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Image processing-based study of soil porosity and its effect on water movement through Andosol intact columns

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ABSTRACT

The soil pore network and marcoporosity are important factors affecting water and solute transport. The transfer of contaminants to water resources is of particular importance in the Valle de Bravo watershed as it provides 10% of the drinking water for the 20 million inhabitants of Mexico City. This watershed is composed mainly of Andosols with unique mineralogical and physical characteristics. Soil porosity is usually examined on thin sections, using various image analysis techniques. We propose a novel methodology combining image analysis and a displacement experiment to study relationships between soil structure and water tracer transport parameters. $H_2{}^{18}O$ displacement experiments were conducted through intact soil columns sampled at three depths from a representative cultivated Andosol profile. The soil structure and pore characteristics were obtained by image analysis on thin sections obtained from each column at the end of the displacement experiment. The total 2D porosity (for pores larger than 50 μm) varied from 80% of the total section area in the topsoil to around 60% in the subsoil. Tubular pores were the most abundant in the soil profile, but ploughing of the topsoil had destroyed sections of these pores and replaced them with packing pores. Water transport in the intact subsoil columns was always in physical non-equilibrium, showing the existence of preferential flow pathways. In the topsoil, one column out of three showed no preferential flow, demonstrating that soil ploughing also homogenised pore connections. Pore connectivity was larger in the ploughed topsoil than in their deeper soil horizon counterparts. Our methodology offers a 2D quantitative characterisation of the macroporous network at 50 μm resolution and the determination of water transport parameters on the same intact soil samples. 3D characterisation of soil porosity using X-ray computed tomography (CT) gives a better picture of pore connection but usually has lower spatial resolution and a larger cost.

1. Introduction

Solute transport through soil has become a key research topic since contamination of groundwater sources has been observed worldwide. The Valle de Bravo watershed in Mexico needs to be protected from further contamination as it provides 10% of the drinking water for the 20-million inhabitants of Mexico City.

Water and solute transport through soil is a complex process that can be directly related to the pore network. Both soil porosity and other soil characteristics such as structure and texture affect transport processes (Strock et al., 2001). Literature on soil structure characteristics and its relationship with solute transport is ambiguous. Seyfriend and Rao (1987) reported that solute dispersion is related to the soil structure and its water content. Bejat et al. (2000) observed that in an unsaturated soil, there is a linear relationship between the soil water content and the dispersion of a non-reactive solute, as well as between the dispersion and the pore water velocity. They did not find a direct relationship between the soil's structural properties and hydrodynamic dispersion. The pore network, which depends on the soil structure, plays a decisive role in water and solute movement through soil. Walker and Trudgill (1983) found significant correlations between geometric variables describing soil porosity and solute transport parameters. For example, the dispersivity

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coefficient is exclusively determined by pore geometry (Yule and Gardner, 1978). Poletika and Jury (1994) demonstrated that the presence of macropores is one of the factors responsible for heterogeneity in water and solute movement through soil. Some authors have related saturated hydraulic conductivity and residual water content to pore size distribution in soil (Holtham et al., 2007). Macropore networks differ depending on the soil type, morphology, agricultural practices, and faunal activity. Active (i.e. functional) pores change with water content and water pore velocity (Andreini and Steenhuis, 1990; Shipitalo et al., 1990; Edwards et al., 1992; Quinsenberry et al., 1994).

Soil thin section analysis (e.g. Walker and Trudgill, 1983) and dye application in intact soils (Seyfriend and Rao, 1987; Hatano et al., 1992; Vanderborght et al., 2002; Tarquis et al., 2006) are the most common techniques for studying soil structure, porosity, and transport parameters. The application of image analysis techniques to determine pore characteristics and soil structure in thin sections has become an indispensable tool for research in soil science (Protz et al., 1987). The characterisation of the porous network from the image analysis of soil thin sections allows an independent and direct evaluation of the water dynamic in a structured soil (Hallaire et al., 1997, 1998; Cervantes et al., 2003; Holtham et al., 2007). It has been used to measure the pore size distribution in the various soil horizons (Ismail, 1975), to characterise the orientation, shape, and size of different pores (Murphy et al., 1977), and to quantify dye transport in preferential flow pathways (Forrer et al., 2000; Duwig et al., 2008). Image analysis has also been used to determine solute transport parameters (Persson, 2005) and to explain the shape of breakthrough curves obtained from solute transport experiments in soil columns (Walker and Trudgill, 1983; Sugita et al., 1995).

One technique for evaluating solute transport and sorption processes in soil is the displacement of the solute through a soil column. The soil is immobile, and the solute moves through the column only once. Transport and sorption processes are affected by the soil's structure and other properties. Leachates at the bottom of the column are collected and analysed; the breakthrough curve shape is determined by the different processes occurring during the displacement of the solute through the soil matrix (e.g. adsorption and preferential flow). Experimental studies where the breakthrough curve and soil structure characteristics are determined in the same intact soil sample are scarce, and have only been conducted using expensive non-destructive technologies such as soft X-ray radiography (Mori et al., 1999), and a combination of CAT and SPECT scanning (Perret et al., 2000). In the case of Andosols they are nonexistent. This type of study allows the determination of a direct relationship between solute transport parameters (by applying a water tracer as the solute of interest) and the soil pore network (by analysing soil thin sections) (Sugita and Gillham, 1995; Sugita et al., 1995; Bejat et al., 2000).

Thanks to their unique physical characteristics (e.g. low bulk density, high water retention capacity, and usually a high content of organic matter), which derive from the presence of amorphous materials, Andosols usually offer good conditions for agriculture and can support high population densities. However, the presence of these amorphous materials renders their study quite complex and requires the use of adapted methodologies. Andosol structure and porosity has to be studied at field moisture to avoid the irreversible formation of aggregates, when drying. Its dark colour makes it impossible to use dyes other than fluorescent ones.

In the current study, displacement experiments were conducted with the water tracer $H_2{}^{18}O$ through intact columns sampled at different soil depths of an Andosol profile. The soil structure and pore network were obtained by image analysis on thin sections obtained from each column once the displacement experiment concluded. The image analysis technique consisted of three steps: image segmentation, identification of pores (i.e. labelling), and the calculation of geometric and morphologic parameters, namely their perimeters, areas, shapes (through their shape factor), bi-dimensional connectivity and tortuosity.

The specific objectives of this work were to analyse the soil pore network and its variation with depth within the Andosol profile, and to evaluate the relation between these soil properties and water transport processes.

2. Materials and methods

2.1. The soil studied

The soil studied is located in the elementary catchment la Loma, part of the Valle de Bravo basin in Mexico State, 150 km west of Mexico City, at a height of 2500 m (19°16′48.6″N and 99°58′13.7″W). La Loma has been the location for various studies on agrochemical transport through the soil vadoze zone (e.g. Prado et al., 2006; Duwig et al., 2006, 2008; Müller and Duwig, 2007). The Valle de Bravo basin is the most important reservoir of the Cutzamala system, which provides a significant amount of drinking water ($19\ m^3\ s^{-1}$ or 21% of the daily supply, Tortajada and Castelán, 2003) to Mexico City.

A plot under maize in the la Loma catchment was selected, and the water balance, runoff, erosion, and nutrient losses monitored. The soil was characterised and classified as a Pachic Andosol (WRB, 2001). The physical, chemical, and mineralogical characteristics are described in detail in Prado et al. (2007). The whole soil profile presents andic properties: bulk density $< 0.9\ g\ cm^{-3}$, phosphate retention $\geq 70\%$, $Al_{ox} + (1/2)Fe_{ox} \geq 2\%$, volcanic glass content in the fine earth fraction $< 10\%$. Table 1 shows some selected properties of this soil. The unsaturated soil hydraulic conductivity (at $h = -100$ mm) and saturated conductivity vary with depth: they decrease from 0.05 and 0.11 cm min^{-1} at the soil surface to 0.012 and 0.08 cm min^{-1} at 55 cm depth (Prado, 2006).

Table 1
Selected soil properties.

Depth (cm)	SOC[a] (g/kg)	Texture			CEC[b]	WC[c] %	pH H_2O	Allophane[d] (%)	Horizon
		Sand	Silt (%)	Clay					
0–15	54	29	62	9	22.3	25.5	5.5	18.5	Ap
15–20	53	45	50	5	23	26.9	6.1	23.1	A1
20–45	56	23	66	11	20	30.5	6.2	22.5	A2
45–65	53	25	66	9	24	31.1	6.3	25.5	2A1
65–85	47	26	63	11	23.1	37.9	6.3	26.0	2A2
85–110	51	22	68	10	23.6	33.2	6.5	27.7	3A

[a] SOC, Soil Organic Carbon.
[b] CEC, cation exchange capacity ($cmol_c\ kg^{-1}$).
[c] WC, 15 bar water content.
[d] Allophane = 6 × Si extracted by oxalate (Parfitt, 1990).