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Concentration Characteristics of Nitrogen in the Paddy-Wheat Rotation Soil of the Yellow River Irrigation Area in Jinan, China

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Concentration Characteristics of Nitrogen in the Paddy-Wheat Rotation Soil of the Yellow River Irrigation Area in Jinan, China

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Abstract. In view of the lack of research on non-point source pollution in the lower reaches of the Yellow River Irrigation Area in China, an experiment was conducted in typical paddy-wheat rotation fields in Jinan Yellow River Irrigation Area to study the distribution characteristics of nitrogen accumulation in soil and shallow groundwater, and the influencing factors. The results showed that total nitrogen (TN) concentration varied considerably at 0~80 cm soil depth, while there was less variation at the depth of 80~120 cm. The nitrate (NO_3^- -N) concentration showed a similar distribution profile in soil. TN and NO_3^- -N were greatly accumulated in the 0-100 cm layer in both paddy and wheat soils. The TN and NO_3^- -N contents in paddy soil increased at the rates of 96.48% and 300.61%, respectively. Consequently, nitrogen accumulation occurred at deeper levels of soil. NO_3^- -N content in groundwater during paddy growth exceeded the maximum contamination level of 20 mg/L, which is worse than class III of Quality Standard for Groundwater. There was significant correlation between NO_3^- -N in shallow groundwater and the depth of shallow groundwater as well as NO_3^- -N content in deeper soil. Moreover, nitrogen content in soil and shallow groundwater was affected by irrigation. Irrigation after topdressing during paddy growth caused leaching of NO_3^- -N from soils into groundwater. It can be concluded that irrigation caused strong leaching of residual NO_3^- -N in soil without input of nitrogen, which poses a potential threat to the shallow groundwater quality.

1. Introduction

High loads of nitrogen (N) fertilizers in agricultural fields cause several environmental problems and alter ecosystems [1]. With the rapidly increasing use of various fertilizers in agricultural ecosystems, high N loss is becoming an important issue from both environmental and agronomic perspectives [2].

In China, a large amount of N fertilizer has often been applied to farmland [3]. Moreover, the amount of chemical fertilizer application in China is expected to increase steadily [4]. In recent years, fertilizer application growth rate has reached 3%. The utilization ratio in China is 30%~40% [5]. The amount of fertilizer application per unit area is significantly higher than the global average [6]. However, the excessive use of N fertilizers has not only decreased the efficiency of N utilization, but also resulted in large amounts of N pollution in atmosphere and water systems [7, 8].

Nitrate nitrogen (NO_3^- -N) and ammonium nitrogen (NH_4^+ -N) are the major available forms of N in soil. NH_4^+ -N has very poor mobility and thus, it is easily absorbed by soil colloids. On the other hand, NO_3^- -N is prone to leaching loss. Over-application of N fertilizer mostly results in enhanced concentrations of nitrate in groundwater [9, 10]. Moreover, loss of nitrogen, as NO_3^- -N, could also reduce soil fertility and potential productivity, and thus decrease soil quality [11].



Due to the poor spread of rational fertilizer recommendations in areas with rapidly expanding production systems in China, farmers have applied fertilizer based on individual habits or inclinations [12]. The majority of farmers considered that high yield could be achieved with higher application of N fertilizer, even at levels that exceeded the crop's requirement, resulting in N loss [13, 14]. Consequently, application of different amounts of N fertilizers during the paddy-wheat cropping phase probably results in different conditions of nitrate accumulation in soil.

Many studies have compared the nitrate concentration of groundwater in fields under intensive cropping to that in fields under non-intensive cropping [15, 16]. In cropping systems of the same intensity, the different nitrate accumulations in soil caused by different application rates of N fertilizer probably result in varying amounts of nitrate leaching to groundwater. Therefore, it should be feasible to study the relationship between soil nitrate and groundwater nitrate in greater detail.

Few studies have addressed nitrogen distribution in the paddy-wheat rotation soil, which could contribute to N loss in soil solution and drainage waters through runoff and leaching in agricultural soils. Hence, the objectives of the present study were to study the distribution characteristics of nitrogen in soil profile and shallow groundwater, and the influencing factors, taking typical paddy-wheat rotation fields in Jinan Yellow River Irrigation Area as an example.

2. Materials and methods

2.1. Description of the study area

The study area was the Gedian Yellow River Irrigation Area, which was established in 1966, located in Jinan city, Shandong Province, China (Fig. 1). The study area is dominated by semiarid continental monsoon climates, and the average annual temperature is 12.8°C. The average annual precipitation is 583.3 mm, of which more than 70% falls from July to September. About 123 km² fields are irrigated by water of 41,500,000 m³ per year brought from the Yellow River through the intake gate. Winter wheat-rice rotation and winter wheat-corn rotation are popular in the study area, and irrigation mainly occurs from March to July.

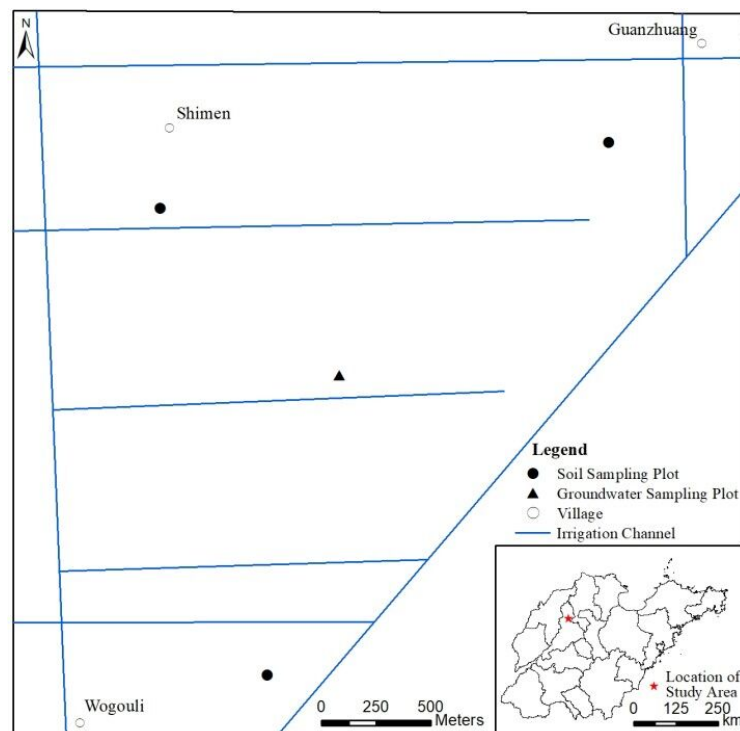


Figure 1. Sampling sites and location of the study area in Jinan, Shandong Province.

In the study area, rice was sown during June 10-12, 2015 and gathered during October 5-8, 2015, while winter wheat was sown during October 12-15, 2015 and gathered during June 5-8, 2016. The crops were irrigated with water from the Yellow River and fertilizer was manually sprinkled in the field. Base manure was applied in both paddy and wheat fields. Topdressing was performed in the paddy fields on July 10, 2015 and August 10, 2015. However, there was no topdressing in the wheat fields.

2.2. Field sampling

Three typical sampling sites in winter wheat-rice rotation fields were selected for soil sampling according to distance from the intake gate (Fig. 1). Six soil cores were collected from each site at 20 cm increments up to a depth of 120 cm using a stainless steel soil drill (5 cm diameter and 120 cm depth) during the growth period of rice and winter wheat from June 2015 to June 2016. Then, plant residues, roots, and stones were removed, and the soil was brought to the laboratory. The soil samples were then homogenized, air-dried and sieved (< 2 mm) for the determination of TN, NO_3^- -N, and bulk density (BD). Cutting ring method was used for the determination of BD. Groundwater samples were collected from the nearby wells (Fig. 1). The groundwater sampling amount was 500~1000 ml, which was collected into clean empty mineral water bottles.

2.3. Soil and water analysis

Soil TN concentrations were determined by the Kjeldahl digestion procedure [17]. Soil samples were extracted with $0.1 \text{ mol L}^{-1} \text{ KCl}_2$, and soil NO_3^- -N content was measured in the extracts using continuous flow analysis (TRAACS 2000; Seal Analysis, Mequon, WI, USA) in the laboratory. The soil particle composition of samples passed through 2-mm sieves was determined by laser diffraction (Rastarizer 2000, Malvern Instruments, Malvern, UK) [18], and the BD was determined based on the volume-mass relationship for each oven-dried core sample [19]. All water samples were tested by ultraviolet (UV) spectrophotometric method [20].

2.4. Statistical analyses

Data were expressed as the mean of three replicates unless otherwise noted. The statistical analyses were conducted using SPSS for Windows version 14.0 software (SPSS Inc., Chicago, IL, USA).

3. Results and Discussion

3.1. TN concentrations in soil during paddy and wheat growth

For the quantitative determination of TN in paddy and wheat soil, soil samples were collected at varying depths at different periods of rice and wheat growth (Fig. 2).

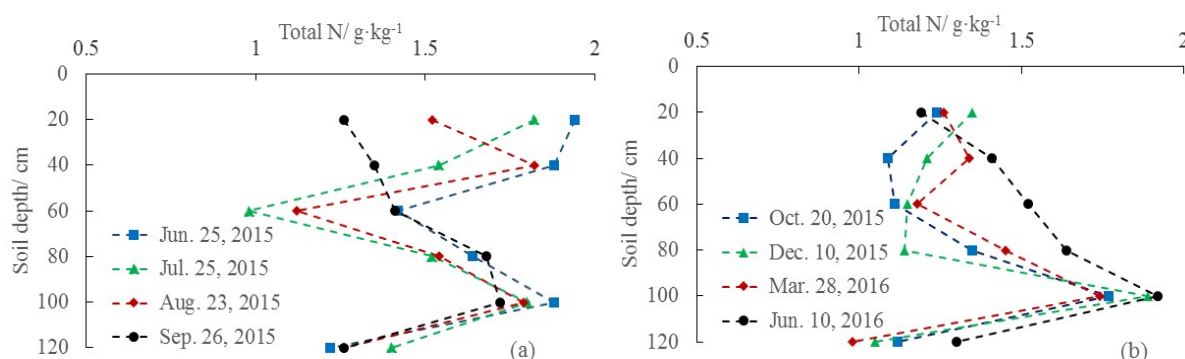


Figure 2. Soil TN concentrations in paddy-wheat rotation fields.
(a) Paddy fields; (b) wheat fields

The results showed that TN concentrations in the upper layer (0-60 cm) changed more than those in the deeper layer (80-120 cm) during rice growth period, while TN concentrations showed no obvious changes during wheat growth period. The upper layer (0-40 cm) showed the highest TN concentrations at the beginning of rice growth, which indicated that base manure had a significant effect on soil TN concentrations. There was no noticeable increase in soil TN concentrations after two topdressings in the paddy fields. The difference in TN concentrations between rice and wheat fields was larger in the upper layer (0-80 cm layer) compared to the deeper layer (80-120 cm layer).

3.2. NO_3^- -N concentrations in soil during paddy and wheat growth

For the quantitative study of NO_3^- -N in paddy and wheat soil, soil samples were collected at varying depths at different periods of rice and wheat growth (Fig. 3).

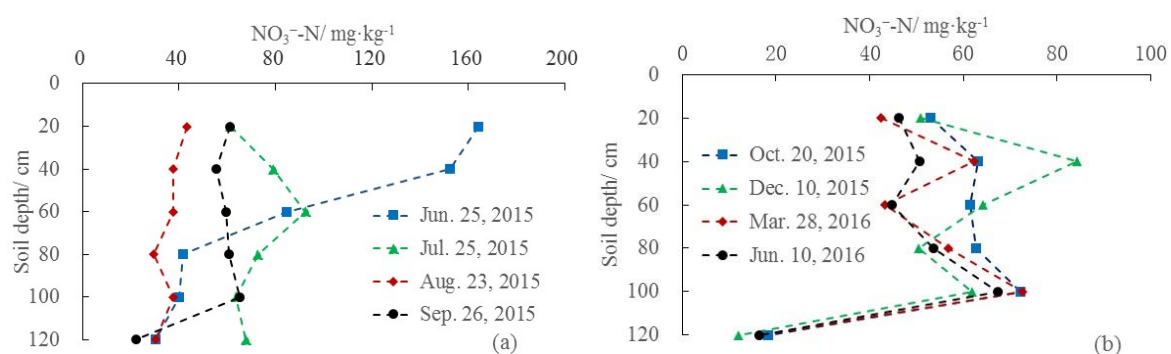


Figure 3. Soil NO_3^- -N concentrations in paddy-wheat rotation fields.
(a) paddy fields; (b) wheat fields

The concentrations of NO_3^- -N showed no obvious decrease along with increase in the soil depth, which indicated that NO_3^- -N could transfer to the deeper layer. The upper layer (0-40 cm) showed the highest NO_3^- -N concentrations at the beginning of rice growth due to base manure. No noticeable increase in soil NO_3^- -N concentrations occurred after two topdressings in the paddy fields. In general, NO_3^- -N concentrations in the wheat soil were not higher than those in the paddy soil. However, it is noteworthy that NO_3^- -N was significantly accumulated at the depth of 80-100 cm in the wheat soil, suggesting that more N fertilizer was applied in the fields than what the plants could take up. Another possible reason for this accumulation could be the soil particle composition. In this study, the soils had more clay at depth of 80-100 cm, which could absorb more nitrogen due to the formation of soil colloids in this layer [21].

3.3. Contents of TN and NO_3^- -N in paddy-wheat rotation fields

3.3.1. Calculation method. The contents of TN and NO_3^- were calculated using the following equation [22]:

$$N = H \cdot C \cdot BD / 10 \quad (1)$$

Where N is the content of TN ($103 \text{ kg} \cdot \text{hm}^{-2}$) or NO_3^- ($\text{kg} \cdot \text{hm}^{-2}$); H is the soil layer thickness (cm); and C is the concentration of TN ($\text{g} \cdot \text{kg}^{-1}$) and NO_3^- ($\text{mg} \cdot \text{kg}^{-1}$). BD is the bulk density ($\text{g} \cdot \text{cm}^{-3}$), which is $1.2 \text{ g} \cdot \text{cm}^{-3}$ in soils deeper than 20 cm, and is the measured value in soils at 0-20 cm.

3.3.2. Distribution of TN and NO_3^- -N contents. Contents of TN and NO_3^- -N in the 0-100 cm layer were calculated. Soil samples collected from a woodland in the study area were analysed to obtain the background value in order to evaluate N pollution in soil (Table 1). As shown in Table 1, TN and NO_3^- -N were greatly accumulated in the 0-100 cm layer in both paddy and wheat soils compared to that in the

woodland. The TN and NO_3^- -N contents increased at the rates of 73.60% and 200.45% respectively in wheat soil, and 96.48% and 300.61% respectively in paddy soil. Soil NO_3^- -N contents at 0-90 cm layer are required to be no more than 450 $\text{kg}\cdot\text{hm}^{-2}$ in the European Union [23], indicating serious NO_3^- -N pollution in soil in the study area.

Table 1. Contents of TN and NO_3^- -N in soil during paddy and wheat growth.

Sample sites	Contents of TN $10^3 \text{ kg}\cdot\text{hm}^{-2}$	Increasing rate %	Contents of NO_3^- -N $\text{kg}\cdot\text{hm}^{-2}$	Increasing rate %
woodland	9.66	-	246.55	-
paddy fields	18.98	96.48	987.70	300.61
wheat fields	16.77	73.60	740.77	200.45

3.4. Groundwater NO_3^- -N concentrations and influencing factors

Fig. 4 shows that the average content of NO_3^- -N in groundwater varies from 4.13 mg/L (Aug. 5, 2015) to 74.32 mg/L (Oct. 20, 2016). In general, the NO_3^- -N concentrations in groundwater (41.70 mg/L on average) during paddy growth were much higher than those during wheat growth (10.39 mg/L on average). According to the groundwater criteria in China (GB/T14848-93), groundwater NO_3^- -N concentrations are classified into the following five types: class I ≤ 2.0 mg/L, class II ≤ 5.0 mg/L, class III ≤ 20 mg/L, class IV ≤ 30 mg/L, and class V > 30 mg/L. Among these groundwater types, class IV and class V are not suitable for drinking. As shown in Fig. 3, groundwater during paddy growth in the study area exceeded the maximum contamination level of NO_3^- -N (20 mg/L), i.e., it was undrinkable water.

It was found that NO_3^- -N concentrations in groundwater were closely related to groundwater depth (Fig. 4). There was more precipitation and irrigation in the study area during paddy growth, and the groundwater depth was also shallower. Hence, a large amount of nitrogen which cannot be absorbed by plants may leach into the groundwater beneath irrigated lands, usually as NO_3^- -N [24].

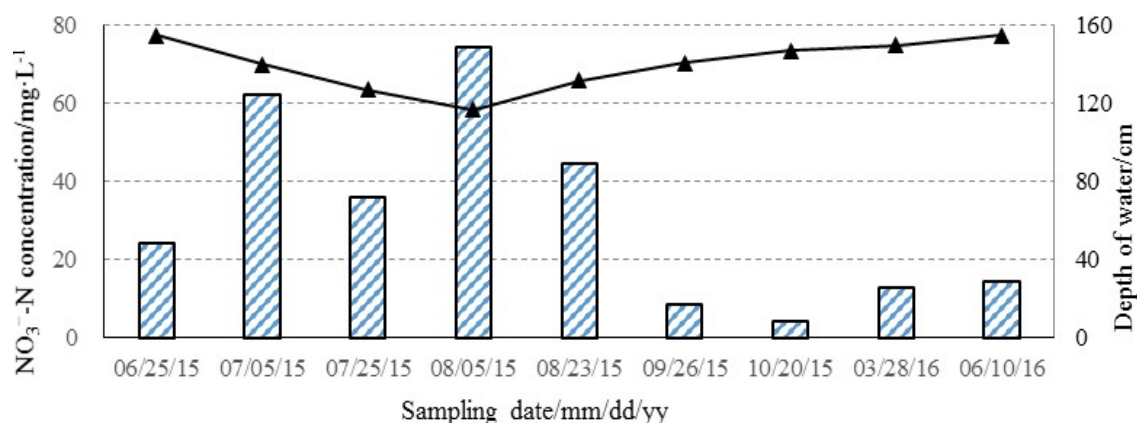


Figure 4. Relationship between groundwater NO_3^- -N concentrations and depth of water.

Pearson correlation analysis between NO_3^- -N concentrations in groundwater and in soils at 100-120 cm layer was performed to identify the correlation relationship (Fig. 5).

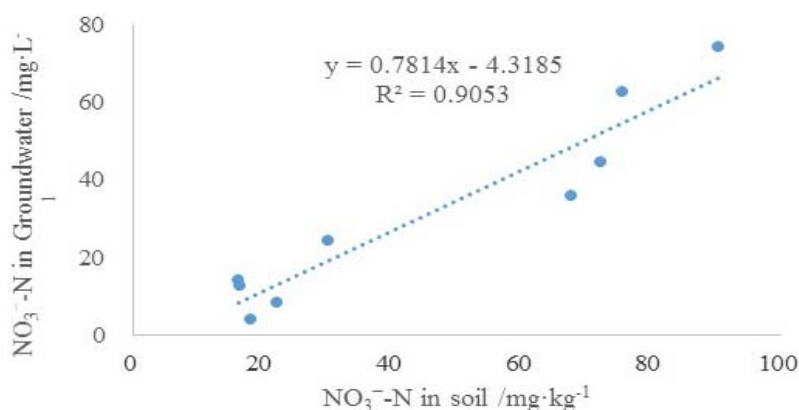


Figure 5. Correlation analysis between NO₃⁻-N concentrations in groundwater and in soils at 100-120 cm layer.

The results showed that NO₃⁻-N concentrations in groundwater were positively correlated with those in soils at 100-120 cm layer, with $r=0.951^{**}$. The correlation was significant at the 0.01 level (2-tailed). Studies have shown that paddy and wheat can absorb little nitrate in soil deeper than 100 cm [25], which suggested that NO₃⁻-N in deeper soil could have a significant impact on NO₃⁻-N in groundwater.

4. Conclusion

In the present study, we have investigated the accumulation and distribution of nitrate in soil and groundwater during rice and wheat growth. It was found that the TN concentrations in soil were the highest at the beginning of rice growth, especially in the upper layer, indicating that base manure had a significant effect on soil TN concentrations. It is noteworthy that both TN and NO₃⁻-N were accumulated at the depth of 80-100 cm in the wheat soil, suggesting that more N fertilizer was applied in the fields than what the plants could take up.

Compared with soils in woodland, TN and NO₃⁻-N were greatly accumulated in the 0-100 cm layer in both paddy and wheat soils. The contents of TN and NO₃⁻-N in paddy soil increased at the rate of 96.48% and 300.61%, respectively. As a result, NO₃⁻-N in groundwater during paddy growth exceeded the maximum contamination level (20 mg/L). This level is worse than class III of Quality Standard for Groundwater, which indicated that unreasonable fertilization and irrigation had polluted the shallow groundwater. A significant correlation was found between NO₃⁻-N in shallow groundwater and the depth of shallow groundwater as well as NO₃⁻-N content in deeper soil.

Moreover, nitrogen contents in soil and shallow groundwater had a strong response to irrigation. Irrigation after topdressing during paddy growth diluted the leached NO₃⁻-N in groundwater, which brought more NO₃⁻-N from soils into groundwater. It can be concluded that irrigation caused strong leaching of residual NH₄⁺-N and NO₃⁻-N in soil without any further input of nitrogen, thus posing a potential threat to the shallow groundwater quality.

In summary, our results indicate that nitrogen was clearly accumulated in the deeper layers of paddy-wheat rotation soil, suggesting that excess N fertilizer was applied for the crops in the study area. Factors such as groundwater depth and NO₃⁻-N content in deeper soil could influence the NO₃⁻-N content in shallow groundwater. Future studies will need to address approaches to assess the leaching of NO₃⁻-N load into groundwater.

Acknowledgments

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