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Effect of infiltration rate on nitrogen dynamics in paddy soil after high-load nitrogen application containing ^{15}N tracer

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ABSTRACT

Flooded paddy fields perform many ecological and conservation functions and are also reported to facilitate livestock waste disposal. Paddy field infiltration rates are important for nitrogen dynamics. A laboratory study was conducted to compare the effects of infiltration rate on nitrogen dynamics including nitrogen leaching, soil adsorption, microorganism assimilation, plant uptake and denitrification. Two infiltration rates were applied to paddy soil: 18.6 ± 10.3 mm d^{-1} (High Infiltration Columns: HIC) and 4.49 ± 3.15 mm d^{-1} (Low Infiltration Columns: LIC). Total nitrogen load was 484 kg-N ha^{-1}, with the ammonium ion form including basal fertilizer and a double supplemental fertilizer application. A $(^{15}NH_4)_2SO_4$ tracer was applied in each infiltration rate as supplemental fertilizer.

Nitrification and denitrification, plant uptake, soil adsorption, and leaching differed between infiltration rates. Compared with high nitrate concentration in HIC soil water, little nitrate appeared in the LIC, and it maintained relatively higher soil water ammonium concentrations long after application. The ^{15}N assimilated by rice and contained in the LIC soil was higher than in the HIC, suggesting that low infiltration is beneficial to nitrogen assimilation, adsorption and fixation. Although loss of nitrogen via leaching was higher in the HIC than the LIC, it accounted for only 3.94% of total ^{15}N input. About 69.4% of total ^{15}N input was unaccounted for in the HIC, whereas 38.3% of total ^{15}N input was unaccounted for in the LIC. According to the denitrification rate calculated from changes in $^{29}N_2/^{28}N_2$ and $^{30}N_2/^{28}N_2$ ratios, the denitrification rate after HIC application was higher than the LIC, reaching a maximum rate of 2.9 g m^{-2} d^{-1}. This suggests that high infiltration rate enhances nitrification and denitrification, with most of the unaccounted inputted ^{15}N in the HIC was probably lost through nitrification and denitrification.

1. Introduction

Rice is an important cereal crop in 111 countries (Ghosh and Bhat, 1998), which include 0.15 billion ha of paddy field globally (Tabuchi, 1999). Flooded paddy field performs many ecological and environmental conservation functions, as well as rice production. A flooded paddy field can also be considered an artificial wetland since it is flooded periodically with water, and is included as a human-made wetland in the Ramsar Classification System for Wetland Type (Ramsar COP10, 2008). Since the paddy field is efficient in nitrogen removal (Yang et al., 2001; Iamchaturapatr et al., 2007; Zhou et al., 2009a), it has been used for nutrient-rich waste disposal (Shen and Wu, 1998; Zhou et al., 2009b) and river water purification (Takeda and Fukushima, 2006; Zhou and Hosomi, 2008).

A typical paddy soil profile consists of a saturated muddy upper layer with low density and high permeability, which grades into a relatively impermeable layer (hard pan). Paddy field infiltration rates are affected by a variety of soil factors including soil texture and structure, bulk density, floodwater depth, depth to the water table, hard pan hydraulic conductivity, and puddling intensity (Wickham and Singh, 1978; Bouman et al., 1994; Kukal and Aggarwal, 2002).

Paddy field infiltration rates have been reported as being slightly more variable than other agricultural land uses due to soil puddling before rice transplanting. Infiltration rates have ranged from 10 mm d^{-1} to 15 mm d^{-1} in Japan (Tabuchi, 1999), 2–4 mm d^{-1} in the Philippines (Yoshida, 1981), and at 1 mm d^{-1} in Malaysia (Sugimoto, 1971). The higher the intensity of paddy field puddling, the lower the infiltration rate due to puddling eliminating

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large soil pores (Aggarwal et al., 1995; Kukal and Aggarwal, 2002). The hard pan has also been shown to be the key layer controlling infiltration in a flooded paddy field (Chen and Liu, 2002). Infiltration rate influences the redox potential of paddy soils, which may further influence nitrogen dynamics, including leaching, soil adsorption and fixation, rice uptake and removal by microbial activities. Although much research has evaluated the effect of infiltration rate on water balances and water use efficiency (Bouman et al., 1994; Liu et al., 2004; Ting et al., 2005), a paucity of information is available on the effect of paddy field infiltration rate on nitrogen dynamics. Although nitrogen dynamics have been investigated in a vertical flow wetland at different infiltration rates, most of this research was conducted with continuous or intermittent flow at infiltration rates >50 mm d^{-1} (Stepanauskas et al., 1996; Brix and Arias, 2005). These results are not applicable to the aforementioned low infiltration rate paddy field system with high nutrient load applications.

Production of livestock residue in 2000 in Japan was estimated to be 90.5 Mt (Fujino et al., 2005). Using livestock residues for biomass production disposes of livestock waste, and supplements the use of chemical fertilizers. After solid–liquid cattle waste separation, the liquid phase is aerated and applied generally to paddy field for rice production (Zhou et al., 2009b). However, in common rice cultivation, the nitrogen fertilizer load is limited to ~100 kg ha^{-1} to prevent rice lodging before harvest. Approximately 750,000 t of nitrogen is discharged from livestock residues in Japan every year. This is a high-load, even when livestock waste is spread throughout all arable land in Japan. Therefore, it is necessary to evaluate nitrogen dynamics under high-load application of livestock waste. In addition, paddy field infiltration rates vary widely under natural conditions (Tabuchi, 1999), leading to continuous flooding at low infiltration rate or alternating flooded and drained paddies at high infiltration rates. Flooding status affects oxygen transfer into the soil and nitrogen biogeochemical processes, including nitrification and denitrification (Tanner et al., 1999; Hernandez and Mitsch, 2007), and soil redox potential (Minamikawa and Sakai, 2006). In this study, we evaluated the effect of different infiltration rates on paddy soil nitrogen dynamics after two high-load nitrogen applications.

2. Materials and methods

2.1. Experimental design

Laboratory columns were constructed and installed with pebbles, paddy soil, rice, Eh sensors, and soil water samplers as shown in Fig. 1. The columns were made from acrylic pipe (50 cm high, 22.6 cm diameter). The bottom 5 cm of each column was packed with 0.5 cm diameter pebbles, and then 30 cm of paddy soil layer was added. The soil was collected from a paddy field at Saitama Prefecture, Japan. The soil was mixed thoroughly in the laboratory before filling the columns. Particle size distribution was 25.6% sand, 46.8% silt, and 27.6% clay, and organic matter content was 25 g kg^{-1}. Two infiltration rates (High Infiltration Column: HIC; Low Infiltration Column: LIC), each with three replicate columns, were constructed through altering paddy soil bulk density and controlling effluent flow with a faucet at the outlet. The average infiltration rate of HIC was 18.6 ± 10.3 mm d^{-1}, which was significantly higher ($p < 0.05$) than that of LIC (4.49 ± 3.15 mm d^{-1}).

Columns were irrigated to a depth of 5 cm once every 4 d. This resulted in continuously flooded conditions for the LIC, but the HIC drained after 2 d. After the first application, columns were not irrigated for 1 week (26th September–2nd October 2008) to simulate the "mid-summer drainage" conducted in real paddies. Three young shoots of a new variety of forage rice (*Oryza sativa* L. cv. Hamasari), which tolerates high nitrogen loads, were planted in each column on 20 July, 2008. Before transplanting, basal fertilizer was applied at a rate of 84 kg-N ha^{-1}. Synthesized liquid waste (NH_4^+-N: 2000 mg L^{-1}, PO_4^--P: 120 mg L^{-1}, TOC: 2500 mg L^{-1}) was applied twice as a supplemental fertilizer (2× 200 kg-N ha^{-1}) on 19 September and 18 October, 2008. The total nitrogen load was 484 kg-N ha^{-1}, which is approximately five times higher than that found in general rice cultivation. Synthesized liquid waste containing $(^{15}NH_4)_2SO_4$ (60% atom) tracer was applied to one column of each infiltration rate. Floodwater in all columns was drained on 15 November and rice harvested on 26 November, 2008. The column operation sequence is also shown in Fig. 1.

2.2. Analysis of water, soil, and rice

Redox potentials of paddy soil were measured at 1 cm, 5 cm, and 10 cm depth, as shown in Fig. 1. To investigate nitrogen transformations in the rhizosphere, soil water samplers with porous cups (DIK-8390, Daiki Rika, Saitama, Japan) were inserted into the soil at 5 cm depth. Surface water, soil water, and leached water samples were collected weekly throughout the study period. Water samples were analyzed for ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N) and nitrate nitrogen (NO_3^--N) using an ion chromatograph (ICS-90, Dionex, Sunnyvale, USA), and total organic carbon (TOC) concentration was determined by a TOC analyzer (TOC 5000A, Shimadzu, Kyoto, Japan).

Soil samples were taken before transplantation and after harvesting from the soil surface to its bottom. Air-dried soil samples were sieved through a 2-mm mesh for assessing changes in total nitrogen content. Seedling and harvested rice samples were air-dried for 2 weeks and then divided into major organs (leaves, stems, and grains) to determine dry weights. Some roots from each column were also analyzed. Nitrogen contents of soil and each rice organ and determined using a CHN elemental analyzer (Micro-corder JM10, J-Science, Kyoto, Japan).

2.3. ^{15}N analysis of soil adsorption, leaching, microorganism assimilation and plant uptake

Soil samples from throughout the profile (surface layer: 0–5 cm depth; deeper layer: 5–30 cm depth) were taken before transplantation and after harvesting and analyzed for ^{15}N (soil-adsorbed ^{15}N and total soil ^{15}N). To avoid the influence of soil sampling on infiltration rate during the experiment, samples were taken from three points in the surface layer (0–5 cm depth) in each column before and after two applications of ^{15}N-labeled fertilizer. Air-dried soil samples from the three sampling points were mixed and then sieved through a 2-mm mesh. For adsorbed ^{15}N analysis, soil was extracted three times with 0.01 M KCl (Sparks and Bartels, 1996). The extracted solution was filtered through a GF/F glass filter, and soil-adsorbed NH_4^+-^{15}N and NO_x^--^{15}N and ^{15}N abundance in leached water were measured following a modified ammonia diffusion procedure (Holmes et al., 1998; Sebilo et al., 2004). The ^{15}N abundance in soil microbial biomass nitrogen extracts was also determined following the same procedure after chloroform fumigation extraction.

The ammonia diffusion procedure in this experiment was conducted as follows. The extracted solution of soil or leaching water containing NH_4^+-N and NO_x^--N was transferred to incubation bottles to which NaCl and a NH_4^+ trap was added. The NH_4^+-N trap consisted of an acidified 1 cm diameter GF/F filter sandwiched by 10-μm pore size Teflon membrane filters that floated on the saline samples. Samples were incubated for 7 d so that all NH_4^+-N was volatilized from the basic solution to NH_3, which is trapped as