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Resolving compactness index of pores and solid phase elements in sandy and silt loamy soils

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ABSTRACT

Soil structure is expressed by the size, shape, and arrangement of structural elements. Shape indices of pores and solid phase elements along with the physical soil parameters allow for thorough evaluation of soil structure. Therefore, the aim of the research was the analysis of properties of an index of shape – a compactness index $CMP = (16\ \text{area})/\text{perimeter}^2$ – of pore ("pore c-s") and solid phase element cross-sections ("solid c-s") $\geq 100\ \text{pix}^2$ ($0.045\ \text{mm}^2$) of 4 soils. *CMP* was calculated via image analysis of resin-impregnated soil blocks prepared from intact soil specimens. The morphometric parameters of the objects assigned to selected *CMP* classes (≤ 0.2, the lowest compactness; 0.201–0.4; 0.401–0.6; 0.601–0.8; 0.801–1; 1.001–1.2; > 1.2, the highest compactness) were compared via 2-way ANOVA for two horizons (A, C) and two textures (sand, silt loam). The usability of *CMP* in the description of soil structure was then tested. Moreover, the relations of the morphometric parameters of the objects in *CMP* classes and soil physical and chemical properties (total organic carbon *TOC*; bulk and particle density; texture; field water capacity *FWC*; field air capacity *FAC*; available water capacity *AWC*; air permeability at −15 kPa lg*FAP*; saturated hydraulic conductivity $\lg K_S$) were examined by way of single and multiple linear regressions. For pore and solid c-s of $CMP > 0.2$ their number, area, and average areas in *CMP* classes decreased with increasing *CMP* value. The distributions of pore and solid c-s among *CMP* classes depended on soil texture and structure (aggregate, non-aggregate), allowing for the diagnosis of soil structure status and change. Number and area of objects in *CMP* classes showed numerous strong relations ($R^2 > 0.7$) to the soil physical and chemical parameters for the studied soil textures and horizons. The relations differed for pore and solid c-s and depended also on the object shape (spread, compact or very compact). The average areas of the compact and very compact pore and solid c-s increased with the increase of clay and silt content and the decrease of sand content. The number of pore c-s of $CMP > 0.2$ was related to the texture or particle density. On the other hand, the number of solid c-s of $CMP > 0.2$, and the average area of the most spread solid c-s were related to *TOC* and bulk density. *FWC* and *AWC* increased with the decrease of the number of mainly compact and very compact pore c-s by the decrease of the average area of the most spread solid c-s. Both water capacities increased with the increasing average areas of pore c-s of $CMP > 0.2$ and the average areas of the compact and very compact solid c-s. *FAC* increased with the increase of the number of the compact and very compact pore c-s. $\lg K_S$ increased with the increase of the number and area of mostly compact and very compact pore c-s. lg*FAP* increased with the area and the average area of the majority of pore classes and some of the relations were also controlled by the number of pore c-s and the average area of the most spread solid c-s. The study showed moreover that *CMP* increased with the decreasing size of the objects when measured via computer-aided image analysis. Small cross-sections revealed usually larger *CMP* values, and large cross-sections were more often classified as irregular or spread. Therefore the analysis of shape of soil structural elements should encompass a wide range of element sizes in relation to the image resolution to obtain the unbiased shape distributions.

1. Introduction

Soil structure is defined as the physical constitution of soil material: the solid particles and the voids. Included are both the primary particles forming compound particles, and the compound particles themselves (Canarache et al., 2006). Soil structure is expressed by the size, shape, and arrangement of structural elements. These geometric parameters of soil structure, along with the physical soil parameters related to the soil structure status (bulk density, porosity, air and water permeability, etc.), should be taken into account for thorough evaluation of soil structure. The shape and orientation of soil pores and solid phase elements allows for diagnosis of soil structure change upon external factors

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(Skvortsova, 2009; Skvortsova and Utkaeva, 2008).

The use of shape indices in the analysis of soil structure has a long history. The initial source of information on the soil structure, allowing for its morphological and morphometric analysis, were 2D images derived on the basis of resin-impregnated thin sections or soil blocks. Most indices developed for 2D analog or digital photographs of structure utilized the area (*area*) and perimeter (*per*) of the pore or solid phase element cross-section. Beckmann (1962) applied "Lappungsquotient" calculated as $per/(4\pi \cdot area)^{0.5}$; Pardini et al. (1996) – index calculated as $area/per^2$; Bouma et al. (1977), Grevers and de Jong (1992), Puentes et al. (1992), Holden (1993), Sakai et al. (1996), Chun et al. (2008) – a roundness (or compactness) index calculated as $4\pi \cdot area/per^2$; Droogers et al. (1998) – "shape" = $per/(4\pi \cdot area)^{0.5}$ and "convex shape" = $(convex\ per)/(4\pi \cdot area)^{0.5}$; Panini et al. (1997), Pérès et al. (1998), Beaudet-Vidal et al. (1998), Hallaire et al. (2000), Pagliai et al. (2004) used an index which equalled $per^2/(4\pi \cdot area)$, referred to as shape or lengthening or elongation index. Skvortsova and Morozov (1993) and Skvortsova and Sanzharova (2007), in the form factor $F = (4\pi \cdot area/per^2 + W/L)/2$, incorporated also the longer (L) and shorter (W) axes of a minimal rectangle bounding a pore cross-section. New possibilities for soil structure studies emerged in the 1980s when the methods of high-resolution X-ray tomography, commonly called micro-CT, developed rapidly allowing for 3D recognition of numerous soil properties (Cnudde and Boone, 2013; Gerke et al., 2012). In consequence, shape indices for the evaluation of the 3D voids and particles were proposed (e.g. Garbout et al., 2013; Zhou et al., 2012). Although generally applied for 3D visualization and analysis, the micro-CT technique could also produce 2D soil images resembling those of thin sections (e.g. Gerke et al., 2012; Skvortsova et al., 2016). 2D data were also generated by throat-finding algorithms that locate planar cross-sectional areas in the void network to evaluate the drainage process in porous media (e.g. Lindquist, 2006). In both cases the above mentioned shape indices originally developed to study 2D images could still be employed.

The choice of the most appropriate indices describing geometrical properties of soil structural elements depends primarily on the purpose of the research (Droogers et al., 1998). In the classification of soil pore or aggregate cross-sections in the 2D images, probably the most widely used is the circularity (roundness, compactness) index expressed in the general form $b \cdot area/per^2$ (where b usually equals 1 or 4π). The "shape factor" $G = area/per^2$ (Mason and Morrow, 1991; Øren et al., 1998), along with the equivalent roundness (compaction) index $4\pi \cdot area/per^2$ which is the conventional shape factor G normalized by 4π, are applied also in pore-network models which describe flow and transport mechanisms and are used in predicting flow properties of different porous media. The shape factor G and its analogues are important in pore-network models for accurate prediction of fluid volumes and wetting layer conductivities in one- and multi-phase flow and are used to assign the shape of pores and throats during flow simulations (Helland et al., 2008; Miao et al., 2017), because the dimensionless shape factor G shows a strong and monotonic relationship with the dimensionless conductance (e.g. Miao et al., 2017; Patzek and Silin, 2001; Sholokhova et al., 2009).

The parameters describing the shape of soil pores or solid phase elements are morphological indices which do not have their direct physical analogues. At the same time, the numerical shape indices of soil structural elements are of the major diagnostic value and they support the quantitative evaluation of soil structure status (Skvortsova and Utkaeva, 2008). Consequently, they are widely used. However, even in the recent literature dealing with soil structure studies via computer image analysis, important information about conditions of the shape analysis (number of pixels in the minimal object, method of perimeter calculation, image resolution per pixel, etc.) is neglected rendering the presented results hardly usable. In addition, a systematic knowledge of the shape indices is lacking which hinders the correct interpretation of the shape analysis, since the main attention is paid to the object (soil, geological material, etc.) characterized with the use of shape indices rather than a shape index itself.

Therefore, the aim of the research was the analysis of properties of an index of shape – a compactness index analogous to the above mentioned shape factor G – in order to (1) draw attention to its specific characteristics resulting from its measurement via digital images of soil structure, and (2) test its usability in the description of soil structure and soil water and air properties. The compactness index was calculated as $CMP = 16 \cdot area/per^2$, which reflected the shape of cross-sections of soil pore or solid phase element relative to a square, to account for the fact that soil structure was studied via scanned raster images consisting of square pixels. The compactness index was employed in the study, because it was among the most popular indices, i.e. the ones of the "$b \cdot area/per^2$" type, which were commonly used both in the soil structure studies and for the evaluation of hydraulic properties of porous media. The index was calculated via image analysis of resin-impregnated soil blocks prepared from intact soil specimens taken from 4 soils. Then, the morphometric parameters of the objects in the selected compactness index classes were compared for two horizons (A, C) and two textures (sand, silt loam). Moreover, the relations of the morphometric parameters of the objects in the compactness index classes and soil physical and chemical properties were examined.

2. Materials and methods

2.1. Study site

Soil samples were taken from: Albic Podzol (PZ-ab), Dystric Brunic Arenosol (AR-br.dy), Haplic Chernozem (CH-ha), and Eutric Cambisol (CM-eu) (IUSS Working Group WRB, 2015) located in a possibly slightly changed forest areas of south-eastern Poland. Albic Podzol developed from eolian sand and Dystric Brunic Arenosol – from glaciofluvial sand, while Haplic Chernozem and Eutric Cambisol developed from loess (Table 1).

2.2. Sampling and analysis methods

For the study, A and C or Ck horizons were chosen since they show contrasting chemical and physical properties. The upper A horizons were influenced by a variety of external factors. On the other hand, C horizons were little affected by pedogenetic processes, so they represented a suitable point of reference in the research. From the chosen layers of the soils' A, C or Ck horizons (Table 2), samples with preserved structure were taken in 2 replicates in the vertical plane into metal boxes measuring 8 × 9 × 4 cm. Dried soil samples were impregnated with a resin solution following the method described earlier (Bryk and Kołodziej, 2014). After hardening each soil sample was cut and polished into 3 ca. 8 × 9 × 1 cm slices, 2 with one and 1 with two sides ready for analysis. For each tested layer in total eight soil block faces were thus obtained. Afterwards, the soil block faces were scanned with a flatbed scanner at a constant resolution of 1200 × 1200 dpi ($1\ pix^2 = 21.17 \times 21.17\ \mu m^2$) with 24-bit colour depth. Finally, each image was ca. 4000 × 4000 pixels. The areas of the scanned images varied, because for each sample the maximum rectangle was chosen which omitted the uneven edges of soil blocks. On the basis of the soil blocks and their enlarged photos, morphographic and morphological structure analyses of the tested soils were performed. The structure was described using the terminology given by Słowińska-Jurkiewicz et al. (2012) and Aguilar et al. (2017). The scanned images were used also for morphometric analysis. First, the blue channel which was characterized by the best contrast was isolated from the colour images. The obtained images were recorded in 256 shades of grey, with prior improving of their contrast and intensity. Subsequently, on the images a sequence of operations and measurements was made using the image analysis program Aphelion (Adcis SA). First, the images were thresholded, i.e. the limit value of grey level between the solid phase and pores was selected