Geoderma xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Multifractal analysis of 3D images of tillage soil

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ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form 7 January 2017
Accepted 16 February 2017
Available online xxxx

Keywords:
Multifractal
3D-images
Gliding method
Cube Counting
Spatial distribution

ABSTRACT

Recently, X-ray microtomography (*μCT*) has open a new way to study soil pore structures. However, *μCT* data originally comes as gray scale images and the selection of segmentation method to binarized it has an important influence in the structure characterization. Three soil *μCT* 3D images, corresponding to ploughed soil with different tillage tools, were used in this study. A multifractal analysis was applied to the original gray images avoiding image binarization to characterize and differentiate different soil structures. In this analysis we took into account the effect of image resolution and the subdivision method applied, Cube Counting (CC) and Gliding Cube (GC). Comparisons among the multifractal spectrums (MFS) estimated indicated that the reduction in resolution affected more in Molboard image in which the minimum scale included in the analysis was one voxel and it was almost imperceptible in the Chisel image. The three multifractal spectrums were quite distinctive when the maximum resolution was chosen and the GC method was used, meanwhile the CC method obtained the MFS of Chisel and Roller too close to be differentiated. The amplitude and symmetry of the multifractal spectrums point out the influence of each tillage tool in the hierarchy of soil structure. Moldboard creates a higher complexity in soil structure as it physically removes the soil. Chisel tends to destruct the aggregates homogenizing soil structure and presents a weak multifractal nature. Finally, Roller is an intermediate case with a scaling character mainly in the lower gray values of the soil image.

1. Introduction

There is increasing evidence that quantitative characterization of the soil structure and of its heterogeneity holds the key to a deeper understanding on physical, chemical and biological processes that take place within them (Young and Crawford, 2004; Blair et al., 2007). Recent advances in imaging techniques, such as X-ray Computer Tomography (X-ray CT) have opened new perspective for the quantification of the internal pore structure of soils as well as characterizing their heterogeneity (Pierret et al., 2002; Anderson et al., 2003; Rachman et al., 2005; Gibson et al., 2006b; Taina et al., 2008; Garbout et al., 2012). X-ray CT provides qualitative and quantitative information on the 3D physical structure and the spatial distribution of the pore space (Houston et al., 2013) and reveals the extraordinary complexity of this system (Santiago et al., 2008; Cárdenas et al., 2010). At the same time, these techniques reduce the physical impact of sampling and allow to a rapid scanning to study sample dynamics in near real-time (Garbout et al., 2013a). This is a significant step to study natural porous media at micro-scale.

Therefore, X-ray CT soil images can give a good understanding of soil structural changes due to soil tillage and compaction (Taina et al., 2008). We can found in the literature several studies documenting these soil management effects on soil physical properties using X-ray CT systems (Olsen and Børresen, 1997; Munkholm et al., 2003; Papadopoulos et al., 2009; Garbout et al., 2013b; Munkholm et al., 2013 among others). For example, Gantzer and Anderson (2002) highlighted the number and size of macropores importance in tillage-induced structures. Rasiah and Alymore (1998) found that macropore physical properties affect water flow rate and retention using an X-ray CT analysis.

Fractal geometry has been increasingly applied to quantify soil structure, using fractal parameters derived directly through image analysis, due to the complexity of the soil structure, and thanks to the advances in computer technology (Tarquis et al., 2003). First, several works have been done extracting mass fractal and surface

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http://dx.doi.org/10.1016/j.geoderma.2017.02.013
0016-7061/

fractal dimensions (Brakensiek et al., 1992; Pachepsky et al., 1996; Giménez et al., 1997; Gimenez et al., 1998; Oleschko et al., 1998; Bartoli et al., 1999; Dathe et al., 2001; Dathe and Thullner, 2005; Rogasik et al., 1999; Gantzer and Anderson, 2002; Perret et al., 2003). There are many studies on soil tillage research applying fractal methods focused on macroporosity or pore surface area based on CT-scan soil images (Perfect and Kay, 1995 see references therein).

Later on, the studies based on soil images have evolved to a multifractal analysis -MFA (Posadas et al., 2003; Bird et al., 2006; Dathe et al., 2006; Martínez et al., 2010) becoming widely applied. Even we focused this work on the use of MFA to study the relation of the characterization of soil structure among scales, there are several works studying wider scaling behaviours. These analyses include extended power-law scaling (linear relations between log structure functions of successive orders) at all lags, and frequency distributions of the variable's increments tending to be symmetric with peaks that grow sharper, and tails that become heavier, as the lags between pairs of values decreases (Guadagnini et al., 2014).

However, searching on multifractal methods in soil tillage research almost of them are dedicated to soil microtopography (Vázquez et al., 2008), soil surface roughness (Roisin, 2007; García Moreno et al., 2008) and quantify distributions of soil properties (Siqueira et al., 2013; Jonard et al., 2013).

Despite these progresses, there remains a lack of general agreement to the appropriate pore-solid CT threshold (Tarquis et al., 2008; Cortina-Januchs et al., 2011), which is used to obtain a black and white image from the original gray scale data, before calculating any of these parameters. Gibson et al. (2006a) compared three fractal analytical methods to quantify the heterogeneity within soil aggregates; in this work, the frequency distribution of pore and solid components was clearly dependent on thresholding, which could not be generalized. Tarquis et al. (2009) point out that a practical problem in the MFA of binary images is that the thresholding method have a pronounced effect on the porosity and resulting generalized dimensions. It has been suggested to further study grayscale soil images for multifractal characterization of soil structure avoiding any intermediate thresholding step (Zhou et al., 2010; Zhou et al., 2011). This MFA applied in grayscale images is very common in other type of images (Lovejoy et al., 2008; Tarquis et al., 2014).

On the other hand, MFA normally involves partitioning the space of study into non overlapping boxes (cubes in the case of this study) to construct samples with multiple scales, known as the box counting method and named in this study as Cube Counting (CC) method. The number of samples at a given scale, applying it, is restricted by the size of the partitioning space and data resolution, which is usually another main factor influencing statistical estimation in MFA (Cheng and Agterberg, 1996). To avoid these problems several methods have been proposed being one of them the Gliding box method (GB) already applied in several type of images (Grau et al., 2006; Tarquis et al., 2007) and in this study we will named it as Cube Gliding (CG) method..

The two objectives of this work are to study: 1) the effect of the subdivision method applied in the calculation of the multifractal parameters, comparing the CC and CG method and the effect of image resolution; 2) the effect of the different soil structure in the multifractal parameters calculated on gray scale soil images. With these purposes, 3D CT scan gray scale soil images, extracted from areas ploughed with different tools, were used.

2. Material and methods

2.1. Study area and image acquisition

For this study we have analysed 3 real soil samples. All of them have been extracted from the same experimental farm in Cordoba (Spain) but ploughed with different tillage tools.

The trials were conducted at the Alameda del Obispo experimental farm (38N, 5W, altitude 110 m), Cordoba, Spain (see Fig. 1). The climate is Mediterranean with a mean annual rainfall of 595 mm. Summer in Cordoba is dry and hot while autumn and winter are mild and rainy (Peel et al., 2007). The soil is a loamy alluvial with particle-size distribution in the upper (0–15 cm) soil layer: sand, 350 $\frac{g}{kg}$; silt, 443 $\frac{g}{kg}$; and clay 207 $\frac{g}{kg}$ (Boulal et al., 2011). It is classified as Typic Xerouvent (Soil Survey Staff, 2010).

Intact cores of soil samples for each of the tillage treatment were packed into polypropylene cylinders of 8 cm diameter and 10 cm high. These were imaged using an mSIMCT at 155 keV and 25 mA. An aluminium filter (0.25 mm) was applied to reduce beam hardening and later several corrections where applied during reconstruction. All 3D volumes were converted using VGStudioMax v.1.2.1 into image stacks with voxel-thick slices. All soil samples were scanned and reconstructed into 3-D volumes with a voxel size of 80 µm. From the reconstructed volumes a centred volume of $256 \times 256 \times 256$ voxels (20.5mm × 20.5mm × 20.5 mm) were selected for all samples.

Fig. 2 shows the original 3-Dimensional model reconstructed from the slices obtained with CT-scan. We have selected a $256 \times 256 \times 256$ voxel subsample for the analysis of each different tillage. The full size is computed through the Cube Counting and Gliding method, and then scaling it with Bilinear Interpolation algorithm using ImageJ 3D software to $128 \times 128 \times 128$ voxel and analysing again with both methods.

2.2. Multifractal analysis

An object has its topological measure which is one of the several ways of defining the dimension of the space. For example, the topological dimension of a line is one,the dimension of surface is two, and the dimension of a 3D object is 3. However there are some natural and mathematical objects that exceeds their topological dimension. A geometrical fractal is a mathematical object which can exceed its topological dimension and typically displays self-similar patterns, e.g., the borders of a country (Mandelbrot, 1967), the Koch snowflake (Mandelbrot, 1983) or Sierpinski triangle.

When we pass from a geometrical object to a measure, as gray values in an image could be interpreted, we are passing to another type of analysis that can be seen as an extension of fractals. Multifractal analysis initially appeared to study of energy dissipation on multiplicative cascades models in the context of the fully developed turbulence (Mandelbrot, 1999). After that it has been implemented on several different natural systems.

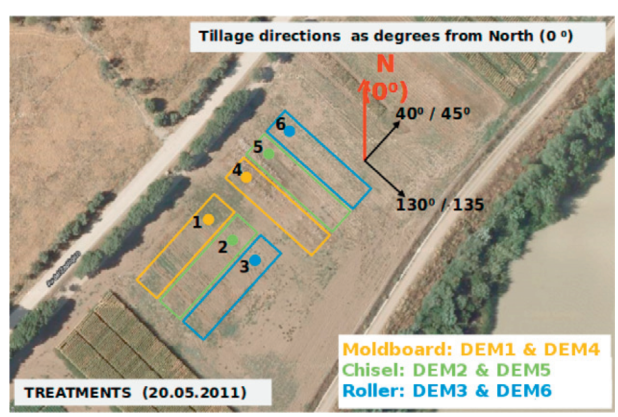

Fig. 1. Soil samples were extracted from different areas ploughed with three different tools: Moldboard in yellow, Chisel in green and Roller in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: I. Torre et al., Multifractal analysis of 3D images of tillage soil, Geoderma (2017), http://dx.doi.org/10.1016/j.geoderma.2017.02.013