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Nitrogen and phosphorus leaching losses from intensively managed paddy fields with straw retention

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ABSTRACT

A field experiment was carried out for three years to examine the concentrations of NH_4^+-N, NO_3^--N and dissolved total phosphorus (TP) in leachates and cumulative leaching losses in rice fields with straw retention under different rates of fertilizer N application. With straw retention, the percolation rate had a significant ($p < 0.05$) negative exponential relationship with the day after rice transplanting, accounting for an average 2.57 mm d^{-1}. NH_4^+-N and NO_3^--N concentration in percolation increased with increasing of N fertilizer application rate. Compared to the control (without straw or fertilizer), the wheat straw incorporation with nil N fertilizer decreased the concentration of NH_4^+-N and NO_3^--N but promoted TP concentration. Cumulative inorganic N (NH_4^+-N + NO_3^--N) and P losses were about 14.4 and 0.53 kg ha^{-1}, accounting for 5.6% and 3.5% of N and P fertilizer applied. NH_4^+-N leaching losses accounted for 62–97% of the total leaching of inorganic N. Nitrogen leaching losses occurred mainly at the basal fertilizer application stage, accounting for 76.8% of total N leaching. Straw retention reduced the N leaching losses because the straw can enhance microbial N immobilization due to its high C:N ratio. However, the mechanism of straw incorporation impacts on N and P leaching requires more detailed study.

1. Introduction

Nitrogen (N) and phosphorus (P) are essential nutrients for plant growth and application of N and P is a key factor in the maintenance of high crop yields in intensively managed agricultural systems (Zhu and Chen, 2002; Guo et al., 2004; Vitousek et al., 2010). Conventional organic materials (straw and manure) were the main sources of N and P in Chinese traditional agriculture before the 1950s (Vitousek et al., 2009; Ju et al., 2009). Since the introduction of chemical fertilizers conventional organic fertilizers have gradually been replaced by chemical fertilizers and this trend is set to continue to meet the increasing demand for food (Zhu and Chen, 2002; Ju et al., 2009). By 2011 the total consumption of chemical N and P fertilizers in China was about 36.9 and 12.8 million tonnes (Mt), accounting for 35.1 and 33.8% of the global agricultural consumption of N and P, respectively (National Bureau of Statistics of China, 2011). Average N use efficiency is relatively low in irrigated rice cropping (Zhu and Chen, 2002; Xu et al., 2012) and excessive N is lost rapidly through ammonia volatilization, de-nitrification, surface runoff, and leaching (Galloway et al., 2008; Conley et al., 2009; Wang et al., 2012). However, P is relatively immobile in soils and runoff and leaching are the main routes of excessive P loss (Lu, 2003).

Leaching losses are the major pathway of N and P loss from paddy fields (Choudhury and Kennedy, 2005; Shan et al., 2005) and occur as a continuous series of short-term events which are affected by several factors such as soil properties, irrigation, rainfall, catch crops, residues, manure and nutrient type (Song et al., 2005; Aparicio et al., 2008; Constantin et al., 2010; Hansen et al., 2010; Xiong et al., 2010; Tan et al., 2013; Kopácek et al., 2013). Nonetheless, the key factors regulating N losses are hydrological processes at the short temporal scale and biogeochemical processes in the longer term. Leaching losses can occur any time when the hydrological conditions permit (Tian et al., 2012; Kopácek et al., 2013), and when accumulation of N and P exceeds the critical values leaching losses from the soil will accelerated with additional fertilizers applications (Haygarth and Jarvis, 1999; Conley et al., 2009; Vitousek et al., 2010; Feyereisen et al., 2010; Kopácek et al., 2013). The mitigation of the negative environmental influences of N and P leaching might threaten the safety of surface and

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groundwater quality (Ju et al., 2009; Conley et al., 2009; Vitousek et al., 2009; Zhao et al., 2009; Xu et al., 2012) and this has become an important issue for the development of sustainable agriculture (Galloway et al., 2008).

Taihu Lake region is one of the three major food production areas in east China and is faced with very serious eutrophication resulting from intensive agricultural systems (Reidsma et al., 2012). Annual fertilizer N and P application rates to paddy fields have increased greatly over the past two decades and currently range from 300 to 350 kg N and 15 to 60 kg P ha^{-1} (Wang et al., 2012; Zhao et al., 2012), much higher than the optimal rates of N (185–270 kg N ha^{-1}) and P (about 10–45 kg P ha^{-1}) in this region (Lu, 2003; Wang et al., 2004; Ju et al., 2009; Xu et al., 2012), Leaching of excessive N and P has contributed to the eutrophication of Taihu Lake (Zhao et al., 2012; Reidsma et al., 2012). Several studies have shown effects of N and P leaching on water bodies in the Taihu Lake region (Wang et al., 2004; Shan et al., 2005; Ju et al., 2009). Tian et al. (2007) reported that more than 20% of wells surveyed were found to contain water with >10 mg NO_3^--N L^{-1}. About 48% of N and 38% of P inputs to water bodies are from agricultural land (Guo et al., 2004). Controlling the N and P inputs to aquatic ecosystems from agriculture is key to protecting drinking water supplies and to reducing eutrophication (Choudhury and Kennedy, 2005; Conley et al., 2009; Reidsma et al., 2012).

In Taihu Lake region the return of cereal straw (rice and wheat) with large amounts of N and P fertilizers is a widespread practice in agricultural field management to increase productivity (Wang et al., 2012). Continuous fertilization and straw incorporation can result in changes in field conditions including soil organic matter content, soil pH, and some soil biological properties (Hansen et al., 2010) and these may in turn affect N and P leaching (Song et al., 2005; Hansen et al., 2010). Previous studies have illustrated the leaching characteristics of paddy fields without straw retention in this region and have evaluated N and P leaching losses using the water balance method (Shan et al., 2005; Tian et al., 2007; Zhao et al., 2012). The percolation volume have been estimated by water balance methods usually using parameters such as soil conductivity coefficients, soil evaporation, crop transpiration, irrigation and precipitation (Wang et al., 2004; Shan et al., 2005; Lu et al., 2006; Tian et al., 2007). The method has introduced some uncertainty in the estimation process with low accuracy. Additionally, most previous studies were based on short-term annual observations or microplots or monolith lysimeters studies on N or P leaching which were limited in time and space (Shan et al., 2005; Guo et al., 2004; Zhao et al., 2012). However, there were no continuous field studies on the leaching characteristics and leaching losses of N and P in paddy fields with straw retention. We therefore established a field study on a rice paddy soil for three consecutive years. The objectives of the present study were to assess accurately the percolation rate and quantify N and P leaching rates using soil seepage instrument in situ and to clarify the effects of different fertilizer N rates together with incorporation of straw into the soil on N and P leaching rates and to estimate a suitable N application rate with retention of all harvested straw.

2. Materials and methods

2.1. Experimental site

The field experiment began in June 2007 with the transplanting of the rice seedlings. The field leaching experiment was conducted over three consecutive rice seasons (June 2008–October 2010) on a typical plot of agricultural land at Changshu Agro-Ecological Experimental Station (31°32′45″ N, 120°41′57″ E), Chinese Academy of Sciences. The site has an oceanic subtropical humid monsoon climate at an altitude of 3.2 m above sea level and has 224 frost-free days each year with rainfall occurring in the spring and summer. The groundwater depth was about 80 cm. Mean annual rainfall and temperatures were about 1200 mm and 16.9 °C, respectively, during the experiment. The soil is a gleyic paddy soil (Gleyic Anthrosols, WRB) with clay loam texture (clay 385, silt 513, and sand 102 g kg^{-1}) and a bulk density of 1.23 g cm^{-3}. Selected initial properties in the top 15 cm of the soil profile were: pH(H_2O) 7.4, organic matter (OM) 30.8 g kg^{-1}, total N 1.79 g kg^{-1}, total P 0.93 g kg^{-1}, alkali extractable-N 123 mg kg^{-1}, Olsen-P 13.1 mg kg^{-1} and rapidly-available potassium (K) 121 mg kg^{-1}. The paddy field was used solely for a rice–wheat rotation before the study commenced.

2.2. Experimental design and treatments

The experiment had two straw treatments, CK (control treatment without straw or chemical fertilizers) and straw retention with five different N treatments, i.e., SN0, SN1, SN2, SN3 and SN4 (receiving 0, 120, 180, 240, and 300 kg N ha^{-1} and 6.5 t ha^{-1} of wheat straw, respectively). A randomized complete block design with all six treatments and three replicates were established to give a total of 18 plots each about 30 m^2 (5 m × 6 m). Adjacent plots were separated by a 30 cm soil ridge with plastic film buried to a depth of 25 cm to keep them hydrologically isolated. A standing water depth of 3–5 cm was maintained in each plot after transplanting except at the late tillering and maturity growth stages. Urea (46% N), superphosphate (6% P) and potassium chloride (54% K) were applied to supply N, P and K, respectively. Urea was divided into three applications with 40% as a basal application (BF), 20% broadcast at tillering (TF) and 40% broadcast at panicle formation (PF). Phosphorus and K were applied as basal fertilizers at rates of 15 kg P ha^{-1} and 90 kg K ha^{-1} in all treatments except the control. BF was incorporated into the topsoil using a rotary cultivator and TF and PF were surface broadcast by hand.

2.3. Straw return and percolate volume

Wheat straw was chopped into pieces about 5 cm long and incorporated in the top 15 cm of the soil with a two-wheel walking tractor one week before rice transplanting. Each plot received about 19.5 kg wheat straw. Organic carbon and total N contents of the straw were 441 and 4.0 g kg^{-1}, respectively.

The percolation rate was monitored using a paddy field percolation metre which was a modification of the metre designed by the International Rice Research Institute (1987). A schematic view of the metre is illustrated in Fig. 1. The primary measurement of percolation was done on the second day after rice transplanting and was then repeated at weekly intervals, with five locations measured within each plot. The percolation rates in 2008 and 2010 were the actual measured values and the results showed no significant difference ($p < 0.05$) between the two years by analysis of variance procedures. Therefore the percolation rate of 2009 was calculated by the mean values of 2008 and 2010 as estimates.

2.4. Sampling and analytical procedures

The percolation sampling device consisted of a porous suction cup and a polyvinyl chloride (PVC) pipe and was buried in 2007 before the rice was transplanted. The set-up of the device and sampling method followed Zhu et al. (2000) and Peng et al. (2011). In brief, the suction cup was connected to the PVC pipe and inserted vertically 60 cm into the soil profile with three replicates per plot. The suction cup was surrounded with fine quartz sand and the PVC pipe was surrounded by dried clay soil to prevent water flowing directly from the upper soil layers down to the suction cup. All PVC