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Characteristics of cracks in two paddy soils and their impacts on preferential flow

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ABSTRACT

Soil cracks generated in paddy fields upon drying may be main pathways of preferential flow. In this paper we aimed to characterize soil cracks in paddy field and to assess their role in preferential flow. Two paddy fields, one cultivated for 20 years (YPF) and the other cultivated for more than 100 years (OPF), were subjected to either alternate flooding and drying (AFD) or continuous flooding (CF) as a control during rice growing season. After the harvest of late rice crop, soil cracks were analyzed in 2D and 3D, and their contributions to hydraulic conductivity and preferential flow were assessed by tension infiltrometer and dye tracer, respectively. Our results showed that cracks were generated under AFD condition but not under CF condition. Under AFD condition, the YPF presented 10-fold more cracks in quantity but these cracks were finer and shallower as compared to those generated in the OPF. All the cracks did not penetrate through the plow pan existed at 15–25 cm. Soil hydraulic conductivity at near saturation (> −6 cm pressure head) was increased by 2.5–4.5 times in paddy field with cracks, as compared to non-crack paddy field. Cracks represented the pathways of preferential flow. However, the preferential flow was considerably reduced by the dense plow pan. This study indicates that paddy soil cracks generated by AFD cycles can improve water infiltration but its role in preferential flow is minor below the plow pan.

1. Introduction

Paddy field is generally subjected to many cycles of alternate flooding and drying (AFD) during rice growing (Bouman et al., 2007). AFD may create many remarkable cracks in the field (Janssen and Lennartz, 2007; Sander and Gerke, 2007; Yoshida and Adachi, 2004). These cracks become the pathways of preferential flow, improving water infiltration (Liu et al., 2003; Tuong et al., 1996) and increasing pollution risk of groundwater (Jarvis, 2007).

Preferential flow refers to all phenomena where water moves along preferred pathways through the soil profile allowing water to bypass part of the soil matrix (Hardie et al., 2011). Some evidences from field studies confirmed that 70–85% of water flux was ascribed to preferential flow, which is responsible for the difficulty in predicting water and solute movement in field condition (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988). Cracks and biopores are major pathways of preferential flow (Beven and Germann, 1982). The geometry of soil cracks depends much upon dynamics of soil water content (Novak et al., 2000), different from the other pathways created by plant root and soil fauna which are more or less independent of soil water content. Cracks formed during drying increased hydraulic conductivity considerably. Liu et al. (2003) reported that a cracked paddy field had a higher water infiltration rate than a non-cracked one, and the infiltration rate of cracked soil was reduced when cracks were closed during wetting. They further demonstrated that preferential flow in cracked soils was a matter of very short time due to crack closure resulted from rapid and heterogeneous swelling processes. However, other researchers (Tuong et al., 1996; Wopereis et al., 1994) reported that cracks did not close after rewetting, leading to high percolation under wetting condition. Soil cracks can remain pathways for preferential flow even after they are closed on soil surface (Greve et al., 2010; Sander and Gerke, 2007). Such inconsistent results of cracks' effect on water infiltration may primarily stem from the difference in soil properties (e.g., clay mineral, and clay content) for determining soil shrinkage and swelling behavior.

The geometry of cracks determines the pattern of preferential flow. However, the quantification of soil cracks is still a challenge due to their complicated and irregular geometries. Baer et al. (2009) characterized soil crack network using fractal theory. Vogel et al. (2005) quantified crack patterns by a means of Minkowski functions. Velde (1999) determined the length, width, and area of soil surface cracks with image analysis of their photographs. The quantification of crack structure is typically limited to soil surface that is easily accessible or to two-dimensional (2D) sections. Recently, the three-dimensional (3D) structure of cracks has received increasing attentions. Sand displacement (Dasog and Shashidhara, 1993), flexible plastic rulers (Ringrose-Voase and Sanidad, 1996), and latex filling (Abou Najm et al., 2010) have been used to identify crack volume. These methods are

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inexpensive and do not require special equipment, however, their accuracy is not very satisfying. Image analysis of CT scans has been utilized to investigate 3D macropores by synthesizing a series of 2D images (Gantzer and Anderson, 2002; Luo et al., 2007). This tool can provide us with nondestructive 3D crack geometry in details.

Preferential flow phenomenon is widely investigated using tension infiltrometer and/or dye tracer in the field (Cameira et al., 2003; Hu et al., 2009; Schwen et al., 2011). A major advantage of tension infiltrometer is that it can characterize soil macropores and assess their contributions to water flow by measuring water infiltration at different pressure heads near saturation *in situ*. The dye tracer Brilliant Blue is often used to visualize and qualify water flow along soil profile and has superior beyond traditional methods in separating a distinction between areas of the soil that are active in water flow and those that are not (Droogers et al., 1998; Mooney and Nipattasuk, 2003; Morris and Mooney, 2004). Using dye tracer, Sander and Gerke (2007) observed that paddy soil cracks below plow pan still functioned as pathways for preferential flow although they were dissimilar in pattern with respect to surface cracks. Although the dye tracer method cannot quantify water flow, it may yield valuable qualitative information for charactering preferential flow.

In this study, the two paddy fields with different cultivation years (one for 20 years and another for more than 100 years) were chosen. Alternate flooding and drying (AFD) and continuous flooding (CF) as a control were set during rice growing period in each field. Our objectives were to characterize soil cracks in 2D and 3D, and then to investigate preferential flow patterns between cracked soils under AFD condition and non-cracked soils under CF condition in the two paddy fields. Tension infiltrometer and dye tracer experiments were used to assess the role of cracks in preferential flow.

2. Materials and methods

2.1. Experimental site

The experimental site, as described by our previous work (Zhang et al., 2013), is located in Sunjia agricultural catchment, 4 kilometer northwest away from Ecological Experimental Research Station of Red Soil in Yingtan, Jiangxi province, China. This region has a typical warm and humid subtropical monsoon climate with an annual rainfall of 1706 mm and an annual mean temperature of 17.8 °C. The soils in the catchment are characterized by loam and clay loam texture and mainly derived from Quaternary red clay. The soil from upland is classified as Ultisols based on the USDA Soil Taxonomy (Soil Survey staff, 2010). The main crop in the catchment is double cropping rice, which is grown from April to July for early rice and July to November for late rice.

Two paddy fields derived from Quaternary red clay were chosen from the catchment for this study. One paddy field, cultivated for 20 years, was considered as young paddy field (YPF) in this study. The other one has been rice production for more than 100 years, which was considered as old paddy field (OPF). The YPF is located on terraced slope where the elevation is 37 m and the OPF is at valley where the elevation is 34 m. Each paddy field was divided into two portions by a ridge covered with a plastic film to prevent water penetration but water exchange in subsoil may occur. One part was continuous flooding (CF) under 5-cm ponding water except a few days before harvest. The other part was under alternate flooding and drying cycles (AFD) except the beginning of rice growing. During the first three weeks of rice growing, this AFD plot was subjected to a slight drying in order to keep the survival and green up of rice seedling. The depth of the ponding water in the flooding cycle in the AFD plot was identical to that in the CF treatment, while the drying cycle in the AFD plot lasted about one week except the interruption by rainfall. In this study, four plots were thus available as follows: young paddy field under alternate flooding and drying (YPF–AFD), young paddy field under continuous flooding (YPF–CF), old paddy field under alternate flooding and drying (OPF–AFD), and old paddy field under continuous flooding (OPF–CF).

The four plots started flooding under 5 cm ponding water on April 13, 2011, then were plowed and harrowed (puddling) on April 26. Early rice seedlings were manually transplanted on April 27 with the space of 20 cm × 20 cm. Early rice was harvested on July 23. Then paddy soils were harrowed again before the late rice was transplanted on July 31. The late rice was harvested on November 20. During the growth of rice, the soil water content of each plot was monitored by a 5TE sensor (Decagon Devices, Pullman, WA, USA), which was installed horizontally at 5 cm depth in the middle between two rice plant rows. The two paddy fields under AFD were subjected to many cycles of wetting and drying (Fig. 1). In this study, characteristics of soil cracks and its consequence on water infiltration, and preferential flow as indicated by dye tracer were investigated after the harvest of late rice crop.

2.2. Soil sampling

Soil samples were taken from the plow layer (0–15 cm), the plow pan (15–25 cm), and the percogenic layer (25–40 cm) in the two paddy fields prior to plowing (March, 2011). They were air-dried at room temperature, and ground to <2 mm for determining some basic soil properties by routine methods (Lu, 2000). Particle size distribution was by pipette method; SOC was by oxidation with potassium dichromate; cation exchange capacity (CEC) by the ammonium acetate method, pH by a pH meter in suspension of 1:2.5 soil: water; and clay minerals by X-ray diffraction technique. Five undisturbed soil cores (5 cm in diameter, 5 cm in height) were also collected from each layer for determining soil bulk density.

2.3. Soil cracks in 2D and 3D

Soil cracks in 2D were photographed *in situ* with a digital camera (Canon IXUS 300 HS) from the two AFD plots. Before photographing, a rectangular ruler (80 cm × 80 cm) was put on the soil surface as a reference for calibrating the size of cracks, and an umbrella was used to shield sunshine if necessary. Three replications were carried out in each AFD plot. The digital images were firstly calibrated by the georeferencing software WGEO 4.0 (WASY GMBH, 2006) and then cropped to a size of 80 cm × 80 cm, equivalent to 1048 pixels × 1048 pixels. They were converted into binary images based on a segmentation threshold, to distinguish between cracks and non-cracks area. The segmentation threshold, depending on each soil sample, was subjective to some extent, but the error became negligible when the pixel intensities of surface soil clearly contrasted with those of the soil cracks. Finally, 2D crack geometry parameters including length, width,

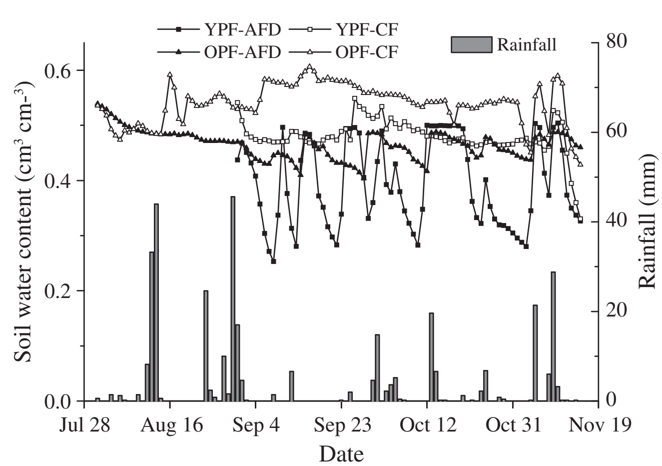

Fig. 1. Temporal change of soil water content at 5 cm depth during the late rice season in the YPF and OPF under AFD and CF conditions.