Soil microstructure alterations induced by land use change for sugarcane expansion in Brazil

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Running Title: Soil microstructure alterations by land use change.

Summary

Land use change (LUC) alters soil structure and consequently, the functions and services provided by these soils. Conversion from extensive pasture to sugarcane is one the most large-scale land transitions in Brazil due to the growth of the domestic and global demands of bioenergy. However, the impacts of sugarcane expansion on the soil structure under extensive pasture remains unclear, especially when considering changes at the microscale. We investigated if LUC for sugarcane cultivation impacted on soil microstructure quality. Undisturbed soil samples were taken from two soil layers (0-10 and 10-20 cm) under three contrasting land uses (native vegetation – NV, pasture – PA and sugarcane – SC) in three different locations in the central area of southern Brazil. Oriented thin sections (30 µm) were used for micromorphological analysis. The total area of pores decreased following the LUC in the following order; NV > PA > SC in both soil layers. The area of large complex packing pores (>0.01 mm²) also decreased with the LUC sequence: NV>PA>SC. Qualitative and semi-quantitative micromorphological analysis confirmed porosity reduction was driven by the decrease in complex packing pores and that biological features decreased in the same LUC sequence as the quantitative parameters. Therefore, LUC for sugarcane expansion reduced microscale soil porosity, irrespectively of soil type and site-specific conditions, indicating the adoption of more sustainable management practices is imperative to preserve soil structure and sustain soil functions in Brazilian sugarcane fields.

Keywords: Soil micromorphology, sugarcane, soil physical quality, complex packing pores, bioenergy production

Introduction

The growing interest in biofuels has resulted in a new demand for arable land for bioenergy crop production. Land use change (LUC) is one of the greatest threats to soil quality (Cherubin *et al.*, 2016a; Bonilla-Bedoya *et al.*, 2017), as it can have significant impacts on soil biodiversity (Franco *et al.*, 2016), carbon storage (Mello *et al.*, 2014) and ecosystem services (Foley *et al.*, 2011). Brazil is the world' largest sugarcane producer with 8.59 million ha of cultivation area and production of 29 Mt of sugar and 33 billion L of ethanol (CONAB, 2019). Conversion from extensive and degraded pastureland to sugarcane production is the main scenario of LUC used to support sugarcane expansion in Brazil (Adami *et al.*, 2012; Strassburg *et al.*, 2014).

However, the intensive mechanization used in sugarcane fields, including soil tillage by ploughing and disking and heavy machinery traffic during mechanical harvesting degrades soil structure, affecting multiples processes and functions in these soils (Cherubin *et al.*, 2016; Robot et al., 2018). Soil structure is typically defined by the arrangement of soil particles and aggregates and the pores among the structural units, which regulates multiple processes and services such as: water retention and conductivity, soil aeration, soil organic matter turnover, nutrient cycling (Six *et al.*, 2004), soil erodibility (Barthès & Roose, 2002) and plant growth. Therefore, parameters related to soil structure are considered key indicators of soil quality (Bünemann *et al.*, 2018). Soil microstructure relates to the compositional arrangement of soil at a smaller scale (i.e. at the micron scale)) and can be assessed by the use of thin sections, also known as micromorphology (Bullock *et al.* 1985). Although microstructure assessment by thin section can be time-consuming and generally does not provide 3D structural information, it provides more detail than other approaches where visualization of the soil micro-fabric is concerned.

Although traditional soil physical properties (e.g. bulk density, soil porosity, soil penetration resistance, soil aggregation etc.) along with visual assessment methods can efficiently infer the stability, and even resilience of soil structure (Cherubin *et al.*, 2016b, 2017; Castioni *et al.*, 2018), these methods cannot reveal the precise spatial arrangement of soil structure and the geometrical form of pores and aggregates. Imaging methods, such as micromorphology, can be used to further study the dynamics of soil structural development across the time and/or space and help improve understanding concerning the impact of soil structure on soil functioning (Guimarães *et al.*, 2013; Silva *et al.*, 2015; Souza *et al.*, 2015; Pires *et al.*, 2017). Whilst other imaging methods such as X-ray Computed Tomography (CT) have become more popular for the analysis of soil pore space in recent years, particularly as they facilitate faster acquisition of images and 3D visualisation, micromorphology is still an important technique for the analysis of soil structure as it permits the microscopic visualization of some soil properties, such as those derived from organic matter, e.g. fecal deposits, that are currently not straightforward to image by X-ray CT (Helliwell *et al.*, 2013).

Considering the intense mechanization applied to sugarcane soils, we conducted a field study to evaluate the impact of LUC for sugarcane expansion on soil microstructure characteristics using soil thin sections. The hypothesis was that the intensity of sugarcane cultivation had a significant impact of the alteration on soil microstructure and subsequent soil quality.

Materials and methods

Study sites

Undisturbed soil samples for 0 – 10 and 10 – 20 cm soil depth were taken in the central region of southern Brazil at three different locations within the main sugarcaneproducing region of the country, as follows: Lat_17S near the city of Jataí – Goáis State (17º56’16”S 51º38’31”W), Lat_21S near the city of Valparaíso – São Paulo State (21º14’48”S 50º47’04”W) and Lat_23S near the city of Ipaussu – São Paulo State (23º05’08”S 49º37’52”W) with soil orders was classified as Oxisol, Alfisol/Ultisol and Oxisol by the USDA Soil Taxonomy (Soil Survey Staff, 2014), respectively. The climate was classified according to Köppen-Geiger’s system as mesothermal tropical (Awa), humid tropical (Aw) and tropical (Cwa), respectively. The mean annual temperature and precipitation is 24.0 ºC and 1600 mm (Awa) at Lat_17S, 23.4 ºC and 1240 mm (Aw) at Lat_21S and 21.7 ºC and 1479 mm (Cwa) at Lat_23S, with the rainy season in the Spring-Summer (October to April) and the dry season during the Autumn-Winter (May to September). More detailed climate information (mean monthly temperature and precipitation) are available in Cherubin *et al.* (2015).

In each site, we sampled a LUC sequence, including native vegetation (NV, baseline), pasture (PA) and sugarcane (SC) areas. Selected physical and chemical soil properties are found in Table 1. The land use and management history of each site, as well as chemical and physical characterization of the soils are further described in Cherubin *et al.* (2015; 2016). For all sugarcane areas, the soil was prepared by ploughing and disking previously to cropping. The SC fields at Lat_17S, Lat_21S and Lat_23S was in the third, third and fourth ratoon, respectively. In SC fields fertilizer was applied annually and harvesting was performed using a 20 Mg harvester and transported by a tractor and wagon (10 + 30 Mg). A controlled traffic system was not used in these areas.

Soil sampling and preparation

One undisturbed soil sample (7 x 12 x 6 cm) was collected in the Lat_17S, Lat_21S e Lat_23S for NV, PA and SC in two soil layers (0-10 and 10-20 cm), totaling 18 samples (3 sites x 3 land uses x 2 soil depths). For sugarcane, the soil was sampled in the inter-rows. The soils were air dried for 35 days and then placed in an oven at 40 ºC for 48h. The dry samples were impregnated with a polyester resin, styrene monomer and fluorescent dye (Tinopal BASF®) by capillarity in a vacuum chamber. After impregnation, vertically oriented soil thin sections (c. 30 μm thick) were obtained for qualitative and semi-quantitative description (Bullock *et al.*, 1985; Stoops, 2003; Cooper *et al.*, 2017) and quantitative image analysis (Cooper *et al.* 2016). Figure 1 illustrates the sampling procedure adopted in the field.

Micromorphological analysis

The thin sections were analyzed using a Zeiss petrographic microscope. The qualitative description of thin section was made following the classifications described in Bullock *et al.* (1985) and Stoops (2003) only for thin sections from Lat_23S. This method provides reference images for a semiquantitative assessment of porosity and the description of pore morphology. The pores were classified as packing pores, i.e. those that result from the loose packing of soil components; channel pores, i.e. tubular smooth pores with a cylindrical or arched cross section which are uniform over much of the length; vughs, i.e. more or less equidimensional, irregularly shaped, smooth or rough, usually not interconnected; and planar pores, i.e. flat, accommodating or not, smooth or rough, resulting from shrinkage or compaction (Stoops, 2003). The soil coarse/fine (c/f) fabric was classified as either porphyric (i.e. coarse grains embedded in fine material), enaulic (i.e. fine material appears as micro-aggregates between coarser components) or combinations of these as described in Stoops (2003).

Micromorphometrical analysis

Ultraviolet light was used to enhance the contrast between the pore space and soil matrix, and images were obtained using a charged couple device photographic camera (DFW-X700, Sony®). For each soil sample, fifteen images of 180 mm² were randomly obtained (Figure 1). The images were digitalized with a resolution of 1024 x 768 pixels in 256 shades of gray in a 10x amplification giving a pixel size of 12.5 µm. Pore segmentation was undertaken in Noesis Visilog version 5.4 by means of a user defined threshold (maintained throughout the study), opening and closing filtering, and labelling, which correspond to the individualization of each object followed by its identification. The smallest segmented pore had a diameter of 37.5 µm, which is classified in the meso/macro-pore size range; the size class most sensitive to soil compaction (Richard *et al.*, 2001).

The total area of pores (Tap) for each image was calculated as the percentage of the sum of the areas of the individual pores divided by the total area of the assessed image (Hallaire & Cointepas, 1993). Pore shape was classified into three groups as in Cooper *et al.* (2016): rounded, elongated and complex. Two indexes were used to determine the pore shape, as described in Eq. 1 and Eq. 2:

$$I1 = \frac{P^2}{4\pi A} \qquad \text{(Eq .1)}$$

Where P is the perimeter of the pore and A is the area.

$$I2 = \frac{\frac{1}{m}\sum_i (NI)i}{\frac{1}{n}\sum_j (DF)j} \qquad \text{(Eq. 2)}$$

NI is the number of intercepts of the object in direction *i* (*i* = 0°, 45°, 90°, and 135°), DF is the Feret diameter of the object in the direction *j* (*j* = 0° and 90°), *m* correspond to the number of *i directions* and *n* to the number of *j* directions. The I2 index was used complementary to I1 for a better pore segregation according to shape.

When morphometric shapes are compared with the micromorphological classification, rounded pores correspond to vughs, elongated pores to channel and planar pores, and complex pores to packing pores.

Data analysis

The mean soil porosity of each site was derived from 15 subsamples (every image from a single thin section), which were used as pseudo replicates (Hurlbert, 1984) to compare the difference in LUC porosity for each site; to compare the LUC effect on soil porosity for the central-southern region each site was considered as a replicate (n=3). Data normality was tested by Shapiro-Wilk's test ($p > 0.05$), followed by an analysis of variance (ANOVA) and *post hoc* via a Duncan's test ($p < 0.05$).

Results

Micromorphological analysis

Regardless of land use, the soils presented a dominant porphyric relative distribution with secondary areas presenting as porphyric-enaulic, enaulic-porphyric and enaulic related distributions. The porphyric-enaulic related distribution areas only occured in agricultural land uses (PA and SC) whilst the enaulic-prophyric areas were only observed in NV soils (Table 3).

The soil micromorphological descriptions also showed a reduction in soil porosity in both layers due to the LUC from native vegetation to pasture (Table 3). Also, the pore morphology observed for native vegetation showed more complex packing pores than in the pasture. In the pasture soils, there was a reduction in complex packing pores and an increase in policoncave vughs in both layers whereas planar pores were generally identified in the subsurface layer (Table 3).

The porosity of soil under sugarcane was lower than pasture only for the 0-10 cm layer. The pore morphology analysis showed a further reduction of complex packing pores from pasture to sugarcane and an increase in spherical and policoncave vughs and channels (Table 3). When pedofeatures were analyzed, a reduction in biological features from native vegetation soil to pasture was observed. However, the bio-pores, characterized by the infilling of pores, and aggregates had no clear differences in diameter. The LUC from pasture to sugarcane also led to a reduction in biological features (pores, aggregates and coprolites) and the size of biological-derived aggregates in the 0.1-0.2 m layer (Table 3).

Micromorphometrical analysis

Considering all sites, the total area of pores (Tap) was 1.2 to 2.1 times higher in the surface layer (0-10 cm) of NV soils than pasture soils, whereas, sugarcane soil had a Tap 1.5 to 2.2 times lower than pasture soils (Table 2). The same pattern of change induced by LUC (Table 2) was observed at site scale, except for Lat_21S where PA did not differ from NV. For the subsurface layer (10-20 cm), LUC did not induce changes in Tap (Table 2) when considered at the regional scale. However, for Lat_23S, the NV had a higher porosity than PA and SC, and the Tap of NV was higher than PA, which was higher than SC at Lat_17S (Table 2).

For the top soil layer (0-10 cm), the soil pores at NV were rounded, elongated and predominantly, complex pores. A reduction in complex and larger pores was observed in accordance with a reduction in Tap with the LUC sequence; NV > PA > SC. This indicates the reduction of the Tap was driven by large and complex pores representing a loss of in the portion of complex packing pores, which is observed in Figure 2, where the 10-20 cm soil layer was less sensitive to this alterations at Lat_21S and Lat_23S (Figure 3 and 4).

Discussion

Impacts of conversion from native vegetation to pasture on soil microstruture

Land transition from native vegetation to pasture promoted reduction in porosity in surface and subsurface soil layers at Lat_23S e Lat_17S. However, considering the data at the regional scale, this conversion induced a reduction of the soil porosity only for the superficial layers (Table 2). These results are in agreement with a higher soil bulk density (BD), reduced macroporosity (MaP) and hydraulic conductivity (K_{fs}) of these same pasture soils found by Cherubin *et al.*, (2016b). In addition, despite the contrasting scales of evaluation, our micromorphometric analysis confirmed the results obtained by on-farm visual evaluation by Cherubin et al. (2017), using the Visual Evaluation of Soil Structure (VESS) method (Guimarães et al., 2011). Based on VESS assessment, pasture soils presented larger, harder and less porous aggregates than native vegetation soils, resulting in lower overall soil physical quality in the 0-25 cm layer (Cherubin et al., 2017).

Cattle trampling may be the main driver of soil porosity reduction in pastures. Mulholland & Fullen (1991) observed higher BD and penetration resistance in pastureland soil after trampling using a thin section evaluation. Also, soils under native vegetation can have higher organic matter inputs than the anthropic land uses, increasing organic matter content (Franco *et al.*, 2015), which is responsible for aggregate formation and stabilization (Six *et al.*, 2004), providing better soil physical conditions (Cherubin *et al.*, 2016b).

The quantitative pore shape results showed a reduction in larger complex pores (Figures 3 and 4). This reduction did not alter the soil microstructure between these LUC's, but changes were identified in the qualitative pore morphology analysis showing a decrease in complex packing pores and an increase in spherical and policoncave vughs and fissures from NV to PA (Table 3). These changes in the quantitative and qualitative pore morphology assessments are also reflected in the changes in the related c/f distribution with a transformation of enaulic and enaulic-porphyric related distribution in NV to a porphyric-enaulic related distribution in PA. This morphological evidence suggests an incipient compaction process in PA that caused by animal trampling and poor pasture management that may reduce the benefits of soil macrofauna bioturbation, which is partly responsible for the formation of these morphological features. Compaction causes a reduction in the total volume of pores, and this reduction not only alters pore morphology but changes the pore size distribution (Boivin *et al.*, 2006). Therefore, the pore size and shape results obtained in this study can be useful indicators or proxies for pore connectivity and tortuosity properties, which are important for the evaluation of changes in key soil functions and services (Silva et al., 2015; Rabot *et al.*, 2018), such as regulation of water fluxes and soil aeration, induced by land use change and soil management practices. Although, the observation in 2D is a limitation in this instance as assessment of pore connectivity in 3D is more appropriate for prediction of some soil functions e.g. soil hydraulic behaviour. Further investigations combining both the data from thin sections and X-ray imaging would improve our understanding concerning the soil structure changes induced by agricultural land uses, as well as to better establish the linkage between soil structure dynamics and the provision of soil functions and ecosystem services.

Impacts of conversion from pasture to sugarcane on soil microstruture

Our results indicated a reduction on total porosity, mainly in the surface soil layer (0-10 cm), when sugarcane was converted from pasture (Figure 2). The decrease of packing pores observed in the micromorphological analyses (Table 3) confirms the reduction of porosity and complex pores observed in the quantitative image analyses.

Overall, land transition from pasture to sugarcane increases the mechanical compressive stresses applied on the soil surface, causing microstructural degradation due to the coalescence of aggregates by compaction. The effect of this microstructural degradation in this study is evidenced by the significant reduction in the complex pore areas due to LUC, and in some sites, by the increase of less connected and more rounded pores (Figures 3 and 4). This pore morphology change was also observed in the decrease in the percentage of complex packing pores and increased percentage of spherical and policoncave pores from PA to SC (Table 3). Microstructure changes from a microgranular to blocky structure, both with well developed aggregates, and an increase in porphyric c/f distributions, were also observed. These modifications in microstructure, c/f distribution and pore morphology occur due to mechanical stress (Silva *et al.*, 2015), and reduce soil aeration, water and nutrient uptake and crop yield (Lipiec *et al.*, 1996). Soil compaction creates a restrictive environment for plant growth due the physical impediment for roots development (Lipiec & Hatano, 2003) and the reduction of soil aeration and consequentially, the redox potential (Eh) (Czyz, 2004), creating a poor bio-chemical environment (Husson, 2013). Otto *et al.* (2011) showed the inverse relationship between soil penetration resistance and diverse root parameters (root length, area and density). The background for these limitations for plant and root growth could lie in changes in microstructure and pore morphology due to LUC as we have shown in this study.

Our results highlighted the urgent need for more sustainable management practices to improve soil physical quality, especially those related to the improvement of soil microstructure and pore morphology, mitigating the negative impact of biofuel production. As sugarcane planting typically occurs between September and March (in the central region of southern region in Brazil), which is also the rainy season, it is important to avoid, or at least restrict, machinery traffic under high soil moisture conditions and to encourage the introduction of conservation agriculture cropping systems that reduce or eliminate soil tillage (Barbosa et al., 2019) and recommend the use of cover crops as an alternative to prevent soil structure degradation and mitigate other agronomic issues, such as weeds, pests and soil fertility. In this context cover crops can also be used to improve soil structure at scales as fine as considered here through root modification of the soil porous architecture (Bacq-Labreuil et al. 2019). As there is an increasinginterest in sugarcane straw to cogenerate bioelectricity or produce 2G ethanol, maintaining part of the sugarcane straw in the field is an important practice to improve several soil physical quality properties, such as soil structure, pore size and morphology, BD, resistance to penetration, among others (Castioni *et al.*, 2018; Castioni et al., 2019).

Other soil parameters, such as soil organic matter, soil fauna and soil texture (Vreeken-Buijs *et al.*, 1998; Six *et al.*, 2004; Porre *et al.*, 2016; Bonetti *et al.*, 2017), are important for soil structuring, and may contribute to the differences in changes in pore morphology and size observed in this study. However, irrespectively of the site-specific conditions (climatic, biological, chemical and physical), the results of the micromorphological and micromorphometrical analysis, together with the physical attributes provided by Cherubin *et al.* (2016b and 2017), show that the soil compaction process occurs following LUC. More sustainable management practices are necessary to maintain the soil physical properties (e.g. soil structure, pore morphology and size, pore connectivity, etc.) that influence soil functions, (e.g. hydraulic conductivity, air permeability, C storage, physical stability to resist against degradation, etc.) in Brazilian sugarcane fields to achieve the expected productivities.

Conclusions

Land use change from native vegetation to pasture to sugarcane degraded the soil microstructure, reducing the porosity of the soil and negatively influencing the pore shape and size distribution, irrespectively of the soil texture and site environmental conditions. As changes in soil microstructure and pore morphology affect important soil hydrological and physical attributes, which in turn can negatively affect crop yield, the adoption of more sustainable management practices in sugarcane fields (e.g. reduced soil tillage, cover crop incorporation, straw retention and machinery traffic control) is imperative to preserve and/or enhances soil structure, and consequently sustain soil function in a productive capacity.

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References

Adami, M., Rudorff, B.F.T., Freitas, R.M., Aguiar, D.A., Sugawara, L.M. & Mello, M.P. 2012. Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. *Sustainability*, **4**, 574–585.

Barbosa, L. C., Magalhães, P. S. G., Bordonal, R. O., Cherubin, M. R., Castioni, G. A. F., Tenelli, S., Franco, H.C.J. & Carvalho, J. L. N. (2019). Soil physical quality associated with tillage practices during sugarcane planting in south-central Brazil. *Soil and Tillage Research*, **195**, 104383.

Barthès, B. & Roose, E. 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena*, **47**, 133–149.

Boivin, P., Schäffer, B., Temgoua, E., Gratier, M. & Steinman, G. 2006. Assessment of soil compaction using soil shrinkage modelling: Experimental data and perspectives. *Soil and Tillage Research*, **88**, 65–79.

Bonetti, J.A., Anghinoni, I., Moraes, M.T. & Fink, J.R. 2017. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. *Soil and Tillage Research*, **174**, 104-112.

Bonilla-Bedoya, S., López-Ulloa, M., Vanwalleghem, T. & Herrera-Machuca, M.A. 2017. Effects of Land Use Change on Soil Quality Indicators in Forest Landscapes of the Western Amazon. *Soil Science*, **182**, 128–136.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T. & Babel, U. 1985. *Handbook for soil thin section description*. Albrington: Waine Research.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W. & Brussaard, L. 2018. Soil quality – A critical review. *Soil*

Biology and Biochemistry, **120**, 105–125, (At: https://doi.org/10.1016/j.soilbio.2018.01.030.).

Castioni, G.A., Cherubin, M.R., Menandro, L.M.S., Sanches, G.M., Bordonal, R.O., Barbosa, L.C., Franco, H.C.J. & Carvalho, J.L.N. 2018. Soil physical quality response to sugarcane straw removal in Brazil: A multi-approach assessment. *Soil and Tillage Research*, **184**, 301–309, (At: https://doi.org/10.1016/j.still.2018.08.007.).

Castioni, G. A. F., Cherubin, M. R., Bordonal, R.O., Barbosa, L. C., Menandro, L. M. S., & Carvalho, J. L. N. (2019). Straw removal affects soil physical quality and sugarcane yield in Brazil. *BioEnergy Research*, 1-12, (At: https://doi.org/10.1007/s12155-019-10000-1).

Cherubin, M.R., Franco, A.L.C., Cerri, C.E.P., Oliveira, D.M.S., Davies, C.A. & Cerri, C.C. 2015. Sugarcane expansion in Brazilian tropical soils-Effects of land use change on soil chemical attributes. *Agriculture, Ecosystems and Environment*, **211**, 173–184.

Cherubin, M.R., Franco, A.L.C., Guimarães, R.M.L., Tormena, C.A., Cerri, C.E.P., Karlen, D.L. & Cerri, C.C. 2017. Assessing soil structural quality under Brazilian sugarcane expansion areas using Visual Evaluation of Soil Structure (VESS). *Soil and Tillage Research*, **173**, 64–74, (At: http://dx.doi.org/10.1016/j.still.2016.05.004.).

Cherubin, M.R., Karlen, D.L., Cerri, C.E.P., Franco, A.L.C., Tormena, C.A., Davies, C.A. & Cerri, C.C. 2016a. Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. *PLoS ONE*, **11**, 1–26.

Cherubin, M.R., Karlen, D.L., Franco, A.L.C., Tormena, C.A., Cerri, C.E.P., Davies, C.A. & Cerri, C.C. 2016b. Soil physical quality response to sugarcane expansion in Brazil. *Geoderma*, **267**, 156–168, (At: http://dx.doi.org/10.1016/j.geoderma.2016.01.004.).

Companhia Nacional de Abastecimento - CONAB 2019. Acompanhamento de safra brasileira de cana-de-açúcar. v.5. - Safra 2018/2019, Nº 4 - Quarto levantamento, Brasília. https://www.conab.gov.br/info-agro/safras/cana Accessed 20 Oct. 2019.

Cooper, M., Boschi, R.S., Silva, V.B. & Silva, L.F.S. 2016. Software for micromorphometric characterization of soil pores obtained from 2-D image analysis. *Scientia Agricola*, **73**, 388-393.

Cooper, M., Castro, S.S. & Coelho, M.R. 2017. Micromorfologia do solo. In: *Manual de metodos de análise de solo* (eds. Teixeira, P.C., Donagemma, G.K., Fontana, A. & Teixeira, W.G.), p. 574. 3rd ed.

Czyz, E.A. 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. *Soil and Tillage Research*, **79**, 153-166.

Foley, J. A, Ramankutty, N., Brauman, K. A, Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O’Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D. & Zaks, D.P.M. 2011. Solutions for a cultivated planet. *Nature*, **478**, 337–42, (At: http://www.ncbi.nlm.nih.gov/pubmed/21993620. Accessed: 9/7/2014).

Franco, A.L.C., Bartz, M.L.C., Cherubin, M.R., Baretta, D., Cerri, C.E.P., Feigl, B.J., Wall, D.H., Davies, C.A. & Cerri, C.C. 2016. Loss of soil (macro)fauna due to the expansion of Brazilian sugarcane acreage. *Science of the Total Environment*, **563**, 160–168, (At: http://dx.doi.org/10.1016/j.scitotenv.2016.04.116.).

Franco, A.L.C., Cherubin, M.R., Pavinato, P.S., Cerri, C.E.P., Six, J., Davies, C. A. &

Cerri, C.C. 2015. Soil carbon, nitrogen and phosphorus changes under sugarcane expansion in Brazil. *Science of The Total Environment*, **515**, 30–38, (At: http://linkinghub.elsevier.com/retrieve/pii/S0048969715001618. Accessed: 15/2/2015).

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., Giarola, N.F.B. & Silva, A.P. 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. *Soil and Tillage Research*, **127**, 92–99.

Hallaire, V. & Cointepas, J. 1993. Caractérisation de la macroporosité d ' un sol de verger par analyse d ' image. *Agronomie*, **13**, 155–164.

Helliwell, J.R., Sturrock, C.J., Grayling, K.M., Tracy, S.R., Flavel, R.J., Young, I.M., Whalley, W.R. & Mooney, S.J. 2013. Applications of X-ray computed tomography for examining biophysical interactions and structural development in soil systems: a review. *European Journal of Soil Science*, **64**, 279–297, (At: http://doi.wiley.com/10.1111/ejss.12028.).

Hurlbert, S.H. 1984. Pseudoreplication and design of ecological field experiments. *Ecological Monographs*, **54**, 187–211.

Husson, O. 2013. Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: a transdisciplinary overview pointing to integrative opportunities for agronomy. *Plant and Soil*, **362**, 389–417, (At: http://link.springer.com/10.1007/s11104-012-1429-7.).

Lipiec, J. & Hatano, R. 2003. Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, **116**, 107-136.

Lipiec, J., Ishioka, T., Szustak, A., Pietrusiewicz, J. & Stepniewski, W. 1996. Effects of soil compaction and transient oxygen deficiency on growth, water use and stomatal resistance of maize. *Acta Agriculturae Scandinavica B-Soil and Plant*

Science, **46**, 186–191.

Mello, F.F.C., Cerri, C.E.P., Davies, C.A., Holbrook, N.M., Paustian, K., Maia, S.M.F., Galdos, M. V, Bernoux, M. & Cerri, C.C. 2014. Payback time for soil carbon and sugar-cane ethanol. *Nature Climate Change*, **4**, 605–609, (At: http://www.nature.com/articles/nclimate2239.).

Mulholland, B. & Fullen, M.A. 1991. Cattle trampling and soil compaction on loamy sands. *Soil Use and Management*, **7**, 189–193, (At: http://doi.wiley.com/10.1111/j.1475-2743.1991.tb00873.x.).

Otto, R., Silva, A.P., Franco, H.C.J., Oliveira, E.C.A. & Trivelin, P.C.O. 2011. High soil penetration resistance reduces sugarcane root system development. *Soil and Tillage Research*, **117**, 201–210.

Pires, L.F., Borges, J.A.R., Rosa, J.A., Cooper, M., Heck, R.J., Passoni, S. & Roque, W.L. 2017. Soil structure changes induced by tillage systems. *Soil and Tillage Research*, **65**, 66-79..

Porre, R.J., van Groenigen, J.W., De Deyn, G.B., de Goede, R.G.M. & Lubbers, I.M. 2016. Exploring the relationship between soil mesofauna, soil structure and N2O emissions. *Soil Biology and Biochemistry*, **96**, 55–64, (At: http://linkinghub.elsevier.com/retrieve/pii/S003807171600033X.).

Rabot, E., Wiesmeier, M., Schlüter, S. & Vogel, H.J. 2018. Soil structure as an indicator of soil functions: A review. *Geoderma*, **314**, 122–137, (At: http://dx.doi.org/10.1016/j.geoderma.2017.11.009.).

Richard, G., Cousin, I., Sillon, J.F., Bruand, A. & Guérif, J. 2001. Effect of compaction on soil porosity: consequences on hydraulic properties. *European Journal of Soil Science*, **52**, 49–58.

Saff, S.S. 2014. *Keys to soil taxonomy*. 12th ed. Washington, DC. (At:

http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051546.pdf.).

Silva, L.F.S., Marinho, M.A., Matsura, E.E., Cooper, M. & Ralisch, R. 2015. Morphological and micromorphological changes in the structure of a Rhodic Hapludox as a result of agricultural management. *Revista Brasileira de Ciência do Solo*, **39**, 205-221..

Six, J., Bossuyt, H., Degryze, S. & Denef, K. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, **79**, 7–31.

Souza, G.S., Souza, Z.M., Cooper, M. & Tormena, C.A. 2015. Controlled traffic and soil physical quality of an Oxisol under sugarcane cultivation. *Scientia Agricola*, **72**, 270-277..

Stoops, G. 2003. *Guidelines for analysis and description of soil and regolith thin sections*. Soil Science Society of America.

Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., Silva, V.P., Valentim, J.F., Vianna, M. & Assad, E.D. 2014. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, **28**, 84–97.

Vreeken-Buijs, M.J., Hassink, J. & Brussaard, L. 1998. Relationships of soil microarthropod biomass with organic matter and pore size distribution in soils under different land use. *Soil Biology and Biochemistry*, **30**, 97–106, (At: http://www.sciencedirect.com/science/article/pii/S0038071797000643.).

TABLES

Table 1. Soil physical and chemical characteristics of Lat_21S, Lat_17S and Lat_23S.

Soil attributes	**Soil layer**	**Lat_21S**			**Lat_17S**			**Lat_23S**		
		NV[1]	**PA[2]**	**SC[3]**	**NV[1]**	**PA[2]**	**SC[3]**	**NV[1]**	**PA[2]**	**SC[3]**
Sand (g/kg)	0-20	738	760	767	612	827	587	195	231	230
Silt (g/kg)	0-20	82	66	76	70	24	83	150	192	118
Clay (g/kg)	0-20	180	175	157	318	149	350	655	578	651
BD[4] (g/cm^3)	0-10	0.99	1.22	1.21	0.97	1.18	1.26	0.71	1.05	1.07
	10-20	1.08	1.34	1.29	1.01	1.26	1.19	0.83	1.03	1.06
C (g/kg)	0-10	21.8	13.3	11.1	15.6	9.5	10.8	36.7	36.4	18.9
	10-20	16.0	9.5	9.9	12.9	8.4	10.4	33.7	27.6	18.4

Values represent the mean of each land use. [1] – Native Vegetation; [2] – Pasture; [3] - Sugarcane; [4] – Bulk density. Adapted from Franco *et al*. (2015).

Table 2. Mean comparison of the total area of pores (Tap) in three land use in region scale (all evaluate sites) and for each location.

Location	**Layer (cm)**	**Tap (%)**		
		Land use		
		Native vegetation	**Pasture**	**Sugarcane**
Region Scale	0 – 10	36.5^{aA} ± 8.7	22.3^{bA} ± 1.3	12.8^{cA} ± 2.3
	10 – 20	36.3^{aA} ± 22.0	23.9^{aA} ± 6.4	18.9^{aA} ± 5.4
Lat_23S	0 – 10	37.2^{aA} ± 14.8	22.2^{bA} ± 8.2	10.2^{cB} ± 9.8
	10 – 20	33.4^{aA} ± 12.8	25.1^{bA} ± 12.2	24.8^{bA} ± 12.8
Lat_21S	0 – 10	27.3^{aA} ± 8.5	23.7^{aA} ± 6.5	14.5^{bA} ± 6.0
	10 – 20	15.8^{aB} ± 6.0	16.9^{aB} ± 6.8	14.7^{aA} ± 8.6
Lat_17S	0 – 10	45.1^{aB} ± 8.3	21.1^{bB} ± 3.1	13.8^{cB} ± 3.0
	10 – 20	59.6^{aA} ± 10.6	29.6^{bA} ± 6.0	16.5^{cA} ± 6.0

Different lowercase letter indicates statistical difference beteween the land use, and uppercase letter indicates the statistical difference between layers by Duncan test with 5% probability.

Table 3 Micromorphological description of the different land uses of two soil layers at Lat_23S.

		Native Vegetation		**Pasture**		**Sugarcane**	
		0-10 cm	**10-20 cm**	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**
Soil matrix Composition	Coarse material	25 %	25 %	30 %	35 %	35 %	30 %
	Fine Material	35 %	40 %	40 %	35 %	40 %	40 %
	Porosity	40 %	35 %	30 %	30 %	25 %	30 %
c/f Related Distribution*	Porphyric	97 %	97 %	95 %	98 %	99 %	95 %
	Porphyric-enaulic	-	-	5 %	2 %	1 %	5 %
	Enaulic-porphyric	2 %	2 %	-	-	-	-
	Enaulic	1 %	1 %	-	-	-	-
Coarse Material		The coarse material is composed by polycrystalline quartz, sub accommodated and poorly selected.					
Fine Material		The fine material is composed by clay and iron oxides.					
Pores	Complex packing	60 %	60 %	50 %	40 %	30 %	40 %
	Spherical and policoncave vughs	15 %	20 %	25 %	30 %	30 %	30 %
	Channels	15 %	10 %	15 %	15 %	20 %	10 %
	Fissures	10 %	10 %	10 %	15 %	10 %	20 %
Microstructure		Predominantly micro-granular with strong to moderate pedality and partially accommodated.				Complex microstructure composed by one predominantly micro granular with strong to moderate pedality and partially accommodated zone; and the other zone	

						composed by subangular blocks with strong pedality and partially accommodated.	
Pedofeatures	Biological features	30 %	30 %	25 %	25 %	15 %.	20 %
	Charcoal	5 %	5 %	1-5 %	1-5 %	1-5 %	1-5 %
Basic Organic Material	Biological pores diameter (mm)	0.6 to 3	0.2 to 2.2	0.1 to 3.7	0.4 to 2.5	0.5 to 3.4	0.4 to 1.9
	Biological aggregates diameter (mm)	0.1 to 0.7	0.1 to 0.5	0.2 to 0.6	0.1 to 0.7	0.1 to 0.5	0.2 to 0.4
	Coprolite	Present					

*c/f: Ratio between coarse (c) and fine (f) material.

FIGURE CAPTIONS

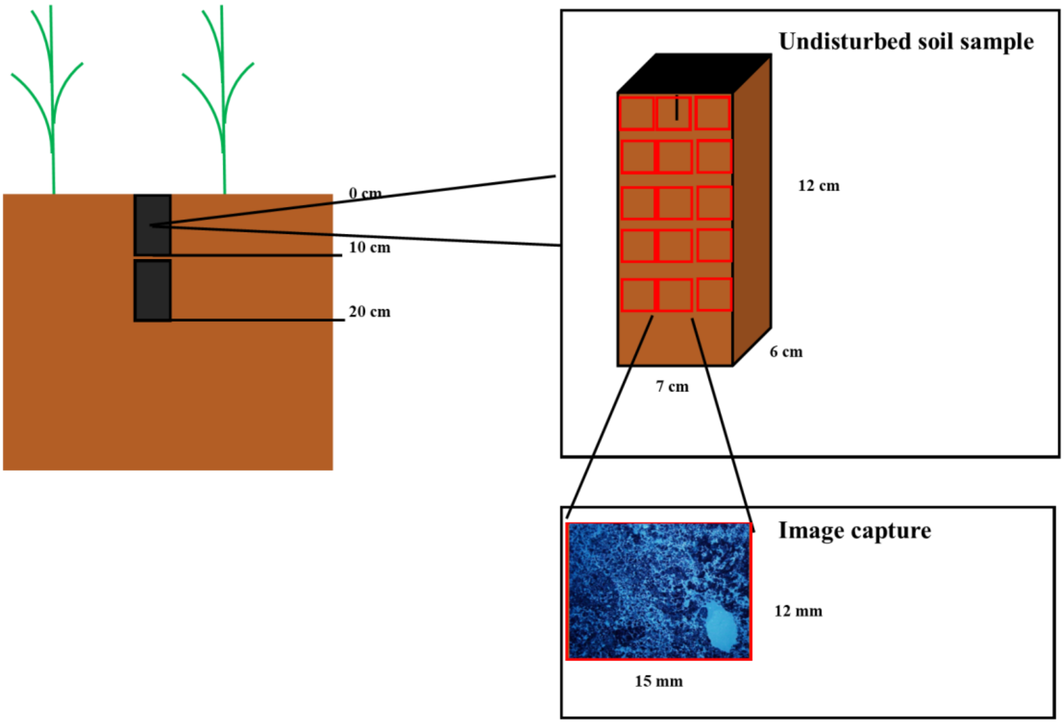

Figure 1. Illustration of soil sampling procedure adopted in the field and details of orientation and scale of samples.

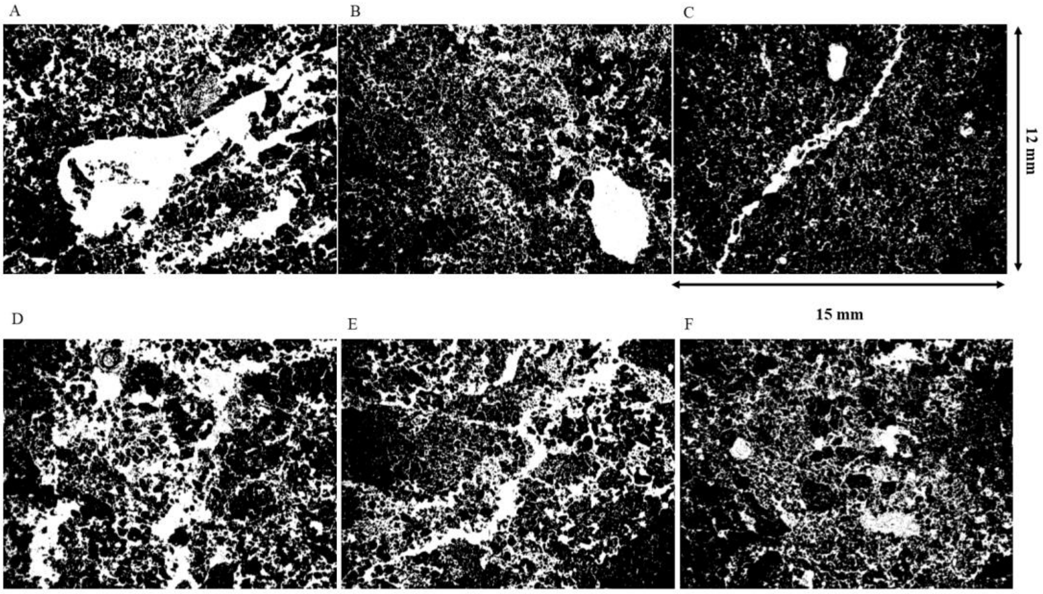

Figure 2. Binary microphotographs of representative thin section's areas (180 mm²) of the 0 – 10 cm soil layer of native vegetation (A), pasture (B) and sugarcane (C); and the 10 – 20 cm soil layer of native vegetation (D), pasture (E) and sugarcane (F) where black is soil matrix and white is the pore space of microaggregates coalescence.

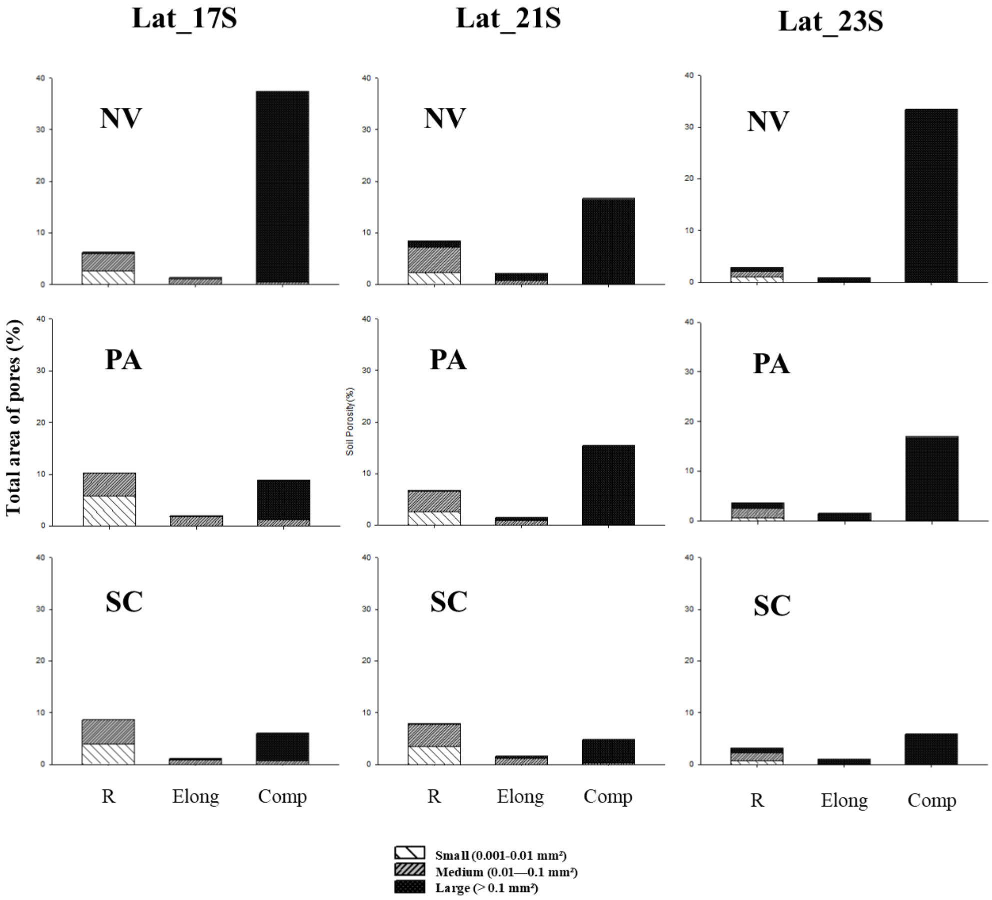

Figure 3. Pore shape and size distribution for 0-10 cm soil layer. R, Rounded; Elong, Elongated; Comp, Complex; SC, sugarcane; PA, pasture; NV, native vegetation.

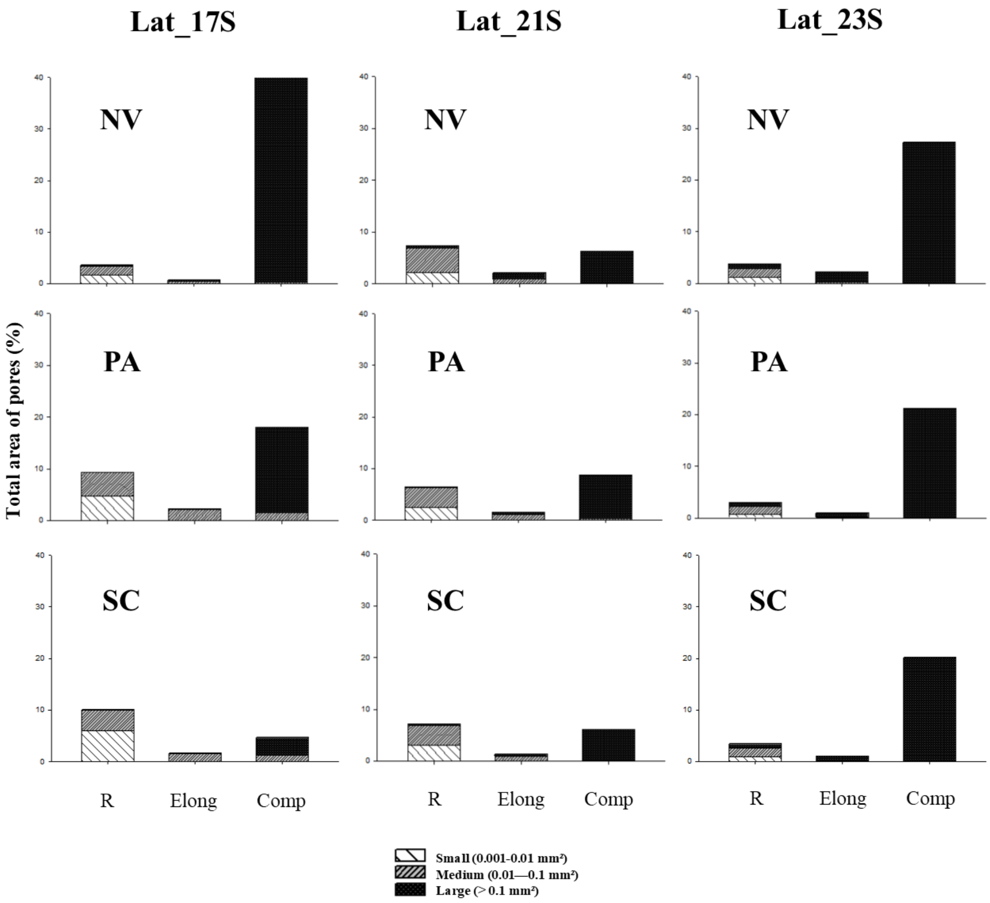

Figure 4 Pore shape and size distribution for 10-20 cm soil layer. R, Rounded; Elong, Elongated; Comp, Complex; SC, sugarcane; PA, pasture; NV, native vegetation.