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Characterizing preferential flow in cracked paddy soils using computed tomography and breakthrough curve

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ABSTRACT

Soil cracks generated in paddy fields may change soil structure and provide pathways for preferential flow. However, the quantitative relationship between soil cracks and preferential flow remain unclear in paddy soils. The objectives of this study were to (1) reveal the effect of soil cracking on soil structure and preferential flow, (2) find a quantitative relationship between characteristics of soil structure and preferential flow in two paddy fields. 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. Undisturbed soil columns (10 cm in diameter and 20 cm in height) were sampled in the four plots. Macropores (including cracks) were quantified using computed tomography (CT), and preferential flow was assessed by breakthrough curve (BTC). The results showed that the presence of soil cracks under the AFD increased average macropore length but decreased the number of macropores significantly ($P < 0.05$), and it also changed macropore size distribution and macropore area density distribution with soil depth. The three-dimensional structures of soil cracks were complicated but can be quantified using CT. The BTCs were well fitted by the convection-dispersion model (CDE) as well as by the two-region (mobile–immobile) transport model. Quick breakthrough, long tail and asymmetrical shape of BTCs for all soil columns indicated the extensiveness of preferential flow in these paddy fields. The relationships between soil macropore features and solute dispersivity parameters (λ and λ_{eff}) were poor ($P > 0.05$). Both the shape of BTCs and fitting parameters demonstrated that soil cracks (5.31–11.9 cm depth) did not increase preferential flow because they did not perforate through the dense plow pan. Soil columns in the CF plots displayed a bit more preferential flow due to a deeper macropore distribution as compared with the AFD plots. While macropore features were different at the two paddy soils, the difference in preferential flow was reduced due to the presence of plow pan. This study demonstrates that soil cracks significantly affect macropore structure but their impact on preferential flow may be poor when they do not penetrate through the plow pan.

1. Introduction

Paddy soils with harrowing and puddling easily crack under alternate flooding and drying cycles (AFD), which helps release nutrients from soils and increases root activity (Yang et al., 2004). Upon flood irrigation, water often moves preferentially through soil cracks at a rapid rate without being absorbed into the soil matrix, resulting in significant loss of water (Liu et al., 2004). Even worse, fertilizer and other agrochemicals can easily move downward with water along cracks, causing a decrease in use efficiency and an increase in pollution risk of underground water (Jarvis, 2007).

There is no universal definition of preferential pathways in soils despite a variety of approaches to depict and quantify them in different ways (Beven and Germann, 1982; Watson and Luxmoore, 1986; Schaap and Van Genuchten, 2006). Abou Najm et al. (2010) defined preferential path into two parts: one is cracks or fissures that are caused by soil shrinkage and swelling, and the other is the volume of pores that results from a wide spectrum of biological activities (including insect and earthworm burrows and biodegraded roots). In paddy fields exposed to alternate flooding and

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drying cycles (AFD), soil cracks are the most important paths for preferential flow (Bandyopadhyay et al., 2003; Liu et al., 2003). This is because paddy fields are often subjected to wetting or flooding condition, making soils anaerobic and unsuitable for living insects and earthworms. In addition, topsoils in paddy fields are tilled and puddled every growing season, which destroys those macropores formed by decayed roots in topsoils.

The presence of soil cracks in paddy soils may change soil structure and water flow patterns. In a previous work (Zhang et al., 2013), it has been found that soil cracks increased water infiltration in a young paddy field but not in an old paddy field because the former was subjected to more intense wetting and drying cycles. Tuong et al. (1996) reported that bypass flow (water flows through cracks into the subsoil) in cracked paddy soils accounted for 41–57 % of the total water (equivalent to about 100 mm of water) applied in the field during land soaking. Favre et al. (1997) found that bypass flow in cracked Vertisols was in a matter of hours only due to crack closure within 4.5 h resulting from rapid and heterogeneous swelling processes. In contrast, other studies found that cracks in paddy soils did not close long after rewetting, leading to high percolation under flooding condition (Wopereis et al., 1994; Tuong et al., 1996; Cabangon and Tuong, 2000). Some researchers (Sander and Gerke, 2007; Greve et al., 2010) highlighted that soil cracks can remain as preferential flow pathways even after they are closed at the soil surface. The effect of soil cracks on preferential flow in paddy fields also depends significantly on the depth of soil cracks (Tuong et al., 1996). Zhang et al. (2014) reported that cracks in paddy fields increased soil hydraulic conductivity and represented preferential flow pathways in the topsoil, but preferential flow was considerably reduced by the dense plow pan because the maximum depth of soil cracks did not penetrate into the plow pan. However, Liu et al. (2003) and Cabangon and Tuong (2000) reported that cracks may reach down far beyond the plow pan under excessive drought conditions. If cracks develop extensively and penetrate through the plow pan, the infiltration rate could increase significantly (Liu et al., 2004) and substantial preferential flow result (Sander and Gerke, 2007). Due to the conflicting results, preferential flow in cracked paddy fields must be studied thoroughly under different environmental conditions. Furthermore, a quantitative relationship between soil cracks and preferential flow has not been directly related yet for paddy soils..

The X-ray computed tomography (CT) technique has been increasingly used to determine soil internal pore structure in three dimensions without soil destruction (Anderson et al., 1990; Naveed et al., 2013). Anderson et al. (1990) reported that CT has good potential as a technique for evaluating structural characteristics in soils. Naveed et al. (2013) found immense potential in linking X-ray CT-derived soil-pore parameters with classical soil physical measurements for quantifying soil architecture and functions. The resolution of CT scanners has evolved from 500 μm (medical CT) to 200 nm (nano-CT), making it convenient to describe three-dimensional structure of different pore sizes and their connectivity. However, scanning at higher spatial resolution has often been limited to smaller (0.1–1 cm) samples while medical CT facilitates scanning of larger (10–100 cm) samples (Cnudde et al., 2006). Sander et al. (2008) assessed Chinese paddy soil structure of large soil columns (10 cm in diameter and 38 cm in height) using medical CT with spatial resolution of 0.25 mm horizontally and 1 mm vertically. Peth et al. (2010) studied three-dimensional soil cracks of small cylinders (5 cm in diameter and 4 cm in height) using X-ray microtomography (resolution about 40 μm) but did not relate three dimensional cracks to actual water movement.

Preferential flow can be assessed using a tension infiltrometer and dye tracer in the field (Angulo-Jaramillo et al., 2000; Allaire et al., 2009). Under field conditions, preferential flow is often affected by some factors difficult to control such as initial water content and water table (Hardie et al., 2012; Zhang et al., 2014). However, the breakthrough curves (BTC) of conservative tracers have been commonly used to detect preferential flow in the laboratory (Vervoort et al., 1999; Yang et al., 2013), which is usually quick and inexpensive, with simple instrumentation (Allaire et al., 2009). Preferential flow can be identified from the shape of BTCs and related parameters inversely estimated from BTCs (Vervoort et al., 1999; Haws et al., 2004). Luo et al. (2008) reported that BTC for the macropore domain showed higher concentration and faster arrival time as compared to that for the matrix domain. Many models have been developed to fit BTCs and quantify related preferential flow (Köhne et al., 2009). Traditional convection–dispersion model (CDE) and two-region (mobile–immobile) transport model are the most popular models for fitting BTCs and a number of published papers have explained the physical meaning of the estimated parameters and their relationships with preferential flow (Vervoort et al., 1999; Luo et al., 2010b). However, to our knowledge, the relationship between BTC parameters and characteristics of soil cracks has not been reported.

The objectives of this study were to (1) reveal the effect of soil cracking on soil structure and preferential flow, (2) find a quantitative relationship between characteristics of soil structure and preferential flow. Two paddy topsoils, one from a younger (20 years) and the other from an older (>100 years) field were compared. Soil macropore and crack characteristics were investigated using CT and preferential flow under saturated condition was estimated using BTC.

2. Materials and methods

2.1. Experiments and soil sampling

The experimental site is in Sunjia agricultural catchment, 4 km northwest of Ecological Experimental Station of Red Soils in Yingtan, Jiangxi province, China. This region has a typical warm and humid subtropical monsoon climate with a mean annual rainfall of 1706 mm and an annual mean temperature of 17.8 °C (1954–1999). The soils in the catchment originated mainly from Quaternary red clay, and are characterized by loam and clay loam texture (Table 1). The soils from upland are classified as Plinthosols

Table 1
Basic soil properties of young paddy field (YPF) and old paddy field (OPF).

Paddy soils	Depth	Bulk density	SOC	ρ_s	Sand	Silt	Clay	Vermiculite	Hydromica	Chlorite	Kaolinite
	cm	g cm^{-3}	g kg^{-1}	g cm^{-3}	——— % ———			————————— % —————————			
YPF	0–15 (A)	1.36	9.79	2.67	31.4	35.4	33.2	31	14	20	31
	15–25 (P)	1.49	5.3	2.68	38.1	29.7	32.2	28	18	18	31
	25–45 (Big)	1.33	4.2	2.67	37.1	29.2	33.7	23	19	22	32
OPF	0–15 (A)	0.95	21.7	2.60	35.7	44.1	20.1	36	8	22	30
	15–25 (P)	1.59	12.4	2.65	39	40.5	20.5	36	10	22	26
	25–45 (Big)	1.54	6.4	2.69	29.9	34.8	35.3	37	14	16	27

A is the plow layer; P is the plow pan; Big is the percogenic layer; ρ_s is particle density.