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Comprehensive environmental impacts of fertilizer application vary among different crops: Implications for the adjustment of agricultural structure aimed to reduce fertilizer use

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ABSTRACT

Although empirical correlations between fertilizer application rate and nitrogen (N) loss have been demonstrated, the differences in overall environmental impacts of fertilizer application among different crops have not been thoroughly elucidated to date. We investigated the fate of ^{15}N-labeled fertilizer in the plant-soil-air-water system across various crops (i.e., garlic, oilseed rape, and broad bean) by quantifying the N fluxes of various pathways combined with a pot experiment, a rainfall-simulating experiment, and ^{15}N tracer techniques. Hence, we compared the differences between different crops in the overall environmental impacts of fertilizer application. We found that N amount by plant uptake varied among these different crops but with little variation in fertilizer use efficiency (FUE). The residual N amounts in soil were significantly different in these crops due to statistically non-differential soil residual percentages, consistent with the differences in the application rate of N fertilizer and FUE. Further, evidently different overall environmental impacts of fertilizer application occurred among these crops, including gaseous loss of fertilizer N and potentially hydrologic loss of soil residual N from fertilizer. The highest gaseous N loss, including ammonia (NH_3) volatilization and nitrous oxide (N_2O) emissions occurred in garlic system, and the lowest occurred in broad bean. Moreover, potentially hydrologic loss of soil residual N in the garlic system was higher than in the other two crop systems, and the least was observed in the broad bean system. Therefore, attempts to reduce fertilizer application could benefit from considering the difference in overall environmental impacts of fertilizer application between different crop systems. The shift from crops with high environmental impacts to that with low impacts can largely reduce the regional N pollution.

1. Introduction

Increased application of fertilizer nitrogen (N) has significantly improved food production, but has simultaneously resulted in a cascade of environmental problems (e.g., global warming, air pollution, water quality degradation, and soil acidification) due to excessive or unreasonable application (Conant et al., 2013; Gu et al., 2015; Ju et al., 2009; Sutton et al., 2011; Zeng et al., 2017; Zuo et al., 2018). Approximately 27 Tg of the fertilizer N was used annually for food production during 2001–2010 in China (Yan et al., 2014), however, only 36–39% was taken up by plant (from 2003 through 2010) (Gu et al., 2017), which resulted in a substantial percentage of fertilizer N lost to the environment through ammonia volatilization, denitrification, leaching and runoff, etc. (Ju et al., 2009; Zhou et al., 2017a). A significant fraction of the fertilizer N applied to the cropland enters the freshwater systems and is transported by rivers to coastal areas, resulting in eutrophication of coastal and marine ecosystems (Huang et al., 2017; Mabaya et al., 2017; Strokal et al., 2014).

China started to reduce the fertilizer use dating from 2015 by implementing an announced ‘Zero Increase Action Plan’ for the national fertilizer use by 2020, which aimed to reduce the environmental costs associated with food production (Liu et al., 2016b). Improving the N use efficiency (NUE) is central to fertilizer reduction (Chen et al., 2014). Enhanced-efficiency fertilizers (e.g., polymer-coated fertilizers, nitrification inhibitors, urease inhibitors, and double inhibitors) (Li et al., 2018a), knowledge-based N management (e.g., controlled-release N fertilizer, nitrification inhibitor and urease inhibitor, higher splitting frequency of fertilizer N application, lower basal N fertilizer proportion,

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deep placement of N fertilizer, and optimal N rate based on soil N test) (Islam et al., 2018; Li et al., 2015; Muschietti-Piana et al., 2018; Xia et al., 2017; Zhang et al., 2017a,c; Zhang et al., 2018) and reasonable irrigation management (Pan et al., 2017; Wang et al., 2017) are common measures to achieve the reduction of fertilizer application.

Agricultural structure adjustment through the interconversion of different land uses (e.g., paddy field and upland) characterized by different crops rotation could be an alternative approach to reducing the fertilizer application rate. Li et al. (2018b) found that N export varied between upland and paddy fields in response to input. Hu et al. (2018) found that converting paddy fields to upland reduced 42.1% of the total N (TN) export. However, conversion of domestically cultivated N-fixing soybeans to high N-demanding crops (wheat, corn, rice, and vegetables) due to large importation of soybean increased N pollution in China (Sun et al., 2018). The difference in the environmental impacts among different crops that are characterized by contrasting N surpluses (i.e., the difference between N input and output by plant uptake) is the core of agricultural structure adjustment for fertilizer reduction. For example, Ju et al. (2007) found that soil pH in the vegetable fields was significantly lower than in the wheat-maize fields, while soil electrical conductivity (EC) was significantly higher in the vegetable soils. Different N losses among rice, wheat, and maize in response to N inputs were also found in previous studies (Cui et al., 2014; Liu et al., 2016a). However, the overall environmental impacts of fertilizer application among different crops have not been evaluated thoroughly and systematically.

Knowledge of the TN budgets of agricultural systems including all N fluxes is essential for evaluating the overall environmental impacts of the fertilizer application (Zhou et al., 2016b). The ^{15}N isotope tracer technique is a useful approach to investigating the fate of fertilizer N in agricultural systems (Chen et al., 2016; Quan et al., 2017; Sebilo et al., 2013; Zhou et al., 2016b). For example, Zhou et al. (2016b) investigated all N fluxes (e.g. gaseous and hydrologic loss) and the total N balances of agricultural systems with different fertilizers using this approach. Sebilo et al. (2013) found the long-term fate of fertilizer N in agricultural soil using the ^{15}N isotope tracer technique. However, few studies compared the overall environmental impacts of fertilizer application among different crops.

In the present study, we conducted a comprehensive study on the fate of N in three crops (i.e., garlic, oilseed rape, and broad bean) that were characterized by contrasting fertilizer N surplus (i.e., the difference between N input from fertilizer and output by the plant uptake) (Tang et al., 2012). We investigated the fate of ^{15}N-labeled fertilizer in the plant-soil-air-water system across different crops by integrating a pot experiment, a rainfall-simulating experiment, and ^{15}N tracer techniques. The main goal of this study was to improve our understanding of the different overall environmental impacts (i.e., the impacts of gaseous loss and hydrologic loss) of fertilizer application across different crops. Specifically, three objectives were defined: (i) to explore the fate of fertilizer N that was taken by plant and retained in soil; (ii) to quantify the fluxes of fertilizer N lost via gaseous and hydrological pathways; and, (iii) to compare the differences between different crops in overall environmental impacts of fertilizer application. We hypothesized that fertilizer application could show evident variations in environmental impacts between different crops due to the difference in fertilizer N surplus.

2. Materials and methods

2.1. Study site and experimental design

The present study was conducted in Xiaguan County (100.2119 °E, 25.6531 °N), in the southwest of Erhai Lake, Yunnan Province, Southwest China (Fig. 1). The study area falls in the southwest monsoon climate zone in a typical low latitude plateau, the annual mean temperature is 15.3 °C and mean annual precipitation is 1048 mm. The monthly mean temperature and precipitation during the experimental period was shown in Fig. 2. The soil was collected from a farmer's paddy field at a depth of 0–20 cm near the experimental site and was passed through a 2 cm sieve for mixing. The soil in pots had an organic matter of 36.4 g kg^{-1}, a TN of 1.96 g kg^{-1}, total of phosphorus of 0.88 g kg^{-1}, total of potassium of 18.9 g kg^{-1}, Olsen-P of 22.1 mg kg^{-1}, pH of 6.33, Eh of 17.1 c mol kg^{-1}, and bulk density of 1.16 g cm^{-3}.

To understand the variations in the overall environmental impacts of fertilizer application among different crops, three field experiments were conducted: garlic (*Allium Sativum*), oilseed rape (*Brassica Napus*), and broad bean (*Vicia Faba*). All experiments were conducted in a randomized complete block design with three replicates. The size of each plot was 100 cm (length) × 30 cm (width) × 20 cm (height). The planting density was accordance with local conventional management in all experiments. In the garlic, oilseed rape and broad bean experiments, the plots received 423, 212, and 95.2 kg N ha^{-1}, respectively, and all were applied as the basal fertilizer (Table 1). The N, P_2O_5 and K_2O fertilizers applied were urea (46.4% N), superphosphate (18% P_2O_5) and potassium chloride (60% K_2O), respectively. Approximately 50% of urea was ^{15}N-labelled by 50% urea as the atomic percent.

2.2. Sample measurement and analysis

2.2.1. Plant and soil measurement and analysis

These crops including grain, straw and root in each plot were all fully harvested. Plant samples were dried at 70 °C to constant weight after being washed with distilled water and weighed to calculate the dry biomass of the aboveground and root. Soil samples were collected immediately after crop harvest and were air-dried to analyze TN content and ^{15}N abundance in soil.

Parts of dried plant samples and soil samples were air-dried and ground to pass through a 150-μ m screen for TN and ^{15}N analysis. Plant and soil samples were analyzed for TN content using an elemental analyzer (Costech ECS4010, Costech Analytical Technologies Inc., Valencia, CA, USA). ^{15}N abundance ratio analyses were performed using gas isotope ratio mass spectrometry (IRMS, Isoprime 100) system (Delta V plus; Thermo Scientific, Bremen, Germany).

2.2.2. N_2O emissions

The N_2O emissions were monitored with the static chambers-gas chromatography technique, as described by Zhou et al. (2017b). In the present study, gas samples were collected from the chamber in polyethylene-coated aluminum gas bags between 9:00 am and 11:00 am in regular intervals of 10 min (four gas samples per flux measurement: 0, 10, 20 and 30 min after closure), because the effluxes measured during this period were considered a representative of daily mean N_2O flux rate (Xu and Qi, 2001). N_2O fluxes were usually measured twice a week, and the sampling frequency increased with the surrounding fertilization and precipitation events but slowed in winter to once a week during the experimental period. The gas samples were immediately analyzed by gas chromatography (GC 2010, Japan). Detailed measurements and calculations about N_2O flux rates and total N_2O emission are described in Xiong et al. (2002). Cumulative N_2O fluxes were linearly interpolated. The ^{15}N ratios of N_2O in the gas samples were analyzed by using a GasBench + pre-concentration trace gas concentration system interfaced to a ThermoScientific Delta V Plus isotope-ratio mass spectrometer (Bremen, Germany).

2.2.3. NH_3 emissions and analysis

The ventilation method was performed to measure the NH_3 volatilization using a height-rigid PVC cylinder (25 cm in height and 11 cm in diameter) with a phosphoglycerol soaked sponge (2-cm thick and 12 cm in diameter) as an absorbent (Jantalia et al., 2012; Liu et al., 2015; Wang et al., 2004). The phosphoglycerol soaked sponges in the bottom were immersed in the 300 ml of 1.0 mol L^{-1} KCl solution in 500 ml containers and were shaken for 1 h to extract NH_4^+-N in the sponges.