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Preferential flow pathways in paddy rice soils as hot spots for nutrient cycling

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ABSTRACT

Crop rotations with maize and flooded rice lead to temporally aerobic soil conditions. This promotes the development of desiccation cracks in the soil, which can act as preferential flow pathways for water and solutes. We hypothesized that these cracks are enriched with organic carbon (C), plant nutrients and microbial residues (amino sugars) and that they can thus also serve as hot spots of fertilizer and C cycling. To test this hypothesis, we applied ^{13}C-labelled rice straw and ^{15}N-labelled urea to rice fields of the International Rice Research Institute (Los Baños, Philippines). We then traced the fate of the ^{13}C-labelled rice straw and the ^{15}N-labelled urea in crack and bulk soil and in microbial residues in two approaches, i) in the short term, i.e., 24 h after application of straw and fertilizer jointly with a dye tracer (Brilliant Blue) prior to maize seeding in the paddy - maize cropping system, as well as ii) in the long-term, i.e., during one year and for three different crop rotations (continuous paddy rice, paddy rice – maize, and paddy rice – maize with straw mulching and cover cropping). The short-term analyses of the dye tracer depth profiles showed that flow path areas decreased with increasing depth. A typical impermeable plough pan was not identified. Instead, we observed rapid infiltration of irrigation water down to 60 cm soil depth. The dyed flow paths were enriched in organic C (+12%) and plant nutrients (N: +21%, Ca^{2+}: +59%, K^{+}: +39%, Mg^{2+}: +39%) relative to the bulk soil. The labelled straw and fertilizer quickly reached 60 cm depth with the dye tracer. We could not identify elevated microbial biomass along the flow paths, however, we did find larger microbial activities along the cracks in the long-term experiment than in the surrounding bulk soil. The increased activity fostered microbial uptake of fertilizer ^{15}N along the cracks, which was detected mainly for fungal residues and only in the trials receiving straw (crack soil: 0.6 ± 0.1 mg glucosamine-^{15}N kg soil^{-1}, bulk soil: 0.2 ± 0.1 mg glucosamine-^{15}N kg soil^{-1}). We conclude that analysis of homogenized bulk soil samples can underestimate C and nutrient availability, as well as their microbial processing in paddy rice soils, when crack systems are not considered.

1. Introduction

Rice is nourishing nearly 50% of the world's population. In order to meet the demands of the world's growing population, the production of rice will have to increase by at least 1.0 to 1.5% annually (Maclean et al., 2013). As climate changes, there is an urgent need to adapt agricultural systems (FAO, 2009). The climate in many rice growing areas is divided into a dry and a wet season, so that growing an upland crop like dry rice or maize during the dry season may help to save water and to secure livelihoods of farmers, because it can also be used for fodder or biofuel production (Timsina et al., 2010). The introduction of upland crops in the dry season has also other beneficial effects like reduced methane emissions (Weller et al., 2015). Yet, there is a high risk of water and nutrient losses with drainage, especially directly after

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the transition from continuous paddy rice cropping systems to maize – paddy rice cropping systems (He et al., 2017). This drainage and leaching losses of nutrients are probably triggered by desiccation cracks in the soil, which mainly develop during the dry and fallow period (Janssen et al., 2010; Lennartz et al., 2009; Sander and Gerke, 2007). Together with other macropores in soil, like earthworm burrows or old root channels, cracks thus form major preferential flow pathways (Beven and Germann, 1982), which could control overall carbon (C) and nitrogen (N) losses from paddy soil - plant systems (He et al., 2017).

Previous studies provided a visual assessment of cracking patterns during the growing season (Liu et al., 2011; Zhang et al., 2013; Bhushan and Sharma, 2002) or in the soil profile (Sander and Gerke, 2007). Other studies confirmed their significant contribution to infiltration (Liu et al., 2003; Greve et al., 2010; Zhang et al., 2013; Janssen and Lennartz, 2007; Wopereis et al., 1994; Lennartz et al., 2009; Mitchell and van Genuchten, 1993; Tuong et al., 1994). Much less studies, however, addressed the role of cracks also for related turnover and losses of C, N and other plant nutrients. Most of these experiments took place in forest soils in temperate climates (Bogner et al., 2011; Bundt et al., 2000; Vinther et al., 1999; Bogner et al., 2012), whereas studies at paddy sites mainly focused on crack appearance or infiltration rates rather than on physiochemical properties of cracks (Bhushan and Sharma, 2002; Mitchell and van Genuchten, 1993; Sander and Gerke, 2007).

In forest soils, Bogner et al. (2012) indeed found larger C and N concentrations in flow pathways than in the bulk soil, which the authors assigned to root activity and the transport of dissolved organic matter along the walls of these flow paths. Because of frequent solute transport, Bundt et al. (2001) additionally measured an elevated effective cation exchange capacity and base saturation in the preferential flow pathways compared to the soil matrix. Due to the increased nutrient supply, the preferential flow pathways were thus considered as biological “hot spots”, with an enormous agglomeration of active microbial biomass, though not necessarily of different microbial communities (Bundt et al., 2001). Vinther et al. (1999) underlined the importance of flow pathways for denitrification processes through larger bacterial biomass and larger concentrations of NO_3-N and water soluble C in macropore soil compared to the soil matrix. Hence, preferential flow pathways also promoted the emission of CH_4 and N_2O from anaerobic parts of deeper soil layers (Xing et al., 2002). Nothing is yet known on the role of such cracks for nutrient cycling in paddy soils, which are usually anaerobic during the rice cropping season, with unknown legacy effects for nutrient cycling during aerobic periods under upland crops. It seemed thus reasonable to assume that cracks also provide hot spots of nutrient cycling and thus of related nutrient turnover and microbial C and N sequestration processes in paddy soils.

The quantitative polymerase chain reaction (qPCR) allows the quantification of microbial populations and to track changes in the abundance due to changed environmental conditions (Smith and Osborn, 2009). Denaturing gradient gel electrophoresis (DGGE) enables the determination of the genetic diversity of the microbial community in soil (Muyzer, 1999). To detect also dead microbial cells, the analysis of amino sugars in soil served as biomarkers for the residues of bacteria and fungi (e.g. Amelung et al. (2008); Murugan and Kumar (2013)). Four amino sugars are detectable in soil and indicate different microbial communities. While glucosamine primarily originates from the chitin of fungal cell walls and muramic acid uniquely from bacterial cell wall residues, the origin of galactosamine and mannosamine is less clear (Amelung et al., 2008; Glaser et al., 2004; Liang and Balser, 2010; Joergensen, 2018). As amino sugars represent a specific portion of the microbially bound N (Roth et al., 2011), they can, in combination with ^{15}N stable isotope mass spectrometry, help to evaluate the microbial utilization of applied N. To our knowledge, none of these techniques have been used for microbial analysis along flow pathways in paddy rice soils.

The appearance of cracks in paddy soils may contribute to nutrient and fertilizer leaching, particularly after introduction of dryland crops into permanent paddy cropping systems (Fuhrmann et al., 2018). Yet, the addition of straw may reduce evaporation and thus crack development by maintaining and conserving soil moisture (Cabangon and Tuong, 2000). Therewith, also nutrient leaching along cracks should be reduced by straw application (Cassman et al., 1996). Moreover, the incorporation of rice straw into upland cropping systems could also improve crop performance and increase the soil organic carbon concentration (Liu et al., 2014). The application of straw can thus increase the release of greenhouse gases especially methane by an increased growth of methanogens (Conrad et al., 2012; Shrestha et al., 2011).

The objective of this study was to characterize preferential flow pathways in a rice - maize cropping system with and without rice straw mulching during the wet-to-dry fallow period, and to characterize desiccation cracks in comparison to bulk soil in different rice crop rotations. We hypothesized that

(i) Cracks contain larger concentrations of organic C and other nutrients compared to matrix soil, because they are pathways for irrigation water, fertilizer and roots entering deeper horizons of paddy soils.
(ii) Due to elevated organic C and nutrient concentrations, cracks are hot spots of microbial biomass and activity.
(iii) Straw application reduces crack formation but increases C inputs in remaining cracks compared to bare soil.

2. Material and methods

2.1. Study site

The field experiments were conducted at the International Rice Research Institute (IRRI) in Los Baños, Philippines (14° 11′ N, 121° 15′ E). The long-term mean annual temperature in this area is 25.7 °C (1979–2014) and the average precipitation equals 2059 mm. In 2016, the mean annual temperature was 28.2 °C, and the annual precipitation was 1806 mm. Three quarter of the rain fell during the wet season from June to November (dry season: December–May; for details on rainfall and temperature data as recorded by the IRRI climate unit, see Fig. S1; Supplementary information). The soil at the site of the experiment is classified as Anthraquic Gleysol (see Supplementary data for soil profiles, Tables S1 and S2) according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

To answer our hypothesis, we conducted this study in two approaches, a) a short-term dye tracer experiment, carried out for 24 h in the wet-to-dry fallow period in 2016, and b) a long-term crack monitoring study, which ran over one year to assess the fate of C and N as affected by desiccation cracks. The long-term crack monitoring study included different cropping trials. Both experiments started with the first straw application during the wet-to-dry fallow period 2015/2016, when all fields were drained.

2.2. Experimental setup of the dye tracer experiment

The dye tracer experiment was carried out on two separate fields: both fields were treated equally before and had a maize - paddy rice crop rotation without straw incorporation or cover cropping for five years. One field was treated with and the other without rice straw. The rice straw was applied twice ($2 \times 300\,\mathrm{g\,m^{-2}}$, chopped to approximately 5 cm length). We applied the first $300\,\mathrm{g\,m^{-2}}$ on December 8, 2015, after the harvest of the rice, and mixed the straw with the uppermost 5 cm of soil with a rotary tiller. The second $300\,\mathrm{g\,m^{-2}}$ were applied on January 12, 2016, as mulch layer to reduce evaporation of water.

For the application of the dye tracer, we inserted metal frames (100 cm × 100 cm × 50 cm) into the topsoil of each of both fields down to about 18 cm depth below soil surface, in order to prevent lateral