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Optimized fertigation maintains high yield and mitigates N_2O and NO emissions in an intensified wheat–maize cropping system

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ABSTRACT

Agricultural soil is a major source of N_2O and NO. In this study, we tested whether optimized N fertigation and water-saving irrigation methods could improve nutrient and water use efficiency while maintaining productivity in the intensified farmed winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.) cropping system of northern China. A field experiment was conducted to test different flood irrigation (FN600, conventional N fertilization of 600 kg N ha^{-1} yr^{-1} and flood irrigation; FN0, no N input and flood irrigation) and drip fertigation (N0, no N input and drip irrigation; N420, optimized N fertilization of 420 kg N ha^{-1} yr^{-1} and drip irrigation; N600, conventional N fertilization of 600 kg N ha^{-1} yr^{-1} and drip irrigation) treatments. Compared with the FN600 treatment, the N600 treatment reduced water use by 62.5% (wheat season) and 36.4% (maize season). The N600 treatment significantly reduced N_2O emissions (by 19.9%) during the maize season, but not during the wheat season. The N600 treatment increased NO emissions by 20.9% and 11.0% during the wheat and maize seasons, respectively. Compared with the N600 treatment, the N420 treatment significantly decreased N_2O and NO emissions by 21.8% and 29.8%, respectively, during the wheat season, and by 31.5% and 41.6%, respectively, during the maize season, while achieving higher crop yield. The direct emission factors (ratio of the cumulative N_2O or NO emissions of fertilized treatment minus CK to N rate) of N_2O and NO were 0.19%–0.25% and 0.21%–0.27% for the wheat season and 0.38%–0.63% and 0.34%–0.42% for the maize season, respectively. Optimal fertilization (N420) significantly increased the water use efficiency, intrinsic water use efficiency, partial factor productivity, and apparent nitrogen use efficiency in both the wheat and the maize seasons. In addition to nitrification, nitrifier denitrification contributed to the generation and diffusion of N_2O and NO, especially during the summer maize season. Considering the higher productivity, more efficient use of irrigation water and nitrogen, and lower N_2O and NO emissions, drip irrigation combined with optimized N fertilization is recommended in northern China.

1. Introduction

Globally, agricultural soils contribute approximately 67% and 18% of total anthropogenic N_2O and NO emissions, respectively (Reay et al., 2012; Gaihre et al., 2015). Total fertilized cropland annually emits 1.7–4.8 Tg of N_2O-N and 1.6–8.9 Tg of NO-N (IPCC, 2007; Cui et al., 2012; Yao et al., 2017). Accordingly, it is important to mitigate N_2O and NO emissions through optimized farming practices in agricultural sectors.

Drip irrigation combined with dissolved N fertilizer (fertigation), which provides an appropriate amount of N and water to crop roots in a more precise and timely manner than does broadcast fertilization, has been confirmed to be an efficient method of irrigation and fertilization (Abalos et al., 2014; Farneselli et al., 2015). Many studies have shown that drip fertigation can decrease N losses (Badr et al., 2012; Koocheki et al., 2014) and reduce transformable N to N_2O and/or NO (Maris et al., 2015). Wang et al. (2016a) reported a significant reduction (14.6%) of N_2O in the winter wheat season under drip irrigation, compared with flood irrigation. However, Tian et al. (2016) found that drip fertigation reduced N_2O emissions by 7.7%, but increased NO emissions by 21.7% during the summer maize season. These findings indicated that edaphic properties, climate conditions, and farming practices may exert different effects on soil N_2O and NO emissions (Barnard et al., 2005; Deppe et al., 2016; Zhou et al., 2017).

Northern China, one of the most intensified agricultural regions in China, produced 67% and 28% of the nation's wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), respectively, in 2014 (NBSC, 2015). Various sound farming practices have been implemented to reduce

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fertilizer N and water inputs and maintain the high crop yield in this region since the 1990s (Zhang et al., 2011). The fertilizer N efficiency in the region has been reported to be < 30% for maize and wheat (Miao et al., 2011). The reported proportions of N losses from applied fertilizers via nitrification and denitrification range from 0.9% to 10.9% (Zhang et al., 2008; Ju et al., 2009). Such gaseous N losses (including NH_3) exert potential pressure on the aquatic environment (Chien et al., 2009) and air quality (Xu et al., 2016), and contribute to regional and global greenhouse gas emissions (Zhang et al., 2017). In northern China, agriculture is dependent on pumping deep groundwater for irrigation, and irrigation water accounts for 80% of total water use in the region (Deng et al., 2006). As a result, the groundwater level is declining rapidly at a rate of 0.8 m yr^{-1} in this region (Fang et al., 2010). Heavy irrigation has also increased NO_3^- leaching from cropland (Deng et al., 2006), resulting in the entry of NO_3^- to deeper profiles, after which it infiltrates groundwater or is permanently lost from the system (Currell et al., 2012). Optimizing fertilization and irrigation by methods such as sprinkling and drip irrigation has been suggested as a priority farming measure and is being expanded in the region. Currently, these processes are applied to > 1 million ha of maize and > 0.3 million ha of wheat agricultural areas, with a target of total 2.7 million ha in China by 2020 (the "Promotion of Implementation of Fertigation" policy; MOA, 2016).

In this study, we hypothesized that drip fertigation would substantially decrease N_2O emissions but increase NO production because of higher oxidation of N_2O to NO during drip fertigation than during flood irrigation. To test this hypothesis, we monitored the N_2O and NO losses, crop production, and soil conditions in northern China under flood and drip irrigation with different N rates in the typical winter wheat–summer maize cropping system of the region. We aimed to analyze the effects of optimized fertilization and irrigation on crop production and N_2O and NO emissions. The overall aim of this research is to develop appropriate practices to mitigate the production of greenhouse gases and improve resource use while maintaining high land productivity.

2. Materials and methods

2.1. Study area

We initiated the field experiment in 2015 at the Huantai Experimental Station of China Agricultural University, Shandong province (36°51′50″–37°06′00″N, 117°50′00″–118°10′40″E). The region has a typical continental monsoon climate, with an annual average temperature of 12.5 °C (Chen et al., 2010). Rainfall occurs mainly in June, July, and August. The annual precipitation is 542.8 mm and the annual frost-free season is about 198 days (Liao et al., 2015). The soil parent materials are mainly mountain diluvium and Yellow River alluvial deposits, which have developed into loamy soils classified as Calcaric Fluvisols (Chen et al., 2010; Liang et al., 2013) with a bulk density (BD) of 1.40 g cm^{-3}, pH (H_2O:soil = 2.5:1) of 7.8, soil organic matter content of 17.3 g kg^{-1}, a total N content of 1.1 g kg^{-1} (Zhao et al., 2017), field water capacity of 30.5%, and permanent wilting point of 10.3%. The predominant cropping system in the region is the annual double cropping of winter wheat (*T. aestivum* L.) and summer maize (*Z. mays* L.). The crop evapotranspiration of winter wheat and summer maize were determined to be 497 mm yr^{-1} and 340 mm yr^{-1}, respectively (Holst et al., 2014).

2.2. Experimental design

Five treatments were applied in the field experiment: 1) local farmers' conventional level of N fertilizer and flood irrigation (FN600, 600 kg N ha^{-1} yr^{-1}); 2) local farmers' conventional level of N fertilizer and drip fertigation (N600, 600 kg N ha^{-1} yr^{-1}); 3) optimal level of N fertilizer and drip fertigation (N420, 420 kg N ha^{-1} yr^{-1}); 4) no N fertilizer and drip irrigation (N0, 0 kg N ha^{-1} yr^{-1}); and 5) no N fertilizer and flood irrigation (FN0, 0 kg N ha^{-1} yr^{-1}). The five treatments were arranged in a randomized block design with three replications, resulting in a total of 15 plots (each 10-m long and 5-m wide). The varieties used were Luyuan 502 for wheat and Zhengdan 958 for maize. For the FN600, N600, and N420 treatments, winter wheat and summer maize received N fertilizer at a ratio of 9:11 (pre-experiment data). In line with local farming practices, winter wheat was sown in mid-October and harvested in early June of the following year, while summer maize was sown in mid to late June and harvested at the end of September. The row spacing was 40 cm for wheat and 60 cm for maize. Mechanically chopped wheat straw and maize straw (lengths of 2–5 cm and 5–8 cm, respectively) were tilled into the soil at a depth of 20 cm (Hu et al., 2013; Huang et al., 2017).

2.3. Irrigation and fertilization

In addition to precipitation, conventional crop production treatments (FN600 and FN0) were flood-irrigated depending on climatic conditions. The fertigation (N600, N420, and N0) treatments were irrigated using a soil surface drip irrigation system that included 12 pressure-compensated drip irrigation lines per plot for wheat and eight per plot for maize. The pressure-compensating emitters had a water flow of 0.15 L h^{-1} and were spaced 30-cm apart.

The drip fertigation system consisted of one pressure differential fertilizer tank, a sand filter, a screen filter, and a pressure gauge to ensure that irrigation and fertilization could be separated appropriately. This system had a total pressure of 0.3 Mpa in each district. The amount of drip water was calculated using Eq. (1):

$$Q = 10 \times H \times (\theta_{fc} - \theta_0) \quad (1)$$

where H = depth of wetting soil layer plan, cm; θ_{fc} = field water holding capacity, %; and θ_0 = planned moisture content of soil layer, %. The lowest limit of irrigation in the current study was 85% of the field water holding capacity. We determined the soil moisture content in the planned wetting soil layer (0–20 cm and 20–40 cm) in advance of the key growth stage using time domain reflectometry (TDR, IMKO Micromodultechnik GmbH, Ettlingen, Germany).

The fertilizers used were urea (46% N), potassium sulfate (52% K_2O), and super phosphate (16% P_2O_5). For all five treatments, 84.7 kg P_2O_5 ha^{-1} and 118.3 kg K_2O ha^{-1} in the wheat season and 189 kg P_2O_5 ha^{-1} and 84.7 kg K_2O ha^{-1} in the maize season were applied as basal fertilizers. For drip fertigation, the proportions of total N fertilizer applied at each growth stage were as follows: 0% (basal), 15% (tillering), 20% (jointing), 25% (booting), 25% (flowering), and 15% (grain filling) in the wheat season, and 0% (basal), 15% (jointing), 15% (small bell), 20% (large bell), 20% (tasseling), 20% (grain filling), and 10% (ripening) in the maize season. Detailed irrigation and fertilization times and amounts for all treatments are shown in Table 1.

2.4. Measurement of N_2O and NO fluxes

From Oct 20, 2015 to Oct 10, 2016, N_2O and NO fluxes were measured *in situ* simultaneously using the closed chamber method (Yan et al., 2015; Zhao et al., 2017). To facilitate air sampling, a square stainless-steel frame with a cross-sectional area of 0.25 m^2 was inserted into the soil to a depth of 20 cm in each experimental plot. This frame was kept in place throughout the entire study period, except when it was temporarily removed for necessary field operations such as tillage. On each sampling day, gases were collected from 8:00 am to 11:00 am local time in the morning within 7–14 d of fertilization, rainfall, tillage and irrigation events. Sampling was conducted twice per week during other periods.

Before air sampling, chambers (bottom area of 0.25 m^2; height ranging from 0.5 to 1.5 m depending on crop size) were mounted onto base frames and sealed with rubber strips and clamps. Five air samples