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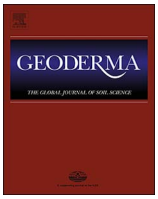

Characterising and linking X-ray CT derived macroporosity parameters to infiltration in soils with contrasting structures

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ABSTRACT

Soils deliver the regulating ecosystem services of water infiltration and distribution, which can be controlled by macropores. Parameterizing macropore hydraulic properties is challenging due to the lack of direct measurement methods. With tension-disc infiltrometry hydraulic properties near saturation can be measured. Differentiating between hydrologically active and non-active pores, at a given water potential, indirectly assesses macropore continuity. Water flow through macropores is controlled by macropore size distribution, tortuosity, and connectivity, which can be directly derived by X-ray computed tomography (CT). Our objective was to parameterize macropore hydraulic properties based on the imaged macropore network of three horizons of an Andosol and a Gleysol. Hydraulic conductivity K_{unsat} was derived from infiltration measurements. Soil cores from the infiltration areas were scanned with X-ray CT. K_{unsat} was significantly higher in the Andosol than in the Gleysol at all water potentials, and decreased significantly with depth in both soils. The *in situ* measurements guided the definition of new macroporosity parameters from the X-ray CT reconstructions. For the Andosol, K_{unsat} was best predicted using the imaged-limited macroporosity. A low total macroporosity, coupled with a high macropore density, indicated the abundance of smaller macropores, leading to homogeneous matrix flux. Imaged macropores were not well connected. In contrast, the Gleysol had a bi-modal macropore system with few very large, but well-connected macropores. K_{unsat} was best predicted using the imaged macroporosity consisting only of macropores with diameters between 0.75 and 3 mm. Our research demonstrates that linking traditional soil physical measurements with soil-visualization techniques has a huge potential to improve parameterizing macropore hydraulic properties. The relevance of the relationships found in this study for larger scales and other soil types still needs to be tested, for example by a multi-scale investigation including a much wider range of different soils.

1. Introduction

Macropores are pores with a diameter larger than 0.3 mm (Jarvis, 2007) which are arranged in a complex and connected network intermixed with unconnected matrix elements. They are made of earthworm channels, fissures, channels from decaying roots, and inter-aggregate voids. The importance of macropores as preferential pathways of water, air, and chemicals in the soil has long been recognized (Clothier et al., 2008; Jarvis et al., 2007). Some 30 years ago, Watson and Luxmoore (1986) reported that water flux through macropores can be as high as 70% of the total flux and thus are the governing process, even though macropores form only a small fraction of the total soil volume. Despite intensive research over many decades, macropores still constitute a major challenge for modelling flow and transport processes due to their high spatio-temporal variability (Jury et al., 2011). In addition, there is a lack of methods to parameterise hydraulic properties of macropores in order to account adequately for their contribution to fluxes.

Recent advances in 3-D X-ray computed tomography (CT) and image analysis technologies, as well as the increasing availability of X-ray CT, have rekindled the interest in modelling preferential flow

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processes at the pore scale (Jarvis et al., 2016). The X-ray CT has been applied to characterize *inter alia*, pore networks, biomass distribution, root architectures, bulk density, organic matter distribution and transport parameters (Hamamoto et al., 2016; Naveed et al., 2013; Nunan et al., 2006; Pierret et al., 2002; Tracy et al., 2010; Wang et al., 2012). In fact, a number of reviews have been published on the successful application and the potential of applying X-ray CT in soil science (Cnudde et al., 2006; Helliwell et al., 2013; Schlüter et al., 2014; Wildenschild et al., 2002). One reason for applying X-ray CT in soil science is to link the geometrical features analysed, applying X-ray CT to soil functions such as water flow, gas exchange, and solute transport (Deurer et al., 2009; Katuwal et al., 2015; Larsbo et al., 2014; Paradelo et al., 2016; Rabbi et al., 2016). The outcome of such a linkage could be that the prediction of properties and processes that cannot be easily measured and observed might be improved and facilitated with structural parameters (Vogel et al., 2010). Vogel et al. (2010) concluded that there are basically two alternative approaches. The first method is to use the structural parameters derived from X-ray CT and use them directly as realistic boundary conditions for the simulation of soil functions (Naveed et al., 2016; Vogel et al., 2005). A problem with this approach is the large computational power required which dictates the scale of the simulations. Scheibe et al. (2015) discussed the problem associated with pore-scale modelling at a smaller scale than the representative elementary volume (REV) of the macroscopic behavior of the processes. They successfully demonstrated pore-scale modelling at the decimetre scale integrating structural parameters measured with X-ray CT. The aim of the second approach is to establish a quantitative, statistically based relationship between measured structural parameters and hydraulic properties (Samouëlian et al., 2007). The direct quantification, reconstruction, and visualization of 3-D macropore networks allow correlating macropore characteristics to the water and solute transport, as well as gas exchanges in soils. Here we have applied this indirect approach to link structural parameters to the hydraulic parameters of macropores derived with tension-disc infiltrometry.

Tension-disc infiltrometry enables measuring near-saturated hydraulic properties *in situ* (Reynolds and Elrick, 2005). Soil macropores are only hydraulically active in this water pressure head range close to saturation (Ankeny et al., 1990). Macroporosity, the number of macropores, pore length, their pore size distribution, and also their 3-D geometry and topology including continuity, tortuosity, and connectivity are important characteristics impacting on water and solute flow through macropores (Bastardie et al., 2005; Luo et al., 2010a). However, these 3-D characteristics are difficult to quantify with traditional methodologies such as the analysis of thin sections (Prado et al., 2007). While tension-disc infiltrometry allows to differentiate between hydrologically active and non-active pores at a given tension, the continuity of macropores can only be indirectly derived from these measurements.

To link soil structure and function, relevant soil macropore features need to be identified and quantified. Our objective was to investigate the role of macropore topological features on the hydraulic properties derived with *in situ* infiltration measurements of soils with different parent materials and textures.

2. Material and methods

2.1. Soils studied

The sites represent two soil orders with contrasting soil texture and structure that were known for differing filtering behavior for bacteria and viruses (Aislabie et al., 2001; McLeod et al., 2001). The first soil was classified as a Typic Orthic Allophanic Soil ((Hewitt, 1998); Andosol (IUSS Working Group WRB, 2006); Typic Hapludand (US)) and the second soil was classified as a Typic Orthic Gley Soil ((Hewitt, 1998); Gleysol (IUSS Working Group WRB, 2006); Typic Endoaquept (US)). Both sites were under permanent pasture and grazed by cattle and are located in Waikato, North Island, New Zealand.

Table 1
Selected physical and chemical properties of the two soils and for the three horizons studied.

Soil	Andosol			Gleysol		
Horizon	Ah	Bw1	Bw2	Ah	Bg1	Bg2
Depth (cm)	0–15	15–31	31–64	0–20	20–38	> 38
Sand (%)	24	19	n.d.[a]	10	0	n.d.
Silt (%)	50	47	n.d.	38	31	n.d.
Clay (%)	26	34	n.d.	52	69	n.d.
Organic carbon (%)	6.8	1.7	n.d.	5.4	0.8	n.d.
Bulk density (g cm^{-3})	0.8	0.8	0.8	0.9	1.1	1.0
Total porosity (%)	65.5	70.7	71.8	63.8	60.8	61.5
Macroporosity − 10 kPa (vol%)	11.8	22.8	25.4	1.7	6.7	1.8

[a] n.d. not determined.

2.2. Tension-disc infiltration measurements

In March 2011, we measured infiltration rates at four different tension heads ($h = -10, -20, -40, -70$ mm) over three depths of both soils. The depths were chosen to represent three distinct soil genetic horizons: the topsoil (Ah), the upper (Bw1 or Bg1), and lower subsoil (Bw2 or Bg2) layers of the two soils (Table 1). All measurements were conducted in triplicate with a tension-disc infiltrometer with a 100-mm radius base. To ensure good contact between the disc and the topsoil, the grass was cut to the ground, and a thin layer of acid-washed sand was evenly spread across the soil surface. Flow measurements were stopped when steady-state flow was reached, as defined in Deurer et al. (2008). The theoretical basis for using tension infiltrometry to derive hydraulic properties has been detailed elsewhere (*e.g.*, Ankeny et al., 1991; Perroux and White, 1988; Reynolds and Elrick, 1991; Reynolds and Elrick, 2005; Vandervaere et al., 2000). We derived the unsaturated hydraulic conductivity at several tensions, following Reynolds and Elrick (2005) who adapted the theory of infiltration from a shallow circular pond (Wooding, 1968).

Applying the capillary-rise equation allows calculating the maximum water filled pore size r (m) at a specific height h (m):

$$r = 2\sigma\cos(\alpha)/\rho g h \tag{1}$$

where σ is the surface tension of water (N m^{-1}), α the contact angle between water and the pore wall, which is assumed to be zero, ρ the specific density of water (kg m^{-3}), and g the acceleration due to gravity (g m^{-2}). According to the capillary rise equation, infiltration at tension heads of −10 mm, −20 mm, −40 mm and −70 mm will exclude pores from flow processes, which have equivalent pore radii > 1.48, 0.74, 0.37 and 0.21 mm, respectively.

2.3. Basic soil properties

Intact soil cores for determining bulk density and bulk soil for measuring texture and organic carbon contents were collected close to all measurement points. The bulk soil was air dried, sieved to 2 mm prior to further analysis. The texture was determined by a combined sieve and hydrometer method (Gee and Or, 2002). Total soil organic carbon (SOC) was analysed by the Dumas method for %C using a 'Leco TruMac' instrument (Blakemore et al., 1987). Bulk density was determined following standard procedures on intact soil cores of 100 cm^3, which were also used for measuring the total porosity and macroporosity at $h = -10$ mm (Blakemore et al., 1987).

2.4. X-ray computed tomography

We extracted undisturbed soil cores (40 mm diameter and 50 mm