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Sustaining crop productivity while reducing environmental nitrogen losses in the subtropical wheat-maize cropping systems: A comprehensive case study of nitrogen cycling and balance

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ABSTRACT

Balancing the nitrogen (N) budgets of agricultural systems is essential for sustaining yields at lower environmental costs. However, it is still rare to find reports on the total N budgets of agricultural systems including all N fluxes in the literature. Here, we conducted a comprehensive study on the effects of different N fertilizers (control, synthetic fertilizer, 60% synthetic fertilizer N plus 40% pig manure N, pig manure N applied at the same rate of 280 kg N ha^{-1} yr^{-1}) on N pools, cycling processes, fluxes and total N balances in a subtropical wheat-maize rotation system in China by monitoring in situ N fluxes combined with field ^{15}N-tracer and ^{15}N isotope-dilution techniques. The warm and wet maize season was associated with significantly larger N losses via gaseous and hydrological pathways than the cooler and drier wheat season. Nitrate leaching and NH_3 volatilization were the main N loss pathways, accounting for 78% and 93% of the annual hydrological and gaseous N losses, respectively. The field ^{15}N tracing experiment showed that the wheat system had a high N retention capacity (~50% of ^{15}N application), although the N residence time was short. In the subsequent maize season, 90% of the residual ^{15}N-labeled fertilizer in the soil that had been applied to the wheat system was utilized by plants or lost to the environment. The combined application of synthetic and organic fertilizers (pig manure) or application of pig manure resulted in significantly higher soil N retention and lower NO_3^- leaching, while yields remained unaffected. However, the application of manure resulted in larger NH_3 volatilization losses compared with the application of synthetic fertilizer alone. Thus, our study suggests that a combination of synthetic and organic N fertilizers is suitable for sustaining agricultural productivity while reducing environmental N losses by fostering interactions between the soil C and N cycles.

1. Introduction

Nitrogen (N) fertilization contributes to approximately 30–50% of crop yield increases worldwide (Erisman et al., 2008). However, N fertilizer application rates in agricultural systems often exceed plant N requirements (Galloway et al., 2008; Ju et al., 2009; Robertson and Vitousek, 2009), and the excessive use of N fertilizers has contributed to serious environmental issues such as the degradation of the qualities of water, soil and the atmosphere, increases in atmospheric nitrous oxide (N_2O) concentrations and biodiversity losses (Galloway et al., 2008; Sutton et al., 2011; Vitousek et al., 1997; Zhou et al., 2013). How to manage N fertilization with the dual purposes of increasing yields while reducing the environmental costs of agricultural production has become a major concern of the scientific community and agricultural and environmental policymakers worldwide (Ladha et al., 2005; Bodirsky et al., 2014; Foley et al., 2011; Tilman et al., 2011; Zhou and Butterbach-Bahl, 2014).

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Balancing the N budgets of an agricultural system is critical to the simultaneous achievement of gains in crop yield and environmental quality (Blesh and Drinkwater, 2013). Most available N balances have been simply calculated by deducting crop N uptake from N inputs without sufficient consideration of N losses (e.g., Richter and Roelcke, 2000). However, gaseous and hydrological N losses are often comparable, or even larger, than crop N uptake in most intensive agricultural systems (Ju et al., 2009). The lack of knowledge about total N budgets, including all N fluxes, is one constraint for diagnosing N-driven problems and designing their solutions (e.g., Vitousek et al., 2009); it also hampers the development of biogeochemical models (Haas et al., 2013). Thus, recent studies have been conducted to quantify N losses via different pathways for calculation of the N balances of various cropping systems (e.g., Ju et al., 2009). However, these studies did not simultaneously consider soil N transformations and their underlying mechanisms even though the turnover of soil N, especially mineralization and immobilization, is of vital importance to soil N availability and N loss and retention in most ecosystems (e.g., Murphy et al., 2003; Schlesinger, 2009).

Manure incorporation, which adds N together with organic carbon (C), has been hypothesized to reduce N loss and increase soil N retention through interaction of the C and N cycles (e.g., Zhou et al., 2014a); however, this hypothesis was mainly examined by meta-analysis studies (e.g., Gardner and Drinkwater, 2009). Thus, experimental studies to illustrate the effects of combined synthetic and organic fertilizer incorporation on N cycling, fluxes and balances in agricultural systems are useful for testing hypotheses and to determine the underlying mechanisms. Several previous studies investigated the effects of manure incorporation on N loss pathways and fluxes but led to inconsistent findings about the roles of the various N loss pathways and fluxes in agricultural systems (Bakhsh et al., 2005; Matsushima et al., 2009; Vallejo et al., 2006; Van Groenigen et al., 2004). Nevertheless, compared with the application of synthetic N fertilizer alone, manure incorporation favors the coupling of the C and N cycles (Blesh and Drinkwater, 2013) and tends to significantly reduce N loss and improve soil N retention (Aber et al., 1998; Drinkwater and Snapp, 2007; Zhou et al., 2014a). However, until now, how manure incorporation reduces N losses and improves N retention in intensive agricultural systems has remained unclear.

The ^{15}N isotope tracer technique has been widely applied for investigating N flows and fates in agricultural systems. However, most previous studies only quantified the ^{15}N recoveries in soil and plant N pools with few efforts made to monitor gaseous and hydrological ^{15}N losses (Gardner and Drinkwater, 2009; Sebilo et al., 2013; Wells et al., 2014). For example, the most recent *meta*-analysis of ^{15}N tracer studies in cereal cropping systems showed that only approximately 10% of the studies reported ^{15}N losses via gaseous and hydrological pathways (Gardner and Drinkwater, 2009). Due to the insufficient measurements of gaseous and hydrological ^{15}N losses, total ^{15}N mass balances could not be calculated, and the unrecovered ^{15}N-labeled fertilizer in soil and plant N pools was simply assumed to comprise gaseous and hydrological N losses (Gardner and Drinkwater, 2009; Ghaley et al., 2010; Hoekstra et al., 2010; Zhang et al., 2012). Therefore mechanistic uncertainties may exist in the quantification of ^{15}N mass balance in a given agricultural system because the unrecovered fractions of ^{15}N-labeled N fertilizer could also result from experimental errors (e.g., Gardner and Drinkwater, 2009).

Several studies have indicated that N-fertilizer application rates of 280–300 kg N ha^{-1} yr^{-1} are optimal for double-cropping systems to sustain yields while largely reducing N pollution compared with common N application rates (550–600 kg N ha^{-1} yr^{-1}) in Chinese double cropping systems (e.g., Zhu and Chen, 2002; Ju et al., 2009; Ju and Christie, 2011). Moreover, not only N fertilizer rates but also N fertilizer types can significantly affect crop yields and N losses (e.g., Zhou et al., 2014a; Zhou et al., 2015). However, the potential to further reduce N losses and sustain yields by combining organic and synthetic N fertilizers within recommended fertilization rates remains unknown.

Here, we conducted a comprehensive study on the fate of N and the complete N budgets of an intensively managed subtropical wheat-maize rotation system, which is representative of cereal production systems in China (Li et al., 2014). The aim of the study was to provide deeper insight into soil N transformation and N loss pathways to allow the identification of more efficient agricultural N management practices in intensive agricultural systems in China and worldwide. We used a combination of field monitoring and in situ ^{15}N isotope dilution and ^{15}N tracer techniques to investigate the fate of ^{15}N-labeled fertilizer in the plant-soil-water-air system, to quantify the different N loss pathways and fluxes and to calculate the complete N budgets. We hypothesized that partial substitution of synthetic N fertilizer with manure could stimulate microbial N retention and in turn reduce N losses and sustain crop yields by fostering interactions between the soil C and N cycles.

2. Materials and methods

2.1. Description of study site and experimental treatments

The field experiment was conducted at the Yanting Agro-Ecological Research Station of Purple Soil, a member station of the Chinese Ecosystem Research Network (CERN) of the Chinese Academy of Sciences, in southwest China (N 31°16′, E 105°28′). Briefly, annual average air temperature is 17.3 °C and annual precipitation is 826 mm; approximately 70% of annual precipitation occurs from May to September (values given are from the meteorological station at the research station during the period 1981–2009). During the experimental period, the monthly mean air temperature and precipitation were comparable to the corresponding long-term averages (Fig. 1). The experimental soil is a Eutric Regosol (FAO Soil Classification), known as 'purple soil' in China (Zhu et al., 2008, 2009). Further details about the site description and soil physicochemical properties can be found in Zhou et al. (2014a).

The field nitrogen flux monitoring and ^{15}N tracing studies were conducted in sloped large-scale, free-drainage lysimeter plots (slope: 11%; size: $8 \times 4\,m^2$) that had been constructed in 2001. These free-drainage lysimeters allowed the measurement of different N loss pathways and fluxes simultaneously and crop productivities (9Zhou et al., 2012). We included three different N fertilization treatments and one control with three replicates each in a randomized complete block design: (i) control (CK, no fertilizer); (ii) synthetic N fertilizer only (conventional treatment, NPK); (iii) pig manure only (OM); and (iv) synthetic N fertilizer (60% of applied N) plus pig manure (40% of applied N) (OMNPK). All fertilization treatments received an identical N application rate of 280 kg N ha^{-1} yr^{-1} (all applied as basal fertilization once per season: 130 kg N ha^{-1} for the wheat season and 150 kg N ha^{-1} for the maize season). The experimental N application rate followed the recommended N fertilizer application rate for sustaining crop yields and minimizing environmental costs in Chinese double cereal cropping systems (e.g., Zhu and Chen, 2002; Ju et al., 2009). All N fertilization treatments and the control received the same rates of calcium superphosphate (90 kg P_2O_5 ha^{-1} equivalent) and potassium chloride (36 kg K_2O ha^{-1} equivalent) as basal fertilization. Additional details about the fertilizer treatments and field management can be found in Zhou et al. (2014a).

2.2. Field ^{15}tracing experiment

To investigate the fate of N fertilizer in the plant-soil-water-air system, an *in situ* ^{15}N tracing experiment was conducted from