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Multiscaling properties of soil images

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Soil structure may be defined as the spatial arrangement of soil particles, aggregates and pores. The geometry of each one of these elements and their spatial arrangement has a great influence on the transport of fluids and solutes through the soil. Soil thin sections (STS) have been widely used to characterise them and more recently computed tomography (CT) has provided an alternative for observing intact soil structure in 3D. Both types of images are grey-scale, normally with 8 bit depth.

In this work we propose to quantify the structural complexity of their spatial arrangement by applying multifractal analysis (MFA) to the original grey images no previous binarisation and compare the results in 2D and 3D. Their singularities (α) and $f(\alpha)$ spectra calculated have been used for this comparison. With this purpose, an original CT-scan image of $256 \times 256 \times 256$ voxel-thick slices of a soil was used. Three 2D subsamples were extracted in three different directions to analyse and compare with the 3D structure.

All images analysed presented a multiscaling character, in 2D and 3D, pointing out that the lower grey values are mainly influencing the scaling behaviour. The multifractal parameters were influenced by 2D slice position and direction and their values were lower than the ones obtained in the 3D image analysis. Therefore, in order to compare soil structures based on grey images, a 3D volume is desirable.

The multiscaling nature of these images suggests using these algorithms as a basis to create synthetic images for testing thresholding algorithms.

1. Introduction

Over the last decade, major technological advances in X-ray computed tomography (CT) have allowed the investigation and reconstruction of two and three-dimensional natural porous media architectures at very fine scales (Pierret, Capowiez, Belzunces, & Moran, 2002; Anderson, Wang, Peyton, & Gantzer, 2003, pp. 135–149; Rachman, Anderson, & Gantzer, 2005; Gibson, Lin, & Bruns, 2006; Taina, Heck, &

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Nomenclature

α	Singularity index
BC	Box counting method
CT	Computed tomography
D_q	Generalized dimensions
$\Delta\alpha$	$\alpha_{max} - \alpha_{min}$
Δf	$f(\alpha_{max}) - f(\alpha_{min})$
ε	Size of boxes or cubes (depending on 2D or 3D)
$f(\alpha)$	Multifractal spectra function
GB	Gliding box method
i	Index of each box with size ε
MFA	Multifractal analysis
MFS	Multifractal spectrum
N_ε	Total boxes of size ε that contained more than 0 pixels
$P_i(\varepsilon)$	Mass density of cube i and size ε
q	Scaling exponent for MFA
STS	Soil thin sections
$\tau(q)$	Mass exponents function
$\chi(q,\varepsilon)$	Statistical moment of the distribution

Elliot, 2008; Garbout et al., 2011). Soil scientists can use this quantitative characterisation of the soil structure and of its heterogeneity to understand more deeply the physical, chemical and biological processes that take place within them (Young, 2004; Blair, Falconer, Milne, Young, & Crawford, 2007). At the same time, these techniques reduce the physical impact of sampling and allow rapid scanning to study sample dynamics in near real-time (Garbout, Munkholm, & Hansen, 2013). This is a significant step to wards the studying natural porous media at micro-scale.

Later, some studies have analysed the internal soil structure from a fractal point of view due to its complexity (Tarquis, Giménez, Saa, Díaz, & Gascó, 2003, and references therein). The first works were focused on extracting mass fractal and surface fractal dimensions from black and white images (Brakensiek, Rawls, Logsdon, & Edwards, 1992; Pachepsky, Yakovchenko, Rabenhorst, Pooley, & Sikora, 1996; Giménez, Allmaras, Nater, & Huggins, 1997; Oleschko, 1998; Bartoli, Bird, Gomendy, Vivier, & Niquet, 1999; Dathe, Eins, Niemeyer, & Gerold, 2001; Gantzer & Anderson, 2002; Perret, Prasher, & Kacimov, 2003; Dathe & Thullner, 2005). Quite recently, these types of analysis have evolved to a multifractal analysis (MFA) as they showed that the complexity of the images could not be described with a single dimension (Posadas, Giménez, Quiroz, & Protz, 2003; Bird, Díaz, Saa, & Tarquis, 2006; Dathe, Tarquis, & Perrier, 2006; Martínez et al., 2010). Despite this progress, there remains a lack of general agreement on the appropriate pore-solid CT threshold (Cortina-Januchs, Quintanilla-Dominguez, Vega-Corona, Tarquis, & Andina, 2011), which should be used to obtain a black and white image from the original grey scale data, before calculating any of these parameters. In the field of soil science, several algorithms has been proposed and tested with synthetic images created with different types of noise (Wang, Kravchenko, Smucker, & Rivers, 2011; Houston, Otten, Baveye, & Hapca, 2013; Hapca, Houston, Otten, & Baveye, 2013).

Multifractal analyses can be applied to grey scale soil images to determine parameters such as generalised fractal dimensions, Holder exponents and multifractal spectra (Zhou, Perfect, Li, & Lu, 2010; Zhou, Perfect, Lu, Li, & Peng, 2011). It has been suggested soil that grayscale soil images should be further studied for multifractal characterisation of soil structure avoiding any intermediate thresholding step (Zhou et al., 2011). This MFA applied in grayscale images is very common in other type of images (Lovejoy, Tarquis, Gaonach, & Schertzer, 2008; Tarquis et al., 2014).

The objectives of this work are to investigate in this type of image: 1) the scaling nature of the grey values in the 2D and 3D images; 2) the effect of the direction in the 2D images selected from a 3D soil image in the calculation of the multifractal parameters; 3) the comparison of the information extracted from 2D and 3D images. With these purposes, 3D CT scan grayscale soil images, extracted from a sandy loam soil, were used.

2. Material and methods

2.1. Study area and image acquisition

An arable sandy loam soil from a field of Scotland was packed into polypropylene cylinders of 6 cm diameter and 5 cm high at 1.2 Mg m^{-3} bulk density and air-filled pore volume 0.17. For further details see Harris, Young, Gilligan, Otten, and Ritz (2003).

The soil sample was imaged using a Metris X-Tek X-ray micro-tomography system at 160 kV, 201 μA and 3003 angular projection. In order to minimise beam hardening, aluminium filter (0.10 mm) was applied, and the reconstruction process also implied several corrections. Radiographs were reconstructed into a 3-D volume using CT-Pro (Nikon), and then they were imported into VGStudio Max Software (Volume Graphics), and converted into 8-bit binary TIFF images.

An image stack of 256 × 256 × 256 voxel-thick slices with a resolution of 30 μm (voxel length size) was used in this study. For further details see Pajor, Falconer, Hapca, and Otten (2010). The subsamples of the analysis have been extracted from here.

In Fig. 1 shows the original 3 dimensional model reconstructed from the slices obtained with CT-scan. The full size and some of the slices oriented in different directions are computed through gliding method using scripts programmed with ImageJ 3D software.

2.2. Multifractal analysis

We are all used to working with the topological dimension which is a natural measure around us. The topological dimension of the common object in our life is three, and sometimes we also work with the surface, which has a dimension of two. We are even able to be more abstract and use topological dimensions of one and zero for lines and points respectively. However there are other cases where the object can not be defined properly by a topological dimension because exceeds the measure. There are many examples both in nature (the borders of a country, galaxy clusters,

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