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Soil structure and its influence on microbial biomass in different soil and crop management systems

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ABSTRACT

Methods for assessment of soil structure in the field are useful for determining the sensitivity of soil to different management systems. Soil and crop management have a fundamental role in the maintenance and improvement of soil quality, as they have a direct influence its structure and on microbiota habitats. The aim of this study was to qualify and quantify homogeneous morphological units (HMUs) in a dystroferric Red Latosol, in a 22-year experiment with treatments consisting of a no-tillage planting system (NT), no-tillage with chiseling every 3 years (NTC) and conventional tillage (CT), using crop rotation (CR) [with five different crop species in 3 years] and succession systems (CS) [only two crop species]. The NT and NTC treatments presented HMUs with a continuous and cohesive structure and increased visible porosity at the surface, and continuous and cohesive units with lower porosity below this layer. The surface layer of the NT treatment presented free units made up of small and medium sized clods, and below this layer, compact, continuous units with little porosity. The soil management systems with crop rotation presented less compact units and roots with fewer morphological deformities than in the treatments with succession systems. Significantly higher levels of carbon and nitrogen microbial biomass (CMB and NMB) were observed in the HMUs in NT and NTC systems under both crop rotation and succession systems, and these had higher visible porosity than the units found in the CT system. On average, HMUs in the NT and NTC treatments presented 20% more CMB and 51% more NMB than in the CT treatment. NMB was the parameter most highly affected by the soil management. At depths of 0–20 cm, total organic carbon (TOC), was higher by an average of 21% than in the NT and NTC treatments. Total nitrogen (TN) was also affected by the soil management, increasing by an average of 50% in the NT and NTC treatments. This demonstrates how the tillage of the soil exposes the organic matter in the aggregates to oxidation and nitrogen mineralization.

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1. Introduction

The biggest challenge within modern agriculture is to find soil management systems that contribute to the economic and environmental sustainability of production systems. The no-tillage planting system (NT), in which the soil is not disturbed through tillage, reduces impacts on soil structure and has been indicated as an alternative means of sustainable soil management. Since this method was introduced in Brazil in the 1970s, studies have demonstrated the advantages of NT compared to systems involving tillage of the soil. The benefits of NT include the control it provides over wind and rain erosion (Barthès and Roose, 2002; Franzluebbers, 2002; Batey, 2009), better soil humidity conditions (Franzluebbers, 2002; Batey, 2009; Jin et al., 2011) and higher levels of organic carbon (Babujia et al., 2010; Jin et al., 2011; López-Fando and Pardo, 2011).

In addition, studies have indicated that NT has contributed to a reduction in carbon dioxide (CO_2) emissions (Ball et al., 1999; Bayer et al., 2002; Drury et al., 2004). In 2010, the Brazilian government introduced its Low-Carbon Agriculture Program (ABC), which aims to increase the current 26 million hectares of land under NT farming to 33 million hectares, with the objective of

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reducing emissions by around 20 million tons of CO_2 by 2020 (MAPA, 2012). This combination of factors has contributed to the adoption of the NT planting system across approximately 100 million hectares of land (FEBRAPDP, 2012).

Soil preparation is the activity with the most influence on the physical properties of the soil, as it has a direct impact on its structure (Ralisch et al., 2010). On the other hand, cropping systems that involve crop rotation or succession have a fundamental role in the formation and stability of aggregates (Munkholm et al., 2013).

Performing qualitative and quantitative evaluation on soil structure in the field in order to verify the effect of soil use and management on the morphology of the soil is challenging. The French cultural profile methodology (Gautronneau and Manichon, 1987), modified by Tavares Filho et al. (1999) for tropical conditions, has proved to be promising in this area. This methodology identifies soil volumes that are affected by the intervention of agricultural tools, root systems and natural factors, providing a differentiated picture of the effects of agriculture on the conservation and quality of the soil. Tamia et al. (1999) use the term Homogeneous Morphological Units (HMUs) to describe the soil volumes in the cultural profile affected by soil use and management activities.

Changes in soil structure directly affect the habitat of microorganisms, which are considered to be critical components of natural and anthropogenic ecosystems as they regulate the level of decomposition of organic material and the cycling of nutrients (Barros et al., 2007). Due to the sensitivity of this parameter, microbial biomass has been used in studies as an indicator of changes provoked by soil and crop management and in the tropics (Franchini et al., 2007; Hungria et al., 2009; Babujia et al., 2010; Silva et al., 2010). Positive correlations between microbial biomass and crop productivity have been observed (Hungria et al., 2009; Silva et al., 2010).

The hypothesis raised in this study is that morphological alterations observed in soil structure may be related to modifications in microbial biomass, validating the cultural profile method as a tool capable of providing an indication of the microorganisms present in the HMUs found in soil profiles. Soil samples to evaluate microbial biomass are generally collected up to depths of 30 cm (Baker et al., 2007) and potential alterations to soil structure along the profile are not taken into account, meaning that they may not represent the actual conditions of the soil.

The aim of this study was to quantify carbon and nitrogen microbial biomass in the Homogeneous Morphological Units (HMUs) in a dystroferric Red Latosol, in a 22-year experiment with treatments consisting of a no-tillage planting system (NT), no-tillage with chiseling every 3 years (NTC) and conventional tillage (CT), using crop rotation (CR) and succession (CS) systems, in order to determine the relationship between alterations in soil structure and modifications in the contents of microbial biomass.

2. Materials and methods

2.1. Characterization of the experimental area

The experiment began in the summer of 1988/1989, in the experimental area of the Soybean Research Center at the Brazilian Agricultural Research Agency (EMBRAPA Soja) (23°11′ S, 51°11′ W), Londrina, in the state of Paraná in Brazil.

The local climate is classified according to Köeppen as Humid Subtropical (Cfa) and has an average annual temperature of 21 °C, with an average maximum of 28.5 °C in February and an average minimum of 13.3 °C in July. The average annual rainfall is 1.651 mm, with the highest rainfall in January (217 mm) and the lowest in August (60 mm). The altitude is 620 meters with a slope of 6%. According to the Brazilian classification system, the soil is a very clayey dystroferric Red Latosol, and according to the American classification system, it is a Rhodic Eutrudox with 710 g clay, 82 g silt and 208 g sand per kg^{-1} of soil.

Before the experiment, the area was cultivated for around 40 years with coffee (*Coffea arábica* L.). The area was split into experimental units of 7.5 m width by 30 m length (225 m^2), with four repetitions per treatment, distributed over randomized blocks in a factorial arrangement. The profiles were prepared and soil sampling was carried out 22 years into the experiment, in April 2010, after the maize harvest in the units under crop rotation and the soybean harvest in the units with crop succession.

The study compared the effects of three soil preparation systems: no-tillage planting (NT), where sowing is carried out on the residues of the previous crop and mechanical intervention is restricted to the digging of a narrow planting row (~4 cm deep); no-tillage with chiseling every 3 years (NTC), with the objective of breaking up the compact surface layer (~25 cm deep) but without the use of soil leveling operations; and conventional tillage (CT), where the soil is prepared every year with a disc plow (~20–25 cm deep), followed by a leveling harrow (~15 cm deep) before the planting of the summer crop, and a heavy harrow (~15 cm deep) followed by a light harrow (~15 cm deep) in the winter. The chisel plow used in the NTC treatment was last used 3 years before the soil evaluation took place.

In addition, each soil preparation system was submitted to the effects of crop rotation and succession. Six management systems were evaluated in total: NT (rotation and succession), NTC (rotation and succession) and CT (rotation and succession). The crop rotation (CR) consisted of five different crop species: white lupine (*Lupinus albus*)-maize (*Zea mays*), black oat (*Avena strigosa*)-soybean (*Glycine max*), wheat (*Triticum aestivum*)-soybean, every 3 years; and crop succession (CS) with soybean in the summer and wheat in the winter.

At the start of the experiment, the soil received two tons of limestone per hectare to achieve a base saturation of 60% and to adjust the pH to approximately 5.5, and maintenance was carried out every 3 years. Similar quantities of fertilizer were applied to all of the treatments. Along the 22 years of the experiment, an average of 47 kg P ha^{-1} (triple superphosphate) and 41.2 kg K ha^{-1} (potassium chloride) were added to the soybean culture, with no nitrogen fertilization being carried out. The soybean seeds were inoculated with *Bradyrhizobium japonicum* and *B. elkanii* before planting. After 10 years of soybean cultivation, 20 g Mo ha^{-1} (sodium molybdate) and 2 g Co ha^{-1} (cobalt chloride) were added to the soil every year. For the maize culture, an average of 19.2 kg N ha^{-1} (urea), 51.5 kg P ha^{-1} (triple superphosphate) and 47 kg K ha^{-1} (potassium chloride) were added every year.

The insects and diseases were controlled as necessary. The residues of previous cultures were desiccated using glyphosate. After planting, other herbicides were applied to the CT treatment as necessary.

2.2. Cultural profile

Two 1.0 m long × 1.0 m wide × 1.0 m deep trenches were dug for each treatment (two repetitions per treatment) in the middle of the experimental units and perpendicular to the direction of the agricultural machinery. The cultural profile method was used for the evaluations, as described by Tavares Filho et al. (1999). Cultural profile methodology classifies HMUs into two levels: (1) organization of clods in the soil profile (C – continuous; F – cracked; L – free and Z – laminar), and (2) internal state of the clods (μ – not compact; Δ – compact and $\mu\Delta/\Delta\mu$ – ±compact). For more details see Neves et al. (2003): L – Free soil volume – Loose soil and aggregates of varied sizes (0–10 cm) with no cohesion; C –Continuous soil volume – The soil elements are together, developing a very homogeneous structure, making it impossible for clods to be individualized; and, F – Cracked soil volume –Great number of cracks in all directions, forming clods of varied sizes.

To provide a more detailed description of the internal state of the clods, the following classification scale was used: $\mu\Delta$ – porous with indications of compression; $\mu\Delta/\Delta\mu$ – intermediate porosity; $\Delta\mu$ – compact with some porosity; Δ – compact with no visible porosity.

For each soil profile, maps with a scale of 1:10 were prepared and imported using ArcView software (version 10.0). Another three maps were then prepared for each of the profiles, the first of the perimeter of the profile, which served as a template to ensure the other two maps were of the same size, the second detailing the HMUs and the third detailing the depths. A fourth map was obtained through the superposition of these three maps, producing a map of the areas of each HMU according to profile depth.

2.3. Soil sampling

Soil samples for the analysis of microbial biomass were collected from two midpoints in each volume affected by the soil management, forming a sample of around 1.2 kg of soil per HMU. In the laboratory, the samples were homogenized, sieved (<4 mm, 5 mesh) and stored in plastic bags in a refrigerator at 4 °C.

The soil samples taken to determine pH and total organic carbon and nitrogen were collected from depths of 0–20 cm from the four experimental units (4 repetitions).

2.4. Determination of pH and total organic carbon and nitrogen

The soil samples were dried in an air circulating oven at 60 °C for 48 h, then disaggregated and sieved with a 2 mm mesh sieve. Soil pH was determined in 0.01 M $CaCl_2{\cdot}2H_2O$ (8 g of soil in 20 mL $CaCl_2{\cdot}2H_2O$) according to the method described by Babujia et al. (2010). Total organic carbon (TOC) and total nitrogen (TN) were determined through combustion in a Thermo Scientific FLASH 2000 NC Analyzer.

2.5. Evaluation of microbial biomass

The modified version of the fumigation-extraction method described by Vance et al. (1987) was used to analyze the levels of carbon in the microbial biomass (CMB), and the method by Brookes et al. (1985) was used to analyze the levels of nitrogen (NMB), both with the modifications described by Hungria et al. (2009).

All measurements were made on moist soil, previously adjusted to 40% Water Holding Capacity (WHC) and soil weights, and all results were expressed on an oven-dry basis (105 °C overnight). Soil samples of 20 g were weighed for both the fumigated and non-fumigated samples. To determine soil humidity, 10 g of soil was weighed and placed in an oven for 16 h at 105 °C. Fumigated samples were placed in a vacuum box, with each vertex inside the box containing 50 mL of chloroform, and were left for 16 h. The fumigated and non-fumigated samples were kept out of the light for 16 h. After this period, the samples were submitted to vacuum three times to eliminate the chloroform and suspended in 50 mL 0.5 M K_2SO_4 extraction solution.

The CMB concentrations in the extracts were determined through oxidation with Mn^{3+} and estimated colorimetrically at a wavelength of 495 nm (Bartlett and Ross, 1988). CMB levels were determined by calculating the difference between the fumigated and non-fumigated samples, using the correction factor (K_{CE}) of 0.41 recommended for tropical soils (Feigl et al., 1995; Oliveira et al., 2001).

NMB concentrations were determined through the addition of 0.5 g of the catalyst $CuSO_4$: K_2SO_4 (10:1) and 1.5 mL H_2SO_4 concentrated in 20 mL extract. The samples were left in an oven at 105 °C for 16 h to reduce their volume and were digested for approximately 3 h at 350 °C. After digestion, the residue was diluted with distilled water and nitrogen levels were determined colorimetrically at a wavelength of 630 nm using the indophenol blue method (Feije and Anger, 1972). NMB levels were determined by calculating the difference between the fumigated and non-fumigated samples, using a correction factor (K_{NE}) of 0.54 (Brookes et al., 1985).

The values obtained for microbial biomass were expressed in mg of CMB or NMB per kg^{-1} of dry soil.

2.6. Statistical analysis

For the analysis of the cultural profiles, Detrended Correspondence Analysis (DCA) was used to verify the linearity of the data, and then Principal Component Analysis (PCA) was applied. PCA was carried out with the purpose of determining the relationship between soil use and management systems, the structural characteristics of the profiles and the carbon and nitrogen concentrations in the microbial biomass. Multivariate analysis was carried out using the Canoco program for Windows 4.5 (Braak and Smilauer, 1998).

All statistical analyses were carried out using SAS (Version 8.2, SAS Institute, Cary, NC) (SAS Institute, 2005). Averages were calculated for each plot and used to calculate mean and standard error. The averages were first submitted to the tests of normality of the variables and of homogeneity of variances, and then to ANOVA. When confirming a statistically significant P value, the Tukey test ($P < 0.05$) was applied for comparison purposes.

3. Results

3.1. Description of soil profiles

Figs. 1–3 show a graphical representation of the cultural profiles. The determining factor in the morphological changes to the soil was the degree of mechanical intervention it was subjected to during preparation and planting. Higher volumes of compact soil were found in the profiles taken from treatments with a higher degree of tillage. For all profiles, the HMUs that were visibly unchanged by soil use and management were represented by the structure Cμ, which corresponds to the Bw microaggregated structure of the Latosols.

In general, the surface layer of the soil in all of the units was covered with residues of recently harvested maize in the crop rotation treatments and soybean in the succession treatments. In addition to these residues, all of the treatment areas contained weeds and some maize or soybean regrowth.

Another revealing factor observed in the profiles was the abundant presence of macrofauna, mainly individuals from the Oligochaeta, Formicidae, Melolonthidae, Diplopoda and Chilopoda families. Biological activity was intense on the surface, with a huge number of holes (1.0–2.0 cm Ø), and in the soil profile that contained holes, galleries (3–10 cm Ø) and chambers (>10 cm Ø) (Figs. 1–3).

The profiles for the NT treatments under crop rotation (Fig. 1) presented continuous units in the surface layer, which were homogeneous, cohesive and porous, with medium roughness and indications of compression, corresponding to a C$\mu\Delta$ structure. The roots were branched without much twisting and were positioned vertically in the profile. Below this layer, the units presented medium porosity, corresponding to a C$\mu\Delta/\Delta\mu$ structure, with highly branched roots that were slightly flattened and also situated vertically in the profile.

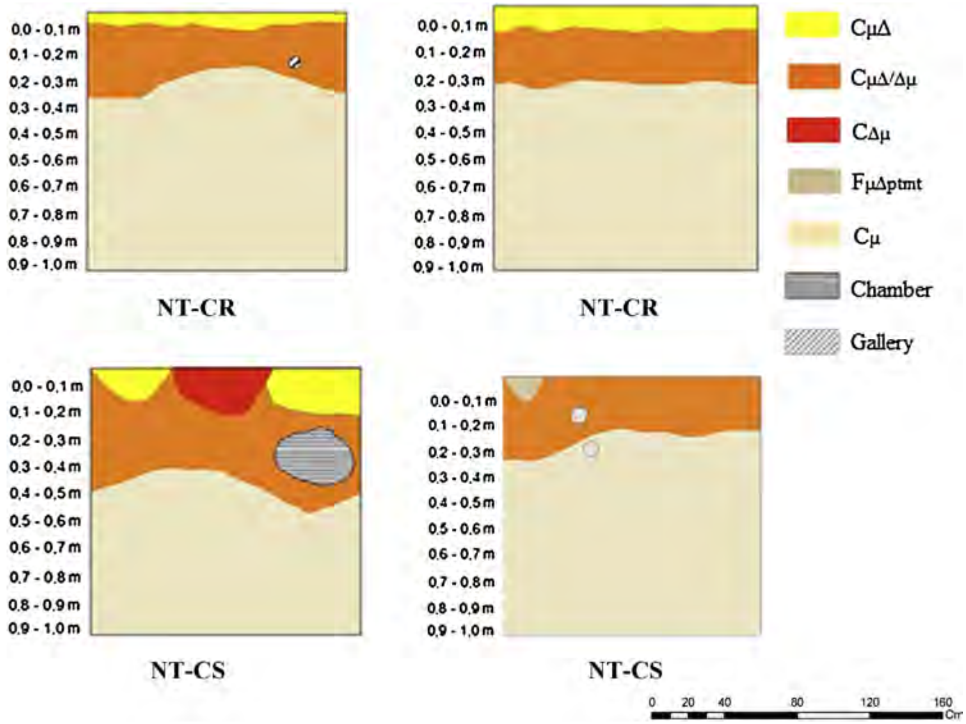

Fig. 1. Cultural profiles of a dystroferric Red Latosol under no-tillage system (NT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity. Size of clods: pt, small clods; mt, medium clods. Structure resulting from macrofauna activity: G, gallery (3–10 cm Ø); C, chamber (>10 cm Ø). Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

One of the NT profiles with crop succession presented units at the surface corresponding to a C$\mu\Delta$ structure (Fig. 1), with root morphology similar to that described for the NT treatment with crop rotation. A compact unit was also observed in this profile, which presented low porosity, flattened and twisted roots and was mostly positioned horizontally in the profile, corresponding to a C$\Delta\mu$ structure. Cracked units were observed in the other profile, with the presence of small (3 cm Ø) and medium porous clods

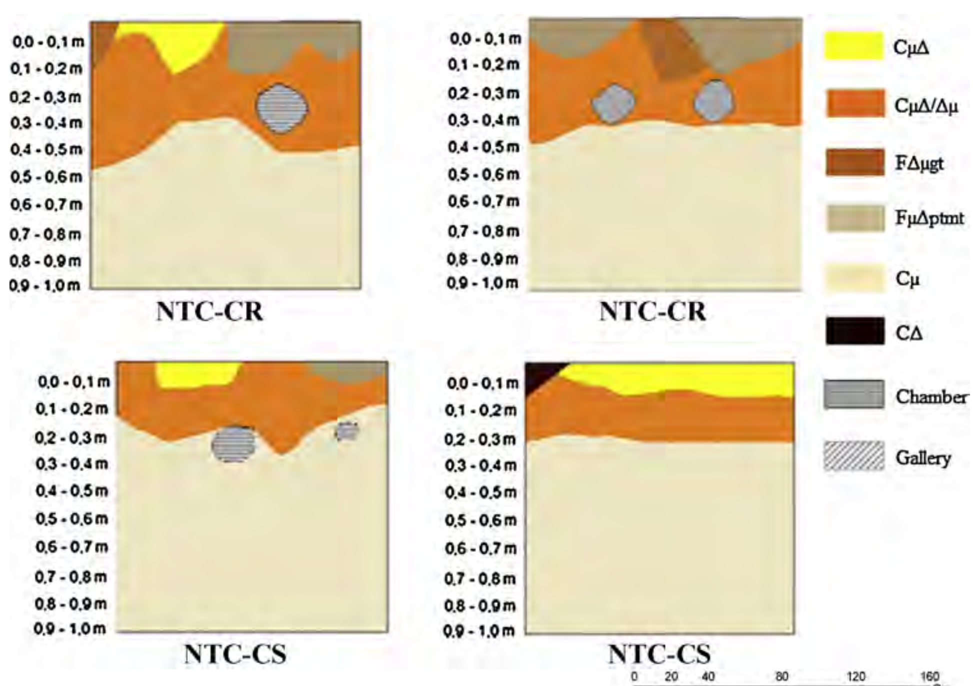

Fig. 2. Cultural profiles of a dystroferric Red Latosol under no-tillage planting system with chiseling every 3 years (NTC) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Structure resulting from macrofauna activity: G, gallery (3–10 cm Ø); C, chamber (>10 cm Ø). Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

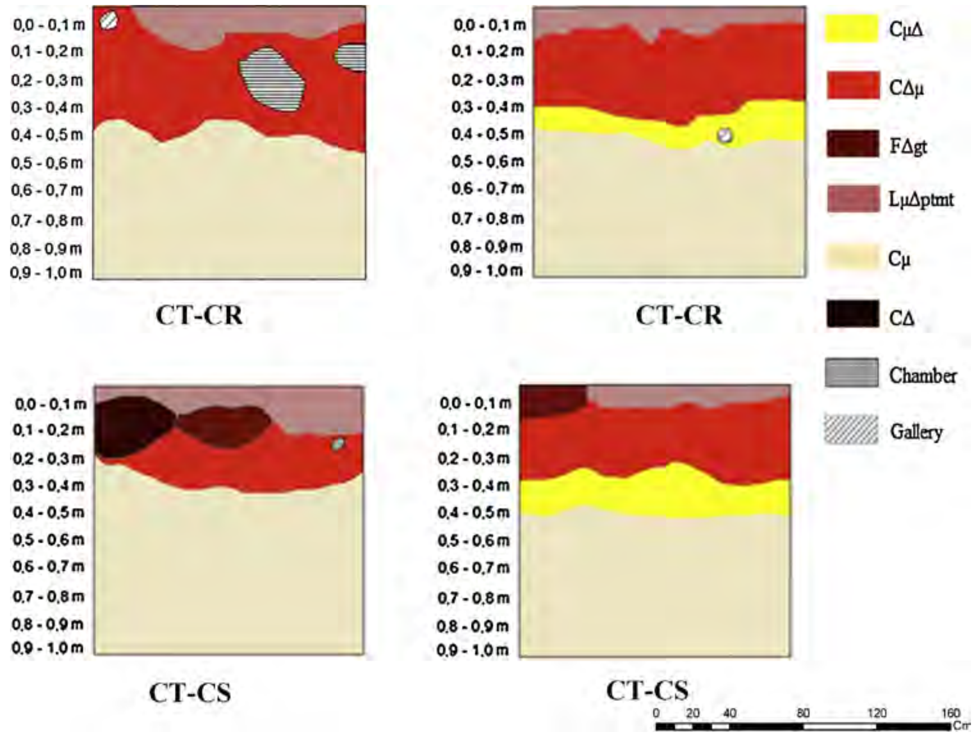

Fig. 3. Cultural profiles of a dystroferric Red Latosol under conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Structure resulting from macrofauna activity: G, gallery (3–10 cm Ø); C, chamber (>10 cm Ø). Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

(7 cm Ø) with medium roughness and indications of compression, corresponding to an F$\mu\Delta$ptmt structure (Fig. 1). This profile had a high concentration of untwisted roots growing inside and between the aggregates. These profiles presented the largest area containing units corresponding to a C$\mu\Delta/\Delta\mu$ structure, with a morphology similar to that described for the NT treatment using crop rotation, although the roots were more flattened, twisted and were positioned vertically and horizontally in the profile.

The NTC profile under crop rotation presented cracked units at the surface. This unit was characterized by the presence of small (5 cm Ø) and medium (9 cm Ø) clods, which were porous but with indications of compression and presented visible medium roughness, corresponding to an F$\mu\Delta$ptmt structure (Fig. 2). This profile presented rectilinear, branched roots growing mainly between the cracks and vertically through the clods. Another cracked unit was observed with large (12 cm Ø) clods, low roughness, compact with some porosity, corresponding to an F$\Delta\mu$gt structure and with a rooting pattern similar to that described for the previous structure. In one of the profiles there was also a C$\mu\Delta$ unit. Below these a unit corresponding to the C$\mu\Delta/\Delta\mu$ structure was observed, with root morphology similar to that described for the NT treatment under crop rotation.

For the NTC treatment with crop succession, the surface predominantly contained units corresponding to a C$\mu\Delta$ structure (Fig. 2), with root morphology similar to that described for the NT treatments with crop rotation and succession. However, a cracked unit made up of small (5 cm Ø) and medium (8 cm Ø) clods was observed in one of the profiles, which was porous with indications of compression and presented medium roughness and rectilinear roots between and inside the aggregates, corresponding to an F$\mu\Delta$ptmt structure. In the other profile there was a small compact unit with no visible porosity and few extremely flattened roots growing horizontally, corresponding to a CΔ structure. Finally, a unit corresponding to a C$\mu\Delta/\Delta\mu$ structure was observed below this level (Fig. 2), with a root morphology similar to that described for the NT treatment with crop succession, which in one of the profiles was present all the way from the surface to the bottom.

The CT treatment under crop rotation and succession presented a unit corresponding to free soil at the surface, made up of small (3 cm Ø) and medium (6 cm Ø) loose compact clods with some visible porosity and slightly flattened roots growing vertically, corresponding to a L$\Delta\mu$ptmt structure (Fig. 3). Below this structure there were continuous and compact units with some visible porosity, with flattened and twisted branched roots positioned vertically and horizontally in the profile, corresponding to a C$\Delta\mu$ structure. A unit corresponding to a C$\mu\Delta$ structure was observed in one of the profiles, with root morphology similar to that described for the CT treatments under crop rotation and succession.

In the CT profiles under crop succession, below the L$\Delta\mu$ptmt structure there was a cracked unit with large (12 cm Ø) clods corresponding to an FΔgt structure, which was compact with low porosity and with flattened and twisted roots with some branching that were positioned vertically between the cracks (Fig. 3). Next to this structure in one of the profiles was a more compact unit with no visible porosity and few very flattened roots positioned horizontally, corresponding to a CΔ structure. Below there was a unit corresponding to a C$\Delta\mu$ structure, with root morphology similar to that described for the CT treatment under crop rotation, but with roots that were visibly more flattened and twisted. In one of the profiles a C$\mu\Delta$ structure was observed, with root morphology similar to that described for the CT treatment under crop rotation.

It was observed that the NT profiles (Fig. 1) under crop succession presented a large area containing the C$\mu\Delta/\Delta\mu$ structure, corresponding to an average of 28.3% of the total profile area (Fig. 4).

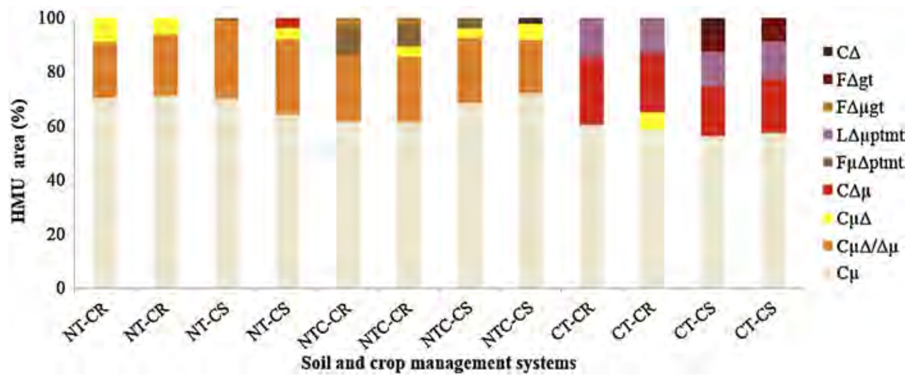

Fig. 4. Percentage of area containing homogeneous morphological units (HMUs) in a dystroferric Red Latosol under a no-tillage planting system (NT), a no-tillage system with chiseling every 3 years (NTC) and a conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

The NTC profiles (Fig. 2) under crop rotation presented a large area at the surface with cracked structures (F$\mu\Delta$ptmt and F$\Delta\mu$gt) compared to the NTC treatment under succession, corresponding to an average of 9.57 and 2.78% of the total area of the profiles respectively. These profiles also presented a large area containing the C$\mu\Delta/\Delta\mu$ structure, corresponding to an average of 24.75% of the total profile area (Fig. 4).

The L$\Delta\mu$ptmt structure represented an average of 13.63 and 13.47% of the total area of the CT profiles (Fig. 3) in rotation and succession respectively. The CT treatment under crop rotation presented profiles with a large area containing the C$\Delta\mu$ structure, corresponding to an average of 23.6% of the total profile area. The CT treatment under crop succession, however, presented FΔgt and CΔ structures covering an area corresponding to 12.96% of the profile, which were not present in the CT treatment under crop rotation (Fig. 4).

PCA was used to demonstrate the relationship between the different soil use and management systems and the structures observed in the cultural profiles. The first axis of the principal component explained 64.6% of the variability, while the second axis explained 14% (Fig. 5). It was observed that the CT areas under crop rotation and succession were positioned on the positive side of axis 1, while the NT areas under crop rotation and succession and the NTC areas under succession were close together and positioned on the other extreme on the negative side of this axis. The NTC area under crop rotation stood out on the upper negative portion of the same axis. This distribution suggests that axis 1 is representative of the forms of use and management, and that axis 2 represents the HMUs. It was observed that HMUs corresponding to the L$\Delta\mu$ptmt, FΔgt, CΔ and C$\Delta\mu$ structures had a positive correlation with the CT treatments under crop rotation and succession and a negative correlation with both the NT treatments under crop rotation and succession and the NTC treatments under succession. On the other hand, the HMUs corresponding to the C$\mu\Delta$ and Cμ structures had a positive correlation with the NT treatments under crop rotation and succession and with the NTC treatments under succession. The HMUs corresponding to the F$\Delta\mu$gt, F$\mu\Delta$ptmt and C$\mu\Delta/\Delta\mu$ structures had a positive correlation with the NTC treatment under crop rotation. It was observed that the C$\mu\Delta/\Delta\mu$ and L$\Delta\mu$ptmt structures plotted on axis 1 of the principal component are those that explain the data variability the most (Fig. 5).

3.2. Microbial biomass in HMUs

Significantly higher levels of CMB and NMB were found in the NT and NTC treatments, where less compact HMUs were predominant, while lower values were found in the CT treatments, where more compact HMUs were observed (Figs. 6 and 8).

PCA was used to demonstrate the relationship between HMUs and levels of CMB and NMB (Figs. 7 and 9). For CMB, the first axis of the principal component explained 66.6% of the variability, while the second axis explained 24.4% (Fig. 7). Lower levels of CMB in the HMUs corresponding to the CΔ, C$\Delta\mu$, FΔgt and L$\Delta\mu$ptmt structures had a positive correlation with the CT treatments under crop rotation and succession, positioning these areas in the positive half of axis 1, and a negative correlation with the NT treatments under crop rotation and succession and the NTC treatment with succession. Higher levels of CMB in the units corresponding to C$\mu\Delta/\Delta\mu$, C$\mu\Delta$ and Cμ structures had a positive correlation with the NT treatments with crop rotation and succession and with the NTC treatment with crop succession, bringing these areas close together in the negative half of axis 1. CMB levels in the HMUs corresponding to the F$\Delta\mu$gt and F$\mu\Delta$ptmt structures had a positive correlation with the NTC treatment with crop rotation.

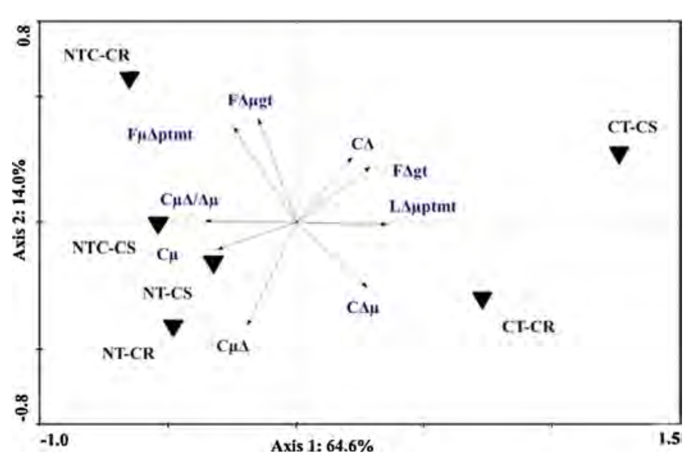

Fig. 5. Principal Component Analysis (PCA) based on the homogeneous morphological units (HMUs) in a dystroferric Red Latosol under a no-tillage planting system (NT), a no-tillage system with chiseling every 3 years (NTC) and a conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

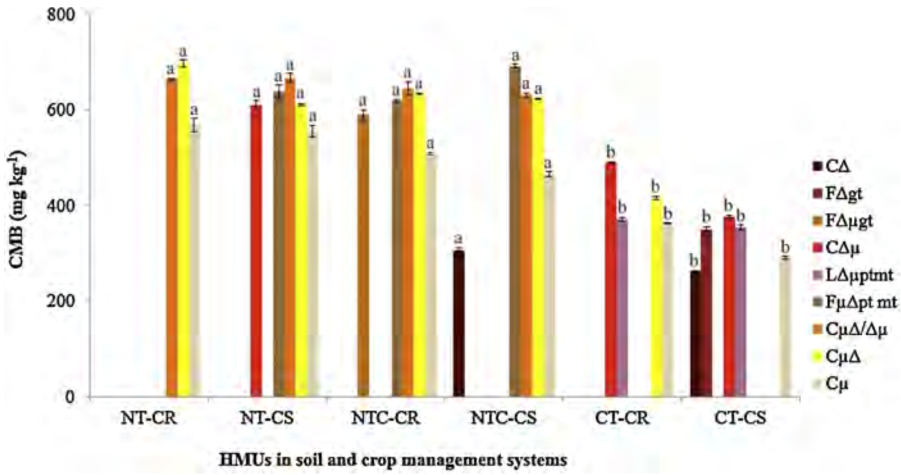

Fig. 6. Carbon microbial biomass (CMB) in homogeneous morphological units (HMUs) in a dystroferric Red Latosol under a no-tillage planting system (NT), a no-tillage system with chiseling every 3 years (NTC) and a conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat. Bars indicate standard error of mean. Figures with the same letter for each HMUs between treatments are not significantly different at $P < 0.05$ level.

NMB levels were more sensitive than CMB levels in indicating changes to the structure of the soil. On average, the soil structures of the NT and NTC profiles presented NMB levels 50% higher than the CT profiles (Fig. 8). For NMB, the first axis of the principal component explained 62.7% of the variability, while the second axis explained 14.6% (Fig. 9). PCA demonstrated that the HMUs corresponding to the L$\Delta\mu$ptmt, FΔgt, and CΔ structures, with lower levels of NMB, have a positive correlation with the CT treatments under crop rotation and succession, positioning these management systems in the positive half of axis 1, and a negative correlation with NT under crop rotation and succession and NTC under succession. The C$\mu\Delta/\Delta\mu$, C$\mu\Delta$ and Cμ structures with higher levels of NMB have a positive correlation with the NT treatments under crop rotation and succession and with the NTC treatments under succession, bringing these management systems together on the far end of the negative part of axis 1. The F$\Delta\mu$gt and F$\mu\Delta$ptmt structures with higher NMB levels had a positive correlation with the NTC treatments under crop rotation. It was observed that PCA separated the NTC treatment under crop rotation from the NTC treatment under succession and from the NT treatments under rotation and succession, positioning this treatment on the positive half of axis 2 due to a higher presence of cracked HMUs (Fig. 4).

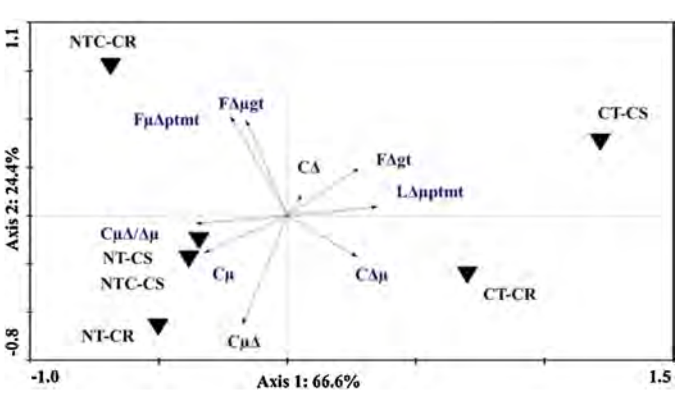

Fig. 7. Principal Component Analysis (PCA) based on the relationship between homogeneous morphological units (HMUs) in the cultural profiles with CMB content. Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

3.3. Total organic carbon (TOC), total nitrogen (TN) and pH

No differences were observed in pH ($CaCl_2$) between the soil management systems and the cultures (data not presented), coinciding with the application of lime (2 ton ha^{-1}) to all of the treatments before the 2009/10 summer harvest, and values varied from 4.96 to 5.18.

TOC and TN levels were higher in the NT and NTC treatments compared to the CT treatments (Fig. 10), independent of the management system. TOC presented levels 20% higher for the NT and NTC treatments compared to the CT treatments. Similarly to NMB, TN was the parameter most affected by the type of soil management. The NT and NTC treatments presented values almost 50% higher for TN compared to the CT treatment (Fig. 10).

4. Discussion

4.1. Changes in the structure of the soil

A range of studies have demonstrated that intense tillage of the soil promotes changes in its physical properties, affecting its chemical and biological attributes (Franchini et al., 2007; Hungria et al., 2009; Babujia et al., 2010; Morris et al., 2010; López-Guarrido et al., 2012) mainly as a result of the changes caused to the structure of the soil (Giarola et al., 2013; Munkholm et al., 2013). The extent of these changes depends on the type of soil and the management systems used.

After 22 years of cultivation, the characterization of different profiles showed that the soil at the superficial layer (~0–12 cm), directly exposed to climatic agents, agricultural tools and crops, underwent a change in structure compared to the soil found at deeper layers (~35–40 cm), which were not directly affected by human activity, such as the Cμ structure, corresponding to the Bw structure of Latosols, which preserved the original properties of the soil. The most pronounced changes were observed in the CT treatment, which involved the highest degree of soil tillage,

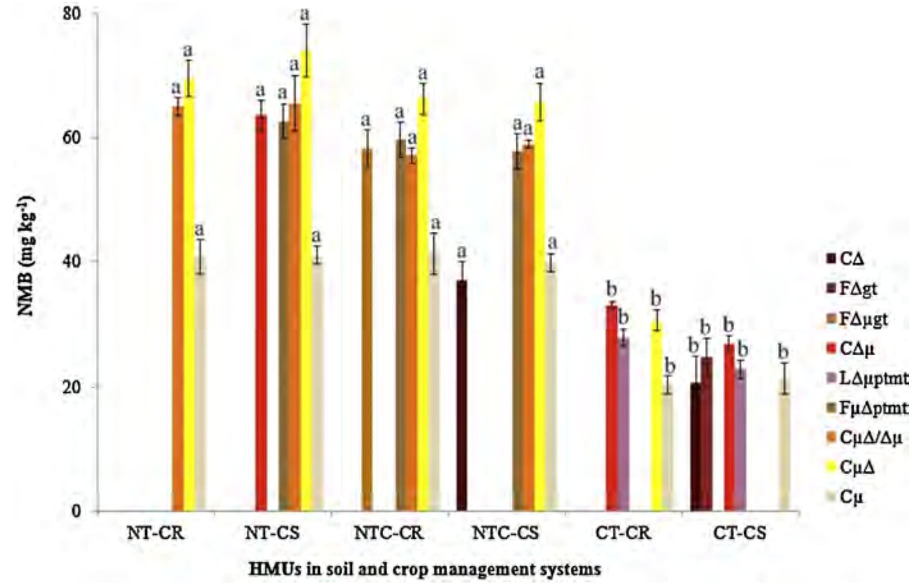

Fig. 8. Nitrogen microbial biomass (NMB) in homogeneous morphological units (HMUs) in a dystroferric Red Latosol under a no-tillage planting system (NT), a no-tillage system with chiseling every 3 years (NTC) and a conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat. Bars indicate standard error of mean. Figures with the same letter for each HMUs between treatments are not significantly different at $P < 0.05$ level.

presenting more compacted volumes with lower visible porosity (Figs. 1–3).

The visible porosity of the aggregates was influenced by the type of crop management used, as the treatments with crop succession presented more compact units with roots that were visibly more morphologically deformed than those observed for the treatments under crop rotation.

The $C\mu\Delta$ structures with higher visible porosity found in the surface layer of the NT treatments (Fig. 1) can be attributed to higher TOC levels, which were higher at the surface due to the presence of crop residues and the higher concentration of roots at this depth (Morris et al., 2010; Giarola et al., 2013). In addition, root growth also promotes aggregation of the soil due to the freeing up of organic compounds that have a cementing and agglutinating effect on soil particles and that create spaces as they age (Six et al., 2004), contributing to an increase in total porosity (Chan et al., 1992).

For the NT profile under succession (Fig. 1), the presence of the $C\Delta\mu$ structure with lower visible porosity is a result of the pressure exerted by the agricultural machinery, which produces aggregates with a compact internal structure. It is worth noting that the NT profile under succession presented a higher percentage of compact structures ($C\mu\Delta/\Delta\mu$) than the profile under crop rotation (Fig. 4).

While evaluating the effects of some crop rotation systems on the physical attributes of the soil, Chan et al. (1992) concluded that soybean/wheat succession systems caused higher superficial compacting of the soil compared to systems involving grasses such as rice and maize. Albuquerque et al. (1995) also verified higher soil densities for soybean/wheat succession systems in the surface layer than in crop rotation systems including crops such as oats, vetch and maize. Soybean and wheat have a lower biomass

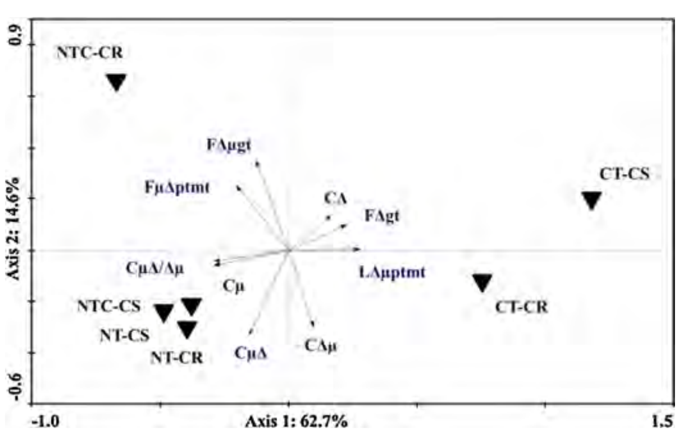

Fig. 9. Principal Component Analysis (PCA) based on the relationship between homogeneous morphological units (HMUs) in the cultural profiles with NMB content. Organization of clods (HMUs): C, continuous soil volume; F, cracked soil volume; L, free soil volume. Internal state of clods: μ, porous; $\mu\Delta$, porous with indications of compression; $\mu\Delta/\Delta\mu$, medium porosity; $\Delta\mu$, compact with some porosity; Δ, compact with no visible porosity. Size of clods: pt, small clods; mt, medium clods; gt, large clods. Crop rotation (CR): lupine/maize/black oats/soybean/wheat/soybean. Crop succession (CS): soybean/wheat.

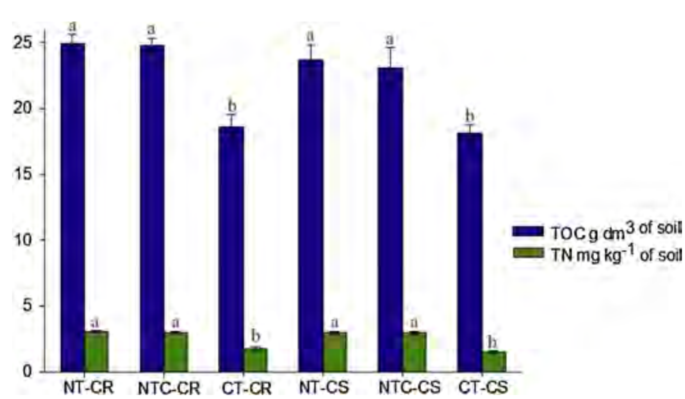

Fig. 10. Total organic carbon (TOC) and total nitrogen (TN) at depths of 0–20 cm in a dystroferric Red Latosol under a no-tillage planting system (NT), a no-tillage system with chiseling every 3 years (NTC) and a conventional tillage system (CT) with crop rotation (CR) and crop succession (CS). Bars indicate standard error of mean. Figures with the same letter between treatments are not significantly different at $P < 0.05$ level.

production than millet and maize crops. In addition, soybean has a low C:N ratio and its biomass undergoes rapid decomposition at the soil surface. In an NT system, long-lasting high volumes of plant residues left at the surface lead to better effects on the physical attributes of the soil (Morris et al., 2010).

In the surface layer at 0–20 cm, the NTC profile under crop rotation presented a large area with cracked structures, and with succession it presented a large area with continuous structures (Fig. 4). The presence of cracked structures in the NTC profiles can be attributed to the crop rotation, which preserved the effects of the chiseling (Fig. 2). In these structures, the roots were mainly present in the cracks. According to Tavares Filho et al. (2001), if structures that allow the diffusion of oxygen and ideal conditions of humidity and nutrients are present, the roots grow towards the points of lowest resistance, although they may suffer morphological deformations.

The NTC profile under crop succession presented a small area of CΔ structures in the surface layer (~0–8 cm) caused by the pressure of agricultural machinery, and the F$\mu\Delta$mtgt structure was observed below this, which still preserved the effects of chiseling. These results demonstrate that the effects of chiseling were short lived in the NTC profile and that few changes to the structure of the soil were preserved 3 years after this took place, corresponding to less than 10% of the total area of the profiles (Fig. 4).

Hamza and Anderson (2005) demonstrated that chiseling makes the soil more vulnerable to deformation by agricultural machinery in such a way that recompression has been observed after both one (Chan et al., 2006) and two (Veiga et al., 2007) agricultural operations. However, Ralisch et al. (2010) observed that mechanical disruption without root complementation promoted short-lived effects on the physical recuperation of the soil, making continuous addition of organic residue through cover crops or green manure necessary in order to produce longer-lasting effects.

Crop rotation including grains (soybean, maize and wheat), cover crops and green manure (lupine, turnip and black oat) seems to have minimized the effects of compression in the NT treatment compared to the treatment with soybean/wheat succession. Crop rotation promotes crop diversification, with different root systems and a higher biomass production, providing increased aeration and infiltration of water in the soil, leading to the maintenance and improvement of its structural quality (Calegari et al., 2008; Ralisch et al., 2010).

According to Franchini et al. (2012), considering that the NT system involves the least tillage, the permanent presence of soil coverage and crop diversification through rotation, chiseling of the soil is not required to break up the compacted layers as was observed in this study. This practice increases production costs through fuel consumption and labor, and the disruption of the structure of the soil can lead to loss of soil, water and nutrients through erosion.

According to Bertol et al. (2007), the financial cost caused by the loss of triple superphosphate (P), potassium chloride (K) and lime (Ca and Mg) through water erosion totaled US\$14.83 ha^{-1} for an NT system, US\$16.33 ha^{-1} for minimum tillage (a single chiseling + a single harrowing) and US\$24.94 ha^{-1} for a CT system (a single aeration + two harrowings).

The C$\mu\Delta/\Delta\mu$ structure was observed below the surface layer (~10 cm) in the NT and NTC treatments under crop rotation and succession, covering the largest area associated with the rotation treatments (Fig. 4). Some studies have described higher soil densities at 10–25 cm in NT areas caused by the pressure applied by agricultural machinery and the lack of soil disturbance (Tavares Filho et al., 2001; Ball et al., 2007; Munkholm et al., 2008, 2013). However, despite the largest areas of this HMU being observed in the NTC treatments under crop rotation (Fig. 4), it did not limit root development. An increase in biological activity was observed in these profiles, caused by the presence of chambers formed by macrofauna occupying part of the C$\mu\Delta/\Delta\mu$ structure (Figs. 1 and 2). This may explain the extensive root development in this unit, which presented less morphological deformities compared to the roots in the soybean/wheat succession treatments.

When evaluating the 0–20 cm layer of the same study area, Franchini et al. (2011) observed that resistance to root penetration in NT and NTC systems was lower under crop rotation than in crop succession treatments. They also observed lower resistance to penetration in an NT system under crop rotation, and these values were not critical in the root development of the crops.

The L$\Delta\mu$ptmt structure observed in the surface layer of the CT profiles is characteristic of the disaggregation provoked by leveling harrows (Fig. 3). However, this structure did not present pulverized soil characteristics, such as the appearance of fine earth, which may be attributed to the presence of plant residues on the surface of the soil (even in the CT treatment) and also as a result of the regrowth of maize and soybean and the presence of weeds, whose root systems had a agglutinating effect on the soil particles.

The CT profiles under rotation and succession presented CΔ, C$\Delta\mu$ and FΔgt structures (Fig. 3) below the surface layer caused by the disc plow, which provoked the formation of more compact layers around depths of 10–25 cm. On the other hand, lower soil disturbance together with the maintenance of mulch on the surface of the NT and NTC treatments resulted in structures with higher porosity. When evaluating soil properties in an 11-year old NT system, Jin et al. (2011) verified that the conservation of soil structure in the NT system increased the storage and availability of water for crops.

Despite being more evident in the NT and NTC areas, crop rotation had a small effect in the CT area, which presented roots that were less flattened and twisted, as was also observed by Munkholm et al. (2013). According to their study, these differences can be observed as the visual evaluation of the soil in the field allows for analysis of the growth and behavior of the roots.

Various studies demonstrate that soil preparation involving aeration and harrowing reduces organic matter content, especially in the tropics (Kaschuk et al., 2010; Balota and Auler, 2011). For this reason, the intense tillage of the soil in CT systems disaggregates the macroaggregates that are important for the protection and preservation of organic matter, resulting in its rapid oxidation and a reduction in the quality of the soil (Morris et al., 2010; López-Guarrido et al., 2012).

Despite the fact that the macrofauna in the soil was not evaluated in this study, its activity in the profiles was intense and certainly had an important role in the aggregation and structuring of the soil. Its role is also recognized in the fragmentation of organic residues, in organic matter dynamics and in the transport and mixing of organic particles and minerals (Aquino et al., 2008; Ayuke et al., 2011), as well as its effect on the composition, abundance and diversity of other organisms (Lavelle and Spain, 2001), such as microbial populations (Beare et al., 1994; Wardle and Lavelle, 1997). Cragg and Bardgett (2001) have described various studies that show how fauna in the soil can affect microbial biomass and its activity, whether via direct alimentation of bacteria and fungi or via dissemination of propagules.

4.2. Microbial biomass

The observed changes in soil structure provoked significant modifications in CMB and NMB levels, as higher levels were obtained for HMUs in the NT and NTC systems under crop rotation and succession (Figs. 6 and 8). The hypothesis that changes in soil structure may be correlated to modifications in microbial biomass was confirmed. The superior soil quality found in NT and NTC planting systems, which contain HMUs that are predominantly less compact and present a higher porosity than those observed in CT systems, produces higher levels of microbial biomass (Figs. 7 and 9).

Changes in soil structure caused by intense tillage affect water percolation, temperature and aeration and increase soil erosion, significantly reducing microbial communities (Sparling, 1997; Gil et al., 2011) and biomass (Hungria et al., 2009; Silva et al., 2010; López-Guarrido et al., 2012), as was observed in this study.

However, management systems involving less tillage encourage the formation and stabilization of macroaggregates (Beare et al., 1994), which coupled with the protection provided by soil coverage results in further retention of humidity, an increased rhizosphere effect in crops, higher availability of organic matter, better chemical and physical soil properties and a reduction in extreme temperatures, providing protection to the habitats of microorganisms that contribute to higher levels of microbial biomass in these systems (Gil et al., 2011; López-Fando and Pardo, 2011).

According to Jiang et al. (2011), microbial biomass is mainly concentrated within macroaggregates, as soil preparation activities in CT systems reduced these aggregates by an average of 67%. In NT systems, increased levels of organic matter and the presence of roots and fungal hyphae encourage macroaggregate stability, mainly at depths of 0–5 cm, compared to CT systems (Mendes et al., 2003). Therefore, soil tillage reduces microbial biomass, mainly by reducing the proportion of macroaggregates and exposing organic matter to rapid oxidation (Kushwaha et al., 2001). Haynes and Beare (1997) and Milne and Haynes (2004) demonstrated that there is a positive correlation between macroaggregates and CMB, indicating the importance of this parameter in soil aggregation.

NMB was more sensitive than CMB in the indication of changes provoked by soil management. According to Babujia et al. (2010), lower levels of NMB in some layers of the soil may indicate a lack of nitrogen caused by the increased mineralization of this element to meet the nutritional needs of the crop. Francis et al. (1992) observed that the mineralization of nitrogen compounds occurs more steadily in NT systems, while in CT systems there is increased liberation of nitrogen soon after soil preparation due to the breaking up of aggregates, intensifying microbial activity and reducing levels of NMB.

4.3. Total organic carbon (TOC) and total nitrogen (TN)

TOC was higher in the NT and NTC systems, independent of the type of crop management, which can be attributed to the reduced tillage of the soil preserving its structure and contributing via aggregation to the protection and stabilization of organic material in these management systems (Siqueira Neto et al., 2010) (Fig. 10). Increased levels of TOC in NT systems compared to CT systems have also been described in other studies (Franchini et al., 2007; Babujia et al., 2010; Boddey et al., 2010; López-Guarrido et al., 2012).

One factor that contributes to the reduction in organic matter is the acceleration of the mineralization process caused by soil preparation activities, which break up macroaggregates and expose organic matter to attack by microorganisms, resulting in a higher turnover (Six et al., 2004). In NT systems, a slower turnover of macroaggregates increases the formation of microaggregates, in which organic carbon particles are stabilized and protected for long periods of time, encouraging increased storage of carbon in this management system (Six et al., 2002).

In tropical and temperate soils, there is an increase in TOC levels in NT systems compared to CT systems of approximately 0.325 ± 0.113 Mg C ha^{-1}year^{-1} (Six et al., 2002). According to Groenigen et al. (2010), NT systems can promote retention of carbon in the soil due to increases in both bacteria and fungi.

In a recent study conducted by Franchini et al. (2012) in the same experimental area, it was observed that NT and NTC systems had a stabilization and maturity phase of 6 years, after which time TOC levels in the soil increased significantly. They also demonstrated that increases in TOC improved the structural quality of the soil, and observed increased soybean productivity in the NT and NTC systems after this period compared to the CT system.

Babujia et al. (2010) demonstrated that carbon levels increased in NT systems by 0.8 Mg C ha^{-1} year^{-1}compared to CT systems, which over a period of 20 years corresponded to 16 Mg C ha^{-1}. This demonstrates the extent to which NT systems contribute to the retention of carbon, as 67% was found to have accumulated at depths of 0–30 cm. Six et al. (2000) proposed that the formation of stable microaggregates inside macroaggregates is vital for the retention of carbon in soils under NT planting systems.

It is clear that NT planting systems are important in hotter regions to encourage the retention of carbon in the soil, as the presence of soil coverage affects the formation and stability of aggregates and reduces the effects of excessive temperatures, decreasing the decomposition of organic matter and emissions of CO_2 into the atmosphere (Álvaro-Fuentes et al., 2008).

Similarly to TOC, TN levels were significantly higher in the NT and NTC systems under crop rotation and succession for all of the depths analyzed, presenting values that were 50% higher than those obtained for the CT system (Fig. 10). This demonstrates that soil tillage substantially reduces nitrogen levels, a factor that can limit crop development and yield. According to Hungria et al. (2009), there is generally an increased immobilization of nitrogen in NT systems, while CT systems increase the nitrogen mineralization process as organic matter and crop residues are exposed to biotic (soil fauna) and abiotic factors (temperature, humidity and light) (Morris et al., 2010).

Data obtained by Babujia et al. (2010) show an accumulation of nitrogen at depths of 0–60 cm of 1.4 Mg ha^{-1} compared to CT, enriching the soil with 70 kg N ha^{-1} year^{-1}. Gál et al. (2007) observed a 1.9 Mg ha^{-1} increase in nitrogen at depths of 30 cm in an NT system that had been cultivated for 28 years.

When evaluating the same experimental area, Franchini et al. (2012) observed higher yields of maize in the first 6 years of a CT system, which coincides with the stabilization phase of NT systems. They explained that this was probably due to an increased immobilization of nitrogen in the NT system, but that this difference reduced over time as intensive cultivation increased oxidation of organic matter in the CT system. According to Barreto et al. (2009), aggregation promotes TN and TOC accumulation in macroaggregates, which explains the high sensitivity of nitrogen to the disruption of the soil. Christopher and Lal (2007) emphasized the importance of nitrogen as a limiting component in the humification process, which is essential for the retention of carbon in the soil.

5. Conclusions

In an experiment conducted over 22 years, the hypothesis of this study that morphological changes in soil structure effect levels of microbial biomass has been confirmed. The superior soil quality found in NT and NTC planting systems, which contain HMUs that are predominantly less compact and present a higher porosity than those observed in CT systems, produces higher levels of carbon and nitrogen microbial biomass. The cultural profile methodology, which has already been used as a soil sampling technique, provides results on soil structure that can be interpreted immediately and has proven to be capable of indicating changes in levels of microbial biomass caused by agricultural practices. Crop rotation contributed to the conservation of the structure of the soil by reducing the effects of soil management. The profiles under crop rotation systems presented less compact soil volumes than those under crop succession systems and with less morphologically deformed roots. TOC and TN were higher for the NT and NTC systems, as TN and NMB were the parameters most affected by soil management, indicating that increased disturbance of the soil reduces nitrogen levels. These results show that in tropical conditions, low tillage systems are fundamental in the maintenance and improvement of soil structure and promote increased carbon accumulation, contributing to a reduction in CO_2 emissions.

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References

Albuquerque, J.A., Reinert, D.J., Fiorin, J.E., Ruedell, J., Petrere, C., Fontinelli, F., 1995. Rotação de culturas e sistemas de manejo do solo: efeito sobre a forma da estrutura do solo ao final de sete anos. Rev. Bras. Ciênc. Solo 19, 115–119.
Álvaro-Fuentes, J., López, M.V., Arrué, J.L., Cantero-Martínez, C., 2008. Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions. Soil Sci. Soc. Am. J. 72, 194–200.
Aquino, A.M., Silva, R.F., Mercante, F.M., Correia, M.E.F., Guimarães, M.F., Lavelle, P., 2008. Invertebrate soil macrofauna under different ground cover plants in the no-till system in the Cerrado. Eur. J. Soil Biol. 44, 191–197.
Ayuke, F.O., Brussaard, L., Vanlauwe, B., Six, J., Lelei, D.K., Kibunja, C.N., Pulleman, M.M., 2011. Soil fertility management: impacts on soil macrofauna, soil aggregation and soil organic matter allocation. Appl. Soil Ecol. 48, 53–62.
Babujia, L.C., Hungria, M., Franchini, J.C., Brookes, P.C., 2010. Microbial biomass and activity at various soil depths in a Brazilian oxisol after two decades of no-tillage and conventional tillage. Soil Biol. Biochem. 42, 2174–2181.
Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration – what do we really know? Agric. Ecosyst. Environ. 118, 1–5.
Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Till. Res. 53, 29–39.
Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality – a development of the Peerlkamp test. Soil Use Manage. 23, 329–337.
Balota, E.L., Auler, P.A.M., 2011. Soil microbial biomass under different management and tillage systems of permanent intercropped cover species in an orange orchard. Rev. Bras. Ciênc. Solo 35, 1873–1883.
Barreto, R.C., Madari, B.E., Maddock, J.E.L., Machado, P.L.O.A., Torres, E., Franchini, J.C., Costa, A.R., 2009. The impact of soil management on aggregation, carbon stabilization and carbon loss as CO_2 in the surface layer of a Rhodic Ferralsol in Southern Brazil. Agric. Ecosyst. Environ. 132, 243–251.
Barros, N., Gallego, M., Feijóo, S., 2007. Sensitivity of colorimetric indicators of soil microbial activity. Thermochim. Acta 458, 18–22.
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.
Bartlett, R.J., Ross, D.N., 1988. Colorimetric determination of oxidizable carbon in acid soil solutions. Soil Sci. Soc. Am. J. 52, 1191–1192.
Batey, T., 2009. Soil compaction and soil management – a review. Soil Use Manage. 25, 335–345.
Bayer, C., Mielniczuk, J., Martin-Neto, L., Ernani, P.R., 2002. Stocks and humification degree of organic matter fractions as affected by no-tillage on a subtropical soil. Plant Soil 238, 133–140.
Beare, M.H., Hendrix, P.F., Coleman, D.C., 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58, 777–786.
Bertol, I., Cogo, N.P., Schick, J., Gudagnin, J.C., Amaral, A.J., 2007. Aspectos financeiros relacionados às perdas de nutrientes por erosão hídrica em diferentes sistemas de manejo do solo. Rev. Bras. Ciênc. Solo 31, 133–142.
Boddey, R.M., Jantalia, C.P., Conceição, P.C., Zanatta, J.A., Bayer, C., Mielniczuk, J., Dieckow, J., Santos, H.P., Denardin, J.E., Aita, C., Giacomini, S., Alves, B.J.R., Urquiaga, S., 2010. Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. Global Change Biol. 16, 784–795.
Braak, C.J.F., Smilauer, P., 1998. CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Odination (Version 4). Microcomputer Power, Ithaca, NY 352 pp.
Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17, 837–842.
Calegari, A., Hargrove, W.L., Rheinheimer, D.S., Ralisch, R., Tessier, D., Tourdonnet, S., Guimarães, M.F., 2008. Impact of long-term no-tillage and cropping system management on soil organic carbon in an oxisol: a model for sustainability. Agron. J. 100, 1013–1019.
Chan, K.Y., Roberts, W.P., Heenan, D.P., 1992. Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices. Aust. J. Soil Res. 30, 71–83.
Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S., Peoples, M.B., 2006. Agronomic consequences of tractor wheel compaction on a clay soil. Soil Till. Res. 89, 13–21.
Christopher, C., Lal, R., 2007. Nitrogen management affects carbon sequestration in North American croplands. Crit. Rev. Plant Sci. 26, 45–64.
Cragg, R., Bardgett, R.D., 2001. How changes in soil faunal diversity and composition within a trophic group influence decomposition processes. Soil Biol. Biochem. 33, 2073–2081.
Drury, C.F., Yang, X.M., Reynolds, W.D., Tan, C.S., 2004. Influence of crop rotation and aggregate size on carbon dioxide production and denitrification. Soil Till. Res. 79, 87–100.
FEBRAPDP (Federação Brasileira de Plantio Direto na Palha), 2012. Área de plantio direto no Brasil. http://www.febrapdp.org.br/download/BREvolucaoP-D2002a2006.pdf (accessed 18.07.12).
Feigl, B.J., Sparling, G.P., Ross, D.J., Cerri, C.C., 1995. Soil microbial biomass in Amazonian soils: evaluation of methods and estimates of pool size. Soil Biol. Biochem. 27, 1467–1472.
Feije, F., Anger, V., 1972. Spot test in inorganic analysis. Anal. Chem. Acta 149, 363–367.
Franchini, J.C., Crispino, C.C., Souza, R.A., Torres, E., Hungria, M., 2007. Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. Soil Till. Res. 92, 18–29.
Franchini, J.C., Costa, J.M., Debiasi, H., 2011. Rotação de culturas: prática que confere maior sustentabilidade a produção agrícola no Paraná. Inform. Agron. 134, 1–13.
Franchini, J.C., Debiasi, H., Balbinot Junior, A.A., Tonon, B.C., Farias, J.R.B., Oliveira, M.C.N., Torres, E., 2012. Evolution of crop yields in different tillage and cropping systems over two decades in southern Brazil. Field Crops Res. 137, 178–185.
Francis, G.S., Haynes, R.J., Knight, T.L., 1992. An overview of results from the long-term no-tillage trials at Winchmore. In: Annual Conference of the Agronomy Society of New Zealand, Camberra, pp. 97–101.
Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Till. Res. 66, 197–205.
Gál, A., Vyn, T.J., Michéli, E., Kladivko, E.J., Mcfee, W.W., 2007. Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Till. Res. 96, 42–51.
Gautronneau, Y., Manichon, H., 1987. Guide méthodique du profil cultural. CEREF-GEARA, Lyon 71 pp.
Giarola, N.F.B., Silva, A.P., Tormena, C.A., Guimarães, R.M.L., Ball, B., 2013. On the visual evaluation of soil structure: the Brazilian experience in Oxisols under no-tillage. Soil Till. Res. 127, 60–64.
Gil, S.V., Meriles, J., Conforto, C., Basanta, M., Radl, V., Hagn, A., Schloter, M., March, G.J., 2011. Response of soil microbial communities to different management practices in surface soils of a soybean agroecosystem in Argentina. Eur. J. Soil Biol. 47, 55–60.
Groenigen, K.J., Bloem, J., Baath, E., Boeckx, P., Rousk, J., Bodé, S., Firristal, D., Jones, M.B., 2010. Abundance, production and stabilization of microbial biomass under conventional and reduced tillage. Soil Biol. Biochem. 42, 48–55.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Till. Res. 82, 121–145.
Haynes, R.J., Beare, M.H., 1997. Influence of six crop species on aggregate stability and some labile organic matter fractions. Soil Biol. Biochem. 29, 1647–1653.
Hungria, M., Franchini, J.C., Brandão-Junior, O., Kaschuk, G., Souza, R.A., 2009. Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. Appl. Soil Ecol. 42, 288–296.
Jiang, X., Wright, A.L., Wang, X., Liang, F., 2011. Tillage-induced changes in fungal and bacterial biomass associated with soil aggregates: a long-term field study in a subtropical rice soil in China. Appl. Soil Ecol. 48, 168–173.
Jin, H., Hongwen, L., Rasaily, R.G., Qingjie, W., Guohua, C., Yanbo, S., Xiaodong, Q., Lijin, L., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. Soil Till. Res. 113, 48–54.
Kaschuk, G., Alberton, O., Hungria, M., 2010. Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol. Biochem. 42, 1–13.
Kushwaha, C.P., Tripathi, S.K., Signh, K.P., 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Appl. Soil Ecol. 16, 229–241.
Lavelle, P., Spain, A.V., 2001. Soil Ecology. Kluwer Academic, Dordrecht, The Netherlands 654 pp.
López-Fando, C., Pardo, M.T., 2011. Soil carbon storage and stratification under different tillage systems in a semi-arid region. Soil Till. Res. 111, 224–230.
López-Guarrido, R., Deurer, M., Madejón, E., Murillo, J.M., Moreno, F., 2012. Tillage influence on biophysical soil properties: the example of a long-term tillage experiment under Mediterranean rainfed conditions in South Spain. Soil Till. Res. 118, 52–60.

MAPA (Ministério da Agricultura Pecuária e Abastecimento), 2012. Programa ABC. Available in: http://www.agricultura.gov.br/desenvolvimento-sustentavel/plano-abc (accessed 03.03.12).
Mendes, I.C., Souza, L.V., Resck, D.V.S., Gomes, A.C., 2003. Propriedades biológicas em agregados de um Latossolo Vermelho-Escuro sob plantio convencional e direto no Cerrado. Rev. Bras. Ciênc. Solo 27, 435–443.
Milne, R.M., Haynes, R.J., 2004. Comparative effects of annual and permanent dairy pastures on soil physical properties in the Tsitsikamma region of South Africa. Soil Use Manage. 20, 81–88.
Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment. Soil Till. Res. 108, 1–15.
Munkholm, L.J., Hansen, E.M., Olesen, J.E., 2008. The effect of tillage intensity on soil structure and winter wheat root/shoot growth. Soil Use Manage. 24, 392–400.
Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil Till. Res. 127, 85–91.
Neves, C.S.V.J., Feller, C., Guimarães, M.F., Medina, C.C., Tavares Filho, J., Fortier, M., 2003. Soil bulk density and porosity of homogeneous morphological units identified by the cropping profile method in clayey Oxisols in Brazil. Soil Till. Res. 71, 109–119.
Siqueira Neto, M., Scopel, E., Corbeels, M., Cardoso, A.N., Douzet, J.M., Feller, C., Piccolo, M.C., Cerri, C.C., Bernoux, M., 2010. Soil carbon stocks under no-tillage mulch-based cropping systems in the Brazilian Cerrado: an on-farm synchronic assessment. Soil Till. Res. 110, 187–195.
Oliveira, J.R.A., Mendes, I.C., Vivaldi, L., 2001. Carbono da biomassa microbiana em solos de cerrado sob vegetação nativa e sob cultivo: avaliação dos métodos fumigação-incubação e fumigação-extração. Rev. Bras. Ciênc. Solo 25, 863–871.
Ralisch, R., Almeida, E., Silva, A.P., Pereira Neto, O.C., Guimarães, M.F., 2010. Morphostructural characterization of soil conventionally tilled with mechanized and animal traction with and without cover crop. Rev. Bras. Ciênc. Solo 34, 1795–1802.
SAS Institute, 2005. Procedure Guide for Personal Computers. Version 8.2. SAS Institute, Cary, North Carolina.
Silva, A.P., Babujia, L.C., Franchini, J.C., Souza, R.A., Hungria, M., 2010. Microbial biomass under various soil- and crop- management systems in short- and long-term experiments in Brazil. Field Crops Res. 119, 20–26.
Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103.
Six, J., Feller, C., Denef, K., Ogle, S.M., Sá, J.C.M., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils – effects of no-tillage. Agronomie 22, 755–775.
Six, J., Bossuyt, H., Degryze, S., Denef, K.A., 2004. History of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. 79, 7–31.
Sparling, G.P., 1997. Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In: Pankhurst, C., Doube, B.M., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health. CAB International, Cambridge, pp. 97–120.
Tamia, A., Moreau, R., Fortier, M., Yoro, G., 1999. Influence du travail du sol sur l'évolution physique d'un sol forestier ferrallitique après défrichement motorisé. Étude Gest. Soils 6, 27–29.
Tavares Filho, J., Ralisch, R., Guimarães, M.F., Medina, C.C., Balbino, L.C., Neves, C.S.V.J., 1999. Método do perfil cultural para avaliações do estado físico de solos em condições tropicais. Rev. Bras. Ciênc. Solo 23, 393–399.
Tavares Filho, J., Barbosa, G.M.C., Guimarães, M.F., Fonseca, I.C.B., 2001. Resistência do solo à penetração e desenvolvimento do sistema radicular do milho (*Zea mays*) sob diferentes sistemas de manejo em um Latossolo Roxo. Rev. Bras. Ciênc. Solo 25, 725–730.
Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707.
Veiga, M., Horn, R., Reinert, D.J., Reichert, J.M., 2007. Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems. Soil Till. Res. 92, 104–113.
Wardle, D.A., Lavelle, P., 1997. Linkages between soil biota, plant litter quality and decomposition. In: Cadisch, G., Giller, K.E. (Eds.), Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, pp. 107–124.