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An in situ study of inorganic nitrogen flow under different fertilization treatments on a wheat–maize rotation system surrounding Nansi Lake, China

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ABSTRACT

Nitrogen (N) loss to the environment through water transport has been a serious challenge to agricultural practices for decades. Although much progress has been made in developed countries, suitable strategies for mitigating agricultural N loss in developing countries, such as China, are still required. In particular, studies that comprehensively measure the effect of fertilizer strategies on N loss through runoff and leaching would be beneficial in the design of fertilizer programs that meet the needs of the dominant cropping systems in China, while protecting nearby water bodies. In this study, agricultural plots ($n = 21$) in the Nansi Lake Watershed of Shandong District, China, were fitted with runoff and leachate collection devices to monitor the effect of different N fertilizer treatment strategies, including OPT, CRN, DMS, and STR for a wheat–maize rotation system on N loss through water transport. Runoff and leachates were collected at 10 typical growth stages of the consecutive wheat and maize seasons throughout a 2-year period. Yield and precipitation data for each plot were also collected. One of the main findings was the significant positive correlation between precipitation levels and the quantity of leachates and runoff. In addition, the amount of water collected in the various treatment was affected by agricultural practices, such as straw incorporation and tillage of surface soils. During the different growth stages, NO_3^--N and NH_4^+-N concentrations varied in the leachate and runoff. The NO_3^--N concentration had a greater impact on water quality during the R1 period of maize. However, NO_3^--N concentrations were too low to cause ground water pollution. The total loss of inorganic N to leaching and runoff was 1.68–5.96 kg ha^{-1} among crops. Run off accounted for 63.4–73.8% of inorganic N loss. The amount of NO_3^--N and NH_4^+-N lost through leaching and runoff was generally greater during the maize season compared to the wheat season. During the form of nitrogen loss, the ratio of NH_4^+-N and NO_3^--N in the leachate was generally similar (the proportion of NO_3^--N during the maize and wheat season was 65.2–70.9% and 46.0–54.6% respectively). However, there was a predominance of NO_3^--N in the runoff (82.5–86.4% and 94.2–96.5% for the maize and wheat seasons, respectively). The NO_3^--N and NH_4^+-N losses through total leachate and runoff were highest in the FP treatment, followed by OPT and DMS, and finally STR and CRN. To reduce N loss through water transport, in parallel to ensuring continued high agricultural production levels, CRN and OPT in conjunction with wheat straw incorporation should be encouraged during maize production, while CRN and OPT should be encouraged during wheat production.

1. Introduction

The increasing modernization of agriculture has generated major scientific interest, as excessive N application through the intensive use of fertilizers has been found to affect air, soil, and water conditions, in addition to human health (CAST, 1985; Keeney and Follet, 1991). In developed countries, N management research has led to a higher efficiency in N fertilizer use and reduced environmental pollution (Archer and Thompson, 1993). However, in many developing countries, N fertilizer application continues to increase, nutrient use efficiency continues to decrease, and concentrations of nitrate-N (NO_3^--N) in surface and ground waters are reaching levels that have not been previously recorded. This difference is due to conditions experienced within developing nations (such as large population size and extensive land areas), as well as a lack of effective N management schemes and associated research.

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In the wheat–maize rotation systems practiced in Shandong Province, North China, N fertilizer application rates of up to 600 kg N per ha per year have been reported (Ju et al., 2006), an estimated 40% of which is lost to runoff. This extensive fertilizer use has significantly affected water bodies in the region, such as Nansi Lake. Nansi Lake, which was constructed during the major south-to-north water diversion project of China, serves as an important water transportation channel. The lake is eutrophic, due to excess nitrogen (N), phosphorus (P), suspended solids, and organic matter (OM), with these elements causing serious degradation (Hoorman et al., 2008). Most of the watershed is dominated by agriculture, particularly wheat–maize double rotation crop systems. The excessive application of N fertilizer by agricultural practices has caused soil pollution, with nutrients flowing into both surface and ground water. The fertilization of crops constitutes the main reason and source of pollution for the lake watershed (Liu et al., 2005; Wo et al., 2007; Zhang and Zhuang, 1998; Zhang et al., 1996). As a result, the lake is now classified as an ecologically fragile region, due to high N loss (Li and Yao, 2007). Furthermore, a large portion of groundwater reservoirs in the North China plain have NO_3^--N levels that exceed WHO and European critical values for drinking water (Zhang et al., 2004).

As the watershed of Nansi Lake is subject to high levels of precipitation, the loss of N nutrients through runoff and leachates has a major impact on the water quality of the lake. Monitoring data for the tributaries within the lake's watershed indicate that agricultural runoff contributes almost 40% of the total N loss entering the lake through various means. This poses a critical risk to the security of the water resources in this region (Li and Yao, 2007; Hoorman et al., 2008). This issue is mainly caused by adherence to traditional agricultural concepts, including the excessive application and poor administration of chemical fertilizers with high N nutrients (Guo et al., 2004, 2008). In China, the amount of arable land per capita is low, while the rate of multiple cropping is high. To meet the primary need for basic sustenance, it is natural for farmers to add more nutrients to the soil to increase yields. Since the management of agricultural plots is decentralized, the only way to reduce pollution is by using local resources or adopting N management measures that are suited to the country's conditions.

The special food production zone, which falls within the study area, is located in the inland lake district. This area has adopted various technical measures to prevent and control non-point source pollution, ensure production volume, and reduce N loss. One measure is the use of balanced NPK fertilization, which effectively promotes N absorption by crops, thereby increasing N efficiency. Another measure that prevents N loss is the application of controlled-release fertilizers. These fertilizers release N nutrients according to the rate of crop growth, facilitating sustained absorption, and utilization. Organic fertilizers (such as duck manure) are used instead of chemical fertilizers. Poultry farming, which is carried out at a large scale in the lake district, is a rich source of organic N. After application, the transformation of organic N into inorganic materials is slow, thus, effectively reducing the rate of N loss. Straw incorporation is also practiced for 2 reasons. First, because there is an abundance of wheat and maize straw, which are rich in nutrients, and second, the presence of a straw cover over the plots reduces the loss of nutrients through runoff.

In China, nutrient use efficiency is significantly lower than many countries where nutrient flow and nutrient use efficiency studies have been conducted (Ma et al., 2005). A survey of recent scientific literature shows that, in China, much of this research centers on cereal yields in the North China Plain, due to the continued, excessive use of fertilizers for cereal production in the region (Liu et al., 2003; Ju et al., 2006; Shi et al., 2012; Cui et al., 2012). Currently, most research on the watershed of the inland lakes is at the surveying stage, and understanding the basic mechanisms (Tuo, 2002; Hu et al., 2008). Technical research on mitigation strategies, suitable for the current situation in China is still lacking, especially in the inner lakes area, where per capita arable land is low and decentralized management is common. It is essential to strengthen research on non-point pollution controls to improve the sustainability of agricultural production and to improve the environmental stability of the Nansi Lake Watershed. It remains unclear which of the aforementioned measure(s) is the most effective at ensuring continued high levels of agricultural production in this watershed, or which measure better contributes toward the reduction and control of the amount of N loss while increasing N efficiency. Therefore, in this study, we evaluated the effect of N fertilizer application strategies on inorganic N runoff, leaching, and yield for the wheat–maize rotation system. Such results are anticipated to provide a foundation for N management with less loss through water transport.

2. Materials and methods

2.1. Description of the study area

Experimental plots ($n = 21$) were selected along the Xuehe Tributary, which flows directly into Nansi Lake, in the Zhaoyang sub-district of Huishan, Shandong (N 34° 46′ 58″, E 117° 08′ 56″, elevation above sea level 36 m). The climate is temperate monsoon, with an average annual precipitation of 550–720 mm, a rainy summer, and a dry winter and spring. The water table ranges from 1.5 to 3.0 m. The average temperatures throughout the entire period of cropping in the experimental site are shown in Table 1. The soil is alluvial clay loam. The topsoil (0–20 cm) has a pH of 8.3, and soil organic carbon (SOC), available P, available potassium (K), nitrate-N (NO_3^--N), and ammonium-N (NH_4^+-N) levels are 8.87 g kg^{-1}, 9.3 mg kg^{-1}, 140.8 mg kg^{-1}, 2.06 mg kg^{-1}, and 1.69 mg kg^{-1}, respectively.

The experiment was conducted from June 2009 to June 2011. The primary cultivation system is an annual rotation of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). The typical growth period for wheat and maize in the study area is 110 d and 235 d, respectively. Maize (Zhongyu No. 9) was planted on 15 June 2009/2010 and harvested on 7 October 2009/2010. Wheat (Jimai No. 22) was planted on 12 October 2009/2010 and harvested on 12 June 2010/2011 of the following year. After the wheat harvest, maize was again planted using a drill. After the maize harvest, the land was plowed, leveled, and planted with wheat by artificial furrow sowing. Throughout this paper, the standard vegetative (V) growth stages and reproductive (R) growth stages are used for maize, and the Feekes (F) scale is used for wheat.

Table 1
The average temperatures throughout the entire period of the crop in experimental site (°C).

Wheat	F2	F3	F4	F10	F11	**Maize**	V1	VT	R1	R3	R6
2009–2010	10.5	1.2	16.6	22.5	27.8	**2009–2010**	28.5	26.7	23.8	21.4	17.9
2010–2011	9.8	0.9	16.9	23.1	28.1	**2010–2011**	28.3	26.9	24.2	20.8	18.1

F2, F3, F4, F10, and F11 represent different periods of wheat growth; V1, VT, R1, R3, and R6 represent different periods of maize growth.