3D analysis of the soil porous architecture under long term contrasting management systems by X-ray Computed Tomography

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ABSTRACT

The development of adequate soil structure is important for achieving good physical status, which influences the sustainability of agricultural areas. Different management systems lead to the development of a wide range of soil pore network characteristics. The objective of this research was to analyze the effect of three contrasting tillage systems (zero-tillage, ZT; reduced tillage, RT; conventional tillage, CT) in the soil porous system of an Oxisol. Samples were collected from the surface layer (0-10 cm). An area under secondary forest (F) was also assessed to provide an undisturbed reference. X-ray Computed Tomography (μCT) scanning of undisturbed soil samples and image analysis were employed for analysis of the pore network. The soil under ZT

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had the smallest porosity in comparison to the other management systems. The conventionally tilled soil had the largest porosity and the most connected pores. One large connected pore was responsible for around 90% of the porosity of the resolvable pores (>35 μm) studied for all the management systems. Pores of elongated shapes, which enhance water movement through the soil, were the most frequent pores in terms of shape.

Keywords: Minimum tillage; Zero-tillage; Conventional tillage; Morphological properties; X-ray microtomography; Soil structure.

1. INTRODUCTION

The use of tillage has been employed for centuries to improve soil structure for enhanced crop development. However, the choice of tillage systems can have a significant impact on a soil heath and quality. Sustainable farming systems greatly depend on soil quality (Bünemann et al., 2018). Soil tillage provokes substantial changes in several soil physical properties such as total porosity, bulk density, water retention and infiltration, penetration resistance, pore size distribution, connectivity and tortuosity (Imhoff et al., 2010; Daraghmeh et al., 2009; Blanco-Canqui et al., 2004; Katsvairo et al., 2002).

In Brazil the adoption of minimum tillage systems such as reduced (RT) and zero tillage (ZT) is common. The total Brazilian area used in crop production is around 66 million hectares and there are over 31 million hectares under ZT (FEBRAPDP, 2013). Conventional tillage (CT) is characterized by the disruption of the top soil due to ploughing and harrowing operations employed to turn over and loosen the soil. As a result of these operations, macropores are created and pore continuity is disrupted, which directly affect the water movement (e.g. hydraulic conductivity and infiltration) and retention (Blanco-Canqui et al., 2017; Ogunwole et al., 2015; Cássaro et al., 2011; Imhoff et al., 2010). Minimum tillage systems such as RT and ZT do not usually lead to drastic soil structure changes. These systems, known as conservation techniques, have been utilized as a means of reducing tillage and field costs as well as for conserving soil structure due to reduced disturbance (Aziz et al., 2013; Cavalieri et al., 2009). The residues of the previous crop are left intact and the absence of harrowing in ZT and RT can increase soil organic carbon and aggregate stability, reduce CO_2 emissions and moderate fluxes of water, air and heat through the soil (Aziz et al., 2013; Daraghmeh et al., 2009; Zibilske and Bradford, 2007).

The fluxes of water and air, organic matter decomposition, plant-available water and soil resistance to erosion are directly linked to the architecture of the soil porous system. Mesopores and macropores play an important role in these processes (Imhoff et al., 2010; Fuentes et al., 2004; Cameira et al., 2003). In CT, the soil porous system is affected by operations such as ploughing and harrowing, which can increase porosity and loosen soil (Mangalassery et al., 2014). This operation allows good root growth and air exchange, while the exposition of the soil to rain in tropical regions can sometimes lead to erosion (Alvarez et al., 2009). On the other hand, the activity of earthworms and root decay help to create channels and burrows under RT and ZT, which facilitate drainage and gaseous diffusion (Soto-Gómez et al., 2018; Carducci et al., 2017; Pires et al., 2017; Pierret et al., 2002).

Based on the important functions that mesopores and macropores fulfill for a healthy soil, techniques to image and measure key properties such as X-ray Computed Tomography (µCT) are very important (Tseng et al., 2018; Yang et al., 2018; Ferreira et al., 2018; Pagenkemper et al., 2014). The spatial distribution of pores can be non-destructively imaged at high resolutions and in three dimensions (3D) by µCT (e.g. Galdos et al. 2018; Helliwell et al., 2013; Peth et al., 2008). µCT has been previously applied with success to study the size, shape, number, connectivity, degree of anisotropy, macropore thickness, fractal dimension and tortuosity of the soil porous system (Wang et al., 2016; Dal Ferro et al., 2014; Garbout et al., 2013; Vogel, 1997).

This provides vital information to characterize the physical structure of the porous system, which allows a better understanding of key processes (i.e. mass and energy transport, nutrient cycling, root development) within the soil (Hillel, 2004).

Previous studies on evaluating the influence of tillage systems at the µm scale in 3D in tropical soils are still scarce. In Brazil, one of the largest food and agricultural producers of the world, previous studies have characterized the soil porous system at µm to measure the porosity and pore size distribution of Brazilian Oxisols (Vaz et al., 2011), assessed the effect of tillage systems on the percentage of macropores (Beraldo et al., 2014) and explored the spatial and morphological configuration of the pore space of Oxisols under CT (Carducci et al., 2017, 2014). Other studies have determined the influence of ZT on the pore size and shape distribution of macropores (Passoni et al., 2015), tested the capacity of soil recovering under different management strategies (Marchini et al., 2015) and measured the impact of ZT and CT on the pore size and shape distribution and water retention (Pires et al., 2017). Recent work has analyzed the soil structure utilizing the geometrical parameters of the soil porous system (Tseng et al., 2018), considered the influence of liming on the structure of aggregates under ZT (Ferreira et al., 2018) and revealed the structural development associated with long term (>30 years) ZT (Galdos et al., 2018).

The objective of this particular research was to apply the X-ray Computed Tomography technique to evaluate, in 3D and at the µm scale, the morphological properties of an Oxisol under contrasting soil management systems. Experimental areas under long term zero-tillage and reduced and conventional tillage systems were investigated. Samples were collected at the soil surface layer (0-10 cm).

2. MATERIALS AND METHODS

The experimental field plots of this study were located in Ponta Grossa, in a humid mesothermal Cfb-subtropical region in southern Brazil (25°09’S, 50°09’W, 875 m above sea level) (Cássaro et al., 2011). The soil was an Oxisol (Rhodic Hapludox) with clay texture according to USDA soil taxonomy (Soil Survey Staff, 2013). The experimental areas have long gentle slopes ranging from 2 to 7%. The Oxisol evolved from the clastic sediments of the Devonian period characterized by a mixture of Ponta Grossa shale (MINEROPAR, 2013). Deep and very structured profiles are found in the experimental site characterized by high porosities and good internal drainage (Sá et al., 2015).

Three tillage systems were compared in this study (conventional tillage – CT, reduced tillage – RT and zero-tillage – ZT). An area under secondary forest (F) was utilized as baseline to assess the management-induced changes in soil structure, which is located close to (≈200 m far) the experimental field plots. Some of the key characteristics of the soil (0-10 cm depth) from the experimental areas are shown in Table 1.

The experimental plots studied here have areas of c. 1.0 ha (ZT) and c. 0.6 ha (CT and RT), respectively. The tillage systems had been employed in the areas for over 35 years at the time of sampling. The experimental areas of CT, RT and ZT were initiated in 1981 after conversion of part of secondary forest to pasture-land (Sá et al., 2015). Under CT, the soil was submitted to discing at 25 cm depth followed by 10 cm harrowing twice a year after summer and winter harvest. For the area under RT, the soil was prepared through the use of a chisel cultivator at 25 cm depth followed by a 10 cm narrow disking, causing minimum soil disturbance, and the crop residues were maintained at the soil surface. The area under ZT was not submitted to soil disturbance. In these areas, crop rotation was performed, with cover crops [oats (*Avena strigosa*) or vetch (*Vicia sativa*)] or wheat (*Triticum aestivum L.*) in winter and corn (*Zea mays*) or soybean (*Glycine max*) in summer (Table 2). The operations of soil and crop management, sowing and harvest, were made with commercial tillage machines (e.g. tractor). The traffic in the ZT area was restricted to sowing equipment with a cutting disc for sowing the summer and winter crops. Each experimental area (ZT, CT and RT) was submitted to 8-9 soil interventions through the year (clearing, planting seed and soil preparation operations) using tractors around four tonnes in weight.

Soil samples were taken from the 0-10 cm layer after corn harvest in April 2017. For CT, sampling occurred almost six months after ploughing and harrowing operations, which allowed the sampling of natural reconsolidated structures. ZT, RT and F samples were also taken at the same sampling time. Core samples of 91 cm^3 (5.0 cm high and 4.8 cm inner diameter) were collected in steel cylinders with an Uhland core sampler (Folegatti et al., 2001). Three samples of each tillage system and forest (3 samples × 4 systems) were collected for the macroporosity and microporosity analyses and other five samples (5 samples × 4 systems) for the µCT analysis (Table 1). After sampling, the samples were wrapped in plastic foil and transported to the laboratory. The soil excess outside the steel cylinders was carefully trimmed off and top and bottom surfaces of the sample were made flat to ensure that the soil volume was equal to the internal volume of the cylinder. This procedure was carried out with the help of a palette knife.

Samples were collected very carefully, in order not to introduce soil compaction during extraction and handling of the steel cylinders. To minimize damages in the soil structure due to the force required for collection, samples were taken some days after a high intensity rainfall event with the soil near its plastic limit. For organic carbon (3 samples × 4 systems) and texture (3 samples × 4 systems) measurements, disturbed soil samples were collected at three different points. Soil organic carbon was determined by the Walkley-Black method and texture by the hydrometer method (Gee and Or, 2002; Nelson and Sommers, 1982).

The soil samples were carefully extracted from the steel cylinders before the µCT scans. Prior to the scanning, the samples were coated with paraffin wax for transport to the United Kingdom. Each soil sample was scanned using a GE v|tome|x m X-ray µCT scanner (GE Measurement & Control Solutions, Wunstorf, Germany) at the Hounsfield Facility (The University of Nottingham, Sutton Bonington Campus, U.K.). The voltage, current and integration time adopted for the image acquisition process were 180 kV, 160 µA and 250 ms. A 0.1 mm Cu-filter was used to minimize beam-hardening effects. A total of 2520 projections were obtained per sample with a pixel resolution of 35 µm. Therefore, it was not possible to quantify pores below the resolution mentioned.

The radiographs of each scan were reconstructed in 32 bit format in order to avoid compression of the greyscale histogram. After reconstruction the images were imported into Volumetric Graphics (VG) StudioMAX® 2.0 and cropped (i.e. resized) to a cubic shape with 30.1 × 30.1 × 30.1 mm^3 (860 × 860 × 860 pixels). The image cropping was carried c. 10 mm away from the borders of the samples to avoid possible artifacts on the edge of the soil core samples that may have arisen from sampling or transport.

The original grey-level µCT images were processed using ImageJ 1.42 software (Rasband, 2007). A *3D median* filter with radius of 2 voxels was applied to reduce noise in the images. Subsequently, an *unsharp mask* with standard deviation of 1 voxel and weight of 0.8 was applied to emphasize edges. The segmentation process was based on the nonparametric and unsupervised Otsu method of thresholding (Otsu, 1979). The *remove outlier* tool with radius of 0.75 was applied in the images after segmentation. The images were also visually inspected to verify the quality of the segmentation procedure. This resulted in a binary image, in which pores and solids were respectively represented by white and black pixels.

For the 3D structure analysis, soil pores were classified according to their shape and size distribution. For the shape classification, parameters known as major, intermediate and minor axes of the ellipsoids that represent each pore were determined by using 3D measuring techniques (Borges et al., 2018; Pires et al., 2017). These parameters were measured by using the *Particle Analyser* tool in the ImageJ. The soil pores were classified according to Zingg (1935) based on the relations of the intermediate by the major (Int./Maj.) and of the minor by the intermediate (Min./Int.) axes. Equant (EQ), Prolate (PR), Oblate (OB) and Triaxial (TR) shaped pores were analyzed (Ferreira et al., 2018; Pires et al., 2017) (Table 3). When one of the axes of a specific pore could not be determined, this pore was not classified (unclassified pore) according to its shape. These pores are generally associated with enhanced complexity of individual pores, which means that a geometrical shape cannot be fitted for them.

3D porosity was determined for all pores >8 voxels and the total number of pore voxels within the region of interest. Isolated pores smaller than 9 voxels were removed from the porous fraction of the images in the quantitative analyses to avoid misclassification from unresolved voxels (Jefferies et al., 2014). The total number of isolated pores within the region of interest was utilized for the 3D pore size distribution based on the volume of pores (0.0004-0.01, 0.01-0.1, 0.1-10 and >10 mm^3) (Ferreira et al., 2018; Pires et al., 2017).

The network tortuosity and connectivity of the pores were calculated using Osteoimage software (Roque et al., 2009). Tortuosity was determined through the geodesic reconstruction algorithm implemented by Roque et al. (2012). The pore network degree of connectivity was estimated by the Euler-Poincare Characteristic (EPC). EPC is a topological property of geometric objects and one of the Minkowski functions used for describing the connectivity of spatial structures (Katuwal et al., 2015). This parameter for a 3D structure is related to the number of isolated parts minus the connectivity of an object (Thurston, 1997). To estimate the EPC, a stack of serial sections called dissectors (Sterio, 1984) is used. In our study 859 disectors were analyzed for each sample. EPC by the volume of dissectors (EPC_V) was then calculated for each sample after the images had been previously submitted to the Purify procedure in Bone J plugin (Toriwaki and Yonekura, 2002; Odgaard and Gundersen, 1993). For EPC_V a positive value indicates a poorly connected structure while a negative value suggests a more connected structure (Vogel and Kretzschmar, 1996). The Euler number was also utilized to evaluate the connectivity of the main pore network (i.e. the largest pore). The degree of anisotropy, which gives the preferred orientation of pores, was determined in 3D by using the BoneJ plugin (Doube et al., 2010).

Differences in the soil morphological parameters due to the treatments were evaluated by a one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc tests. Results were classified as statistically significant at $p<0.05$. Parameters such as the mean, standard deviation and coefficient of variations were also measured for each soil physical property analyzed. Pearson correlations among each pair of variables were measured for some of the morphological properties. The statistical analysis was carried out using PAST software (Hammer et al., 2001).

3. RESULTS AND DISCUSSION

Representative 3D images of the soil porous system from the different management systems are presented in Fig. 1. The undisturbed samples collected at the surface layer for the contrasting tillage systems possessed a main pore network composed of connected pores. The 3D images show that the soil under CT seemed to have a high proportion of small connected pores in relation to F, ZT and RT (Fig. 1). The numerous pores observed for the soil under CT suggest this management system was characterized by higher soil porosity than the other treatments. Larger soil pores were observed for the soil under F, ZT and RT, which may be an indication of biological activity. The existence of biopores in areas under forest or conservation management systems is usually associated with the action of earthworms and root penetration (Peth et al., 2008). Normally these biopores tend to be vertically oriented, continuous and round shaped (Pagenkemper et al., 2015). Earthworm activity in the soil modifies its structure and can affect the transport and exchange processes such as preferential flows and lateral water movement (Rogasik et al., 2014).

Porosities calculated from binary images were higher for CT compared with the other management systems (Fig. 2a). Porosity was c. 2.3 times higher for CT than ZT. Significant differences ($p<0.05$) were observed for ZT in relation to the other management systems. The number of pores was significantly different between CT, F and ZT (Fig. 2b). The soil under ZT had the highest number of pores followed by F, RT and CT. The number of disconnected pores was c. 1.5 times higher for ZT than CT.

The lowest porosity observed for ZT maybe associated with a “zero-tillage pan”, which can happen in areas under long term ZT as previously observed in the South of Brazil down to 20 cm soil depth (Mazurana et al., 2017; da Silva et al., 2009; Klein and Libardi, 2002). According to Reichert et al. (2007), soil compaction in ZT can occur mainly when this practice is utilized for long periods due to machinery traffic, low soil mobilization and natural soil arrangement. One of the consequences of this densification is the reduction of macroporosity and the increase in microporosity (da Silva et al., 2016; Mangalassery et al., 2014). Similar findings for areas under ZT close to the experimental plots studied were observed by Borges et al. (2018) and Pires et al. (2017) for samples collected in different periods of time. Normally, for soils under ZT it is expected that the traffic effects can be compensated by the creation of macropores originating from the fauna activity, high organic content and root development, but this was not observed in this study. Similar results were recorded by Blanco-Canqui et al. (2017) and Soracco et al. (2012).

The large porosity observed under CT is probably associated with the soil loosening and disturbance, which favours the formation of macropores at the surface layer (Jabro et al., 2009). Conventional management can cause an increase in the volume of pores, permeability and air flow, which is related to the harrowing and ploughing operations (Rossetti et al., 2013). For the soil under RT, the porosity can be explained by reduced soil disturbance combined with the incorporation of residues from previous crops for this management (Cunha et al., 2015). In terms of porosity, this management presents the most similar results to the reference area (F).

The smallest number of pores was for the soil under CT, which was unexpected (Fig. 2b). The aggregate breakdown induced by harrowing and ploughing operations normally increases the number of pores due to the loosening effect of conventional management systems. Several previous studies have demonstrated that systems with ploughing are characterized by looser soil structures (Dal Ferro et al., 2014; Garbout et al., 2013; Munkholm et al., 2012; Munkholm and Hansen, 2012). Borges et al. (2018) and Pires et al. (2017) also observed a larger number of pores for the soil under CT than ZT for the same experimental area. A possible explanation for the smaller number of pores observed under CT in the current study could be the soil resettling, which is induced by the local wetting and drying cycles, caused by rainfall and dry periods and biological activity including root growth (Daraghmeh et al., 2009).

The contrasting management systems did not demonstrate significant differences in the degree of anisotropy though it was highest in RT, followed by ZT and CT, whereas F had the smallest value (Fig. 2c). This parameter was c. 1.7 times higher for RT than F. The results of degree of anisotropy obtained in this study are in line with those presented by Dal Ferro et al. (2014). These authors obtained values of 0.21 (CT) and 0.25 (ZT) for samples from the topsoil (0-10 cm). However, there was no pattern between the results of degree of anisotropy and porosity among the different management approaches. Strong linear positive and negative correlations were observed for RT (r=0.63), and ZT (r=-0.60) and F (r=-0.86) between these two parameters, which shows that the soil under ZT presented similarities with F. The smallest degree of anisotropy obtained for F indicates a more isotropic porous system, which means that pores are not oriented in particular directions and there are similarities in the pore orientation in the different directions analyzed (Hernández Zubeldia et al., 2016). Therefore, this kind of porous system does not present a tendency for preferential flows but is expected that the water can infiltrate and also redistribute into the soil in all directions in similar conditions as per Darcy's Law. Tseng et al. (2018) also observed small values for the degree of anisotropy for a native forest area in comparison to degraded or recovering pasture land. The degree of anisotropy data indicated that all management systems had a good physical condition as far as water infiltration is concerned. For comparison, Tseng et al. (2018) observed values of 0.64 for an area of degraded soil and Garbout et al. (2013) of 0.37 for a direct drilling management system.

The pore connectivity measured by the volumetric Euler-Poincaré Characteristic was lowest for CT followed by RT, F and ZT (Fig. 2d). Significant differences ($p<0.05$) of this parameter were observed only between CT and ZT. For these two management systems the increase in pore connectivity was also followed by the increase in the degree of anisotropy (strong linear positive correlations: r=0.74 for CT and r=0.60 for ZT) of the soil porous system, which indicates slight differences in the spatial characteristics of the pores in some specific direction in the images (Tseng et al., 2018). The same tendency of the volumetric Euler-Poincaré Characteristic was found for the pore connectivity (Euler number) of the largest pore (CT<RT<F<ZT), which was c. 2.8 times smaller for CT than ZT (Fig. 2e). Surprisingly, the highest pore connectivity was observed for the soil under CT. We expected that the breakdown of aggregates should decrease the pore connectivity due to soil loosening as observed by Dal Ferro et al. (2014). However, as the samples were collected months after ploughing and harrowing operations, the reorganization of the soil particles and aggregates, as function of the corn root system and weather conditions, may favour the connectivity of the pores under CT (Strudley et al., 2008). Muñoz-Ortega et al. (2015) observed that

soils under tilled areas can present structures similar to natural conditions, which can lead to highly connected porous systems.

From a visual inspection of the 3D images (Fig. 1), we observed that all the management systems presented a main, highly connected pore network. The results of the volumetric Euler-Poincaré Characteristic and Euler number indicate that the soils with the largest porosity had the best pore connectivity, which can be associated with the junction of few large pores with many tunnels or a high amount of small connected pores (Vogel, 1997). Although, there was no clear relation between overall porosity and soil pore connectivity (results not shown), which indicates that probably other physical properties have a greater influence on the pore connectivity than the porosity. In the case of ZT and RT, it was expected that the pore connectivity was mainly associated with the biological activity, root decay and low or nonexistent soil disturbance (Aziz et al., 2013; Daraghmeh et al., 2009; Zibilske and Bradford, 2007). Continuous pores can be produced by crack formation, earthworm activity or retention of crop residues maintained after harvesting on the soil surface, which act as physical barriers making the soil less susceptible to erosion or the pressure of agricultural machine traffic under crop residue harvest (Imhoff et al., 2010). In the case of RT, the soil cutting induced by chiseling preserves cracks and channels between aggregates, which creates inter-connected pores with large volumes (Peña-Sancho et al., 2017). Despite low porosity observed for ZT, pore connectivity was positively influenced by the organic matter content at the soil surface, which may have compensated the negative influence of macroporosity reduction (Franzluebbers et al., 2011). Martins et al. (2011), working at the same experimental area of our study, found differences of around 42% in the carbon content at the topsoil between CT and ZT after 27 years of management.

The results obtained here for porosity and pore connectivity are extremely valuable due to the importance of the mesopores and macropores for water infiltration and retention. Changes in the soil porous system induced by tillage can present significant modifications in the hydraulic properties of the soil as pointed out by Alvarez et al. (2009), Daraghmeh et al. (2008) and Buczko et al. (2006). The importance of soil structure to conserve the quality and the health of the soil, reduce net CO_2 emissions, and increase organic carbon pools is another vital aspect for the micrometric characterization of this porous system; conventional and conservational management systems play an important role in all of these processes (Zibilske and Bradford, 2007).

The soil pore system tortuosity was calculated for different directions (x,y,z), and an average tortuosity was obtained considering the three directions together (Fig. 3). The calculation of tortuosity for different directions is related to the influence of this parameter for the movement of water and air through the soil. This movement occurs in all directions across the soil, and changes in the soil porous system in one direction certainly have the possibility of inducing preferential flows in the soil profile. Significant differences ($p<0.05$) in the average τ was observed between CT and F, and ZT (Fig. 3a). The lowest average tortuosity was measured for ZT, followed by RT, CT and F. Porosity and average tortuosity were strongly correlated only for F ($r=0.78$) and ZT ($r=0.77$), which indicates an increase in pore complexity with an increase in porosity for these two cases. The presence of crop residues in decomposition in ZT and soil fauna in F can help to explain these results (Franzluebbers et al., 2011).

The tortuosity in the x- and y-directions was the highest in F, followed by CT and RT, then ZT (Figs. 3b,c). Significant differences were found only between F and ZT for both tortuosity directions. Porosity and x- and y-direction tortuosities were strongly correlated for all the management systems ($r=0.86$ for CT; $r=0.93$ for RT; $r=0.88$ for ZT – x-direction tortuosity and $r=0.87$ for CT; $r=0.78$ for RT; $r=0.93$ for ZT – y-direction tortuosity) and F ($r=0.90$ – x-direction tortuosity and $r=0.83$ – y-direction tortuosity). In general, the results of x- and y-direction and average tortuosities had the same tendency among management systems. The tortuosity in the z-direction was not characterized by significant differences between F, CT and RT, whereas ZT was different from F (Fig. 3d). The highest z-direction tortuosity was observed for F, followed by RT, CT and ZT. The average tortuosity as well as that in the x-, y- and z-directions was c. 1.1 times higher for F than ZT. Porosity was strongly correlated to z-direction tortuosity only for F (r=0.86) and weakly correlated for CT (r=0.17), which was probably associated with the soil loosening and disturbance in the last case (Munkholm et al., 2012; Munkholm and Hansen, 2012).

The lowest average tortuosity was in the ZT soil indicating that pores are more aligned for this management. The same results were found for the tortuosity in the different directions. Usually, more aligned pores can sometimes be associated with a better interconnected network of more continuous flow channels (Peth et al., 2008). However, the better alignment of the pores for ZT did not result in a better pore connectivity as observed by the weak linear negative correlation between average tortuosity and volumetric Euler-Poincaré Characteristic (r=-0.22). This means that the more aligned and continuous pores possibly were not interconnected with other pore networks. Tortuosity is mainly related to the degree of complexity of the sinuous porous path (Pagenkemper et al., 2014; Rezanezhad et al., 2010). Despite the better connectivity measured for CT compared to the other management systems, this connectivity is probably associated with the junction of small pores as observed in the 3D images (Muñoz-Ortega et al., 2015; Vogel, 1997). Therefore, the highest tortuosity observed for CT in comparison to ZT is possibly related to a higher number of connected small pores. Similar findings were found by Borges et al. (2018) and Peth et al. (2008). The highest tortuosity was measured for the soil under F, which can be associated with the complexity of the soil porous system due to biological activity, soil fauna (insects), roots, a greater amount of residues (tree leaves) maintained at the soil surface and the absence of tillage (Blanco-Canqui and Lal, 2007).

The tortuosity of pores in the z-direction directly corresponds to the variation in soil structure associated with soil depth. The more aligned pores in this direction can be associated with wider and more continuous flow channels, which can improve the water infiltration in this direction. The effective transport of fluids through the pore networks is not only dependent on their continuity but also on their tortuosity (Peth et al., 2008). The similarities in the values of tortuosity for the different directions indicate that the pore complexity follows a similar pattern in all directions analyzed. However, average tortuosity was strongly negatively correlated to the degree of anisotropy for CT (r=-0.90), ZT (r=-0.72) and F (r=-0.66), which means that the presence of more tortuous pores does not necessarily affect the distribution of pores.

In general, the tortuosity data described well aligned pores for all the management systems studied. This result is important because the tortuosity is associated with the hydraulic conductivity. This parameter indicates increased resistance to flow, which means high tortuosity can negatively affect the capacity of soil to water transport (Rezanezhad et al., 2010).

The pore morphology characterized by the shape of pores is similar to the other parameters studied in that it directly affects the movement of water, air and the development of roots through the soil. Changes in the shape of pores due to management will influence the water retention and the amount of water available to plants. The highest contribution of equant (e.g. equant spheroid) shaped pores to the total porosity was observed for F, followed by RT, CT and ZT (Fig. 4a). The proportion of equant shaped pores was c. 1.3 times higher for F than ZT. Significant differences ($p<0.05$) were identified between F, ZT and CT. For prolate (e.g. prolate spheroid / rod) shaped pores (Fig. 4b), the highest contribution to porosity was found for RT, followed by F, ZT and CT. The proportion of prolate shaped pores was c. 1.1 times higher for RT than CT. No significant differences were recorded between management systems for this type of pore shape. The highest contribution of oblate (e.g. oblate spheroid / discoid) shaped pores to porosity was measured for F, followed by CT, RT and ZT (Fig. 4c). The proportion of oblate shaped pores was c. 1.3 times higher for CT than ZT.

Similar to the results of prolate shaped pores, no significant differences were observed between the different management systems. The highest contribution to porosity was verified for pores of triaxial (e.g. blade) shape (Fig. 4d). The following sequence among management systems was found for triaxial shaped pores: F<RT<CT<ZT; and the proportion of them was c.1.1 times higher for ZT than F. Significant differences were observed between F, ZT and CT.

The presence of slightly to very flat/elongated (e.g. prolate, oblate and triaxial) pores was greatly influenced by different soil management systems. The presence of earthworms and insects, mainly at the soil surface, will contribute to the appearance of elongated pores (Jarvis et al., 2017; Pagenkemper et al., 2015; Rogasik et al., 2014). According to Pagliai et al. (2004), elongated continuous pores affect plant growth by easing root penetration and increasing the transmission and storage of water and gases. The smallest proportion of platy and equant shaped pores is an indication of a good soil structure (Pagliai et al., 2004; Bouma et al., 1977). The largest proportion of slightly to moderately flat/elongated pores is indicative of soil quality, since they are generally related to the biological activity of living organisms and roots (biopores) (Carducci et al., 2014; Lima et al., 2005). The Euler number showed moderate (r=0.52 for ZT) to strong (r=0.76 for CT and r=0.84 for RT) positive correlations in relation to the contribution of triaxial shaped pores to porosity, which means that the largest presence of these type of pores can positively contribute to water infiltration. However, samples of F had only weak correlation (r=0.17) between these two morphological properties, which can be associated with the increased complexity of the porous system. We observed that the average tortuosity was strongly correlated (r=0.67) to the triaxial shaped pores contribution to the porosity for F. In conventional management, the presence of elongated pores is usually associated with planar shaped pores surrounding or separating aggregates or clods (Pagliai, 1994). The recovery of soil structure, which occurs in soils managed under conventional management systems after months of ploughing and harrowing operation procedures, can also be identified by an increase in the proportion of elongated pores (Zhao et al., 2017). The largest amount of equant shaped pores in F can also be related to the biologic activity. This pore type also plays an important role in the transport and retention of water, since water can infiltrate very quickly in tubular pores (Yang et al., 2018). A strong positive correlation (r=0.61) was found between the volumetric Euler-Poincaré Characteristic and the contribution of equant shaped pores to porosity for F, which highlights the importance of this type of pore in native or secondary forests.

A large portion of the pores were not classified in terms of shape. The contribution of unclassified pores to porosity was around 60% for F and RT, 66% for ZT and 63% for CT, respectively. Moderate to strong positive correlations were found between the volumetric Euler-Poincaré Characteristic and the contribution of unclassified pores for all the management systems (r=0.58 for ZT, r=0.91 for CT and r=0.85 for RT) and F (r=0.56). As unclassified pores were responsible for a considerable part of the porosity, their contribution to pore connectivity is important and suggests the samples analyzed are characterized by good structural quality. Unclassified pores are also an indicative of the complexity of the soil porous system. The well connected pore structures observed in the 3D images give an idea of the complexity of the soil porous system (Fig. 1). Similar results of a high contribution of complex pores to the overall porosity have also been previously measured for Brazilian soils (Ferreira et al., 2018; Borges et al., 2018; Costa et al., 2018; Pires et al., 2017; Passoni et al., 2015).

The small pores (from 0.0004 to 10 mm^3) made only a small contribution to overall porosity. The highest contribution to porosity for 0.0004 to 0.01 mm^3 pores was observed in ZT, followed by F, RT and CT. Significant differences ($p<0.05$) were recorded between management systems for this pore size interval (Fig. 5a). Porosity displayed strong negative correlations to the interval of pore volumes between 0.0004 and 0.01 mm^3 for F (r=-0.79), CT (r=-0.94) and RT (r=-0.99). For the pore sizes of 0.01 to 0.1 mm^3 (Fig. 5b), significant differences were observed between ZT and the other management systems. Porosity also displayed strongly negative correlations to the interval of pore volumes between 0.01 and 0.1 mm^3 for F (r=-0.90), CT (r=-0.92) and RT (r=-0.89). For the last two size intervals of pores, the increase in porosity was followed by a decrease in the contribution of small pores, which highlights the great contribution of large pores to the overall soil porous system of F, CT and RT studied. The correlation between porosity and the two previous pore size intervals analyzed was moderate to weak for ZT (r=-0.41 for 0.0004 to 0.01 mm^3 and r=-0.29 for 0.01 to 0.1 mm^3). This result shows that the variation in porosity was not greatly influenced by changes in the distribution of small pore sizes for this management.

The highest contribution to porosity for 0.1 to 10 mm^3 pores was observed for ZT, followed by F, RT and CT (Fig. 5c). Similar to the results observed for the 0.01 to 0.1 mm^3, significant differences were found only between ZT and the other management systems. For the largest pores (>10 mm^3), the greatest contribution to porosity occurred for CT, followed by RT, F and ZT. The soil under ZT presented significant differences in comparison to the other management systems (Fig. 5d). The proportion of different pore volume intervals to porosity was c. 3.5 (0.0004 to 0.01 mm^3), c. 4.3 (0.01 to 0.1 mm^3) and c. 4.0 (0.1 to 10 mm^3) times higher for ZT than CT and c. 1.1 times higher for CT than ZT for the largest pore sizes (>10 mm^3) studied.

We observed that in general the samples with high porosities were also characterized by a large contribution of the biggest pores (>10 mm^3) to the porosity, which was corroborated by the strong positive correlations obtained for F (r=0.82), CT (r=0.93) and RT (r=0.94) between these two soil physical properties. This is an indication of highly connected pore networks supported by the moderate to strong negative correlations between the volumetric Euler-Poincaré Characteristic and the contribution of pores >10 mm^3 to porosity for ZT (r=-0.73), CT (r=-0.81) and RT (r=-0.50) of the soil samples analyzed.

In terms of pore size distribution, the contribution of pores <10 mm^3 to porosity was around 4% for F, 8% for ZT, 2% for CT and 3% for RT. This indicates that a large part of the porosity is composed of large inter-aggregate pores as observed by Costa et al. (2018). Ferreira et al. (2018) recently showed that >90% of porosity for a soil under ZT consisted of a main pore network as observed in our study. This type of pore system is related to soil structural development and it is indicative of structures that function well for water infiltration (Bullock and Thomasson, 1979). Borges et al. (2018) and Pires at al. (2017) obtained similar results for the same experimental area. Cássaro et al. (2011), in another work in the same site, identified a great concentration of large pores under ZT and CT management systems. The greatest contribution of unclassified pores to porosity is also indication of the presence of a main pore network composed by large pores (Costa et al., 2018; Jefferies et al., 2014). Garbout et al. (2013) determined that the volume of connected pores constituted 91% and 85% for drilling and ploughing areas, which indicates the great contribution of a main pore network to the overall porosity. Dal Ferro et al. (2014) also observed a contribution of around 70% of macropores to porosity, which would contribute to water infiltration and potentially reduce erosion (Imhoff et al., 2010).

CONCLUSIONS

We analyzed the structure of samples of an Oxisol under different management systems using X-ray Computed Tomography. The qualitative results obtained through 3D visual image analysis showed that the soils under all the management systems (zero-tillage, conventional tillage and reduced tillage) and forest are generally composed of a large main pore network which is highly connected. The pore connectivity results demonstrated that even for ZT, which was characterized by a lower comparable mesoporosity and macroporosity, the soil porous system has a strongly connected pore network compared to the forest. We attribute this lower porosity for ZT to a possible development of a zero-tillage pan. However, the results of pore connectivity, degree of anisotropy and tortuosity show that the soil structure under ZT was not negatively affected by the reduction in its porosity. The smallest average tortuosity and the largest contribution of triaxial shaped pores found for ZT can help to explain the pore connectivity results. A moderate positive correlation was also measured between the volumetric Euler-Poincaré Characteristic and the unclassified pores for ZT similar to the results of F. As a great part of the porosity was comprised of unclassified pores for all the management systems and forest, these pores present an important contribution to the overall pore connectivity. The largest proportion of elongated shaped pores also demonstrated that all the management systems examined had positive effects in the quality of the soil porous system. Similar to the 3D image visualizations, the largest contribution to porosity was due to the presence of a main pore network, which means the porous system was well connected in all the management systems. The results of this study provided a detailed characterization of the soil porous system at the micrometric scale. This type of information is extremely important due to the relevance of mesopores and macropores in the transport of mass and energy through the soil. We can conclude that each of the management systems studied here presented positive indications of soil quality, which is surprising given their differences in operation and extremely important from an environmental and agricultural points of view.

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Figure Captions

Fig. 1. 3D reconstruction of selected soil cores (≈5.0 cm high and ≈4.8 cm inner diameter) and pore spaces for the different management systems studied. The soil sample images were reconstructed with a resolution of 35 μm.

Fig. 2. Morphological properties of the soil porous system of a Brazilian Rhodic Hapludox submitted to different management systems (F: secondary forest; ZT: zero-tillage; CT: conventional tillage; RT: reduced tillage). (a) Porosity (P). (b) Number of pores (NP). (c) Degree of anisotropy (DA). (d) Volumetric Euler-Poincare Characteristic (EPC_V). (e) Euler Number (EN) of the largest pore.

Fig. 3. Tortuosity of the soil porous system of a Brazilian Rhodic Hapludox submitted to different management systems (F: secondary forest; ZT: zero-tillage; CT: conventional tillage; RT: reduced tillage). (a) Average tortuosity (τ). (b) Tortuosity in the x direction (τ_x). (c) Tortuosity in the y direction (τ_y). (d) Tortuosity in the z direction (τ_z).

Fig. 4. Contribution of the different pore shapes to porosity for the Brazilian Rhodic Hapludox submitted to different management systems (F: secondary forest; ZT: zero-tillage; CT: conventional tillage; RT: reduced tillage). (a) Pores of equant (EQ) shape. (b) Pores of prolate (PR) shape. (c) Pores of oblate (OB) shape. (d) Pores of triaxial (TR) shape.

Fig. 5. Contribution of different sizes of pores to the volume of pores (VP) for the Brazilian Rhodic Hapludox submitted to different management systems (F: secondary

forest; ZT: zero-tillage; CT: conventional tillage; RT: reduced tillage). (a) Volume of pores between 0.0004 to 0.01 mm^3. (b) Volume of pores between 0.01 to 0.1 mm^3. (c) Volume of pores between 0.1 to 10 mm^3. (d) Volume of pores >10 mm^3.

Table 1. Texture (clay, silt, sand), macroporosity (Ma), microporosity (Mi) and organic carbon (OC) for the experimental areas under zero-tillage (ZT), conventional tillage (CT), reduced tillage (RT) and secondary forest (F) studied.

Property/ System	Clay	Silt	Sand	Ma	Mi	OC
		(g kg^{-1})			(cm^3 cm^{-3})	(g kg^{-1})
ZT	530	300	170	0.10	0.43	55.8
CT	610	220	170	0.19	0.37	31.7
RT	580	260	160	0.15	0.39	41.0
F	590	340	70	0.14	0.38	80.7

Ma: macroporosity; Mi: microporosity; OC: organic carbon. Mi was determined in undisturbed samples submitted at -6 kPa in an Eijkelkamp® suction table. The OC of the secondary forest was extracted from the work of Sá et al. (2015) for the surface layer (0-10 cm).

Table 2. Culture rotations per year for the experimental areas under zero-tillage (ZT), conventional tillage (CT) and reduced tillage (RT) studied.

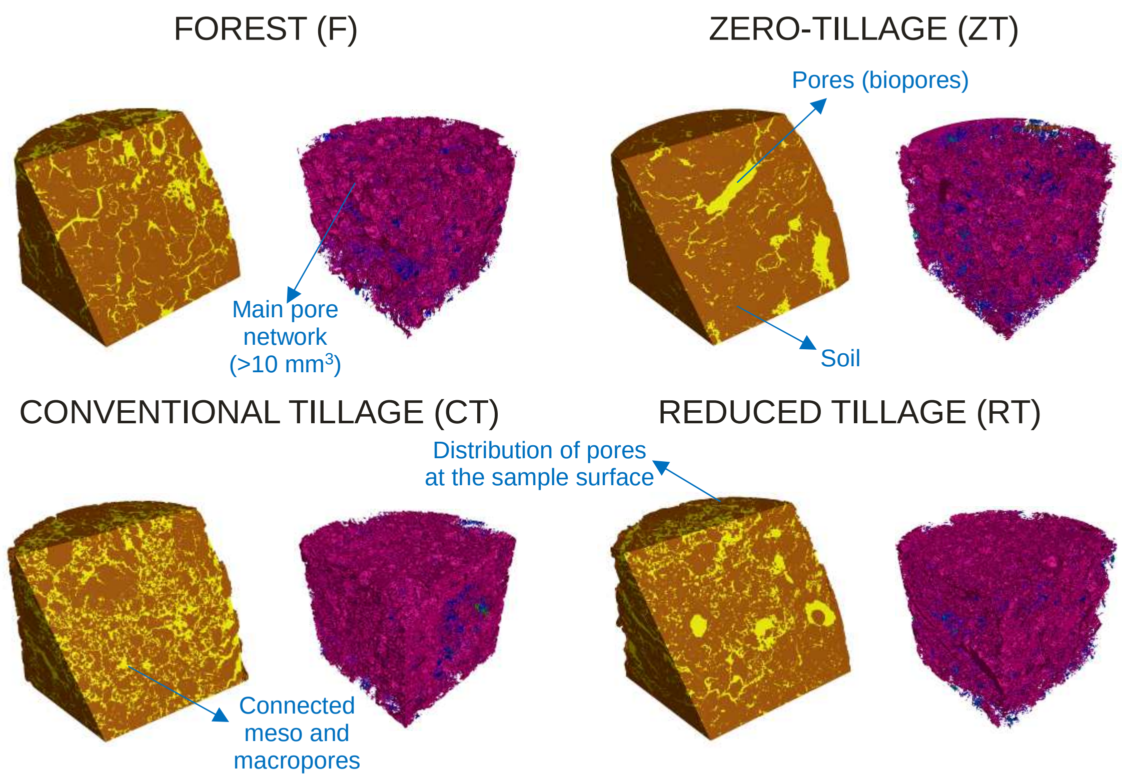
Year	Management system and crop sequence	
	CT and RT	**ZT**
1981-1990	W/S	C/O/S - W/S/L - C/O/S - W/S/L - C/O/S - W/S
1990–1995	O/S - O/C - W/S - O/S - L/C	Similar to CT and RT
1995–2000	O/S - W/S - O+V/C - O/S - W/C	Similar to CT and RT
2000–2009	O/S – O/C - W/S - O+V/S - O/C - O/S - O/C - O/S - O/C - V/S	Similar to CT and RT
2009–2017	O/C	Similar to CT and RT

S: soybean (*Glycine max*); W: wheat (*Triticum aestivum* L.); O: oat or black oat (*Avena strigosa*); C: corn (*Zea mays* L.); V: vetch (*Vicia sativa*); L: Lupine (*Lupinus spp.*). The information presented in the table were adapted from Sá et al. (2015) and Martins et al. (2011)

Table 3. Indices utilized for the classification of pores in terms of shape.

Axes ratio	Shape			
	Equant (EQ)	**Prolate (PR)**	**Oblate (OB)**	**Triaxial (TR)**
Int./Maj.	≥2/3	<2/3	≥2/3	<2/3
Min./Int.	≥2/3	≥2/3	<2/3	<2/3

Int.: intermediate axis; Maj.: major axis; Min.: minor axis



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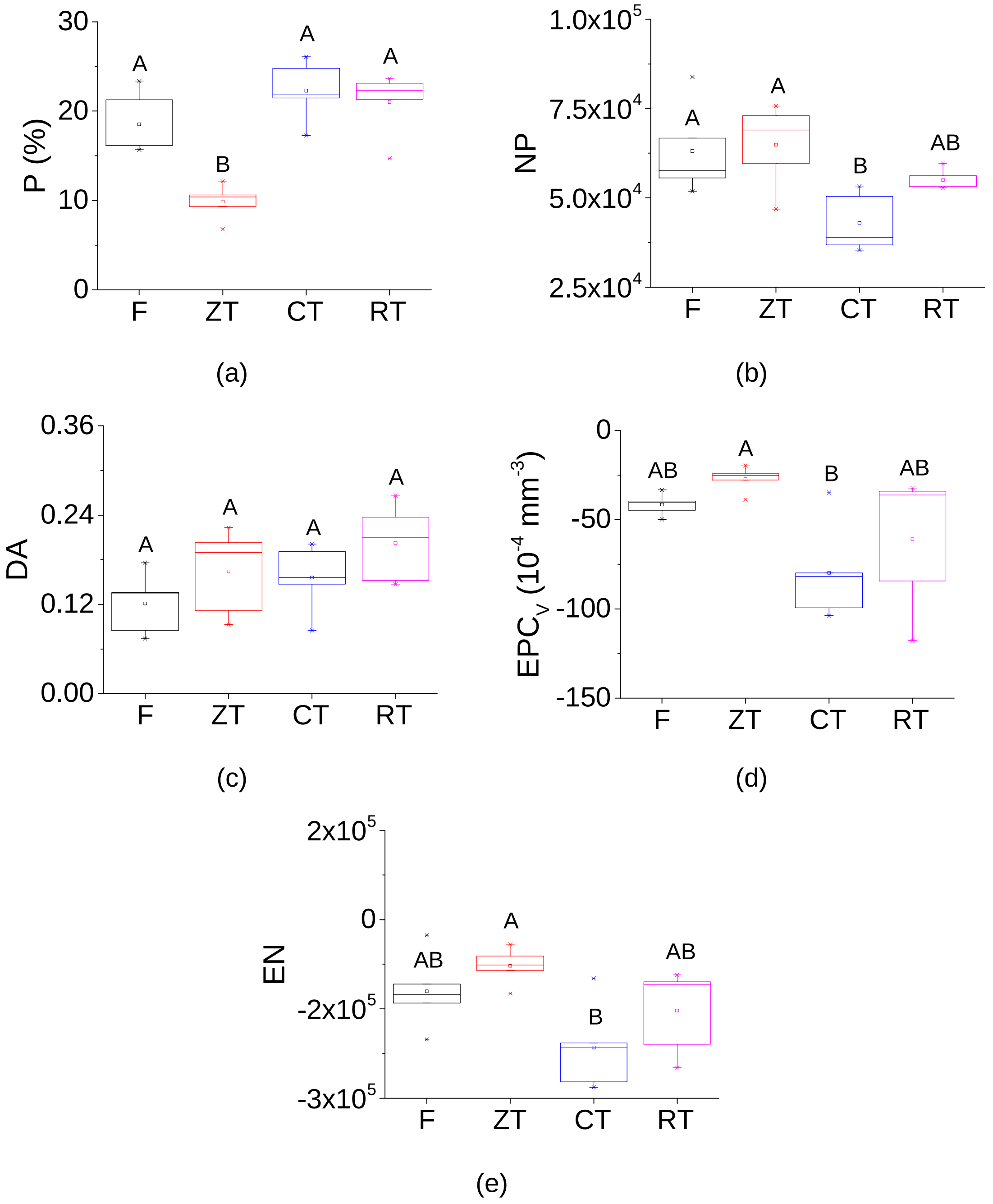

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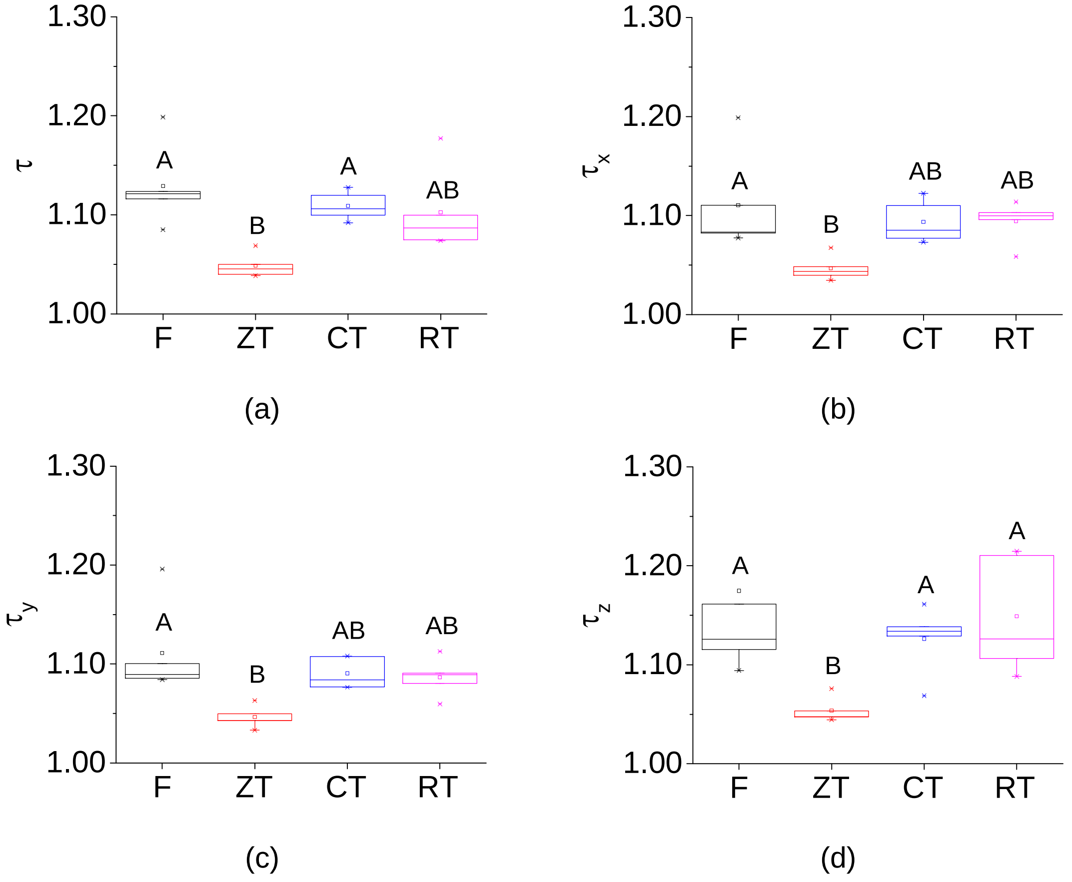

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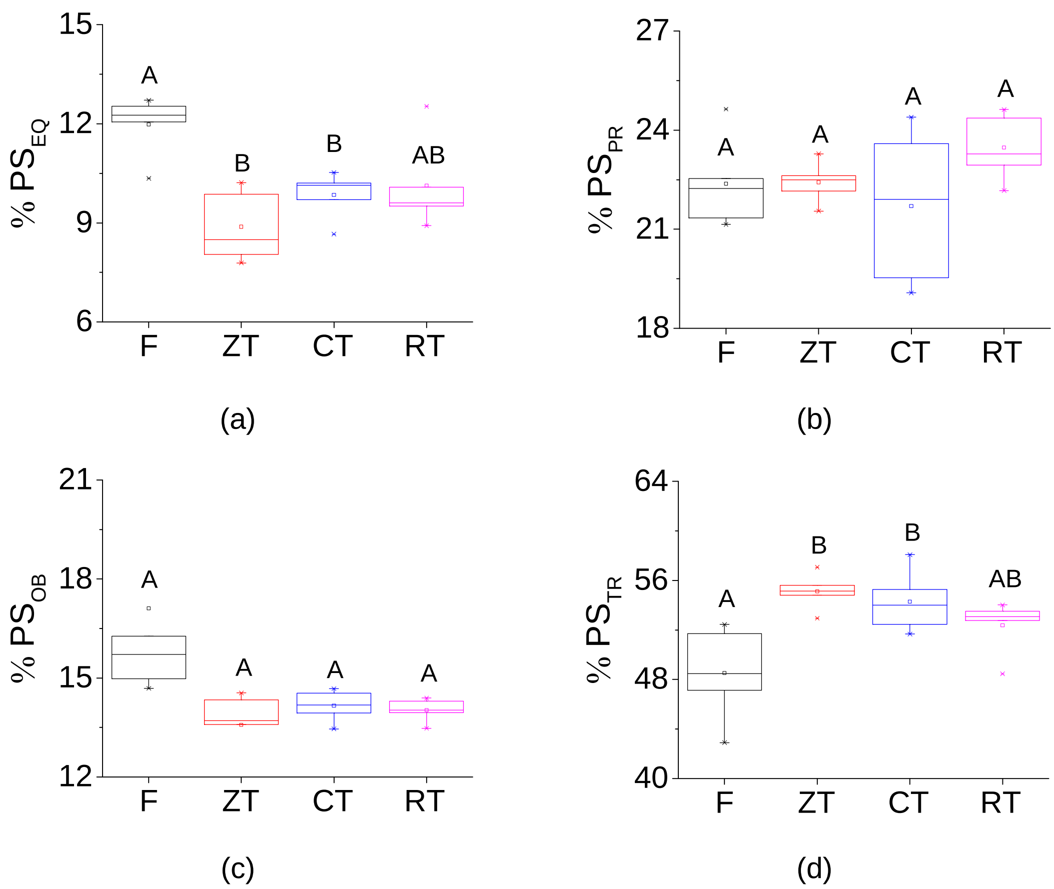

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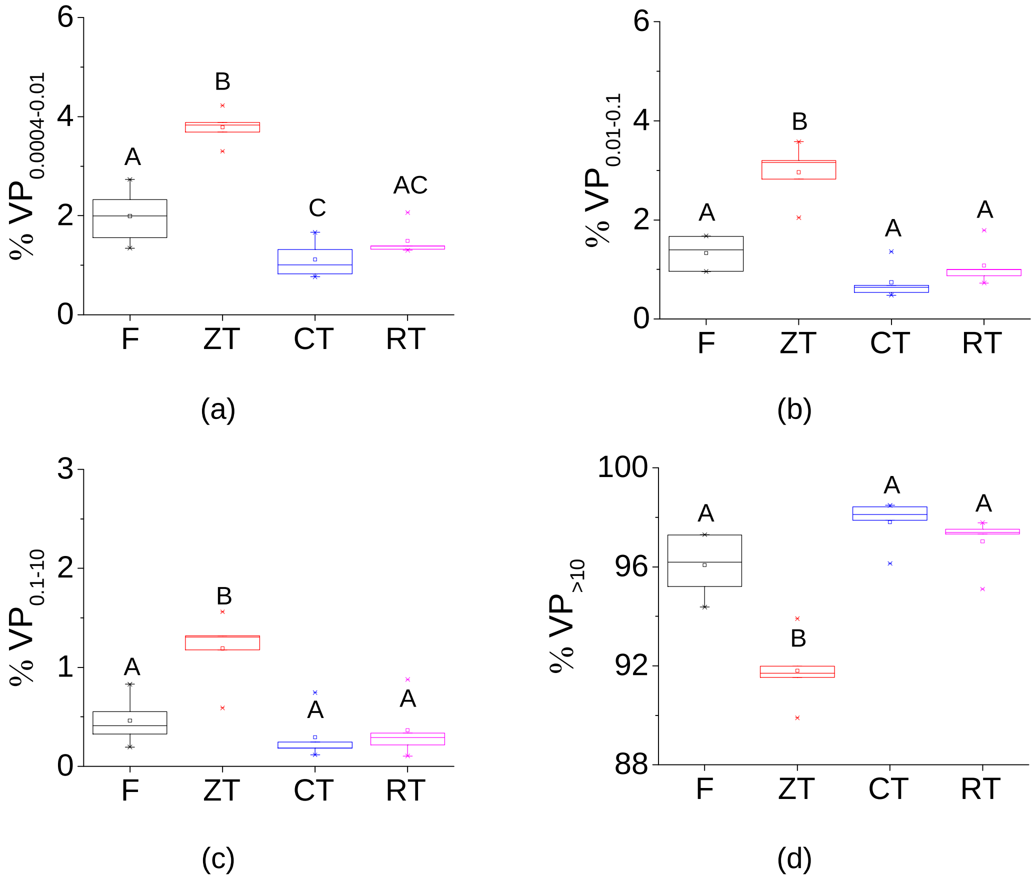

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