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Assessment of water and air permeability of chernozem supported by image analysis

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ABSTRACT

We aimed at the assessment of water and air permeability of a Haplic Chernozem developed from loess. The laboratory permeability measurements were presented against a number of morphometric indices that characterize the pore system in this soil, and were obtained by computer-aided image analysis on the basis of large resin-impregnated soil opaque blocks. Two indices of soil pore connectivity are proposed, i.e. the index of soil pore network growth rate and the percolation number. Basic soil properties were evaluated (soil texture, TOC, carbonates, pH, particle and soil bulk density, total porosity). The saturated hydraulic conductivity, and soil water content, air capacity and permeability at −15.54 kPa and −9.81 kPa were measured. From the samples with preserved structure, resin-impregnated soil opaque blocks 8 cm × 9 cm in size were prepared and then used for morphological and morphometric structure analysis. The preliminary image analysis was made to find the best representation of the actual chernozem pore system. The images were modified by applying the morphological closing with or without the spike noise, which modelled tiny pores missed during scanning. Consequently, the macroporosity of the images approximated the air capacity at potentials −15.54 and −9.81 kPa. During the extended image analysis, we calculated: the index of soil pore network growth rate; the percolation number; the average cross-sectional size of the pore; the total length of pore path; the relative volume of pores overlapping the left and right, and the top and bottom image edge; the relative volume of pores connecting the left and right and the top and bottom edge of the image. The correlation coefficients between the parameters' values obtained from image analysis and from laboratory permeability measurements were calculated.

The water and air permeability and the air capacity of the chernozem decreased with depth into the soil pedon. With decrease in the saturated hydraulic conductivity, measured in the laboratory, there was a decrease in the relative volumes of pores overlapping the left and right and upper and lower edges of the image, obtained from image analysis. The air permeability was positively correlated with the index of pore network growth rate. Morphological and morphometric image analysis confirmed that the most important parameters determining the transport of fluids in the soil are continuity of the pore system and pore volume. Based on the results obtained from image analysis one can formulate qualitative conclusions concerning the water and air permeability of soil.

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1. Introduction

Determining the water and air permeability of soil enables to quantitatively characterize the ability of the soil to transport substances (Słowińska-Jurkiewicz et al., 2001). The rate of movement of solutions in the soil affects the availability of the dissolved nutrients to the organisms living in the soil, while aeration of the soil is related to the air capacity and permeability, and determines the oxygenation of the soil, as well as the soil ability to transport gases. For this reason, water and air permeability of the soil is of interest to a wide range of specialists in agricultural and environmental studies (Badorreck et al., 2013; Bryk et al., 2007; Bryk, 2009; Bryk and Kołodziej, 2009; Horn and Smucker, 2005; Kołodziej et al., 2007; Maruszewski and Dembski, 2008; Schjønning and Thomsen, 2013).

The transport of water, gases and solutes in soil is primarily determined by the soil structure and is shaped by the nature of the pores and the presence or absence of soil aggregates (Kutílek, 2004; Vogel et al., 2006). With regard to transport processes, soil may be treated as a two-phase system consisting of a solid phase and voids. In this respect, the characteristics of the geometric properties of the soil voids and/or solid phase should be expressed in numbers so as to allow the introduction of numerical structural parameters into models describing the fluid transport in the soil.

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Nomenclature

$A_{A(im)}$	relative area of macropores >21.2 μm by image analysis ($cm^2\ cm^{-2}$)
CHha	Haplic Chernozem
K_S	saturated hydraulic conductivity ($m\ d^{-1}$)
L_A	relative perimeter length of pore cross-sections ($cm\ cm^{-2}$)
L_P	total length of pore path (cm)
n_{per}	percolation number
$P_{A(-15.54)}$	air permeability at soil water potential −15.54 kPa ($10^{-8}\ m^2\ Pa^{-1}\ s^{-1}$)
$P_{A(-9.81)}$	air permeability at soil water potential −9.81 kPa ($10^{-8}\ m^2\ Pa^{-1}\ s^{-1}$)
P_O	total soil porosity ($cm^3\ cm^{-3}$)
TOC	total organic carbon ($mg\ g^{-1}$)
ν_G	index of soil pore network growth rate ($cm^3\ cm^{-3}$)
$V_{V(-15.54)}$	relative volume of macropores >18.3 μm derived from soil–water characteristic curve ($cm^3\ cm^{-3}$)
$V_{V(-9.81)}$	relative volume of macropores >29 μm derived from soil–water characteristic curve ($cm^3\ cm^{-3}$)
$V_{V(hor)}$	relative volume of pores connecting left and right edge of image ($cm^3\ cm^{-3}$)
$V_{V(im)}$	relative volume of macropores >21.2 μm by image analysis ($cm^3\ cm^{-3}$)
$V_{V(L+R)}$	relative volume of pores overlapping left and right edge of image ($cm^3\ cm^{-3}$)
$V_{V(U+D)}$	relative volume of pores overlapping top and bottom edge of image ($cm^3\ cm^{-3}$)
$V_{V(vert)}$	relative volume of pores connecting top and bottom edge of image ($cm^3\ cm^{-3}$)
$W_{V(-15.54)}$	soil water content at potential −15.54 kPa ($cm^3\ cm^{-3}$)
$W_{V(-9.81)}$	soil water content at potential −9.81 kPa ($cm^3\ cm^{-3}$)
ε	Euler's number (connectivity number)
λ_P	average cross-sectional size of a pore (mm)
ρ	dry soil bulk density ($Mg\ m^{-3}$)
ρ_s	particle density ($Mg\ m^{-3}$)

Moreover, the parameterization of the soil environment provides the basis for predicting the size of water and air permeability. One of the methods to quantify the soil structure is image analysis, based on large resin-impregnated preparations – soil opaque blocks. In this manner it is possible to link the characteristics of the soil structure with its ability to transport water and air (Kutílek and Nielsen, 2007). This, in turn, enables to predict the impact of the external conditions (e.g. climate or management) upon the ecological functions of the soil (Boizard et al., 2013; Mangalassery et al., 2013). A combination of the results of laboratory measurements of water and air permeability and the results of morphometric analysis provides expanded insight into the level and mechanisms of transport of substances within the soil. To our knowledge, such an approach is not sufficiently covered in the current literature.

This paper aims at the assessment of water and air permeability of a Haplic Chernozem developed from loess. The laboratory permeability measurements are presented against a number of morphometric indices that characterize the pore system in the soil, and were obtained by computer-aided image analysis on the basis of large resin-impregnated soil opaque blocks. Two indices of soil pore connectivity are proposed, namely the index of soil pore network growth rate (ν_G) and the percolation number (n_{per}).

2. Material and methods

2.1. Laboratory tests

The study was conducted on a Haplic Chernozem developed from loess, with a sequence of horizons O-A-AC-Ck, located in Marysin Kolonia (50°30′39″ N, 23°56′05″ E, SE Poland) in a mesophytic deciduous forest composed of oak *Quercus robur* and *Quercus petraea*, hornbeam *Carpinus betulus*, and lime *Tilia cordata*.

While making the basic soil pit, the profile of the chernozem was carefully analyzed. The soil under study was characterized by similar texture throughout the whole pedon. It did not display symptoms of excessive compaction or of the presence of hard-permeable layers. The density of the soil decreased gradually with depth and with the decreasing content of biogenic pores. Taking those observations into account, in the successive genetic horizons, points for taking samples were selected, that were characteristic and representative for the whole soil pedon. The samples were collected in 2010 from 5 soil layers: 0–8 cm (CHha1; horizons O-A), 26–34 cm (CHha2, horizon A), 60–68 cm (CHha3, horizon AC), 90–98 cm (CHha4, horizons AC-Ck), and 120–128 cm (CHha5, horizon Ck).

Samples with disturbed structure were used to determine soil texture (sand 0.05–2 mm, silt 0.002–0.05 mm, and clay <0.002 mm fraction content, $g\ g^{-1}$, by a combination of the hydrometer and the wet-sieve methods; Polish Society of Soil Science, 2009), total organic carbon (TOC, $mg\ g^{-1}$, PN-ISO 14235, 2003), the amount of carbonates ($CaCO_3$, $mg\ g^{-1}$, PN-ISO 10693, 2002), pH (in distilled water and in 0.01 mol dm^{-3} $CaCl_2$; PN-ISO 10390, 1997) and particle density (ρ_s, $Mg\ m^{-3}$, PN-ISO 11508, 2001).

Moreover, in 6 replicates, soil samples with preserved structure were taken vertically into metal cylinders with a volume of 100 cm^3. These were used to determine the dry soil bulk density (ρ, $Mg\ m^{-3}$) and soil water content at potentials −15.54 kPa and −9.81 kPa ($W_{V(-15.54)}$ and $W_{V(-9.81)}$, $cm^3\ cm^{-3}$) equilibrated on pressure ceramic plates. In both states of soil water saturation, air permeability (P_A) was also measured in the device designed to test the permeability of moulding sands (type LPiR-2e, Multiserw-Morek, Poland), to give the values of $P_{A(-15.54)}$ and $P_{A(-9.81)}$. During the measurements pores with an equivalent diameter <18.3 and <29 μm, respectively, were filled with water, and larger pores were accessible for air. These measurements were carried out at the constant ambient temperature (20 ± 0.5 °C), therefore the dynamic viscosity of air did not require consideration. The results of the air permeability were given in $10^{-8}\ m^2\ Pa^{-1}\ s^{-1}$. In the additional 6 samples collected into the corresponding cylinders, saturated hydraulic conductivity (K_S, $m\ d^{-1}$) was measured using the Wit's apparatus (Eijkelkamp).

Total porosity of the soil (P_O, $cm^3\ cm^{-3}$) was then calculated on the basis of the soil bulk and soil particle density. Thus, the relative volume of air-filled pores at both amounts of soil water was determined, hence defining the share of macropores with equivalent diameters greater than 18.3 μm ($V_{V(-15.54)} = P_O - W_{V(-15.54)}$; $cm^3\ cm^{-3}$), as well as greater than 29 μm ($V_{V(-9.81)} = P_O - W_{V(-9.81)}$; $cm^3\ cm^{-3}$).

2.2. Preliminary image analysis

From the above-mentioned layers of the pedon, samples with preserved structure were taken in the vertical plane into metal boxes measuring 8 cm × 9 cm × 4 cm. After being dried at room

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