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Water pollution risk from nitrate migration in the soil profile as affected by fertilization in a wheat-maize rotation system

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ABSTRACT

Reducing nitrogen (N) fertilizer input into the soil is needed by a crop production and environmental pollution control. A field experiment using a wheat-maize rotation system was conducted in North China Plain (NPL) to evaluate agronomic performance and the reduction of nitrate accumulation. The trial consisted of three replicates of five treatments: no nitrogen (CK), recommended N rate (REC) (180 and 210 kg ha^{-1} N fertilizer as urea for wheat and maize, respectively), same amount N in the form of controlled release fertilizer (CRF), with addition of duck manure to achieve the same total N rate as REC (80% REC + DM) and conventional fertilization (CF) (315 and 270 kg ha^{-1} N fertilizer as urea for wheat and maize, respectively). During the continued fertilization of the rotation system, the CRF application had an equal yield, N use efficiency (48%) and residual N (175 kg ha^{-1}) but decreased the estimated N loss (18 kg ha^{-1}) when compared to REC (72 kg ha^{-1}). N accumulated below the root zone in the 40–60 cm soil layer was at a high risk of migrating deeper in the soil profile. Application of CRF could effectively reduce the nitrate N accumulating in the soil, slowing down the rate of nitrate migration to the deep soil.

1. Introduction

Most farmers in China still tend to apply excessive amounts of nitrogen (N) fertilizer to ensure high crop yield, however, the N use efficiency (UE_N) was only 30% or less in cereal production systems (Cui et al., 2008), which was lower than the world average of 50–80% (Cassman et al., 2002; Dobermann et al., 2000; Ladha et al., 2005). The large accumulation of nitrate in the soil profile increases the nitrate concentration in groundwater, risking pollution of the environment (Simpson et al., 2011; Turner et al., 2012). For instance, the research of Zhang et al. (1996) showed that in about 52% of 69 investigated locations on the North China Plain (NCP), samples of groundwater exceeded the allowable limit for nitrate in drinking water. To satisfy the production needs of Chinese farmers in the future and reduce the environmental risks discussed above, nitrogen fertilizer and fertilizer strategy recommendations have been developed for the wheat-maize system on the NCP (Chen et al., 2004; Galloway et al., 2004; Chen et al., 2006; Ji et al., 2012). The recommended N rate was 55 kg ha^{-1} at the time of re-greening and followed by 65 kg ha^{-1} at the shooting stage of the winter wheat on the NCP (Chen et al., 2006). As expected, the UE_N in crop production system is still low due to the large amounts of residual nitrate-N and lost N (Adediran et al., 2005; Cui et al., 2006).

Organic matter in the soil plays a key role in maintaining and promoting soil quality because of the improvement of physical, chemical and biological properties of soils (Reeves, 1997). The research of Xu et al. (2008) showed that the application of a combination of half chemical fertilizer and half swine manure resulted in higher yield and nitrogen use efficiency than chemical fertilizer only. In addition, the controlled release fertilizer (CRF) could improve N utilization and mitigate the impact on the environment (Venterea and Rolston, 2000; Shaviv, 2001; Ji et al., 2012). The ideal CRF is coated with an environmental friendly macromolecule material that has two main properties to increase the nutrient use efficiency and reduce environmental pollution. One is slowing down the nitrogen release to the soil to meet the nutrient requirements for crop growth (Azeem et al., 2014), and the other is maintaining nutrient availability in the soil (Shaviv, 2001). Use of CRF showed a higher potato yield and a lower N fertilizer loss than the application of nitrification inhibitor (Shoji et al., 2007), confirming

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high potential to increase N use efficiency (Amans and Slangen, 1994; Mikkelsen et al., 1994; Shoji and Kanno, 1994; Wang and Alva, 1996).

To better understand these positive features of the various fertilizer strategies for increasing N use efficiency and reducing environmental contamination, two questions remain to be resolved as follows: firstly, would the N use efficiency of these N fertilizer strategies above-mentioned be superior compared with the recommended N rate? Secondly, how does nitrate-N accumulate and migrate in the different soil layers in the early period of the fertilization management? Investigating these questions may help us to more clearly understand the environmental risks posed by the accumulation of N in the soil and help farmers manage N fertilizer application better. The present study was conducted in Shangzhuang County on Weishan Island in Weishan Lake, Shandong Province, within the NCP. A winter wheat-summer maize crop rotation has been widely cultivated here. The objectives of this study were: (1) to study the potential of various fertilization strategies to improve UE_N and decrease the apparent N loss in the soil, (2) to evaluate the nitrate migration in the soil profile of the various fertilization strategies.

2. Materials and methods

2.1. Experimental site

The field experiment was established at Shangzhuang County on Weishan Island in Weishan Lake. The island is located in the south of Shandong Province on an alluvial plain (N 34°39′34″, E 117°14′ 46″). A winter wheat-summer maize cropping rotation has been adopted here. The climate of the research area is temperate, sub-humid, with an average temperature of 13.7 °C and an annual rainfall of 697 mm. Precipitation was recorded during the growing seasons from Sep 29th 2008 to Jul 1th 2010 (Fig. 1). Total amounts of precipitation were 218, 327 and 154 mm in the growing seasons for wheat in 2008–2009, maize in 2009 and wheat in 2009–2010, respectively (Fig. 1).

The soil is fluvo-aquic soil. The soil pH (1:2.5, soil/water) of the topsoil (0–20 cm) is 7.3. The soil contains 20.75 g organic matter kg^{-1}, 9.64 mg nitrate-N kg^{-1}, 6.86 mg Olsen-P kg^{-1}, and 89.69 mg NH_4OAc-K kg^{-1}.

2.2. Experiment treatments and field management

A completely randomized design was employed with five treatments and three replicates. Each plot was 36 (12 × 3) m^2. The five treatments were control (CK, 0 N), recommended N fertilizer as urea (REC, 180 kg N ha^{-1}), REC N as controlled release fertilizer in the form of resin coated urea (CRF, 180 kg N ha^{-1}), 80% of REC N as urea with 1800 kg ha^{-1} duck manure (80% REC + DM, 180 kg N ha^{-1}) and conventional fertilizer as urea (CF, 315 kg N ha^{-1}) for wheat. The N application rates for maize were 0, 210, 210, 210 and 270 kg N ha^{-1} as urea for the CK, REC, CRF, 80% REC + DM (2100 kg ha^{-1} duck manure) and CF treatments, respectively. The duck manure contained 2% N, 3% P_2O_5 and 1% K_2O.

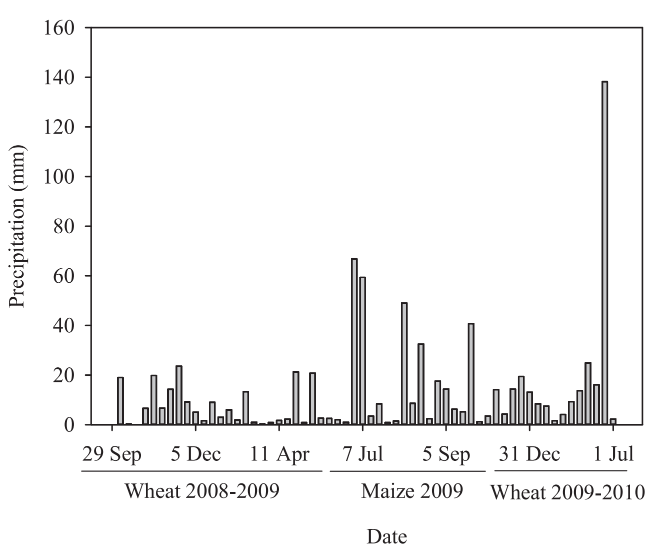

Fig. 1. Precipitation during wheat and maize growing seasons from 2008 to 2010.

The trial period covered two growing seasons for wheat (2008–2009 and 2009–2010) and one season for maize (2009). The wheat cultivar used was Jimai 22, sown at the beginning of October and the maize cultivar used was Zhengdan 958, planted in mid-June. The resin coated urea was provided by KINGENTA (Shandong, China). The release period of the CRF was 180 days and 90 days when it was applied to the wheat in winter and to the maize in summer. Each plot also received 90 kg P ha^{-1} as triple superphosphate and 60 kg K ha^{-1} as potassium chloride. The K and P fertilizers, manure and the coated urea were surface applied as basal fertilizer before planting. The conventional urea was applied with two applications for the REC, 80% REC + DM and CF treatments, half at planting and the other half around the stem elongation stage. Fertilizers and manures were uniformly broadcast onto the soil surface and immediately incorporated into the soil (0–20 cm depth) by tillage prior to sowing. There was no irrigation applied during the growing period, in line with the local field management practices. There was no obvious water, weed, pest or disease stress observed during the growing period.

2.3. Sampling and laboratory procedures

Whole wheat plants were harvested manually in early June and the maize plants were harvested in early October. Stem biomass (stem and leaves) and grain yield were determined after oven-drying at 60 °C. Subsamples of the stem and grain were taken to determine N content using the Kjeldahl procedure (Horwitz, 1980).

Soil samples were collected from each crop four times: the returning green stage, stem elongation stage before topdressing, booting stage and after harvest for the winter wheat; and stem elongation stage, bell stage, tasseling stage and harvest stage for the summer maize. Each sample included five cores per plot taken to a depth of 100 cm at 20 cm increments. Soil samples were extracted with a 1:10 ratio of soil to 0.01 M $CaCl_2$ and analyzed for nitrate-N using Continuous Flow Analysis (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany). Soil water content was measured by oven-drying at 105 ℃ for 24 h. Soil nitrate-N (kg N ha^{-1}) was calculated using the average bulk densities in the researched area, which were 1.22, 1.27, 1.33, 1.41 and 1.48 g cm^{-3} for the 0–20, 20–40, 40–60, 60–80 and 80–100 cm soil layers, respectively.

2.4. Data analysis

Statistical analysis was performed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA). The grain yield, UE_N, residual soil nitrate-N content, estimated N loss and the relative nitrate-N accumulation rate (RNAR) were calculated following the analysis of variance using a one-way ANOVA, followed by the least significant difference test at 0.05 level of probability.

The UE_N was calculated as the percentage of fertilizer N recovered in aboveground plant biomass at maturity stage

$$UE_N = \left(\frac{\text{N uptake in N treatment-N uptake in control}}{\text{N fertilizer applied}}\right) \times 100 \tag{1}$$

Apparent nitrogen mineralization ($N_{mineralized}$) during the crop growing season was estimated by subtracting initial inorganic soil N_{min} in the 0–100 cm soil layer before planting in the 0 N control plot from