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Soil aggregate geometry: Measurements and morphology

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ABSTRACT

Aggregates provide physical microenvironments for microorganisms, the vital actors of soil systems, and thus play a major role as both, an arena and a product of soil carbon stabilization and dynamics. The surface of an aggregate is what enables exchange of the materials and air and water fluxes between aggregate exterior and interior regions. We made use of 3D images from X-ray CT of aggregates and mathematical morphology to provide an exhaustive quantitative description of soil aggregate morphology that includes both intra-aggregate pore space structure and aggregate surface features. First, the evolution of Minkowski functionals (i.e. volume, boundary surface, curvature and connectivity) for successive dilations of the solid part of aggregates was investigated to quantify its 3D geometrical features. Second, the inner pore space was considered as the object of interest. We devised procedures (a) to define the ends of the accessible pores that are connected to the aggregate surface and (b) to separate accessible and inaccessible porosity. Geometrical Minkowski functionals of the intra-aggregate pore space provide the exhaustive characterization of the inner structure of the aggregates. Aggregates collected from two different soil treatments were analyzed to explore the utility of these morphological tools in capturing the impact on their morphology of two different soil managements, i.e. conventional tillage management, and native succession vegetation treatment. The quantitative tools of mathematical morphology distinguished differences in patterns of aggregate structure associated to the different soil managements.

1. Introduction

Soil aggregates are key elements of soil structure that play a major role in several soil processes including the accumulation and protection of soil organic matter, the optimization of soil water and air regimes, and the storage and availability of plant nutrients (von Lützow et al., 2006). Intra-aggregate properties strongly affect all these functions. It has been shown that gradients of a number of soil characteristics exist inside soil aggregates. Among them are gradients in oxygen concentrations of the soil air (Sexstone et al., 1985), gradients in concentrations of a variety of elements, including Ca, Mg, K, Na, Mn, K, Al, and Fe (Jasinska et al., 2006; Santos et al., 1997), and gradients in organic matter compositions (Ellerbrock and Gerke, 2004; Urbanek et al., 2007). These differences in intra-aggregate characteristics in turn influence activities and compositions of soil microbial communities (Blackwood et al., 2006; Jasinska et al., 2006). Aggregates are of particular importance for processes of soil carbon sequestration (Chenu and Plante, 2006; Six et al., 2000). It has been shown that intra-aggregate characteristics, such as size-distributions of intra-aggregate pores, can be directly related to the amount of C stored inside the aggregate (Ananyeva et al., 2013).

The influence of long-term management differences manifests itself not only on the overall soil aggregation but also on the intra-aggregate characteristics. The use of advanced X-ray 3D imaging techniques has greatly increased our ability to explore intra-aggregate features in intact aggregates and resulted in a large number of studies that demonstrated that tillage, land use and fertilization regime can have a major effect on intra-aggregate pore characteristics (Kravchenko et al., 2011; Peth et al., 2008; Wang et al., 2012; Zhou et al., 2013; Zucca et al., 2013).

In particular, it is known that converting the land that has been long under intensive agricultural management back to its natural vegetation will often result in a number of changes in soil characteristics, including increase in soil organic matter and increase in numbers and stabilities of soil macro-aggregates (e.g., De Gryze et al., 2004; Grandy and Robertson, 2007). These changes result from combined influences of a removal of soil disturbance by tillage and of an increase in diversity and duration of the plant biomass inputs to soil. We have observed marked effects on intra-aggregate characteristics of macro-aggregates in the soil that was abandoned from agriculture and was under native vegetation succession for the past 18 years. Such aggregates had greater heterogeneity in intra-aggregate pore distributions as compared with the aggregates from conventional agriculture (Kravchenko et al., 2011).

Another characteristic of the soil macro-aggregates that can have a substantial effect on their functioning is the properties of the aggregate surfaces. The surface of an aggregate enables exchange of the materials and air and water fluxes between the interior and exterior layers of aggregates. Its characteristics along with numbers and properties of soil pore opening at the aggregate surfaces influence the accessibility

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of aggregate interiors to microbes, and thus can influence the ability of aggregates to protect soil carbon. It is likely that long-term differences in land use and management can affect the characteristics of the aggregate surfaces, however, to our best knowledge there have been no studies that specifically addressed this question.

A number of studies have been conducted to explore aggregate structure and investigate soil functioning. Image analysis and conventional mathematical measurements were used to quantify that structure. Whalley et al. (2005) studied the structural differences of adjacent soil to roots and bulk soil with image analysis of thin sections of aggregates. De Gryze et al. (2006) evaluated porosity and pore size distribution of the voids of aggregates as well as its mass fractal dimension with 2D sections of CT images. They were interested in the changes of pore structure during decomposition of fresh residue. Microbial micro-habit structure was investigated by Nunan et al. (2006) by combining synchrotron-based CT, image analysis and geostatistics of soil aggregates. Also fractal geometry have been use to quantify that structure. Young and Crawford (1991) devised a simple method to estimate fractal dimension with the mass and size of soil aggregates. Giménez et al. (2002) studied the changes of this fractal dimension for intact and eroded soil aggregates of cultivated and wooded soils. Image analysis of thin section of soil aggregates was used to estimate porosity and fractal dimension by Papadopoulos et al. (2006). They wanted to quantify the effects of contrasting crop in the development of soil structure. CT technology was used by Gibson et al. (2006) to compare fractal analytical methods on 2D and 3D. Chung Chun et al. (2008) used image analysis of thin section of soil aggregates to examine pore structure inside aggregates with lacunarity and entropy functions. More recently, Kravchenko et al. (2011) explored the effect of long-term differences in tillage and land use on intra-aggregate pore heterogeneity with fractal techniques.

In this work, a quantitative description of the internal geometrical characteristics as volume and connectivity of intra-aggregate pore space and of the external features as area and shape of aggregates' surface with the unified framework that provides mathematical morphology (Serra, 1982) through morphological tools known as the Minkowski functionals is proposed. Mathematical morphology offers a plethora of mathematical techniques to analyze and parameterize the geometry of different features of soil structure. These techniques belong to well established mathematical fields as integral geometry (Santaló, 1976), stochastic geometry (Matheron, 1975) or digital topology and geometry (Klette and Rosenfeld, 2004). They make available a sound mathematical background that guides the process from image acquisition and analysis to the generation of synthetic models of soil structure (Arns et al., 2004) to investigate key features of flow and transport phenomena in soil (Lehmann, 2005; Mecke and Arns, 2005).

In the sixties, the need for analyzing spatial data from geology led to Matheron and his colleagues at the Paris School of Mines at Fontainebleau (France) to the introduction and development of computer technologies and mathematical techniques that now are known as mathematical morphology (Serra, 1982). Dullien and collaborators (see Dullien, 1992 and the references therein) made use of these techniques to investigate the relationship between soil pore structure and fluid flow phenomena. At that time they mostly used stereology to gain three-dimensional information from two-dimensional images obtained by image analysis of soil sections (Horgan, 1998; Moran et al., 1989a, 1989b; Vogel and Kretzschmar, 1996; Vogel et al., 2005).

X-ray computed tomography (CT) provides a direct procedure to use three-dimensional information to quantify geometrical features of soil pore space (Lehmann et al., 2006). In the last few decades mathematical morphology has been successfully used to analyze different characteristics of the rich three-dimensional geometrical information gained through X-ray CT (Banhart, 2008). Among the tools of mathematical morphology, Minkowski functionals are particularly worthy of consideration since they provide computationally efficient means to measure four fundamental geometrical properties of three dimensional geometrical objects such as soil aggregates. Their prominence relies on the mathematical fact (Santaló, 1976) that any other geometrical measurement that meets some self-evident and natural geometrical restrictions is a linear combination of these Minkowski functionals. Moreover, they represent four very familiar geometrical attributes: the volume, the boundary surface, the mean boundary surface curvature and the connectivity of the pore space. These functionals are powerful tools to quantitatively describe 3D geometry. Mecke (1998) and Roth et al. (2005) made use of Minkowski functions based on threshold variation of Minkowski functionals to characterize two-dimensional porous structures. Also, two-dimensional porous structures were investigated by Mecke (2002) and Vogel et al. (2005) with Minkowski functions based on dilations and erosions. Arns et al. (2002, 2004) considered the evolution of Minkowski functionals with dilations and erosions to characterize 3D images of Fontainebleau sandstone.

This paper is organized as follows. The building blocks of mathematical morphology are introduced in Section 2. Firstly, we introduce the morphological operations of dilation, erosion, opening and closing. Then, we described Minkowski functionals and the morphological functions. Technical details are presented in Appendix A. Section 3 is devoted to the description of the data set, the computation of Minkowski functionals and morphological functions, and the partition of aggregate pore space into accessible and inaccessible porosity. Technical details of that partition are given in Appendix B. Section 4 presents the results and discussion in the light of the main goals of this work, which are: (i) to provide a comprehensive quantitative description of soil aggregate structure through the morphological analysis of 3D CT images that includes both, aggregate surface features and intra-aggregate pore space structure, and (ii) to explore the ability of these techniques to detect changes in soil characteristics associated with long-term differences in land use and soil management.

2. Theory: morphological analysis

Morphological analysis mimics other scientific procedures and in some instances can be seen as a two-step process. To illustrate this point, let us consider the procedure to determine particle size distributions by sieving. This technique first generates a series of subsets of primary mineral particles corresponding to each sieve size; then, these subsets are weighted. In morphological analysis, first, geometrical transformations are applied to the object of interest in an image and then, measurements are carried out. When the granulometry – i.e., the grain size distribution – of an image of grains of different sizes shall be determined, successive morphological operations are performed on the image. These operations consist in the elimination of grains smaller than a certain size with a suitable morphological transformation. Each one of these operations is followed by the measurement of the area for 2D images or the volume for 3D images, of the grains left (Serra, 1982). Fig. 1 illustrates this procedure in a CT image of packed sand particles. In the following paragraphs, the basic morphological operations of dilation and erosion will be presented. Other two fundamental operations are opening and closing, that are defined in terms of dilations and erosions, will be introduced latter. Finally the notions of Minkowski functionals and morphological functions will be described. Additional details of these mathematical tools may be found in Appendix A.

2.1. Transformations: morphological operations

Grains or pore space in a 3D CT image will be idealized as 3D shapes (i.e. sets of points, K, in a three-dimensional space). The original object of interest, K, will be transformed by spheres of radius r centered at point x, B_x, – *structuring elements* – that will be called *balls*. The *dilation* by balls of radius r defines a new object $\delta_{rB}(K)$. Roughly speaking it is like a layer of thickness r is added to K. It is the union of all balls of radius r centered at points of object (Fig. 2). The *erosion* by the same type of