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Connectivity and percolation of structural pore networks in a cultivated silt loam soil quantified by X-ray tomography

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The connectivity of macropore networks is thought to exert an important control on preferential flow in soil, although little progress has been made towards incorporating an understanding of these effects into management-oriented flow and transport models. In principle, concepts from percolation theory should be well suited to quantify the connectivity of preferred flow pathways, but so far its relevance for natural soils in the field has not been tested. To investigate this question, X-ray tomography was used to measure soil pore space architecture at an image resolution of 65 μm for 64 samples taken in two consecutive years in the harrowed and ploughed layers of a silt loam soil a few weeks after spring cultivation. The results showed that the pore networks displayed key features predicted by classical percolation theory: a strong relationship was found between the percolating fraction and the imaged porosity, with a percolation threshold of ca. 0.04 to 0.06 $m^3\ m^{-3}$ in the harrowed layer. A percolation threshold was less clearly identifiable in topsoil that had not been recently tilled, although this may probably be attributed to finite size sampling effects in this layer, which showed a more heterogeneous and structured distribution of the pore space. Although further work on more strongly structured soil horizons, especially subsoils, would be desirable, it is tentatively suggested that percolation concepts could prove useful to estimate the conducting macroporosity in management models of preferential flow and transport.

1. Introduction

Soil structural pores (macropores) allow rapid and far-reaching preferential (i.e. non-equilibrium) flows of water, dissolved solutes and particulate matter, with potentially serious consequences for water quality (Jarvis, 2007). Application of non-invasive imaging techniques has revealed that macropores in soils generally form partially-connected networks of rather complex topology (e.g. Perret et al., 1999; Pierret et al., 2002; Mooney and Korošak, 2009; Luo et al., 2010a). It is also empirically quite well established that the connectivity of these macropore networks may strongly influence susceptibility to preferential flow at all scales ranging from columns through pedons to hillslopes (e.g. Noguchi et al., 1999; Luo et al., 2010b; Nieber and Sidle, 2010; Larsbo et al., 2014). The effects of this complex soil pore architecture on flow and transport can be captured by pore-scale modelling at small scales, either directly on X-ray imaged pore systems (e.g. Hyväluoma et al., 2012; Scheibe et al., 2015) or on simplified pore network models that statistically represent the real network (e.g. Köhne et al., 2011). However, with only a few exceptions (e.g. Klaus and Zehe, 2011), only limited progress has been made towards incorporating a quantitative treatment of macropore connectivity into models that are better suited to the much larger spatial and temporal scales relevant for management applications. For example, widely-used dual-permeability models (e.g. Šimůnek et al., 2003; Larsbo et al., 2005; Šimůnek and van Genuchten, 2008) that apply continuum flow equations in two interacting flow domains, implicitly assume that the larger pores comprising the preferential flow domain are perfectly connected. Simple yet realistic methods that can capture emergent effects of the connectivity of complex macropore networks on flow and transport at larger scales would therefore help progress towards more reliable model predictions.

In principle, concepts from percolation theory should be well suited to characterize the connectivity of preferred flow pathways (e.g. Western et al., 2001; Schlüter and Vogel, 2011; Renard and Allard, 2013). In hillslope hydrology, percolation concepts have been employed to understand and model both surface runoff (Darboux et al., 2002) and sub-surface downslope discharge above an irregular soil-rock boundary (Lehmann et al., 2007; Janzen and McDonnell, 2015) as a threshold response to precipitation influenced by the connectivity of topographic depressions along the slope. Nieber et al. (2006) suggested that percolation concepts might describe the connectivity of self-organized macropore networks in soil, but to our knowledge, this idea has not yet been pursued. Liu and Regenauer-Lieb (2011) used percolation concepts to analyze the pore structures of rock, bread and wood samples imaged by X-ray tomography, but we are not aware of any such

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investigations on natural soils. In this study, we investigate whether percolation concepts can be used to describe the connectivity of structural pore networks in a tilled topsoil of a silt loam, as quantified by high-resolution industrial X-ray tomography (Helliwell et al., 2013).

2. Materials and methods

2.1. Field site and sampling

64 soil cores sampled in PVC cylinders each with an inner diameter of 6.7 cm and a length of 10 cm, were taken from a long-term field experiment located at Offer in northern Sweden (63.1°N, 17.8°E), which is described in more detail by Bolinder et al. (2010). The site has a mean annual average temperature of 3.4 °C and an annual precipitation of 567 mm (averages for period 1961–2000). Half of the samples were taken in June 2013 and the other half in June 2014. Each year, eight core samples were taken from each of four plots subjected to four different crop rotations established in 1956, which differed with respect to the number of years of grass ley in the rotation (1, 3, 4 or 5 years of grass ley in a six-year rotation, with arable crops in the remaining years). In both years, we sampled the four plots in the first year of arable cultivation after the break of the grass ley ca. 3 weeks after seedbed preparation (harrowing to a depth of ca. 6 cm) and sowing. The plots had been ploughed to a depth of ca. 20–25 cm the previous autumn. On each sampling occasion, 16 cores were sampled at the soil surface and 16 directly below them in the horizon which had been ploughed, but not harrowed.

The soil at Offer is a silt loam, with clay contents varying between 23 and 40% (with a mean of 30%) and silt contents between 50 and 68% (with a mean value of 57%). The long-term cropping treatments have affected the soil organic carbon contents (Bolinder et al., 2010), which varied between 1.3% and 4.1% among the sampled plots (with a mean value of 2.5%).

2.2. X-ray tomography and image analyses

2.2.1. X-ray scanning

We imaged the samples using the GE Phoenix X-ray scanner (v|tome|x 240), which is installed at the Department of Soil and

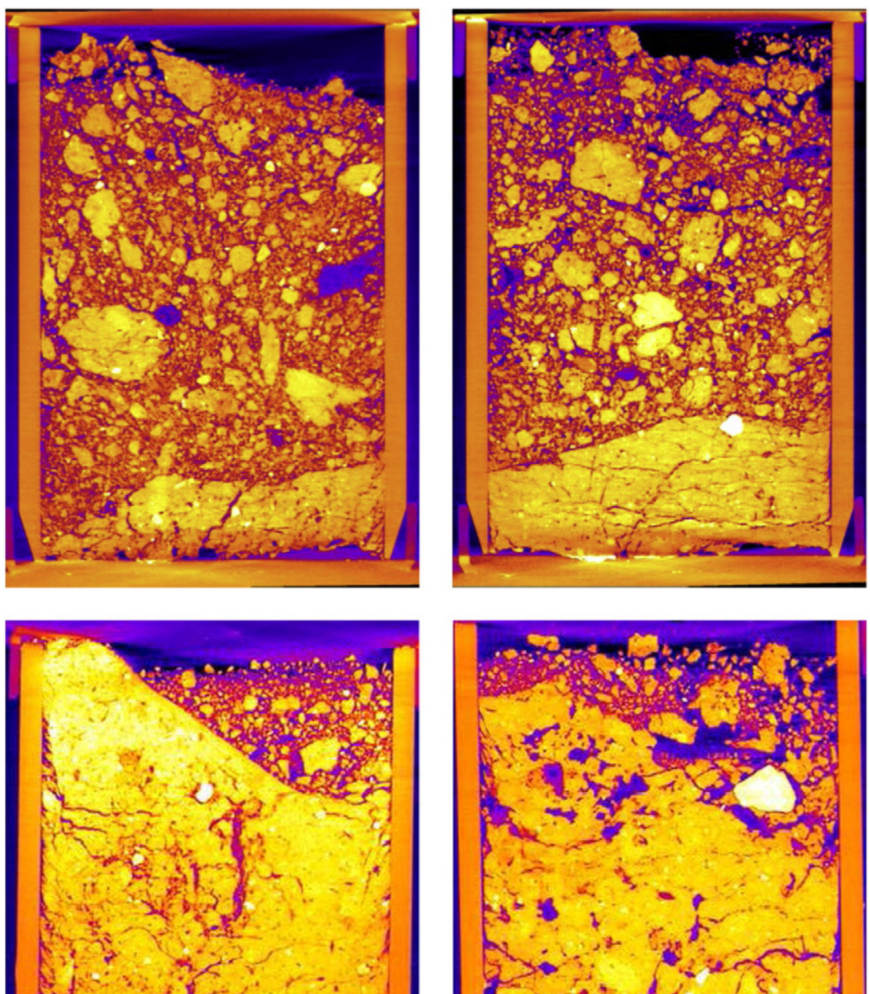

Fig. 1. Four example 2D images of vertical slices through samples (inner diameter 6.7 cm) taken at Offer, illustrating the contrasting structures in the harrowed and ploughed layers. The two uppermost images are samples taken from the soil surface, the two beneath are from 10 to 20 cm depth.