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Lacunarity of soil macropore space arrangement of CT images: Effect of soil management and depth

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ABSTRACT

In this work we make use of 3D digital images of soil macropore space acquired by X-ray computed tomography of intact soil columns from a Mediterranean vineyard north of Spain to investigate how lacunarity describes soil structure. In the framework of fractal geometry, lacunarity can be seen as a test of fractal behavior and an alternative method to estimate fractal dimensions. From a wider perspective lacunarity provides insight into arbitrary spatial configurations. In this investigation, we consider different architectures of the dispersion and clustering of soil macropore space as deviations from the linear pattern of log-log lacunarity functions. We will explore how lacunarity quantifies different geometrical structures of soil macropore volumes and how these structures are affected by soil management and depth. We observed that, in the uppermost 15 cm of soil, treatment has an impact in the spatial arrangement of macropore space and that log–log lacunarity functions could display three different shapes that should be related to three different patterns of dispersion and clustering of macropore space. We also observed changes of soil macropore structure for samples up to a depth of 60 cm that could be described with the same three patterns of the log-log lacunarity functions found in the uppermost 15 cm of soil.

1. Introduction

Soil structure and soil functioning are the two sides of an essential equation in soil sciences that remains a challenge and is far from fully understood. This link between soil structure and soil functioning is of fundamental importance for a range of environmental issues such as C protection in soil (Kravchenko et al., 2015), the response of soil to changing climatic boundary conditions or to agricultural practices (Pot et al., 2015), and the description of water solute and gas transport through the complex geometrical structure of soil pore space (Lehmann et al., 2006; Katuwal et al., 2015). Therefore, detailed knowledge of the geometrical attributes of soil pore network topology is essential to generate precise digital representations of soil-void boundaries at the pore scale to simulate soil processes such as the ones mentioned above, and to ensure that the outputs of such models adequately reflect the reality they purport to represent (Lehmann et al., 2008).

X-ray computed tomography (CT) of soil provides a direct procedure to quantify the geometrical attributes of soil pore space in three dimensions (Wildenschild and Sheppard, 2013). The development of digital image processing has enabled a tremendous expansion in the quantitative analysis of soil structure as 3D geometrical objects and new mathematical techniques have been introduced to gain geometrical measurements of soil pore structure. This will facilitate new methods that might convey enough information to actually predict soil processes such as those previously mentioned (Schlüter and Vogel, 2011).

Lacunarity was first introduced (Mandelbrot, 1983) to characterize fractal objects with the same fractal dimension in order to quantify different patterns of dispersion and clustering of spatial geometrical structures —sometimes referred as texture in image processing analysis. This quantification is related to the translational invariance of the geometrical object of interest. But translational invariance is highly scale dependent; objects that are heterogeneous at small scales could be very homogeneous at larger scales and vice versa. Thus, lacunarity provides a scale dependent measure of the dispersion and clustering of geometrical objects as it measures the deviation from translational invariance for each scale (Plotnick et al., 1993). It is worth noting that translational invariance is not the same as self-similarity.

Fractal self-similar objects display a high degree of heterogeneity at all scales but this heterogeneity follows a precise pattern due to the self-similarity property these particular geometrical objects have. As a consequence, lacunarity as a function of scale displays a distinct behavior for self-similar objects: the log-log lacunarity function is linear and its slope coincides with the fractal dimension of the object up to an additive term that corresponds to the dimension of the embedding space (Allain and Cloitre, 1991). Therefore lacunarity can be used as a test of self-similarity and as an alternative way to estimate the fractal dimension. A

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great number of applications of lacunarity have being developed with different types of extensions of the original concept including the analysis of binary as well as non-binary images (Roy and Perfect, 2014) and ranging from pedodiversity analysis (Caniego Monreal et al., 2013) to food research (Valous et al., 2010). In the context of soil studies, lacunarity has been used to study soil bulk density from 2D CT data (Zeng et al., 1996), to explore management effects on intra-aggregate pore geometry in 2D binary images (Chun et al., 2008) and to analyze soil macropore network and solute transport patterns with 3D CT binary images (Luo and Lin, 2009).

Nonetheless, as pointed out by Plotnick et al. (1996), lacunarity analysis could be approached in a broader framework and it can be used to detect different configurations of dispersion and clustering of spatial patterns that are more general than fractal-like structures. Therefore lacunarity can be seen as an indicator of the deviation from translational invariance as well as from self-similarity. As mentioned above, translational invariance is not the same as self-similarity. This observation opens new avenues to consider lacunarity as a good candidate to characterize the dispersion and clustering of a wide range of geometrical structures that includes fractal-like geometrical objects.

In this paper, we describe and characterize soil structure through the lacunarity of the macropore space geometry. We make use of 3D CT images of intact samples from soil columns extracted from a Mediterranean vineyard in the north of Spain to analyze the lacunarity of soil macropore space. We investigate how lacunarity of soil macropore network is affected by soil management and varies with depth. We also analyze the different types of dispersion and clustering of macropore volumes found in the samples examined in this work.

2. Material and methods

2.1. Experimental field description and columns extraction

Columns were collected at the experimental farm "Finca La Grajera" in La Rioja (Spain), property of La Rioja Regional Government (northern Spain) (42°26′34″18 N lat.; 2°30′53″07 W long.). The field slope was about 10% with a west–east orientation. The soil was classified as Fine-loamy, mixed, thermic Typic Haploxerepts according to the USDA soil classification (Soil Survey Staff, 2006). The depth of the Ap horizon varied between 20 cm and 39 cm due to the slope. The underlying Bw horizon had a thickness of 47 cm. The climate in the area is semi-arid according to the UNESCO aridity index (UNESCO, 1979), with heavy winter rains and summer drought conditions.

The selected vineyard was established in 1996 with *Vitis vinifera* L. 'Tempranillo', grafted on 110-R rootstock. During the 1996 to 2004 period, the soil was conventionally tilled. In 2004, an experiment was established with two different types of soil cover management in-between the rows (row spacing is 5.80 m): (i) conventional tillage and (ii) permanent cover crop of natural vegetation. The conventional tillage — Ti treatment — consisted of soil tillage to 15 cm depth by a cultivator once every 4 to 6 weeks, as required for weed control during the growth cycle of the grapevine. The permanent cover crop of natural vegetation between the rows of the vines — CC treatment — was dominated by annual grass and herb spices common to La Rioja vineyards. This vegetation was mowed to a height of 10 to 15 cm by a flail mower twice a year, namely before vine bud break — in the first week of February — and at vine flowering — at the end of May or first week of June. The cover crop residue from the mowing was left on the soil. More details on the site can be found in Peregrina et al. (2010).

In December 2010, 12 columns were extracted vertically by percussion drilling in between the rows with PVC cylinders 7.5 cm inside diameter and 60 cm in height. Six strips in between rows were selected, three per treatment. Therefore, two columns per strip and six per treatment were collected.

2.2. Image acquisition and processing

Soil columns were scanned using X-ray CT with a Feinfocus FXE 225.51 microfocus beam source tube and a PerkinElmer amorphous silicon (a-Si) detector with 2048 × 2048 pixels. It was operated at 190 kV (53 μA) acceleration voltage and 20 W target power. The tube had a tungsten target installed. In addition, a collimator to reduce stray radiation and a 200 μm steel filter in front of the target was used.

The uppermost 15 cm of each column was scanned. In order to have a pixel resolution of 50 μm, each half of this part of the column was scanned separately. Thus, twenty four tomograms representing a cylindrical region 7.5 cm in diameter and 7.5 cm in height were analyzed for shallow management effects; twelve of them from the first 7.5 cm of soil and another twelve from the layer of soil from 7.5 to 15 cm from soil surface. In each case, half of them were from each one of the treatments. Two columns, one per treatment, were scanned in eight depths intervals of 7.5 cm so that we gained information to a depth of 60 cm. Therefore, eight tomograms, that represent eight cylinders of the same size as before along the 60 cm in height of one complete column per treatment, were considered to analyze changes with depth.

Raw data from X-ray CT of each cylinder corresponds to a stack of 1706 two-dimensional 16-bit grayscale images with a pixel size of 50 μm. These horizontal sections are disks of 7.5 cm diameter 50 μm apart from one another. Thus, 3D images are made up of voxels of 50 μm. Digital images were analyzed with ImageJ software (Ferreira and Rasband, 2012).

In order to quantify macropore space geometrical characteristics original 3D images were segmented. This binarization process assigned value one to voxels of the pore space, the object of interest or foreground, and value zero to voxels of the soil matrix or background. Once the segmentation process was accomplished, each one of the voxels of the image belongs to only one of these two classes. To achieve this goal we use a 3D nonlinear method that employs two filtering steps (Müter et al., 2012) before segmentation. The first enhances solid-void edges using Unsharp Masking and the second reduces noise by median filtering. The mask had a radius of five voxels and strength one while the median filter had a radius of two voxels. Gray-scale volumes were segmented using the local adaptive method proposed by Sauvola and Pietikäinen (2000) — see also Naveed et al. (2012). In order to analyze soil structure, a cube of 5.1 cm ($=1024^3$ voxels) edge size was considered as the region of interest (ROI) in each of the cylinders. Figs. 1 and 2 show views of 3D reconstructions of the pore space of the cubes that were extracted from columns as ROI.

2.3. Measurements: fractal dimension and lacunarity estimation

Let us consider a 3D shape and a 3D mesh of grid size ε in the selected ROI, then let us count the number of cubic boxes of the 3D mesh that are needed to cover the shape at scale size ε, say $N(\varepsilon)$. Typically, these numbers follow a power law rule:

$$N(\varepsilon) \propto \varepsilon^{-D} \tag{1}$$

where ∝ stands for asymptotic behavior as ε goes to zero. In general, fractal 3D geometrical objects will have an exponent less than 3. The fractal dimension D characterizes the irregular behavior that is repeated at different scales due to the property of scale invariance of fractal self-similar geometrical objects. In nature, the self-similar property of fractals is observed over a particular range of scales that is characteristics of each natural shape.

In order to measure lacunarity we have applied the "gliding box" method of Allain and Cloitre (1991). A cubic box of side length r is placed at one of the vertex of the ROI where the shape is confined. The number s of occupied sites or voxels within the box (box mass equal to s) was determined. The box is moved one voxel along the ROI and the box mass is again counted. This process was repeated over the