Optimal cattle manure application rate to maximise crop yield and minimise risk of N loss to the environment in a wheat-maize rotation cropping system

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Abstract

This paper examines the effect of cattle manure application rates on nitrate nitrogen (NO_3^--N) migration and accumulation in a farmland soil and investigates methods for appropriate manure use in order to reduce NO_3^- pollution to the environment. A field experiment was conducted on a fluvo-aquic soil in a cropping area of Caoxian County in Shandong Province, China. The effect of cattle manure (with N concentration of 1.5%), at different application rates (0, 15000, 30000, 45000, 60000 and 75000 kg/ha/year), on vertical distribution of soil NO_3^--N, crop yields, and nitrogen use efficiency was determined in a winter wheat and summer maize rotation on farmland under natural rainfall conditions. The results showed that the NO_3^--N concentrations in the soil profile (0-100 cm) increased with the increase in application rate. When the rate was greater than 45000 kg/ha/year, soil NO_3^--N concentrations were significantly higher than those in the other treatments with lower application rates. The NO_3^--N levels in the 80–100 cm soil layers were several times higher than those of the surface soils at the later growing stage of the winter wheat in early summer, indicating that this NO_3^--N, which had migrated downward and accumulated in the deep soil would be prone to drain to groundwater during the summer rainfall season, as it would be below the root zone of the summer maize. A quadratic relationship between crop yields and cattle manure application rates was found. Wheat and maize silage yields were highest when cattle manure application rate was 45000 kg/ha/year, with the N use efficiencies of wheat and maize silage both being about 50%. We conclude that a cattle manure application rate of 45000 kg/ha/year (equivalent to 675 kg N/ha/year) is optimal for this wheat-maize rotation cropping system.

Key Words

Cattle manure, Wheat–maize rotation, Soil nitrate nitrogen, Crop yields, Nitrogen use efficiency (NUE)

Introduction

With rapid livestock intensification in China, application of a large amount of livestock manure can be an important part of agricultural non-point source pollution (Zhang et al.2007). However, as livestock manure contains nutrients for plant growth, use of the manure as a fertilizer on farmland can be an efficient use of this resource. Many studies have shown that the application of manure can increase availability of soil nutrients and improve soil fertility and organic matter content (Bolan et al. 2003). However, an increasing number of studies have also shown that the excessive application of manures, such as cattle manure, can result in NO_3^-accumulation in soil, which could lead to NO_3^- pollution to surface water and groundwater. Therefore, determining an optimal application rate for animal manure to increase production and reduce adverse environmental effects is required.

The wheat–maize rotation, as one of the most important cropping systems in the North China Plain, is characterized by high nutrient input and output. Detailed studies of NO_3^- accumulation and migration in the soil profile in the wheat–maize rotation cropping system, when cattle manure is applied, would help to understand the leaching risk of applied manure N, so that efficient application methods can be developed. The study presented in this paper analysed the effect of different cattle manure application rates on NO_3^--N migration and accumulation in soil, crop yields and manure N use efficiency. The aim of this study was to provide data for determining optimal manure application rates in order to control N loss from farmland and maximize crop yieldsin the North China Plain. In addition, the data from this study will add to a database that provides a theoretical basis for formulation of a national standard for livestock manure loading rates for arable land in China.

Materials and methods

Overview of the experiment site

The experiment was carried out in Wanglou village, Caoxian county of Shandong Province, China, 34°47′9.78″ N, 115°35′16.32″ E. The area is in the north subtropical region, with an annual mean temperature of 13.6–14.3°C, annual mean sun hours of 2148 h, annual precipitation of 612–711 mm and a mean frost-free period of 212 days. The cropping system is an annual winter wheat–summer maize rotation. The soil at the study site is an alluvial soil, and the basic physical and chemical properties of the 0–20 cm layer were as follows: pH (H_2O, 1:5) of 8.56, organic matter content of 13.25 g/kg, total N of 1.33 g/kg, available P of 17.76 mg/kg, alkali-hydrolyzable N of 93.54 mg/kg and available K of 129.17 mg/kg.

Experimental design

Winter wheat was sown on October 9th 2014 and harvested on June 4th 2015, and maize was sown on June 4th 2015 and harvested on October 10th 2015. The organic fertilizer used for the experiment was cattle manure from a nearby dairy farm. The feed for the cattle was mainly maize silage with alfalfa and wheat grain as supplements. Cattle manure was produced through a composting process after dry-and-wet separation. Manure nutrient contents are shown in Table 1. Six treatments with different manure application rates were applied. The manure application rates were 0, 15000, 30000, 45000, 60000 and 75000 kg/ha/year, corresponding to N rates of 0, 75, 450, 675, 900 and 1125 kg/ha/year. Half of the manure was applied to the wheat and the other half to the maize. Manure was applied at the surface at the time of sowing of the wheat or maize, and mixed well with the soil through mechanical rotary tillage to a20 cm depth. Seeds were sown after soil levelling, and there was no fertilizer topdressing at later stages for either crop.

Table 1. Nutrient content of the cattle manure.

N(%)	P_2O_5(%)	K_2O(%)	Organicmatter (%)	Solid content (%)
1.50	1.70	1.48	29.01	57.07

The wheat cultivar used was Jimai 22, which is locally prevalent, and mechanical row sowing of 25 cm was adopted with a seeding rate of 187 kg/ha. The maize cultivar used was Yuqingchu 23 and was sown using the dibbling method with an even row spacing of 60 cm and plant spacing of 25 cm. All treatments had three replicates and were randomly arranged in blocks with a plot size of 64 m^2. The management practices for the experimental plots were the same as those in local cropping fields. Total precipitation during the wheat growth season was 179 mm and 468 mm during the maize growth season (Figure 1).

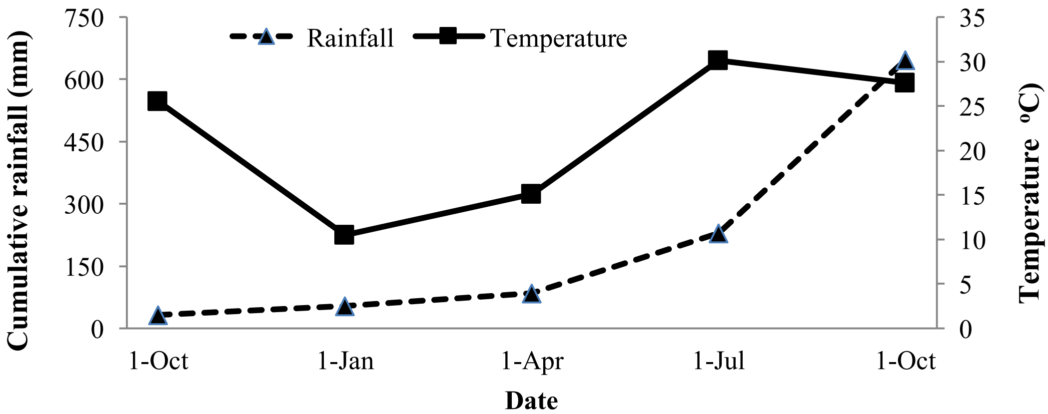

Figure 1: Precipitation and air temperature during the wheat and maize growing seasons.

Sample collection and analysis

Soil samples were collected from each plot at the seedling, heading and maturing stages for both wheat and maize. Soil samples were taken to a depth of 1 m in 0.2 m intervals. Three cores were taken and pooled from each plot. The field-moist soils were sieved (<4 mm) soon after collection and then analysed for soil moisture and NO_3^--N. The soil bulk density of each layer was determined. Accumulation of NO_3^- in the soil profile was determined based on the NO_3^--N content of each soil layer and the corresponding soil bulk density. At the maturing stages, wheat grains and above ground biomass, and maize silage were sampled for determination of crop yields and N concentrations. Cattle manure N use efficiency was calculated as the percentage of applied cattle manure N which was recovered in above ground biomass of crops.

All data were statistically analysed using SPSS 16.0 software. The significance of variation was determined by using the least significant difference method after a single factor variance analysis, with $P < 0.05$ as the significance level.

Results and discussion

Distribution of NO_3^--N in the soil profile

On the 59th day after manure application(wheat seeding stage), soil NO_3^--N contents in the top soil layers (0–40 cm)of the plots with the higher manure application rates (more than 6000 kg/ha/year) were significantly higher than those with lower application rates (less than 30000 kg/ha/year) ($P < 0.05$) (data not shown). In the 40–100 cm soil layers, NO_3^--N contents in the manure treated soils were higher than those in the control ($P < 0.05$), but differences in NO_3^--N content between manure application rates were not significant ($P > 0.05$). Total rainfall for those 59 days was 33 mm and temperature was below 5^{o}C (Figure 1). These data suggest that mineralization of manure organic N had started and some NO_3^--N had gradually moved to the deeper soil layers, despite the low rainfall and temperature for those 59 days. On the 188th day after manure application (heading stage) NO_3^--N contents had further increased in the soil profile, as a result of more organic manure N being mineralised. Much highersoil NO_3^--N contents were found in the 40–100 cm soil layer in the treatments with the two highest manure application rates than in the treatments with lower manure rates. On the 237th day (maturing stage), differences in NO_3^--N contents in the deep layers of soil (60-100 cm) between manure application rates were significant ($P < 0.05$), with much higher NO_3^--N contents in the treatments with the two highest manure application rates. The accumulation of NO_3^--N in the deep soil layers (below soil surface 60cm that out of the root zones) posed a great risk for leaching to groundwater.

The maize growth season coincided with the raining season, and a much higher amount of rainfall was recorded for the maize growth period (82 days) than for the wheat growth period (240 days) (Figure 1). Generally, higher NO_3^--N contents were observed in the soil profiles with higher manure application rates. On the 20th day after manure application (maize seeding stage), soil NO_3^--N contents in the 0–60 cm soil layers were not significantly different between the treatments ($P > 0.05$). However, the NO_3^--N contents in the 60–100 cm soil layers in the treatment with the highest manure application rate(75000 kg/ha/year)were significantly higher than those in all other treatments ($P < 0.05$). Although higher NO_3^--N contents in the 60–100 cm soil layers in the 75000 kg/ha/year treatment were observed at the later stages (e.g. heading and maturing stages), the differences were not significant ($P > 0.05$). It is suggested that by these later stages of the maize growing period the NO_3^--Nis likely to have been drained out of the soil profile (below 100 cm), without accumulation in the soil, as a result of continuous drainage during that rainfall season.

The NO_3^--N accumulation in the 0–100cm soil profile was influenced greatly by temperature, rainfall and plant uptake. The highest NO_3^--N accumulation occurred at the wheat heading stage for each treatment, with NO_3^--N accumulation of up to 176 kg/ha. Some of this accumulated NO_3^--N would be prone to leaching out of the soil profile when the rainfall season commences. There is a trend for increasing amounts of NO_3^--N to accumulate in the soil with increasing manure application rate, with significantly higher amounts of NO_3^--N generally being observed in the soil from the two highest manure application rates.

Effect of manure application rate on crop yield and N use efficiency

Wheat yield increased with increasing manure application rate up to 45000 kg/ha, but decreased when the application rates were higher (Table 2). The relationship between the wheat yield (kg/ha) and manure application rate (kg/ha) can be best described by a quadratic function ($y = -4\times10^{-5}x^2 + 0.1232x + 279.42$, $R^2 = 0.92$). Maize silage yield increased with increasing manure application rate. The yield (t/ha) and manure rate kg/ha showed a significant and linear relationship($y = 0.0006x + 3.3249$, $R^2 = 0.8827$).The agronomic efficiency of applied manure N was highest when the manure application rate was 15000 kg/ha (Table 2); however, the crop yields were lower at this application rate. The corresponding cattle manure application rates for the highest wheat and maize silage yields were 45000 and 75000 kg/ha, respectively, but the maize silage yield showed no significant increase when the application rate was increased from 45000 to 75000 kg/ha. Therefore, the optimum cattle manure application rate would be 45000 kg/ha in the wheat-maize rotation cropping system.

Table 2. Wheat and maize silage yields and N efficiency of treatments with different application rates.

	Wheat			Maize		
Total manure application rate (kg/ha)	Yield (kg/ha)	N agronomic efficiency (kg wheat/kg applied N)	N use efficiency (%)	Yield (ton/ha)	N agronomic efficiency (kg wheat/kg applied N)	N use efficiency (%)
0	4134 c			45b		
15000	5034 b	8.0	125	59 ab	12.0	120
30000	5424 ab	5.7	76	60 ab	6.5	71
45000	5704a	4.7	52	65 a	5.8	50
60000	5136 b	2.2	33	68a	5.1	43
75000	5072 b	1.7	25	71 a	4.5	32

Note: In each column of data, different letters represent a significant difference among treatments, $P< 0.05$; N agronomic efficiency (kg yield/kg N) = (crop yield in N application area − crop yield control) /Manure N application rate.N use efficiency was calculated as the percentage of applied cattle manure N which was recovered in above ground plant material.

The N uptake by wheat and maize increased with increasing manure application rate up to 45000 and 60000 kg/ha, respectively. However, the N uptake decreased when the manure rates were further increased (data not shown). Manure N use efficiency decreased for both wheat and maize with increasing manure rates. Manure N use efficiency in both the wheat and maize was about 50%, when the cattle manure application rate was 45000 kg/ha (equivalent to N input of 337.5 kg/ha for each crop)(Table 2). Ju et al. (2014) reported that average N fertilizer use efficiency for cropping was 50% to 55% globally. The N uptake by crops in the control treatment mainly originated from the soil N pool, and N use efficiency in the 15000 kg/ha treatment for the wheat and maize were over 100%, respectively, suggesting that at this manure application rate, the N uptake by crops exceeded manure inputs and would inevitably cause soil N loss and deficiency in the long term. On the other hand, the manure N use efficiency decreased when the manure N rates were over 45000 kg/ha, potentially resulting in N loss through leaching to groundwater. Although animal manure used as an alternative to chemical fertilizer could reduce chemical fertilizer input, excessive application rates may also represent a serious threat to the soil and water environments. Serious threat to the soil and water environments, including consequences of high phosphorus (P) loads. Therefore, it is important for agricultural sustainable development that an appropriate application rate for manure is used.

Conclusions

Wheat and maize silage yields were highest when cattle manure application rate was 45000 kg/ha/year, with the N use efficiencies of wheat and maize silage both being about 50%. We conclude that a cattle manure application rate of 45000 kg/ha/year (equivalent to 675 kg N/ha/year) is optimal for this wheat-maize rotation cropping system in the North China Plain. Furthermore, at this application rate the N use efficiency was reasonable to protect the environment, as above this rate large amounts of N accumulate in the lower soil depths which creates a pollution risk caused by leaching to groundwater.

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