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Soil nitrogen retention is increased by ditch-buried straw return in a rice-wheat rotation system

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ABSTRACT

Ditch-buried straw return (DBSR) is a novel farming system that not only efficiently eliminates the need to burn straw, but also shows positive effects on soil carbon sequestration and crop yields. Implementation of DBSR, however, may penetrate the tillage pan, increasing the risk of N leaching losses. We therefore determined whether N retention could be increased by DBSR in order to reduce the risk of N loss to the environment. A four-year field experiment and a complementary greenhouse experiment were conducted to test the effects of DBSR on N retention in a rice-wheat rotation system. We found that DBSR altered the spatial distribution of fertilizer N. N content was significantly increased above but reduced below the straw layer in the field experiment. The greenhouse experiment further confirmed the N retention effects by the straw layer. In theory, a maximum of 9.09 mg urea-N could be adsorbed by one gram dry wheat straw. Our results suggest that DBSR has the potential to increase N retention in the soil, thus increasing crop uptake and minimizing leaching N loss in the rice-wheat rotation system.

1. Introduction

As the population of the world continues to increase, food security has become an increasingly important concern, particularly in light of the limitations imposed on agriculture by drought and infertility, and the negative consequences of agriculture including nutrient pollution (Tilman et al., 2002; Brown and Funk, 2008; Tilman et al., 2011). Improvement in grain production is an important component for ensuring global food security (Hu et al., 2013). In the past decades, crop production, especially for rice and wheat, has increased because of breeding, mechanization of soil tillage, increased use of irrigation, pesticides and, especially, synthetic N fertilizers (Mader et al., 2002). However, high N fertilizer inputs coupled with low N use efficiency cause most of the N lost to the environment, an important source of agricultural non-point pollution (Csatho et al., 2007; Miao et al., 2011).

Leaching is one of the main avenues by which N is lost from agroecosystems (Hu et al., 2004). N leaching accounts for about 10% of the total N loss in agricultural soils, which may cause severe groundwater contamination (Ju and Zhang, 2003). Studies show that N loss via leaching may be 16 kg N ha^{-1} in European agricultural soils and 29–48 kg N ha^{-1} in North American agricultural regions (Jaynes et al., 2001; Velthof et al., 2009). In China, annual N losses via leaching are 31.8 kg ha^{-1} in the northern rainfed agricultural regions (Sun et al., 1993) and 6.8–27 kg ha^{-1} in the southern rice paddy fields (Xing and Zhu, 2000). In the Taihu Lake region, 10–34 kg N ha^{-1} is lost via leaching (Zhu and Chen, 2002). Thus, knowing how to effectively manage N inputs has become an important concern in crop production (Mae, 2011).

Incorporating straw into the soil may be an effective organic agricultural practice (Seufert et al., 2012). Improvement in soil ecological processes are often reported after straw incorporation, including enhancement in soil carbon storage, nutrient availability and microbial activity (Pan et al., 2013; Chen et al., 2014) and, possibly, a reduction in N loss via leaching. For example, straw incorporation significantly reduced inorganic N leaching losses in a

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rice-wheat rotation system (Zhang et al., 2008) and in a rice paddy system (Wang et al., 2010). However, reduction of N leaching loss by straw incorporation may depend on N species, and more NH_4^+-N might be retained than NH_3^--N (Geng et al., 2007). Although straw incorporation may reduce N leaching, it may also increase denitrification (Gollany et al., 2004), leading to enhanced N_2O emissions. And the effects of straw on leaching may depend on straw quality, straw having a greater C:N ratio possibly having a larger N retention capability (Gentile et al., 2009).

Rice-wheat rotation is the dominant farming system in the Yangtz River Delta region of China (Yang et al., 2008). This agricultural region is one of the main grain production regions, accounting for 20% of the total land area and 22% of the total yields of rice and wheat in China (Zhu et al., 2014). This double cropping system is characteristic of high productivity (grain and straw), albeit with high N input (Yang et al., 2015). Unfortunately, the N use efficiency is only 20–40% in this system (Wang et al., 2004) and much of the added N is lost to the environment, comprising a potentially important source of non-point pollution in the Taihu Lake basin (Qiao et al., 2012). Rice-wheat rotation systems also produce large amounts of straw residue, about 4500 kg ha^{-1} of wheat straw and 9000 kg ha^{-1} of rice straw annually (Wang et al., 2015). Effectively managing this straw is difficult for local farmers in the two weeks between the crops. Traditionally, straw was directly burnt in the open field to save time. But burning causes severe air pollution and soil degradation and thus is forbidden by law in China (Zhang et al., 2014).

Straw incorporation into soil is advocated by some. However, existing straw incorporation methods cannot utilize all the straw produced, especially the rice straw in the rice-wheat agroecosystems (Chang et al., 2014). Conventional straw incorporation with rotary tillage concentrates the fragmented straw in the plough horizon and may inhibit seedling emergence and establishment, cause N competition between soil microbes and seedlings, and negatively affect tillage (Zha et al., 2013; Zhang, 2014).

In order to overcome these problems, our group developed a novel farming system called ditch-buried straw return (DBSR), combined with deep ploughing (Zhu and Bian, 2010). DBSR includes the following procedures: straw is buried in the soil via deep ploughing after each crop season, the area of the straw burial accounting for 10% of the total field each year. The remaining 90% of the field is shallow-rotary tilled (3–5 cm depth). The position of burial is alternated after each crop season (Wang et al., 2015) such that after five rice-wheat rotations a straw layer under the plough horizon occurs across the entire field. Because of undergoing different durations of decomposition, the straw layer exhibits variation in thickness across the field (Wang et al., 2015). Our previous greenhouse study suggested that DBSR could reduce N loss via leaching with the appropriate amount of the straw at the appropriate depth (Yang et al., 2015). In this study, we conducted a four-year field experiment and a complementary greenhouse trial to test whether DBSR could increase N retention and thus reduce N leaching loss in the soils of rice-wheat rotation systems.

2. Materials and methods

2.1. Experiment 1

A field experiment was conducted at the experimental site of the Academy of Agricultural Sciences of Yanjiang District (32°13′N, 120°63′W). The farming system is a winter wheat (*Triticum aestivum* L.) – summer rice (*Oryza sativa* L.) rotation. Mid-subtropical monsoon climate dominates this agricultural region, with an average annual temperature of 14.4 °C, average annual sunshine of 2078 h and mean annual precipitation of 1057 mm. The soil is a typical sandy loamy containing 20.5 g/kg organic matter, 1.62 g/kg total N, 12.75 mg/kg available P and 44.41 mg/kg available K in the 0–20 cm soil layer.

Experiment 1 had a randomized block design with four treatments: control (no straw), half straw (0.25 kg/m^2 wheat straw or 0.5 kg/m^2 rice straw), single straw (0.5 kg/m^2 wheat straw or 1.0 kg/m^2 rice straw) and double straw (1.0 kg/m^2 wheat straw or 2.0 kg/m^2 rice straw). Each block was replicated three times. In all there were 12 experimental plots. Each plot was 18 m^2 (3 m × 6 m). After crop harvesting, three ditches (with a width of 20 cm and depth of 20 cm) were hand-dug for straw burial. Ditches were 2 m apart from each other and alternated in position after each crop season. In the control plots, three ditches with the same width and depth were hand-dug, but then buried without straws. The experiment was initiated after rice harvest in November 2008. The control treatment was conventional tillage without straw burial. The DBSR treatment was implemented in the following way: after crop harvest, straw was sun-dried for three days, and then bundled. Then, ditches of 20 cm width and 20 cm depth were hand-dug at specific locations in the plots. The bundled straw was then arranged, evenly laid into the ditches, repressed and then covered with the soils and overburdened.

The crops included winter wheat (var. Yangmai 13) and summer rice (var. Nanjing 44) rotation. Yangmai 13 is grown in early spring and is a weak gluten variety. Nanjing 44 is an early maturating late Japonica variety. Winter wheat is generally sown in mid-November and manually broadcast with a seed density of 150 kg ha^{-1} before a shallow rotary tillage. Rice seedlings are usually transplanted in the mid-June with 15 cm × 25 cm between hills and rows.

Compound fertilizer (N: P_2O_5: K_2O = 15: 15: 15) and urea ($CO(NH_2)_2$) were added for both crop seasons. In the rice seasons, compound fertilizer was utilized as the initial fertilizer at 750 kg ha^{-1}. Urea was added as 242 kg ha^{-1} in the initial phase and as 121 kg ha^{-1} in the tillering and grain-filling phases, respectively. In the wheat seasons, compound fertilizer was utilized as the initial fertilizer at the rate of 1167 kg ha^{-1}. Urea was added as 204 kg ha^{-1} in the initial phase and 102 kg ha^{-1} in the tillering and grain-filling phases, respectively.

Soil samples were collected on 25 November 2012 after the rice harvest. At this time, there had been four rice-wheat rotations. At the time of collection, the rice straw buried in November 2008 had been decomposing for 4 years, while that buried in November 2009–2011 had been decomposing for 3, 2 and 1 year, respectively. The wheat straw buried in June 2009 had been decaying for 3.5 years, while that buried in June 2010–2012 had been decomposing for 2.5, 1.5 and 0.5 years, respectively. We had precisely marked the position of each straw burial locations from different years in each experimental plot. Three soil cores were randomly collected along each location. Because there were three ditches in each plot for each crop season, a total of 9 soil cores were collected for individual decomposing times in each plot and then mixed thoroughly, put into zipped plastic bags and transported to the laboratory immediately for further analysis. For each DBSR treatment, we only collected soil samples from the 10 cm-thick soil layer just above and below straw layers using a soil auger (10–20 cm and 20–30 cm deep in the soil). For the control treatment, we also collected the soil samples from 10 to 20 cm and 20–30 cm deep in the soil. Soil samples were air-dried and passed through 100-mesh (0.149 mm) sieves for subsequent determination of total nitrogen (TN) content. TN was measured with a semi-automatic Kjeldahl Azotometer.

Data for TN were subjected to one-way ANOVAs using SPSS 16.00 (SPSS Inc., USA). Before analysis, data were log10-transformed to meet the assumptions of normality and homogeneity of variance. When ANOVAs were significant, means were compared by Duncan's multiple range tests at the 0.05 confidence level.