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3D soil void space lacunarity as an index of degradation after land use change

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ABSTRACT. In this work, lacunarity analysis is performed on soil pores segmented by the pure voxel extraction method from soil tomography images. The conversion of forest to sugarcane plantation was found to result in higher sugarcane soil pore lacunarity than that of native forest soil, while the porosity was found to be lower. More precisely, this study shows that native forest has more porous soil with a more uniform spatial distribution of pores, while sugarcane soil has lower porosity and a more heterogeneous pore distribution. Moreover, validation through multivariate statistics demonstrates that lacunarity can be considered a relevant index of clustering and can explain the variability among soils under different land use systems. While porosity by itself represents a fundamental concept for quantification of the impact of land use change, the current findings demonstrate that the spatial distribution of pores also plays an important role and that pore lacunarity can be adopted as a complementary tool in studies directed at quantifying the effect of human intervention on soils.

Keywords: lacunarity; soil porosity; impact of land use change.

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Introduction

Global social and economic changes during recent decades have led to an increasing demand for the conversion of natural areas for urbanization, agriculture, and livestock, as well as for wood extraction. These processes have begun to threaten most tropical forests, increasing the rate of deforestation to up to 9.1 million hectares per year (Moraes, Mello, & Toppa, 2017). This degradation has immediate and negative effects on biodiversity, in part by causing fragmentation, i.e., the division of the natural environment into small, isolated blocks of land surrounded by human-modified landscapes. The Atlantic Forest region is one of the Brazilian biomes that has been most affected by deforestation. Currently, most of the Atlantic Forest has been replaced by sugarcane plantations, leaving small forest fragments, mostly with less than 1,000 hectares (Haddad et al., 2015).

Current sugarcane management techniques, such as the use of plows, heavy gratings and subsoilers, cause vigorous soil disturbance at the time of planting, which causes changes in the soil structure, mainly in the top layer. Changes in soil structure due to disturbance directly interfere with soil density, mechanical resistance to penetration, total porosity, water storage and availability to plants, and surface water dynamics (Centurion et al., 2007). Despite the extent and significance of these ecosystems, there is little available scientific information about the effects of forest removal on their soil properties.

In the present work, we compared samples of forest and sugarcane soils using computed tomography, image segmentation and lacunarity analysis on the void space. To demonstrate the consistency of this fractal measure as a relevant index in the evaluation of soil degradation, we also conducted multivariate statistical validation.

X-ray computed tomography (CT) of soil provides a direct procedure to quantify the geometrical attributes of soil pore space in three dimensions (Torre, Losada, Heck, & Tarquis, 2018; Wildenschild & Sheppard, 2013). The development of digital image processing has enabled the increased quantitative analysis of soil structure as 3D objects, and new mathematical techniques have been introduced for the calculation of soil pore structure (Schlüter & Vogel, 2011).

From the structural point of view, soil can be defined as a mixture of solid and void components (Martín-Sotoca, Saa-Requejo, Grau, & Tarquis, 2017). This mixture, coupled with the natural variability of the X-ray's attenuation to indicate the structural elements of soil, provides an even greater challenge due to the segmentation of these components. One of the methods that has been used very successfully to address this challenge in several studies is "pure voxel extraction" (Borges et al., 2019; Borges et al., 2018; Caplan et al., 2017; Jefferies, Heck, Thevathasan, & Gordon, 2014; Pires et al., 2017). This approach is used in the present work to identify the pore structure of the images, since it is a relevant parameter that provides useful information about soil functioning (Ojeda-Magaña et al., 2014).

One of the techniques that emerged as a natural candidate for the current study is the analysis of lacunarity (Mandelbrot, 1983) as a measure of the distribution of gap sizes in a fractal object. Homogeneous and translationally invariant geometric objects have low lacunarity, while heterogeneous and non-translationally invariant geometric objects have high lacunarity. Lacunarity can be used with both binary and quantitative data in one, two and three dimensions (Beckers et al., 2014; Dong, 2009; Xia et al., 2019).

In the context of soil studies, lacunarity has been used for many purposes: to study soil bulk density from 2D CT data (Zeng, Payton, Gantzer, & Anderson, 1996), to explore management effects on intra-aggregate pore geometry in 2D binary images (Chun, Giménez, & Yoon, 2008) and to analyze the soil macropore network and solute transport patterns with 3D CT binary images (Luo & Lin, 2009) and soil macropore space arrangement of CT images (Martínez, Caniego, & García-Gutiérrez, 2017) and scaling properties of binary and greyscale images (Torre, Martín-Sotoca, Losada, López, & Tarquis, 2020).

The objective of the current study is to complement the conventional approach in shedding light on the human effects on soil porosity by comparing the structure of the soil under sugarcane and the native forest in nearby locations, using pore lacunarity analysis on three-dimensional X-ray soil images.

Material and methods

Site description and sample and data collection

Two fragments of native forest surrounded by sugarcane cultivation were visited and sampled. The Piedade fragment ($7^0$49'16'' to $7^0$50'54'' S; $34^0$49'26'' to $34^0$00'35'' W) and Cumbe fragment ($7^0$45'51'' to $7^0$46'48'' S; $35^0$02'13'' to $35^0$02'50'' W), located in the Northeastern Brazilian region, state of Pernambuco, and Igarassu and Araçoiaba municipalities, respectively. Both fragments are located in the territory of a sugar and ethanol mill, the São José Sugar Mill. In these forest fragments and the adjacent sugarcane fields, 21 points – 10 from native forest and 11 from sugarcane cultivation – were obtained using a soil auger with an internal PVC cylinder of 7.5 cm height by 7.5 cm diameter.

We evaluated Google Earth satellite images dating from December 1969 and found that these areas have remained under natural conditions for over 40 years. This information corroborates past work on these fragments, which indicates that most of the fragments arose during the intense destruction of the Atlantic Forest between the 1970s and 1980s when a crisis occurred in the petroleum sector, and Proálcool (the National Alcohol Program) was created as an initiative of the Brazilian government to encourage the production of alcohol fuel (Moraes et al., 2017; Ranta, Blom, Niemelä, Joensuu, & Siitonen, 1998).

The points were excavated by careful penetration with a cylinder coupled with a blade. After the insertion of the auger in the soil, the cylinders were carefully removed to ensure maximum preservation of the original structure of the environment inside the PVC cylinders (Figure 1).

In all, 36 samples at depths of 0-10 cm and 10-20 cm were collected, then dried at 40°C to remove the effect of water in the scanning tomography of the samples. The tomography was performed using a third-generation Nikon XT H 225 ST X-ray microtomograph with 150 kV voltage, 180 μA current, 500 ms exposure time, and a 45 μm resolution for voxels. A copper filter with a thickness of 0.5 mm was used to minimize low-intensity photons, which caused beam-hardening artifacts (Scarfe & Farman, 2008) and to maximize the contrast between different phases (solids and air).

After the scanning of the total cylinder volume in the preliminary acquisition, a subvolume of interest was defined and reconstructed using CTPro 3D XT 3.0.3 (Nikon Metrology NV) software The most central part of the cylinder was highlighted to avoid edge influence. The reconstructed 2D axial projections maintained the same spatial resolution of the acquisition (i.e., 45 μm) and were saved at a radiometric resolution of 16 bits. The final volume was 790 stacks with 790 x 790 pixels, an end volume of 790^3 voxels.

Figure 1. Physical collection of the soil samples using a soil auger with an internal PVC cylinder, to guarantee the preservation of the original structure of the soil in PVC cylinder for tomography analyses.

Void space segmentation

To binarize the images and highlight the void space, the pure voxel extraction (PVE) method was adopted. The PVE is a tool that aims to locate relatively pure voxels, usually within a neighborhood of 124 from cubes of five voxels on the side. Searching occurs within this neighborhood to group those that are similar to a proposed coefficient of variation by the researcher. In general, the images generated by this methodology have bimodal or even multimodal histograms, with more evident peaks when compared with histograms of the original image; this is relevant to the segmentation of images of soil tomography, since these peaks provide information with respect to the pure representative values of void and solid components (Costa et al., 2016; Jefferies et al., 2014).

Once the location of pure voxels is determined, the values of the mixed voxels found between the two peaks may be appropriately allocated to the void or solid phases using the edge detection technique (Davies, 2018). Since it is a local segmentation method, this is often superior to global methods (Wang, Kravchenko, Smucker, & Rivers, 2011).

Lacunarity

Various methods for calculating lacunarity (Gefen, Meir, Mandelbrot, & Aharony, 1983; Lin & Yang, 1986; Mandelbrot, 1983) have been developed. Among them is the gliding box algorithm (Allain & Cloitre, 1991), which has been used extensively in ecological (Malhi & Román-Cuesta, 2008; Plotnick, Gardner, & O'Neill, 1993), and geological (Roy, Perfect, Dunne, Odling, & Kim, 2010) studies. In this work, we applied the gliding-box algorithm on a three-dimensional set constructed from CT images of soils from areas of native forest and areas impacted by sugarcane plantations. In this analysis, lacunarity is a measure of the distribution of gaps (soil pores) of the 3D object. We used the thresholds of 0 (absence of soil porosity – solids) and 1 (presence of soil porosity – voids). Large values of lacunarity imply large gaps and greater heterogeneity in soil porosity, whereas small values imply small gaps and a more uniform soil porosity distribution (Mandelbrot, 1983).

To calculate lacunarity, a cube of size $r \times r \times r$ is placed at the origin of the 3D object under study of size $L_X \times L_Y \times L_Z$, and the number s of occupied sites (solids) above a chosen threshold is counted. The cube is then moved along the entire 3D object and its mass is calculated at every position, yielding the mass frequency distribution $n(s,r)$, and, correspondingly, the probability distribution estimate

$$P(s,r) = \frac{n(r,s)}{N(r)} \qquad (1)$$

where: $N(r) = (L_X - r + 1)(L_Y - r + 1)(L_Z - r + 1)$ is the total number of cubes of size $r \times r \times r$ overlapped with the object. Lacunarity of the object is now defined as

$$L(r) = \frac{M2(r)}{[M1\,(r)]^2} \qquad (2)$$

where: $M1(r)$ and $M2(r)$ are the first and second moments of $P(s,r)$, given by

$$M1(r) = \sum_{s=1}^{r^3} s \; p(s,r) \qquad (3)$$

and

$$M2(r) = \sum_{s=1}^{r^3} s^2 \; p(s,r) \qquad (4)$$

respectively. For a scale-free process, lacunarity decreases with window size as a power law

$$L(r) = \alpha \, r^{\beta} \qquad (5)$$

where: the scaling exponent β can be determined as the slope of a linear regression of $\log[L(r)]$ versus $\log(r)$ (Martínez, Lana, Burgueño, & Serra de Larrocha, 2007).

Results and discussion

The normality of the data was observed from the Lilliefors test (Stehlík, Střelec, & Thulin, 2014) at the 1% level of significance. A T-test for independent samples pointed to mean differences between soil porosities of native forest and sugarcane cultivation (p = 0.000, t_0 = -6.09, df = 32.477). The consistency of the PVE segmentation was verified by a higher porosity in native forest soils (Figure 2).

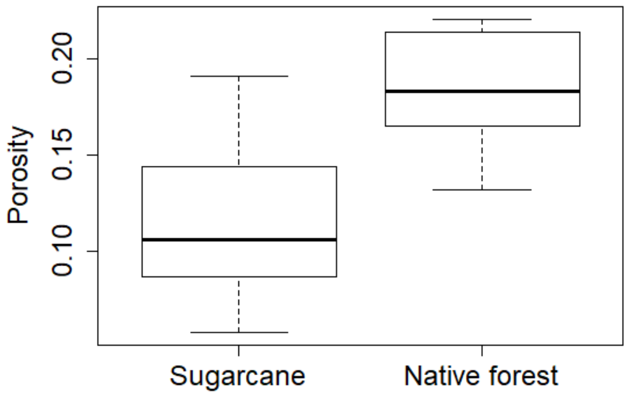

Figure 2. Porosity proportion variation between native forest and sugarcane.

Conversely, higher values of lacunarity were observed in sugarcane soils. This difference was verified by T-test for independent samples for boxes with dimensions 2, 4, and 8 (Table 1).

Table 1. 3D void space lacunarity comparison after land use change.

3D Box size	Lacunarity (Mean ± SD)		T-test statistics p-value; t_0; df
	Native forest	Sugarcane	
2	4.57 ± 0.56	7.11 ± 1.87	<0.0001; -5.38; 34
4	3.69 ± 0.37	4.85 ± 0.96	<0.0001; -4.72; 34
8	2.87 ± 0.32	3.25 ± 0.57	0.0023; -2.38; 34
16	2.26 ± 0.28	2.31 ± 0.40	0.6547; -0.45; 34
32	1.76 ± 0.21	1.82 ± 0.29	0.5000; 0.68; 34

These findings indicate a negative linear correlation between porosity and lacunarity. More precisely, while native forest has more porous soil, the spatial distribution of pores is more uniform. In sugarcane soil, lower porosity is accompanied by a more heterogeneous pore distribution. Since the 3D lacunarity on segmental images is calculated based on porosity, an analysis of Pearson's linear correlation between porosity and lacunarity was evaluated and found to be negative, strong and significant for cubes of dimensions 2 and 4. It was also found to be negative, moderate and significant for the cube of dimension 8, while for cubes with dimensions 16 and 32, the correlations were not found to be significant. In other words, there is no correlation between cubes of a size greater than 16 and soil porosity (see Figure 3).

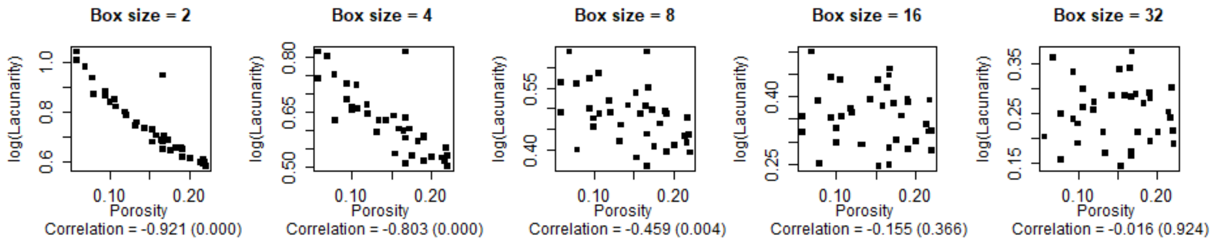

Figure 3. Pearson correlation between lacunarity and porosity in different cube dimensions.

From the mean lacunarity values, the regression exponent was adjusted for each land use, native forest and sugarcane. Figure 4 shows that native forest soils presented a lower beta lacunarity exponent (-0.35), while soils impacted by sugarcane showed a greater slope (beta lacunarity exponent of -0.50). The lower beta exponent of lacunarity indicates more uniform soil porosity distribution in native forest, while the greater beta lacunarity exponent confirms greater heterogeneity in the distribution of pores in the sugarcane soil.

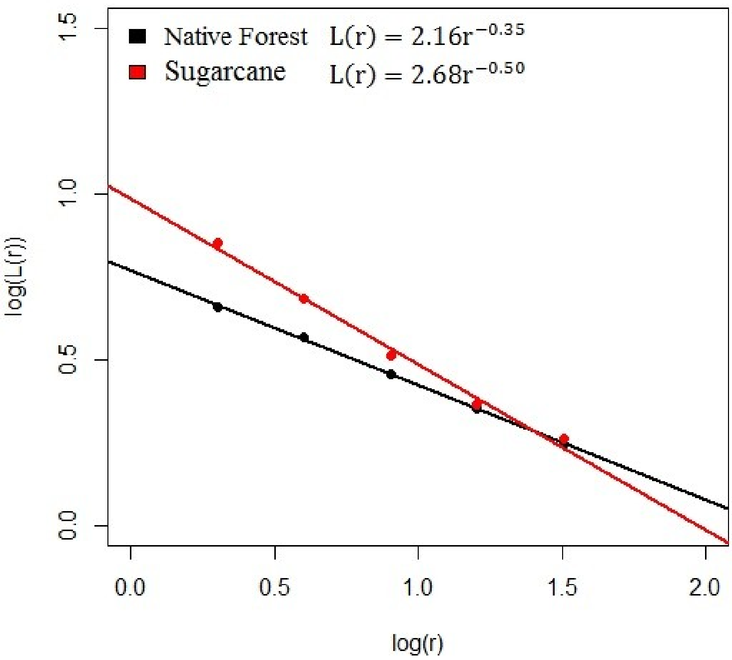

Figure 4. Impact in adjusted beta exponent of lacunarity after land use change from native forest to sugarcane plantation in NE Brazil.

Multivariate analysis validation

Two multivariate statistical techniques, cluster analysis and principal components analysis (Johnson & Wichern, 2018), were combined to obtain patterns and to evaluate the validity of using lacunarity as a measure capable of separating native forest soils from those impacted by land use change. The purpose of cluster analysis is to evaluate the existence of internally homogeneous but relatively heterogeneous groups. In other words, given a sample of *n* individuals or objects, each with measurements in *p* variables, the analysis of clusters may form some criterion of (dis)similarity or distance, combined with a method of linking or grouping to seek an allocation of these individuals in *g* groups. To establish an adequate dendrogram, five measures of dissimilarity (Euclidean, Maximum, Manhattan, Canberra, and Minkowski) and seven methods of linking or constructing the dendrogram (Ward, Average, Complete, Single, Centroid, Median, and McQuitty) were used. The 35 possible combinations were evaluated in relation to the largest cophenetic correlation (Saraçli, Doğan, & Doğan, 2013). Once the dendrogram was defined, the optimal partition of the dendrogram in *g* groups was obtained from the KL criterion (Charrad, Ghazzali, Boiteau, & Niknafs, 2014). The combination that presented the best cophenetic correlation was determined by using a dissimilarity matrix obtained by the Maximum dissimilarity measure with the McQuitty method, as shown in Table 2.

Table 2. Cophenetic correlation comparison.

Cluster method	Dissimilarity matrix				
	Euclidean	Maximum	Manhattan	Canberra	Minkowski
Ward	0.6088	0.7000	0.5907	0.0388	0.6088
Average	0.7671	0.7683	0.7581	0.0387	0.7671
Complete	0.7408	0.7531	0.7535	0.0388	0.7408
Single	0.7399	0.7440	0.7151	0.0202	0.7399
Centroid	0.7348	0.7508	0.7306	0.0387	0.7348
Median	0.7322	0.7348	0.6859	0.0388	0.7322
Mcquitty	0.7424	0.7705*	0.7316	0.0387	0.7424

*best cophenetic correlation.

A dendrogram was constructed with the settings indicated in Table 2 and the groups partitioned by the KL criterion. Five groups of images were obtained: the first one corresponding to three sugarcane images; the second to the other four sugarcane images; the third one sugarcane and three native forest images (33% sugarcane and 67% native forest); the fourth nine native forest images (100% native forest); and the fifth 17 images (65% sugarcane and 35% native forest). Thus, a rate of 86.4% of correct allocation, or more precisely, adequate image separation, was observed (Figure 5).

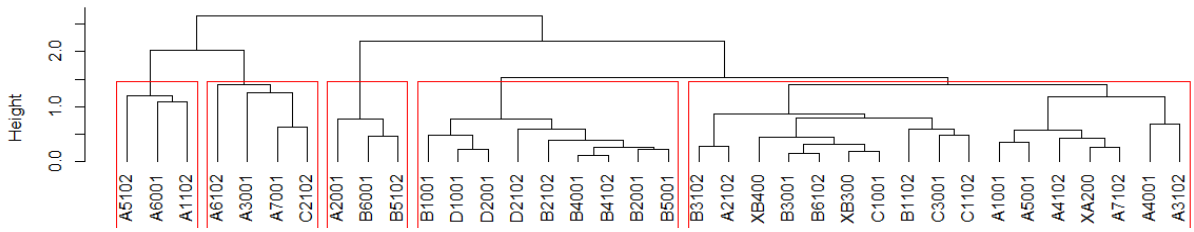

Figure 5. Cluster dendrogram with five groups partitioned by the KL criterion. Names containing the letters A or C represent sugarcane and B or D represent native forest soils.

Finally, a multivariate evaluation (principal components analysis) was conducted, yielding a graphic representation of the components with greater explainability – the highest being 71.2% – and highlighting the groups obtained in the previous cluster dendrogram analysis. It can be seen in Figure 6 that the identified sample clusters are well separated in the two-dimensional principal component space that explains more than 98% of the variance.

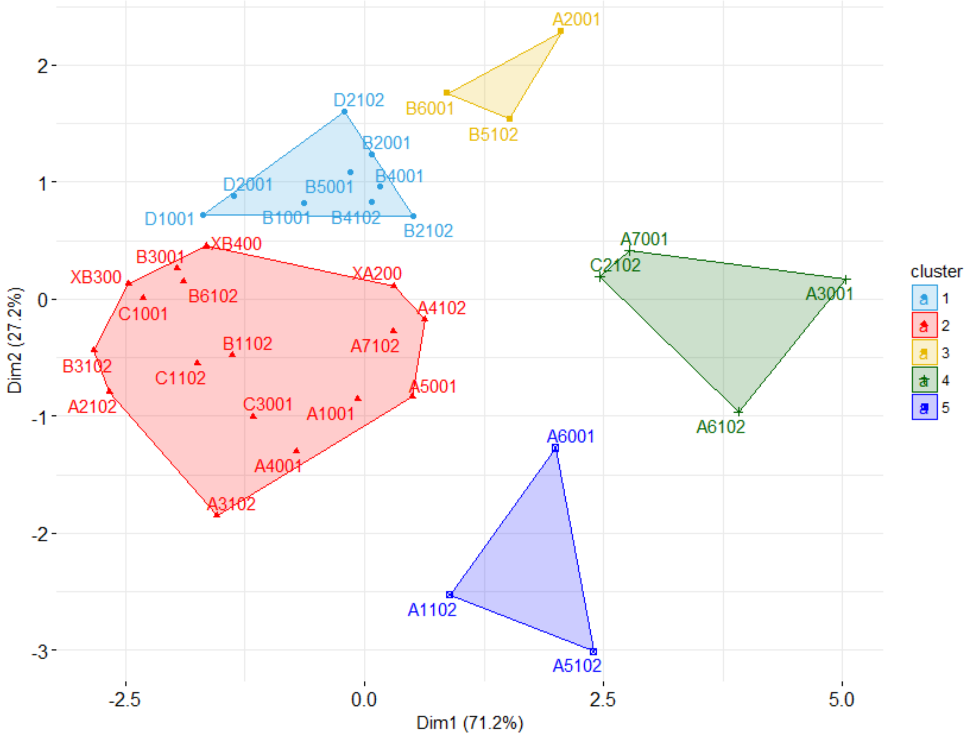

Figure 6. Principal components analysis highlighting five groups partitioned by the KL criterion. Names containing the letters A or C represent sugarcane, and B or D represent native forest soils.

These findings are reinforced by studies that have used lacunarity and soil tomography images and which have detected different patterns of lacunarity in macro soil soils at depths of 15 cm and 60 cm (F. S. J. Martínez et al., 2017). Other studies have verified that there are distinct patterns of lacunarity in different structures of macroporous soils, establishing it as a tool that detects different soil structures and that is useful for determining if there is self-similarity and a definable representative elemental volume for a porous medium (Luo & Lin, 2009). A final study, using a 2D approach, detected three different patterns of lacunarity in different European soil types, establishing it as a tool for the characterization of soils in the region (Caniego, San José Martínez, Ibánez, & Pérez, 2012).

Conclusion

The analysis of lacunarity applied to soil tomography images of the pores segmented by the pure voxel extraction method was consistent in the evaluation of the impact of land use change (conversion of forest to sugarcane plantation), pointing to higher values in sugarcane soils (with lower porosity). Further, validation by means of multivariate statistics has demonstrated that lacunarity can be considered a relevant index in the clustering and explanation of variability among soils of different land use systems.

While porosity by itself represents a fundamental concept for evaluation of anthropic effects on soil structure, the current findings demonstrate that spatial distribution of pores also plays an important role and that pore lacunarity can be adopted as a complementary tool in studies directed at quantifying the effect of human intervention on soils. In particular, lacunarity analysis in the current case has shown that native forest has more porous soil with a more uniform spatial distribution of pores, while soils under sugarcane cultivation presented lower porosity and more heterogeneous pore distribution.

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