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Effects of wheat straw addition on dynamics and fate of nitrogen applied to paddy soils

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ABSTRACT

The effectiveness of plant residue addition to increase crop nitrogen (N) use efficiency while reducing N losses is dependent on whether residue management can improve the match between N immobilization-mineralization turnover and plant demand. To understand the effects of residue management on N cycle processes, we conducted a field study that included three treatments. These were a control without N fertilizer (CK), ^{15}N-labelled urea (UR), and ^{15}N-labelled urea + wheat straw (URS). Nitrogen immobilized in the top soil layer (0–20 cm) in the urea only treatment tended to decrease after the basal application and the second top dressing, but increased after the first top dressing, whereas the urea + straw treatment increased immobilization up to the second top dressing, before decreasing towards the end of the study. The addition of wheat straw led to a 24% reduction in ammonia loss after the basal application, corresponding well to lower soil extractable ammonium contents. The N uptake by the plant in the urea + straw treatment corresponded to 25% of applied N, which was higher than the 20% recorded in the urea only treatment. At harvest, 31% of the applied N was found in the 0–60 cm soil layer after the addition of wheat straw, whereas there was only 25% without straw addition. The results showed that 45% applied N was unaccounted for when wheat straw was added, compared to 55% unaccounted for without wheat straw. These indicate that the addition of wheat straw may increase plant N uptake by contributing to N immobilization early in the season, but then improving its subsequent mineralization later in the season.

1. Introduction

Large inputs of synthetic N fertilizer have contributed to a substantial increase in cereal production over the past half-century (Tilman et al., 2002). However, a significant proportion of the applied N is lost from cereal cropping systems due to low nitrogen use efficiency, which can be 33% or lower (Dobermann, 2007; Raun and Johnson, 1999). This N has caused serious environmental consequences, including acidification, eutrophication of surface waters, loss of biological diversity, greenhouse gas emissions, and formation of photochemical smog (Gu et al., 2015; Vitousek et al., 1997). In response to these problems, higher N fertilizer efficiencies will be needed to ensure that cereal production is sustainable (Zhang et al., 2015).

Nitrogen use efficiency by plants in rice cropping systems is generally low due to the high loss of applied N. The off-site transport of N is restricted by border levees surrounding rice fields, and percolation is negligible due to the occurrence of a plow pan (Cao et al., 2014). The main processes responsible for N loss in flooded paddy soils are ammonia volatilization and denitrification. Ammonia volatilization is regulated by the ammonium concentration and denitrification of the soil nitrate content (Feng et al., 2017; Yang et al., 2017). The key to controlling N losses from rice cropping systems is to reduce the inorganic N concentration in the floodwater and top soil. Microbial processes in arable soils are generally carbon limited (Attard et al., 2016). Returning plant residues to the soil leads to an increase in the abundance, activity, and growth of microorganisms, and consequently improves the immobilization of inorganic N by microbes (Kuzyakov and Xu, 2013). The microbial immobilization limits the accumulation of inorganic N in the soil, which could reduce the risk of N losses from rice cropping systems. Furthermore, microbes in paddy soils are only a temporary sink for applied N. Nitrogen immobilized in microbial biomass has a significantly lower half-life, and could be re-mineralized to

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inorganic forms, which makes them available to plants (Buresh et al., 2008; Kumar and Goh, 1999). Studies examining the effect of plant residue addition on N fertilizer efficiency have reported positive effects (Huang et al., 2013; Pan et al., 2009). However, some studies reported reduced N fertilizer efficiencies in plant residue retention, which has been attributed to increased N immobilization (Aulakh et al., 2001; Bird et al., 2001). The opposite effect indicates a high variation in N dynamics after the application of plant residues. Cereal plants have generally high growth rates and a maximum N demand at the vegetative growth stage (Chen et al., 2014). At this time point, a prompt release of N could contribute to increased N fertilizer efficiency, and vice versa. It appears that the effectiveness of plant residue addition at increasing N efficiency while reducing N losses is dependent on whether or not residue management matches N immobilization-mineralization turnover to plant demand.

Many studies have examined the immobilization-mineralization turnover of applied N after plant residues were added to rice cropping systems. However, most works have been laboratory incubation experiments and there is little information available about the effects of residue addition on N transformation in the presence of plants (Bird et al., 2001). The results from incubation experiment do not necessarily represent actual N processes because they fail to simulate plant uptake. Inorganic N accumulates over the incubation period and may lead to net N mineralization (Mooshammer et al., 2014). In the presence of plants, this N could have been taken up by the plant or lost from the soil-plant system (Ju et al., 2009), which would contribute to increased N immobilization (Mooshammer et al., 2014). Furthermore, the immobilization-mineralization turnover needs to be integrated with the fate of N. An investigation into the effects of plant residue addition on N transformation only characterizes N supply. The challenge is to investigate how plant residue addition affects N availability for plant uptake. Therefore, we conducted a rice-season field experiment and applied ^{15}N-labelled urea with or without the addition of wheat straw. By tracing the temporal changes in ^{15}N-labelled N immobilized in the top soil (0–20 cm) and the N flow from ^{15}N-labelled urea to the plant, soil, and environment at harvest using ^{15}N tracing technology, we have attempted to provide insights into plant N uptake response to altered N dynamics following the addition of plant residues.

2. Materials and methods

2.1. Experimental station summary

The field experiment was conducted at the Shanghai City Zhuanghang Experimental Station in the Yangtze River delta. The site has a subtropical climate with an average annual temperature of 15.8 °C and rainfall of 1 178 mm. The soils at the site are classified as Anthrosols (Shi et al., 2002), which are paddy soils derived from fluvial deposits. In the 0–20 cm soil layer, the pH (H_2O) was 7.6, soil organic matter content was 23.7 g kg^{-1}, total N content was 1.4 g N kg^{-1}, total phosphorus content was 0.2 g P kg^{-1}, total potassium content was 66.0 mg K kg^{-1}, and cation exchange capacity was 17.5 cmol kg^{-1}.

A summer rice (*Oryza sativa* L.) and winter wheat (*Triticum aestivum* L.) has been rotated in the experimental fields, and there is a low permeability layer at about 20 cm depth.

2.2. Experimental design and agricultural management practices

The experiment was a completely randomized design with three treatments and three replications. The three treatments were no N fertilizer (CK), ^{15}N-labelled (10.15% ^{15}N atom %) urea (UR) at 225 kg N ha^{-1}, and ^{15}N-labelled urea at 225 kg N ha^{-1} + wheat straw (URS). The wheat straw had a C/N ratio of 144 (carbon and N content mean 44.5% and 0.3%, respectively), and was applied at a rate of 3000 kg dry matter per ha. Three micro-plots were established within each treatment. The micro-plot was established by inserting a plastic pipe (both internal diameter and height were 0.5 m) into the soil to a depth of 0.35 m before the experiment. The rice seedlings were transplanted at a density of four hills plot^{-1} and at three seedlings per hill on June 29, 2015, and harvested on October 27, 2015. Superphosphate (P_2O_5 12%) and potassium chloride (K_2O 60%) were applied to the entire study area to supply 112.5 kg P_2O_5 ha^{-1} and 255 kg K_2O ha^{-1}, respectively. The 225 kg N ha^{-1} as urea was applied in three applications. These were 50% as a basal application, 30% as the first top dressing, and the remaining 20% as the second top dressing. Wheat straw and phosphorus fertilizer were applied at the same time as the basal application. The potassium fertilizer was applied in two applications, with 44% basally applied and the rest applied at the second top dressing stage. Basal fertilizers were incorporated into the top soil just prior to transplanting the rice seedlings, and the first and second top-dressings were homogeneously broadcast onto the floodwater by hand on July 7 and August 11, 2015, respectively. Pesticide, fungicide and herbicide were uniformly applied to the whole experimental area. Each micro-plot was regularly irrigated to maintain a 5 ± 3 cm height of floodwater until 1 week before rice harvest, but no irrigation was conducted to stimulate plant roots growth at the later tillering stage (lasting 1 week, referred as to mid-season aeration).

2.3. Ammonia volatilization measurement

A dynamic chamber method, as previously described by Cao and Yin (2015), was used to measure ammonia volatilization flux. A gas chamber was established within each micro-plot area and its working gas volume was adjusted by changing the insertion depth to maintain the airflow rate at about 15 L min^{-1} (Hayashi et al., 2006). The gas mixture inside the chamber was pumped to a chemical trap containing 60 mL of 0.1 mol L^{-1} dilute sulfuric acid (H_2SO_4) solution, which collected the gaseous ammonia. The concentration of ammonium in the solution was then analyzed colorimetrically using a continuous flow analyzer (AA3 SEAL, SEAL Analytical-Shanghai, China). Ammonia volatilization was measured twice a day. The sampling time was from 10:00 to 11:00 and from 15:00 to 16:00. The sampling lasted for 5–10 days following each fertilization, which was dependent on the rate and timing of fertilization. The ammonia volatilization flux was estimated according to the equation published by Hayashi et al. (2006). Nitrogen loss through ammonia volatilization over the study period was calculated by summing the ammonia fluxes on the sampling days. Ammonia volatilization after the first top dressing was not recorded due to an equipment malfunction.

2.4. Collection and analysis of soil and plant samples

The 0–20 cm soil layer was sampled using a stainless steel auger (15 mm interior diameter), which was used to take a sample from each micro-plot. Sampling was conducted at six time points. These were at day 1 after each N application, before both topdressings, and at harvest. Soil samples from the 20–60 cm soil layer were also collected at harvest for N fate analysis. The roots and other detritus were removed from the soil samples. The soil subsamples from the 0–20 cm soil layer were shaken for 1 h with 100 ml of 0.5 mol L^{-1} potassium sulfate (K_2SO_4) solution, and then vacuum filtered. The ammonium and nitrate concentrations in the filtrate were determined using a continuous flow analyzer (AA3 SEAL, SEAL Analytical-Shanghai, China). The residual soil was removed from the filter membrane, oven-dried to constant weight at 80 °C, and ground to pass a 284 μm sieve for total N and ^{15}N analysis. Total N content and the ^{15}N stable isotope value (δ^{15}N) of the soil samples after potassium sulfate extraction and at harvest were determined using an elemental analyzer coupled with a stable isotope ratio mass spectrometer (Vario EL III/Isoprime, Elementar Analysen Syteme GmbH Hanau, Germany). At harvest, the bulk density of the soils was measured using the core method. The amount of immobilized N was calculated according to Dong et al. (2012) from the total N