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Impact of plant roots and soil organisms on soil micromorphology and hydraulic properties

Radka Kodešová[1], Vít Kodeš[2], Anna Žigová[3] & Jiří Šimůnek[4]

[1]*Czech University of Agriculture in Prague, Department of Soil Science and Geology, Kamýcka 129, CZ–16521 Prague, Czech Republic; e-mail: kodesova@af.czu.cz*
[2]*Czech Hydrometeorological Institute, Department of Water Quality, Na Šabatce 17, CZ–14306 Prague, Czech Republic*
[3]*Academy of Sciences of the Czech Republic, Institute of Geology, Rozvojová 269, CZ–16502 Prague, Czech Republic*
[4]*University of California Riverside, Department of Environmental Sciences, Riverside, CA 92521, USA*

Abstract: A soil micromorphological study was performed to demonstrate the impact of soil organisms on soil pore structure. Two examples are shown here. First, the influence of earthworms, enchytraeids and moles on the pore structure of a Greyic Phaeozem is demonstrated by comparing two soil samples taken from the same depth of the soil profile that either were affected or not affected by these organisms. The detected image porosity of the organism-affected soil sample was 5 times larger then the porosity of the not-affected sample. The second example shows macropores created by roots and soil microorganisms in a Haplic Luvisol and subsequently affected by clay coatings. Their presence was reflected in the soil water retention curve, which displayed multiple S-shaped features as obtained from the water balance carried out for the multi-step outflow experiment. The dual permeability models implemented in HYDRUS-1D was applied to obtain parameters characterizing multimodal soil hydraulic properties using the numerical inversion of the multi-step outflow experiment.

Key words: soil micromorphology, soil organisms, pore-sizes, soil hydraulic properties

Introduction

Soil pore structure and subsequently soil hydraulic properties are influenced by many factors, including the mineralogical composition, stage of disintegration, organic matter, soil water content, transport processes within the soil profile, weather, plant roots, soil organisms, and management practices. Shapes and sizes of soil pores may be studied on images of thin soil sections, taken at varying magnifications. Macropores form major transport pathways in soil and their impact on saturated hydraulic conductivities, K_s, was previously explored by Bouma et al. (1977). Differently shaped pores in soils under different management practices and their K_s values were studied by Pagliai et al. (1983, 2004). A soil micromorphological study presented here was performed to demonstrate the impact of soil microorganisms on soil pore structure. Their activity is reflected not only in the presence of macropores and subsequently high K_s values and preferential flow in these macropores, but also in the entire shapes of the soil hydraulic properties. Two examples presented in this study illustrate pore structure of soil samples collected from the soil depth of 60 cm and below affected dominantly by soil organisms and roots, without the direct impact of the weather and management practices.

Material and methods

Undisturbed large soil aggregates and undisturbed 100 cm^3 soil samples were taken from each horizon of a Haplic Luvisol and Greyic Phaeozem. Micromorphological properties characterizing the soil pore structure were studied on thin soil sections prepared from large soil aggregates. Thin sections were prepared according to the methods presented by Catt (1990). The soil pore structure was analyzed using a similar procedure to that presented by Rösslerová-Kodešová & Kodeš (1999). Images were taken at one magnification at a resolution of 300 dpi. To detect pores, image-processing filters were used. The ArcGIS raster processing tools were used to analyze pore areas and perimeters. The shape factors [perimeter^2/(4π area^2)] proposed by Pagliai et al. (1983) were calculated to divide pores into different shape groups.

The soil hydraulic properties were studied in the laboratory on the undisturbed 100 cm^3 soil samples. Soil water retention curves were determined for matric potentials to –10 kPa using a sand table and the pressure plate apparatus for more negative matric potentials. Saturated hydraulic conductivities were measured using the constant head method. The multi-step outflow method was applied

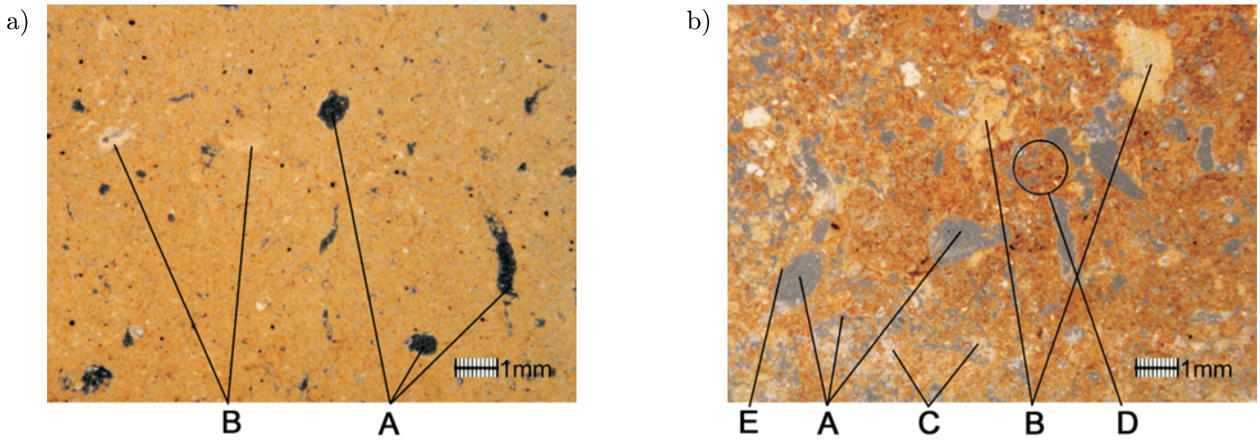

Fig. 1. Micromorphological images of the soil sample characterizing the Ck horizon at depths of 45–125 cm (a) and the image of the krotovina at the depth of 100–110 cm (b) in the Greyic Phaeozem. A – pores, B – amorphous forms of $CaCO_3$, C – calcite needles, D – earthworm and enchytraeid excrements, and E – clay coatings.

to estimate soil water retention curves and unsaturated hydraulic conductivity functions using numerical inversion and assuming either the single-porosity, dual-porosity or dual-permeability models in HYDRUS-1D (ŠIMŮNEK et al., 2003, 2005). The van Genuchten functions (1980) were used to describe both soil hydraulic properties in all cases.

Two examples were chosen to show the impact of plant roots and varying organisms, and subsequent affects of different coatings and fillings on the soil pore structure. First, the influence of earthworms, enchytraeids and moles on the soil pore structure in a Greyic Phaeozem is presented. The impact of such soil porous systems on transport processes within the soil profile was presented by KOČÁREK et al. (2005). Micromorphological images were taken, and image porosities and pore shape factors were calculated to provide the evidence of very different pore structures in soil samples characterizing the Ck horizon at depths of 45–125 cm and krotovina (the soil transported by a mole from the A horizon) discovered at the depth of 100–110 cm.

The second example shows the impact of roots and soil organisms on the soil pore structure in the Haplic Luvisol. Two micromorphological images of the soil sample characterizing the Bt horizon at depths of 75–102 cm are presented. Image porosities were analyzed and the single-porosity and dual-permeability models in HYDRUS-1D were used to reveal the impact of multimodality of soil porous systems on the soil hydraulic properties.

Results

The micromorphological image taken for the soil sample characterizing the Ck horizon in the Greyic Phaeozem is shown in Fig. 1a. The image illustrates a relatively homogeneous structure with many pores less than 100 μm and few larger pores created by small soil organisms. The image of krotovina in the same soil horizon is documented in Fig. 1b. Krotovina consists of mineral grains, earthworm and enchytraeid excrements, clay coatings, amorphous forms of $CaCO_3$, and calcite needles. All these structural components resulted in a very heterogeneous soil pore structure with higher measured porosity and with a very different pore-size distribution compared to the bulk soil. The detected image porosity (pore diameter greater than 40 μm) of krotovina (17.3%) was 5 times higher than the porosity of the Ck horizon (3.4%). Using the shape factor (SF) classification proposed by PAGLIAI et al. (1983) [regular SF = 1–2, irregular SF = 2–5, and elongated SF > 5], the percentages of different shape groups were also very different: regular pores represented 49.0% and 59.4% of the pores in krotovina and the Ck horizon, respectively, irregular pores 45.1% and 37.9%, and elongated pores 5.9% and 2.7%, respectively. The pore irregularity increased with increasing pore sizes. The majority of detectable pores corresponded to a matric potential range between –0.2 and –7 kPa. It is evident from presented images that analyses of pores smaller than 40 μm would require higher magnification (finer resolution) and thinner sections. It is likely that a different pore-size distribution would be obtained for pressure heads below –70 cm. Soil water retention curves obtained on the soil sample characterizing the Ck horizon (not shown here) have therefore a slightly multimodal character. The soil hydraulic properties and numerical inversion for such porous system is discussed in detail below only for the Haplic Luvisol. The soil hydraulic properties of krotovina were not studied since the shape and size of krotovina did not allow taking undisturbed 100 cm^3 samples.

The micromorphological images of the soil sample characterizing the Bt horizon in the Haplic Luvisol are presented in Fig. 2. The figures show the relatively homogeneous matrix structure with many pores less than 100 μm and a system of larger pores created by roots and soil organisms. These pores are affected additionally by clay coatings and infillings that control the water flow interaction between the larger pores and pores of the matrix structure. The image porosities were 9.8% and 5.5%. The percentages of different shape groups were as follows: regular pores represent 64.5% and 62.2% of the pores, irregular pores 33.6% and 35.6%, and elongated pores 1.9% and 2.2%. The

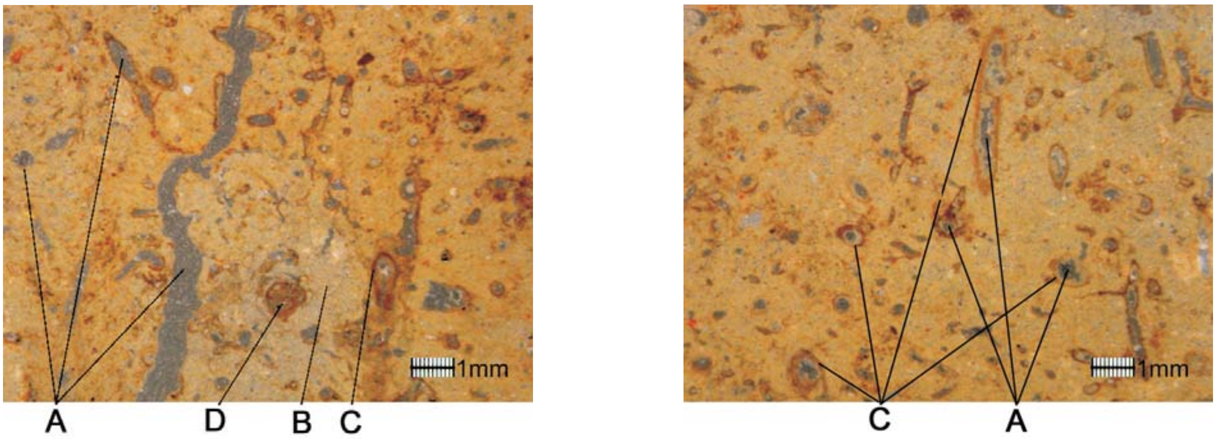

Fig. 2. Micromorphological images of the soil sample characterizing the Bt horizon at depths of 75–102 cm in the Haplic Luvisol. A – pores, B – external part of filling with amorphous forms of $CaCO_3$, C – clay coatings, and D – internal part of filling with clay coatings.

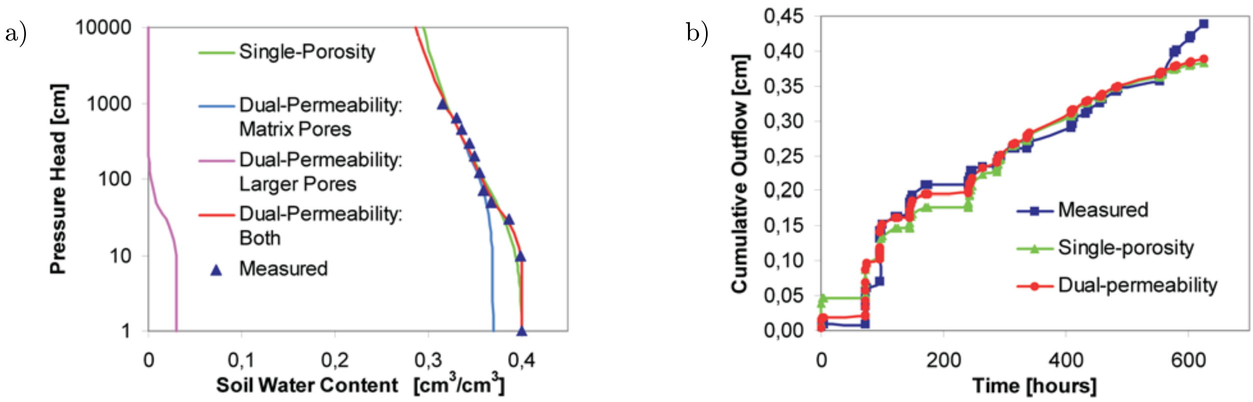

Fig. 3. Soil water retention curves (a) and multi-step outflow data (b) obtained on the soil sample characterizing the Bt horizon at depths of 75–102 cm in the Haplic Luvisol.

pore irregularity again increases with increasing pore sizes.

Corresponding soil water retention data points obtained using the water balance calculated for the soil sample subject to the multi-step outflow experiment is shown in Fig. 3a. The soil pore structure displayed multi-modality of the pore-size distribution that resulted in a multiple S-shaped curve. Soil water retention curves obtained using the numerical inversion of the multi-step outflow experiment are also shown in this figure. The single-porosity model in HYDRUS-1D was used first to analyze multi-step outflow data and to obtain soil hydraulic parameters assuming uniform flow (single continuum approach). Points of the soil water retention curve were also utilized in the inversion. While the saturated soil water content, θ_s, was set to the measured value of 0.401 m^3/m^3, the soil hydraulic parameters θ_r (the residual water content), α (reciprocal of the air entry pressure), n (related to the slope of the retention curve at the inflection point), and K_s (the saturated hydraulic conductivity) were optimized (Tab. 1). The resulting soil water retention curve does not fit the experimental data satisfactorily (Fig. 3a). Also the measured and simulated outflow data do not correspond well (Fig. 3b). The dual permeability model in HYDRUS-1D was then applied to improve numerical inversion results and to obtain parameters characterizing two flow domains defined as matrix (m) and larger pore (f) (two continuum approach). The fraction of the larger pore domain was estimated based on the micromorphological images (elongated pores corresponding to pressure heads between –0.2 and –7 kPa). Values of $\theta_{s,m}$ and $\theta_{s,f}$ (saturated water contents of the matrix and larger pore domains, respectively) were set assuming that the sum of their values multiplied by domains ratios ($w_m = 0.925$, $w_f = 0.075$) was equal to the measured θ_s value. Values of $\theta_{r,m}$ and $\theta_{r,f}$ (residual water contents of the matrix and larger pore domains, respectively) were set equal to θ_r for the single porosity model and zero, respectively. Considering that the larger pores control saturated flow, the saturated hydraulic conductivity of the larger pore domain, $K_{s,f}$, was defined as the ratio of the K_s value (0.496 cm/h), obtained using the constant head experiment on the same soil sample and the domain ratio (w_f). The n_f parameter was set equal to 3 assuming a step-like shape of the soil water reten-

Table 1. Parameters of the van Genuchten functions for the single-porosity and dual-permeability models for the soil sample characterizing the Bt horizon at depths of 75–102 cm in the Haplic Luvisol.

Model – Flow Domain	θ_s [cm^3/cm^3]	θ_r [cm^3/cm^3]	α [1/cm]	n [–]	K_s [cm/h]
Single Porosity	0.401*	0.254*	0.041	1.214	0.310
Dual Permeability – Larger Pore	0.410*	0*	0.036	3*	6.5*
Dual Permeability – Matrix	0.400*	0.253*	0.009	1.240	0.0032

* not optimized

tion curve for the larger pore domain. The effective saturated hydraulic conductivity, K_e, for the mass transfer between the matrix and the larger pore domains was set equal to a low value of 10^{-5} cm/h due to the presence of clay coatings. Parameters α_m, n_f, n_m, $K_{s,m}$ were optimized (Tab. 1). The resulting total soil water retention curve was obtained as the sum of soil water retention curves for the matrix and larger pore domains multiplied by their corresponding fractions. The total soil water retention curve and simulated outflow data are presented in Fig. 3. Agreement between the measured and optimized retention curves and outflow data using the dual-permeability model exhibited significant improvement, especially for the pressure head range corresponding to pores detected in the micromorphological image.

Discussion

The micromorphological study of soil pore structure discovered in all cases the multimodality of the pore system that was caused by roots and different soil organisms. The soil pores were affected by a varying degree of clay coatings or by amorphous forms of $CaCO_3$ and calcite needles. The soil water retention curves also displayed multimodality for both soil types studied, especially for the Haplic Luvisol. This may be due to the presence of clay coatings that limited the interaction between the matrix pores and pore domain originated by roots and soil organisms. Another reason for flow limitation between the two pore domains may be the soil densification around the roots that was described by BRUAND et al. (1996). The impact of a proper description of the multimodal flow domain on water and herbicide transport was shown by KODEŠOVÁ et al. (2005). While the soil water regimes in the soil profile simulated using the single-porosity and dual-permeability models with similar total soil hydraulic properties were almost the same, the solute transport was significantly different. The multimodality of soil hydraulic properties was also previously discussed by DURNER (1994). However, he only compared the multimodal concept for description of the soil hydraulic properties with the single continuum approach, without considering flow and transport. On the other hand the two continuum approach is applied by DUŠEK et al. (2006) to preferential flow and cadmium transport through biopores under heavy rainfall. The soil porous system is highly affected by plant roots and soil organisms. The soil micromorphology helps describe pore configuration and explain flow processes in different flow domains and possible interactions between these flow domains.

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