) and about 30–50% of applied N fertilizer is leached into groundwater (Zhang, 1987). Using best management practices and near optimum N rates, the amount of NO_3–N leaching has been estimated to be 41% for irrigated maize (Kessavalou et al., 1996), $32 \pm 28\%$ (standard deviation) for irrigated wheat (Ottman et al., 2000) and 27.9% for irrigated Orchardgrass (Watts et al., 1991). In addition, when compared to solely rain-fed fields, the amounts of leached NO_3–N have been found to be 17 and 53% higher in low and high volume irrigated fields, respectively (Timmons and Dylla, 1981).

Irrigation is essential for crop cultivation in arid regions in order to increase the water availability in the soil and to leach a fraction of accumulated salts. In the irrigated regions of western China, an autumn flood-irrigation system is being developed since the 1980s to reduce salinity levels in the root zone and increase the water availability for the following spring crops (Meng and Yang, 2002). It has been reported that a large irrigation usually causes the leaching of significant quantities of NO_3–N in the root zone, especially in the non-growing season (Ritter, 1989). Until now, however, for the autumn flood-irrigation system, leaching losses of NO_3–N and salts, and their impact on groundwater contamination, have not been quantified. This study was carried out to determine and compare the effects of the autumn irrigation on the leaching of NO_3–N and salts from different farmlands and to assess its impact on groundwater quality.

2. Material and methods

2.1. Study area

The Hetao Irrigation District (40°19′–41°18′N, 106°20′–109°19′E), situated in the western arid areas of the inner Mongolia autonomous region, is one of the three largest irrigation districts in China, covering a total area of 1.12×10^6 ha with 5.7×10^5 ha under irrigation of which 5.25×10^5 ha are cropland. The irrigation water is mainly drawn from the Yellow River. About half of the irrigated cropland is saline-alkali soil. For the period from 1987 to 1997, the average annual salt accumulation has been estimated to be 3 Mg ha^{-1} (Feng et al., 2003).

The region has an arid continental climate. Annual average temperature is 8.1 °C, with monthly averages ranging from 23.76 °C in July to -10.08 °C in January. The soil is usually frozen for 5–6 months per year from late November to the middle of May. There are about 135–150 frost-free days and an average of 3100–3300 h of sunshine per year. The average annual precipitation amounts to 150 mm, with about 60% of the rain falling in July and August. The annual potential evaporation is about 2200–2400 mm (Lei et al., 2001).

2.2. Soil sampling

The field study was conducted at the Shahaoqu Experimental Station in the Hetao Irrigation District. The physical and chemical properties of the investigated soil are listed in Table 1. Local crops are mainly spring wheat (*Triticum aestivum* L.), sunflower (*Helianthus annuus* L.) and maize (*Zea mays* L.). The studied fields (spring wheat, F_W; maize, F_M; sunflower, F_S; spring wheat–maize, F_{W-M}) were chosen randomly. The applied volumes of irrigation water and amounts of fertilizer N for each field are summarized in Table 2. Soil samples were collected using a 35 mm soil auger. For each type of field, samples were taken from three different sites at five different sampling points per site. At each sampling point, samples were taken from seven layers: 0–20, 20–40, 40–60, 60–80, 80–100, 100–120 and 120–150 cm depth. Soil samples were taken on 21 and 22 October 2002, before the autumn irrigation and on 11 and 12 November 2002, after the autumn irrigation, respectively. The flood-irrigation was applied on 24 and 25 October

Table 1
Soil properties of Shahaoqu Experimental Station

	Soil depth (cm)					
	0–20	20–40	40–60	60–80	80–100	100–120
Bulk density (kg dm^{-3})	1.51	1.52	1.47	1.46	1.46	1.46
Sand (%)	18.0	13.6	11.2	15.5	18.0	2.8
Silt (%)	66.0	70.4	76.8	73.5	68.0	70.2
Clay (%)	16.0	16.0	12.0	11.0	14.0	27.0
pH (H_2O)	8.5	8.7	8.7	8.7	8.8	8.7
Organic C (g kg^{-1})	10.2	6.0	3.1	2.4	1.8	3.7
Available N (mg kg^{-1})	104.1	72.6	75.6	55.8	47.4	51.6
Available P (mg kg^{-1})	55.4	25.1	10.2	7.8	6.5	4.7
Available K (mg kg^{-1})	121.1	86.1	71.9	71	64	117.7

Table 2
Approximate sowing and harvesting time, irrigation amount (mm), fertilizer N applied (kg N ha^{-1}) and irrigation area (10^3 ha) in different crops in Hetao Irrigation District

Field types	F_W (spring wheat)	F_M (maize)	F_{W-M} (spring wheat–maize inter-planting)	F_S (sunflower)
Sowing date	20 March	20 April	20 March and 20 April	10 April
Harvesting date	15 July	20 September	15 July and 20 September	20 September
Irrigation volume	360	455	695	425
Fertilizer N	225	300	450	210
Irrigation area[#]	77.1	52.5	176.1	78.8

[#] The whole Hetao Irrigation District in 1998.

2002. The irrigation volume was limited to about 2200 m^3 ha^{-1} using a water flow meter (LBX-7, China).

2.3. Soil analysis

To determine the NO_3–N content, 10 g fresh soil were weighed into a 250 ml polypropylene bottle, then 50 ml 2 M KCl were added and the suspension was shaken for 1 h. The suspension was allowed to sediment for 5 min and filtered (Whatman GF/A filter). The soil extracts were analyzed spectrophotometrically according to Yang et al. (1998). The soil water content was determined by the conventional oven drying. Electrical conductivity (EC) of the soil was determined in an extract (soil:water, 1:5) after shaking for 3 min. Total dissolved salt (%) of the soil was estimated from a linear regression equation between total salinity considering only the four major constituents (>80% of total; Lei et al., 2001) ($NaHCO_3$:NaCl:Na_2SO_4, 4:3:3) and the measured EC values (dS m^{-1}). The regression equation was calculated as salt (%) = 0.69EC(1:5) − 0.02 (R^2 = 0.9988). The amounts of NO_3–N and salinity per area of each horizon were calculated from the respective concentration by multiplying with the soil bulk density and the horizon thickness.

2.4. Estimation of leached salt and NO_3–N

Since the depth to groundwater was found to vary from 130 to 150 cm during the autumn irrigation, and was at 134 cm at the time when the soil samples were taken, the amount of N and salinity leached from the soil was estimated on a 0–120 cm depth basis. The amount of NO_3–N or salt leached was calculated by subtracting the total NO_3–N or salt amount (0–120 cm depth) after irrigation from the corresponding amount before irrigation.

2.5. Groundwater monitoring

In order to observe groundwater table and quality, two 10 cm diameter PVC tubes were installed at the experimental sites. The groundwater table was measured directly by a measuring tape with a detector at the end. The detector gave a signal when it reached the water surface and the length of the tape was recorded. The groundwater level was calculated by subtracting the above ground tube height from the recorded length of the tape. The water sample was taken in the depth of 50 cm under water surface. NO_3–N in the groundwater was determined using an ion chromatograph (Dionex-120, Dionex Corp., Sunnyvale, CA, USA). Total N was determined after peroxydisulfate ($K_2S_2O_8$) oxidation according to Ebina et al. (1983). EC and pH were measured using an EC meter (B-173, HoRiBa) and a pH meter (B-212, HoRiBa), respectively.

3. Results

3.1. Changes in soil water content

Before the autumn irrigation, the water content ranged between 0.18 and 0.40 $m^3 m^{-3}$ in the observed depth range. At the surface layer (0–20 cm), it was generally found to be in the range of 0.18–0.22 $m^3 m^{-3}$ (Fig. 1). In the profile distribution pattern, however, some differences could be observed because the irrigation schedule was different for each crop cultivated (Table 2). In F_W, water content increased with soil depth, reaching a maximum at 60–80 cm. In the other three field types, however, after an increase of water content with depth down to 60 cm, a distinct minimum could be observed at about 60–100 cm depth and then another increase with depth (Fig. 1). This phenomenon might be attributed to the differences in root distribution of the different crops. At 0–40 cm depth, the soil water content in F_W was the lowest observed (0.21 $m^3 m^{-3}$) as a result of the earlier harvest time (15–20 July). At 40–80 cm depth, the water content in F_W and F_{W-M} was close to maximum field holding capacity (0.43 $m^3 m^{-3}$) and significantly higher than in F_S and F_M due to earlier harvest and higher groundwater table. At 80–150 cm depth, the soil water content in F_W was 41.2% higher than in F_S, but no significant difference to F_M or F_{W-M} was evident.

After the autumn irrigation, the soil was saturated and the water content increased to more than 0.34 $m^3 m^{-3}$ for all field types. The water content distribution was nearly constant throughout the soil profile.

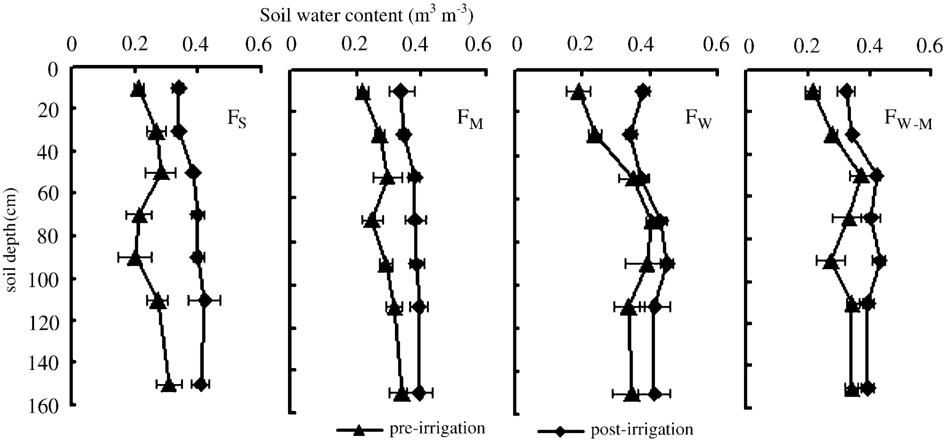

Fig. 1. Changes of soil water content in different farmlands during the autumn irrigation. F_W, spring wheat field; F_M, maize field; F_S, sunflower field; F_{W-M}, spring wheat–maize inter-planting field.

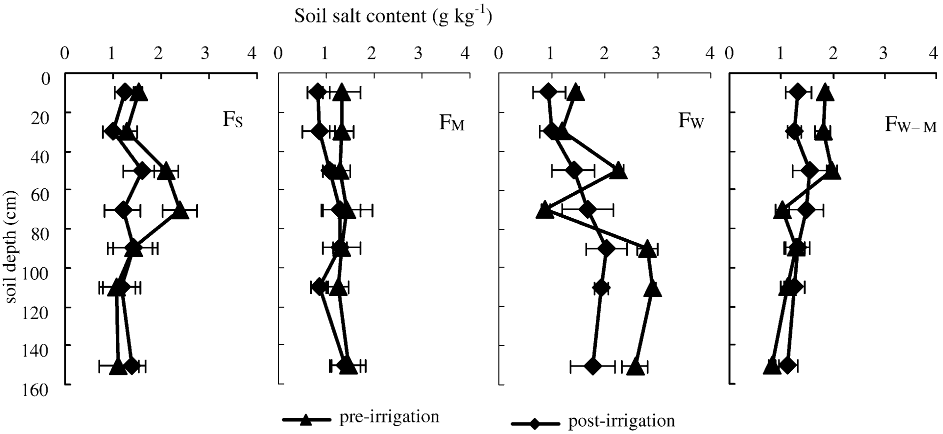

Fig. 2. Changes of soil salt content in different farmlands during the autumn irrigation. F_W, spring wheat field; F_M, maize field; F_S, sunflower field; F_{W-M}, spring wheat–maize inter-planting field.

3.2. Change in soil salinity

Before autumn irrigation, the salinity distribution in the soil profiles showed distinct differences for all field types (Fig. 2). In F_M, the soil salinity was constant from the surface to the deepest layer (120–150 cm). In the other field types, there were distinct maxima in salt accumulation at 60–80 cm for F_S, 80–150 cm for F_W and 0–60 cm for F_{W-M}, respectively. The overall soil salinity from 0–150 cm decreased in the order of F_W, F_S, F_{W-M} and F_M, reflecting the differences in irrigation volume and schedule for the different field types during the growth period (Table 2).

After the autumn irrigation, the salinity distribution throughout the soil profile was found to have changed (Fig. 2). The salinity in the upper layers (0–40 cm) was significantly lower than before irrigation for all field types. Except for F_M, the salinity had increased in the layer below 80 cm depth in F_S, 40–80 cm in F_W and below 60 cm in F_{W-M}, respectively. In addition, the soil salinity in the lowest layer (120–150 cm) was higher than in the surface layer except in F_{W-M} and the distribution pattern throughout the soil profile appeared much more even compared to the pattern before irrigation.

3.3. Changes in soil NO_3–N content

Before the autumn irrigation the average overall NO_3–N content in the soil profile from 0–150 cm depth decreased in the order of F_W, F_M, F_{W-M} and F_S (Fig. 3). The higher NO_3–N content in F_W might be attributed to the short growth period of about 110 days and the topdressing at grain filling period. In F_W, the NO_3–N maximum was detected at the layer 80–100 cm and the average NO_3–N content in the lower layers at 60–150 cm was 63.1% higher than in the upper layers at 0–60 cm. In F_M, the nitrate content had its maximum at 40–80 cm depth. The difference between average NO_3–N content in the upper layers (0–40 cm) and the lower layers (80–150 cm) was much less obvious. In F_{W-M}, the NO_3–N content was higher from 0–60 cm depth and then decreased with soil depth. In F_S, NO_3–N

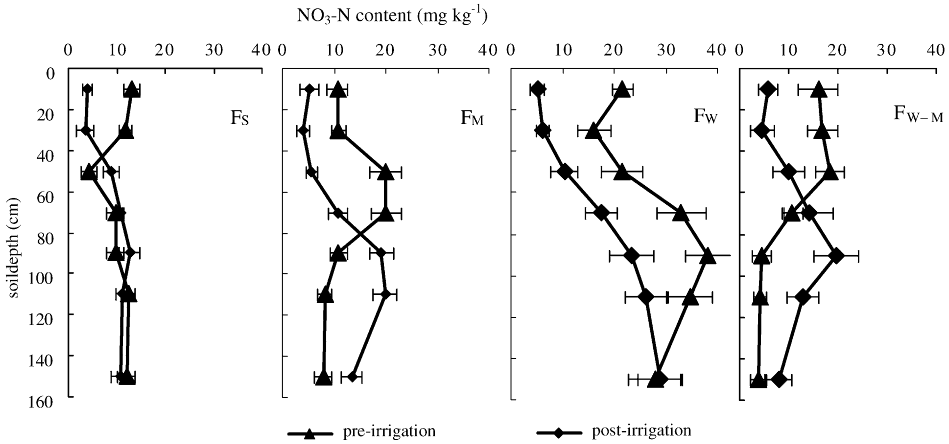

Fig. 3. Changes of soil NO_3–N content in different farmlands during the autumn irrigation. F_W, spring wheat field; F_M, maize field; F_S, sunflower field; $F_{W–M}$, spring wheat–maize inter-planting field.

was the highest in the surface layer (0–20 cm), showed a minimum at 40–60 cm depth and then increased again with depth.

After the autumn irrigation, the NO_3–N distribution pattern throughout the soil profile was significantly altered (Fig. 3). The lowest NO_3–N content was found in the surface layer (0–20 cm) in all field types. NO_3–N content then increased with depth, reaching maximum levels at 80–100 cm in F_S, F_M and $F_{W–M}$, and at 120–150 cm in F_W, respectively.

Even though the NO_3–N content in the upper layers (0–40 cm) was generally found to be lower after the autumn irrigation than before, there were differences in the distribution pattern throughout the soil profile in the different field types (Fig. 3). In F_W, the NO_3–N content in all layers was generally lower after the irrigation, whereas in F_M and $F_{W–M}$, the NO_3–N content in the 80–150 cm layers was higher than before irrigation, suggesting that NO_3–N had accumulated in deeper soil layers due to the irrigation.

3.4. Salt and NO_3–N leaching loss

In the 0–60 cm layers, an irrigation-related loss of soil salt could be observed in all field types. In F_W, this loss was 4.54 Mg ha^{-1}; in F_M, 3.52 Mg ha^{-1}, in F_S, 3.20 Mg ha^{-1} and in $F_{W–M}$, 4.47 Mg ha^{-1} (Table 3). In the layers below 60 cm, the relation was less consistent and some layers were found with increased and some with decreased salt levels upon irrigation. The total leaching loss of soil salt (from 0–120 cm depth) decreased in the order of F_W, F_S, F_M and $F_{W–M}$. The salt leached from the upper layers accounted for 61% of the total salt loss in F_W, 49% in F_M and 68% in F_S. In $F_{W–M}$, 40% of the salt leached from the upper layers (0–60 cm) was accumulated in the lower layers (60–120 cm).

On the other hand, NO_3–N loss in the layers of 0–40 cm was found to have occurred in all field types. NO_3–N loss was 79.03 kg ha^{-1} in F_W, 36.26 kg ha^{-1} in F_M, 52.52 kg ha^{-1} in F_S and 66.82 kg ha^{-1} in $F_{W–M}$ (Table 3). As with the salt, the lower layers gave a less consistent picture, and some layers were found having lost NO_3–N whereas others had

Table 3
The losses of NO_3–N (kg N ha^{-1}) and salinity (Mg ha^{-1}), and ratio of NO_3–N and salinity loss in soil profiles in different farmlands

Soil depth	NO_3–N				Salt				NO_3–N/salinity			
	F_W	F_M	F_S	$F_{W–M}$	F_W	F_M	F_S	$F_{W–M}$	F_W	F_M	F_S	$F_{W–M}$
0–20	49.20	15.99	27.59	30.59	1.52	1.43	0.91	1.57	32.4	11.2	30.3	19.5
20–40	29.83	20.27	24.92	36.23	0.53	1.38	0.82	1.68	56.3	14.7	30.4	21.6
40–60	33.06	42.17	−13.35	25.36	2.49	0.71	1.47	1.22	13.3	59.4	−9.1	20.8
60–80	46.11	28.10	−2.98	−9.99	−2.38	0.42	3.56	−1.37	−19.4	66.9	−0.8	7.3
80–100	43.79	−24.67	−8.90	−44.91	2.31	0.15	0	−0.07	18.9	−164.5	–	641.6
100–120	24.94	−34.88	4.54	−25.63	2.92	1.12	−0.29	−0.35	8.5	−31.1	−15.7	73.2
Total	227	46.98	31.82	11.65	7.39	5.21	6.47	2.68	30.7	9.0	4.9	4.34

F_W, spring wheat field; F_M, maize field; F_S, sunflower field; $F_{W–M}$, spring wheat–maize inter-planting field.

accumulated NO_3–N. The total amount of NO_3–N leaching loss (from 0 to 120 cm depth) decreased in the order of F_W, F_M, F_S and $F_{W–M}$. In F_W, the total amount of NO_3–N leached almost equaled the amount of N fertilizer applied, indicating that the fertilizer application was actually not necessary. Since the previous crop of this field was cabbage and plenty of fertilizer (about 625 kg N ha^{-1}) had been applied, the large quantity of residual N in the soil would actually have been sufficient to also supply the following wheat crop. The NO_3–N loss in the upper layers (0–40 cm) contributed about 35% of the total loss in F_W and 77% in F_M. In F_S and $F_{W–M}$, however, 20.69 and 55.17 kg N ha^{-1} were accumulated at a depth of 40–120 cm, respectively.

3.5. Impact on groundwater

After the autumn irrigation, the groundwater level rose remarkably from 292 to 132 cm below soil surface (Fig. 4A). The NO_3–N content increased from 1.73 before to 21.6 mg L^{-1} after the irrigation (Fig. 4B), thereby exceeding the drinking water standard of the World Health Organization of 11.3 mg L^{-1} (WHO, 1993). Total N in the groundwater also increased due to the irrigation, 74.95% of which was found to be NO_3–N, suggesting that irrigation mainly leaches soil N in the form of NO_3–N. The pH of the groundwater was decreased by the irrigation from 8.42 to 7.5, and the EC was increased from 1.36 to 1.73 dS m^{-1} during the autumn irrigation (Fig. 4C), indicating a higher concentration of dissolved salts in the groundwater.

4. Discussion

4.1. Factors influencing N leaching

Numerous studies (Di and Cameron, 2002; Ottman et al., 2000; Ritter, 1989) have indicated that the leaching of soil NO_3^- from the plant root zone to the groundwater is mainly determined by two important factors: the amount of NO_3^- accumulated in the soil exceeding the requirements of the cultivated plants and the drainage volume. Generally,

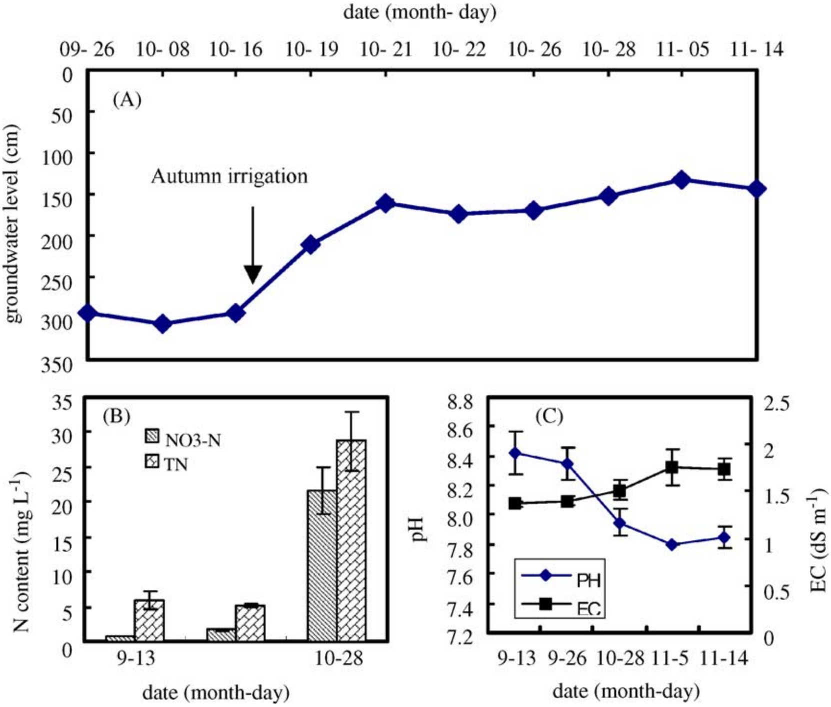

Fig. 4. Changes in groundwater level and quality during the autumn irrigation.

high NO_3^- leaching occurs when there is a high amount of NO_3^- in the soil profile in conjunction with or followed by a high drainage volume. As evident in Table 2, in the region investigated in this study, considerably large amounts of water and N fertilizer are being applied with the effect that any irrigation will move a large quantity of NO_3^- below the root zone of the crops.

The weak correlation between soil NO_3–N concentration and fertilizer N supply (Fig. 5A) indicates that fertilizer N represented only a small fraction of the residual N compared to that of N derived from organic matter mineralization. The average NO_3–N content, however, is negatively correlated to the irrigation volume during the crop growth periods, suggesting that irrigation is an important factor for N leaching despite the application of a rather large amount of N fertilizer (Fig. 5B).

Usually, the autumn irrigation accounts for 25–30% of the total annual irrigation volume, which leads to the drainage of significant amounts of water by percolation. The amount of soil NO_3–N leached is positively correlated to the soil NO_3–N content (0–120 cm) before irrigation (Fig. 5C) as well as the increase of soil water in the upper layers (0–40 cm) (Fig. 5D). Both correlations indicate that the NO_3^- was subject to leaching due to the large water movement in combination with high soil N content. In this study, NO_3–N losses were mainly observed in the upper soil layers (0–40 cm) (Table 3); very likely due to the high initial level and low soil water content (Figs. 1 and 3). The distribution patterns of NO_3–N in the soil profile (Fig. 3) also indicate that a major fraction of the initially present

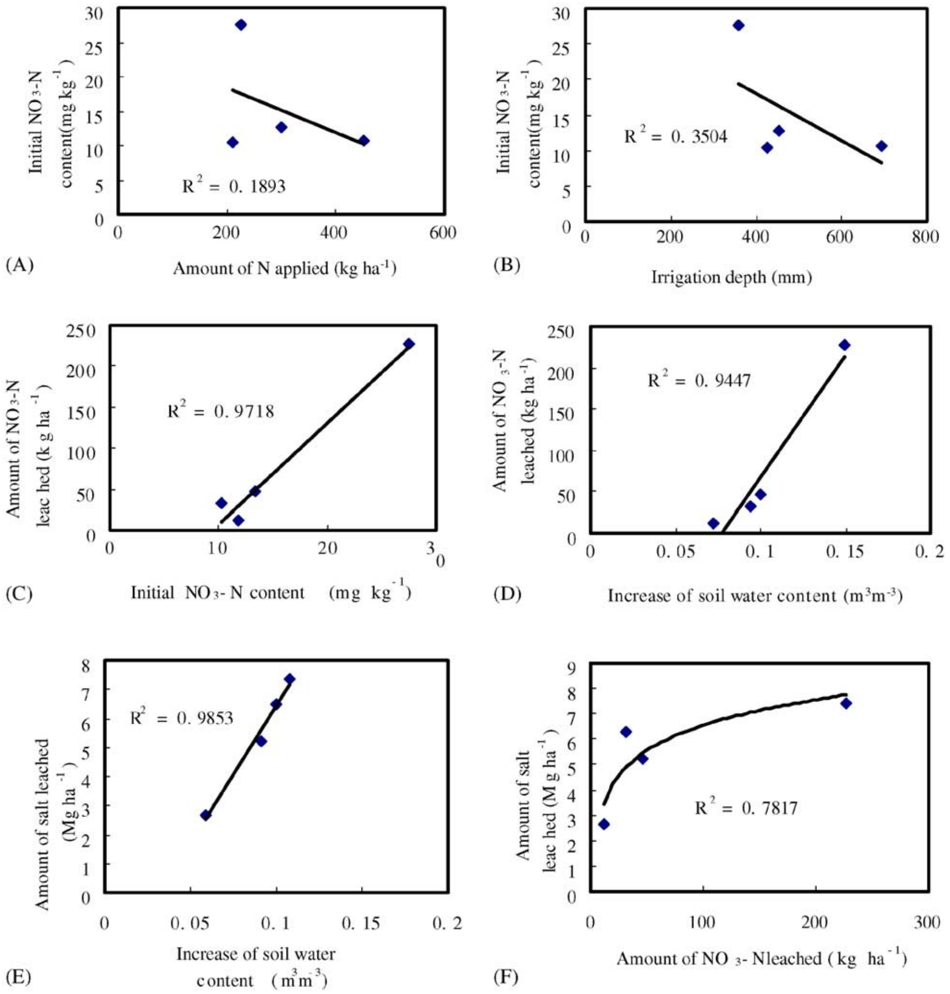

Fig. 5. Correlations between: soil NO_3–N content before irrigation and the amount of N applied (A) and irrigation depth (B) during growth period; the amount of NO_3–N leached and soil average NO_3–N content (0–120 cm depth) (C) and increase of 0–40 cm soil water content (D) before irrigation; the amount of salt leached and increase of 0–60 cm soil water content (E) and the amount of NO_3–N leached (F) during the autumn irrigation.

NO_3–N in the upper layers was not completely leached into the groundwater, but simply moved to deeper soil layers, suggesting that the spring irrigation could cause this NO_3–N to leach into the groundwater as a pollutant.

4.2. Comparison of leaching between salt and NO_3–N

To prevent salt from accumulating in soil profile, leaching a part of this salt is essential in irrigation agriculture, especially in arid regions (Ritter, 1989). Nitrogen remaining in the soil after the harvest, however, is also subject to leaching during the autumn irrigation when N uptake is minimal. For each of the studied field types, the ratio of NO_3–N loss to salt loss was nearly equal in the upper two layers, suggesting that salt and NO_3–N have an identical movement pattern in the upper soil. In deeper layers, however, differences in this ratio between the different field types became evident. As Fig. 5D and E suggested, NO_3–N and salt moved as a solution in the upper layers downward simultaneously, but the leaching of soil salinity did not increase proportionately to the amount of NO_3–N leached (Fig. 5F), which might have been caused by the fact that the salt was introduced intensively by irrigation and accumulated by high evaporation.

4.3. Economic losses due to N leaching

The approximate amount of NO_3–N leached in the Hetao Irrigation District during the autumn irrigation was calculated from the measured NO_3–N leaching loss in the soil profile (0–120 cm depth) per ha extrapolated to the whole irrigated area in the district (Table 2). From those data, we estimate that every year about 24.5×10^6 kg N was being leached from the irrigation farmlands in this area under the present tillage, fertilizer practices and autumn irrigation norm. This amount represents ca. 19% of the total N fertilizer applied and amounts to a financial loss of about 72 million Yuan RMB (8.5 million US$) on the basis of a price of 3.3 Yuan RMB per kg N.

Leaching of soil NO_3–N is one of the major causes for nitrogen loss in farmlands and the major source of NO_3–N contamination of the groundwater (Pereira et al., 1996; Watts et al., 1991; Power, 1989). In this study, a significant decrease in quality of the groundwater was observed after the autumn irrigation, NO_3–N levels actually increased significantly above the WHO drinking water standards of maximally 11.3 mg L^{-1}. It is obvious that the quality of the groundwater in this region will decrease even further in the future unless a more adapted irrigation and fertilization schedule is applied, such as the application of both good water and nitrogen management practices.

5. Conclusion

Soil NO_3–N and salt moved down to deeper soil layers with water simultaneously in the upper layers, but the leaching of salt did not increase proportionately to the amount of NO_3–N leached. The upper soil layers (0–60 cm for salt and 0–40 cm for NO_3–N) were the major contributors to the total profile loss. The amounts of NO_3–N and salt leached at 0–120 cm depth were the highest in F_W and the lowest in $F_{W–M}$. The autumn irrigation caused significant NO_3–N contamination of the groundwater and there are about a total of 24.5×10^6 kg N leached in the irrigated farmlands of Hetao Irrigation District. Therefore, active measures should be taken to determine the proper mode and volume of the autumn irrigation on the basis of soil moisture, salt accumulation and NO_3–N leaching.

How to control the groundwater pollution is very practical and urgent. From our results, inter-planting tillage has been shown to be effective. In addition, the application of optimized minimum amounts of water and nitrogen to meet realistic yield goals, as well as the timely application of N fertilizers and the use of slow release fertilizers can be viable measures to minimize nitrate leaching.

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