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Soil quality indicators after conversion of “murundu” fields into no-tillage cropping in the Brazilian Cerrado

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Abstract – The objective of this work was to evaluate changes in soil quality due to different times of adoption of the no-tillage system in “murundu” (mound) fields converted to agriculture, as well as to identify the best indicators to explain these changes. The study was carried out on a Plinthic Altisol, in the municipality of Portelândia, in the state of Goiás, Brazil. The treatments consisted of different times of conversion and of adoption of the no-tillage system – 8, 12, and 17 years – and of native area between the mounds and on top of the mounds (reference area). After 17 years of the adoption of no-tillage, there was an increase in organic carbon and nitrogen, as well as in their particulate fractions in relation to the reference area. The microbiological attributes showed greater values in the 17-year no-tillage period compared with the native area. For soil aggregation, 12 years of adoption of the no-tillage system were enough to show an increase in this variable. The main attributes to be used as soil quality indicators are microbial biomass carbon, the carbon management index, and the microbial quotient.

Index terms: hydromorphic soils, microbial biomass, organic matter, Plinthosols.

Indicadores de qualidade do solo após a conversão de campos de murundus em plantio direto no Cerrado brasileiro

Resumo – O objetivo deste trabalho foi avaliar as alterações na qualidade do solo devido a diferentes tempos de adoção do sistema plantio direto em campos de murundus convertidos para agricultura, bem como identificar quais seriam os melhores indicadores para explicar essas alterações. O estudo foi realizado em Plintossolo Háplico, no Município de Portelândia, no Estado de Goiás. Os tratamentos consistiram de diferentes épocas de conversão e adoção do sistema plantio direto – 8, 12 e 17 anos – e de área nativa entre murundus e no topo dos murundus (área de referência). Após 17 anos da adoção de plantio direto, houve incremento de carbono e nitrogênio orgânicos, assim como das suas frações particuladas em relação à área de referência. Os atributos microbiológicos alcançaram valores superiores no plantio direto de 17 anos, em comparação à área nativa. Para a agregação do solo, 12 anos de adoção do plantio direto foram suficientes para mostrar incremento nessa variável. Os principais atributos para uso como indicadores da qualidade do solo são o carbono da biomassa microbiana, o índice de manejo de carbono e o quociente microbiano.

Termos para indexação: solos hidromórficos, biomassa microbiana, matéria orgânica, Plintossolo.

Introduction

The growing demand for food is a challenge to sustainable production due to the high pressure for expansion of agricultural frontiers, which increases the deforestation of native lands, mainly in the Brazilian Cerrado (Brazilian savannah). In this biome, some areas incorporated to the production process are considered "murundu" fields, which, according to Paulino et al. (2015), make up a phytophysiognomy characterized by the presence of earth mounds, or microreliefs, forming several "islands" across the field; these mounds can reach approximately 10 m in diameter and up to 2 m in height.

These fields are usually flooded during the rainy season, when the groundwater level rises and water flows to the ground surface; during the dry season, the water that remains on the surface slowly runs off becoming natural water reservoirs (Castro Júnior, 2002). Typical soils in this environment are Plintossolos Háplicos, i.e., xxx, which are closely related to the ecological and environmental functions in this ecosystem (Paulino et al., 2015).

Due to these characteristics and to the great importance of preserving water resources in the state of Goiás, "murundu" fields are considered as permanent preservation areas, where any kind of anthropic activity is prohibited, according to Law no. 16.153 enacted in 2007 (Goiás, 2007). However, the areas that have been already converted and whose period of use is over two years are allowed to continue being used for agriculture.

Little is known, however, about the impact of agricultural activities on soil attributes in these fields, and the conversion of native lands to agricultural systems may affect significantly soil quality and dynamics.

Therefore, to assess soil quality, it is necessary to use indicators that are sensitive to soil management variations and that are correlated with soil functions (Klein & Klein, 2014). In this context, organic matter becomes a key indicator of soil quality due to its connection with other properties, influencing soil nutrient cycling and structuring, infiltration, water retention, and susceptibility to erosion. Souza et al. (2016) concluded that converting "murundu" fields to farming lands reduces organic matter contents in relation to the reference area and that about 34 years would be necessary to recover organic matter stocks in the soil.

Biological attributes also have a great potential for use in studies related to soil quality because microorganisms are a source and deposit of nutrients in all ecosystems, besides participating actively in many beneficial processes such as humus formation, nutrient solubilization for plants, and degradation of persistent compounds applied to the soil (Costa et al., 2015).

Conservation systems, such as no-tillage, may also be used to decrease negative effects of agriculture over time, allowing the areas that have undergone conversion to maintain their ecosystem services (Souza et al., 2014). It is expected that no-tillage, through permanent soil coverage and minimal soil disruption, improve the incorporation of residues, enhance the entry of carbon into the system, and promote greater microbial activity, consequently improving soil quality.

The objective of this work was to evaluate changes in soil quality due to different times of adoption of the no-tillage system in "murundu" (mound) fields converted to agriculture, as well as to identify the best indicators to explain these changes.

Materials and Methods

The study was carried out at a site located at the Boa Vista farm, located 60 km away from the municipality of Jataí, in the state of Goiás, in the Ariranha River basin, Brazil (17°57'11"S, 52°04'45"W, at an altitude of 872 m). The soil is classified as a Plintossolo Háplico (Santos et al., 2013), i.e., a Plinthic Altisol, with clayey texture, restricted water percolation, temporary flooding for a period of four to six months, and plinthite formation at a soil depth greater than 60 cm. The climate in the region, according to Köppen, is of the Cw type. Mean air temperature is 22°C and annual precipitation is 1,600 mm.

Before being converted to farming land, the area was characterized by "murundu" fields, whose mounds reached 20 m in diameter and 2 m in height. To implement the agricultural systems, vegetation was burnt during the dry season and, afterwards, the mounds were leveled using a drag harrow and then a subsoiler to provide an even surface area. To prevent flooding in the crop areas, which is typical of this type of phytophysiognomy in the Cerrado, a drainage system with approximately 100 m between the channels and 0.5 to 2.0 m depth was built to facilitate water drainage from the areas included in the production process.

The experimental areas used in the present study were converted to croplands subjected to different no-tillage times – 8 years (NT8), 12 years (NT12), and 17 years (NT17) – and were demarcated using the Surfer, version 8.0, computer software (Golden Software, LLC, Golden, CO, USA). This software was used to create grids with 100x100-m polygons; five random grids were selected for soil sampling, and ten subsamples were collected from each grid, forming compound samples representative of the studied areas. In addition, a control area was defined in the “murundu” fields without anthropic interference, consisting of two smaller native areas: one between the mounds and the other on top of the mounds, which was considered as the reference area. This decision of considering two native areas was due to the diverse composition of cover plants and flooding propensity on these locations, which cause an anaerobic process in the soil and change the environment. The areas converted to croplands were compared mainly with those on top of the mounds, since both are similar to each other. The history of the soil management and crops cultivated in the areas is described in Table 1.

In early November 2011, during the rainy season, trenches measuring 0.40x0.40x0.40 m were dug, and soil samples were collected using spatulas. To assess microbial biomass, samples were collected at 0–10-cm depth, stored in identified plastic bags, and placed in iceboxes to be sent to the laboratory, where they were stored and kept under refrigeration for further analyses.

To assess carbon and nitrogen contents, soil samples were collected from the 0–5, 5–10, and 10–20-cm depths; for aggregation, soil cores weighing 500 g were taken at 0–5 and 5–10 cm. All these samples were wrapped in plastic film to keep their structure stable, stored in identified plastic bags, and placed in iceboxes to be sent to the laboratory. Then, they were displayed on a sheet of paper, moistened and fractionated at their weak points, air-dried for 72 hours, and, finally, kept in boxes within plastic bags. The methodology proposed by Silva & Mielniczuk (1997) was used to separate bulk soil into aggregate classes. The weighted mean diameter (WMD) was calculated by the following equation: $WMD = \sum^{n}_{i=1} (X_i \times W_i)$ where Wi is the percentage of bulk soil in relation to the total and Xi is the mean diameter (in mm) of the classes.

The fractionation of organic matter was carried out according to Cambardella & Elliot (1992) by stirring horizontally 15 g soil for 16 hours in snap-cap

Table 1. Identification and history of the land management and use of the studied Plintossolo Háplico of the Brazilian Cerrado.

Identification	History
Between mounds and on top of mounds	Area without anthropic intervention. The mounds were 20 m in diameter and about 2 m high. On the base of the mounds, grew grass resistant to the flooding and drought cycles throughout the year. Typical vegetation of the Cerrado (stricto sensu) and termites were found on the top of the mounds.
8-year area (NT8)	The no-tillage system was adopted since 2003/2004. Before that, the area was covered by native forage grass. In 2003, 5.0 Mg ha^{-1} dolomitic limestone were incorporated to the land with a plow and leveling harrow. In 2005/2006 and 2008/2009, 1.5 Mg ha^{-1} dolomitic lime was applied to the surface. In the 2006/2007 and 2009/2010 crop years, yields reached 3.1 and 4.5 Mg ha^{-1}, respectively, when soybean (*Glycine max*) and corn (*Zea mays*) were grown in succession in the main season and the off-season (second crop), respectively. There was a fallow period during the 2007/2008 and 2008/2009 off-season crops. For the 2010/2011 crop year, 1.5 Mg ha^{-1} dolomitic limestone was applied to the ground surface, and there was no off-season crop in 2011.
12-year area (12NT)	No-tillage area since 1999/2000. Before that, it was covered with native forage. In 1999, 6.0 Mg ha^{-1} dolomitic limestone were incorporated with a plow and harrow. In the crop year, 0.6 Mg ha^{-1} orthophosphate was applied (33% P_2O_5). In 2002/2003 and 2007/2008, limestone was applied at a rate of 3.0 and 2.0 Mg ha^{-1}, respectively. Soybean was cultivated in the main season and corn in the off-season. There was no off-season crop after the 2005/2006, 2006/2007, and 2008/2009 crop years, and corn was cultivated during 2007/2008. In 2011, there was also no off-season crop.
17-year area (17NT)	No-tillage land area since 1994/1995. However, the land was cleared in the 1980s, when the rice (*Oryza sativa*)-forage intercropping, without liming and fertilization, was adopted. After conversion, 3.0 Mg ha^{-1} dolomitic limestone were applied, as well as 2.0 and 1.0 Mg ha^{-1} gypsum and orthophosphate (33% P_2O_5), respectively, incorporated with a plow and harrow. In 2005/2006, 2.5 Mg ha^{-1} surface limestone were applied. This area was cultivated with soybean and corn in succession in the main season and in the off-season, respectively. In 1995/2006, 1996/2007, 2005/2006, and 2008/2009, the area lied in fallow. In 2011, there was no off-season crop.

flasks containing 60 mL sodium hexametaphosphate (7.5 g L^{-1}). Total organic carbon (TOC) and particulate organic carbon (POC) were determined as in Tedesco et al. (1995) by oxidation with dichromate. Total nitrogen and particulate nitrogen contents were obtained via micro-Kjeldahl distillation (Tedesco et al., 1995). Then, the total and particulate stocks of carbon and nitrogen in equivalent soil mass were calculated, and the lowest densities – 0.85, 0.98, and 0.95 kg dm^{-3}, respectively, for the 0–5, 5–10, and 10–20-cm layers – found in the reference area (top of mound) were considered. For total and particulate carbon and nitrogen, the sum of the different layers was calculated, and the stock at 0.20 cm was determined.

Microbial biomass was assessed regarding: basal respiration (Alef & Nannipieri, 1995), with soil incubation for 24 hours, without lighting; microbial biomass carbon (Vance et al., 1987), via the fumigation-extraction method; microbial biomass nitrogen, according to Brookes (1995), with micro-Kjeldahl distillation; metabolic quotient, as described by Anderson & Domsh (1993); and microbial quotient (Brookes, 1995).

The carbon management index (CMI) was calculated considering the native area at the top of the mounds as a reference (CMI = 100), based on Blair et al. (1995), adapted by Dieckow et al. (2005). POC was considered as the labile fraction of carbon, whereas the organic carbon associated to minerals (difference between TOC and POC) was considered as the non-labile fraction of carbon. The used equations were:

CL = labile carbon/non-labile carbon

CSI = S-TOC of treatment / S-TOC of reference

ICL = CL of treatment / CL of reference

CMI = CSI × ICL × 100

where CL is carbon lability, labile carbon is the stock of POC, non-labile carbon is the stock of the fraction associated to minerals, CSI is the carbon stock index, S-TOC of treatment is the carbon stock of the assessed treatment, S-TOC of reference is the carbon stock of the reference area, and ICL is the lability index.

Subsequently, based on statistical assumptions, the activity and independence of errors were verified by the graphic analysis, the homogeneity of variances by Barlett's test, and the normality of errors by Shapiro-Wilk's test. Since these assumptions were fulfilled, the analyses of variance were conducted according to a completely randomized experimental design. The obtained results were, therefore, subjected to the analysis of variance and, when significant, to Tukey's test, at 5% probability, using the Sisvar, version 5.3, statistical software (Ferreira, 2011). The relative contribution of each analyzed variable to total data variation was determined by Singh's method (1981) according to Cruz & Regazzi (1997). The variables that showed a relative contribution over 10% formed the group of soil quality indicators.

Results and Discussion

The stocks of total organic carbon were influenced by land use and management (Table 2), being 38.8 and 59.8 Mg ha^{-1} for NT8 and between the mounds, respectively. Regarding the top of the mounds (reference area), the stock of total organic carbon was 15% higher than that of the NT8 area and similar to those of NT12 and NT17 (Table 2). Total nitrogen stocks were also affected by the conversion of the "murundu" fields to no-tillage cropping areas (Table 3). No-tillage cropping for up to 12 years was sufficient to increase total nitrogen stocks in the soil, as observed on the top of the mounds. However, 17 years of no-tillage promoted an 18% increase in nitrogen stock compared with that on the top of the mounds.

The conversion of the "murundu" fields caused a destabilization of the soil system (complex interactions between minerals, plants, and biota), resulting in the rupture of soil aggregates, making organic matter susceptible to microbial decomposition and influencing negatively the stock of organic carbon. However, after the initial soil tillage, the no-tillage method was used, which was sufficient to reorganize the soil system and for the recovery of total organic carbon and total nitrogen stocks after 12 and 8 years, respectively. After 17 years, the total organic carbon and total nitrogen stocks were, respectively, similar to and higher than those on the top of the mounds, but both were higher than those between the mounds. This is due to the rise of the groundwater level, which decreases the amount of oxygen in the soil and reduces the microorganism activity in the organic material decomposition process (Moreira & Siqueira, 2006), favoring the total organic carbon and total nitrogen stocks between the mounds.

By adopting a long-term conservation management system, such as no-tillage or direct seeding, it is possible to achieve greater stocks of total organic carbon and total nitrogen, as observed in the present study. However, this recovery is slow, requiring a long time for these elements to increase – about 34 years for organic matter stocks to reach levels close to the original ones (Souza et al., 2016). Therefore, to reduce the recovery time of organic matter in this area, management systems to ensure more carbon input into the soil should be adopted. Integrated farming systems are an alternative, because pastures, in general, tend to sequester more carbon than annual cropping soils due to a greater production of root biomass, the formation of stable aggregates, and a longer permanence of residues on the topsoil, while livestock grazing introduces new pathways for nutrients and water flow, besides behaving as a catalyzer of the system (Müller-Stöver et al., 2012; Anghinoni et al., 2013).

The greatest stocks of POC were found in NT17, with a 280% increase in relation to the top of the mounds. The value obtained for NT12 did not differ significantly from that between the mounds, but was 78% higher than that on the top of the mounds. The stocks in NT8 also did not differ significantly from those on the top of the mounds, but showed a trend of increase, with a value higher than 19.14% (Table 2). The nitrogen stock in particulate organic matter did not vary between the treatments with no-tillage, regardless of the time of its adoption. However, the stocks were higher than those on the top of the mounds and lower than those between the mounds (Table 3).

This increase in the particulate fraction is related to the continuous apportionment of recent plant material, which explains the greater amount of biomass stored by the system. This becomes evident when the POC/TOC ratio is assessed, which increases with the time of use of direct seeding; this ratio increased from 10% on the top of the mounds to 14, 19, and 29% in the NT8, NT12, and NT17 areas, respectively (Table 2).

The conversion of "murundu" fields to croplands using the conservation no-tillage system affected adversely the carbon content in microbial biomass, causing a decrease in NT8 of up to 57 and 82% in relation to the values obtained on the top of the mounds and between the mounds, respectively (Table 4). However, in NT17, there was carbon recovery in microbial biomass, which reached values similar to

Table 2. Stocks of total organic carbon (S-TOC) and particulate organic carbon (S-POC) at the 20-cm depth of a Plintossolo Háplico of the Brazilian Cerrado[(1)].

Land use system	S-TOC	Variation		S-POC	Variation		POC/TOC
	(Mg ha^{-1})	(Mg ha^{-1})	(%)	(Mg ha^{-1})	(Mg ha^{-1})	(%)	(%)
Between mounds	59.8a	-	-	9.6b	-	-	16
Top of mounds	46.0b	-	-	4.7c	-	-	10
NT8	38.8c	-7.2	15	5.6c	0.9	19	14
NT12	44.4b	-1.6	3	8.4b	3.7	78	19
NT17	45.4 b	-0.6	1	13.2a	8.5	280	29

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's test, at 5% probability. NT8, no-tillage during 8 years; NT12, no-tillage during 12 years; and NT17, no-tillage during 17 years.

Table 3. Stocks of total nitrogen (S-TN) and particulate organic nitrogen (S-PN) at the 20-cm depth of a Plintossolo Háplico of the Brazilian Cerrado[(1)].

Land use system	S-TN	Variation		S-PN	Variation		PN/TN
	(Mg ha^{-1})	(Mg ha^{-1})	(%)	(Mg ha^{-1})	(Mg ha^{-1})	(%)	(%)
Between mounds	8.5a	-	-	0.41a			4.8
Top of mounds	5.9c	-	-	0.25c	-	-	4.2
NT8	6.1c	0.2	3.4	0.33b	0.08	32	5.4
NT12	6.1c	0.2	3.4	0.35b	0.1	40	5.7
NT17	7.0b	1.1	18	0.35b	0.1	40	5.0

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's test, at 5% probability. NT8, no-tillage during 8 years; NT12, no-tillage during 12 years; and NT17, no-tillage during 17 years.

those on the top of the mounds. In NT8 and NT12, there would probably be a carbon increase in microbial biomass due to crop succession, which provides more diversity in the accumulated residues, contributing to an increase in organic carbon. Variations in microbial biomass carbon and its activity have a direct relationship with variations in soil organic carbon (Souza et al., 2014), especially in the particulate fraction, since it is comprised of non-decomposed plant residues and of their products in partial decomposition, consequently forming a reservoir of materials readily available for microbial attack (Cates & Ruark, 2017).

Microbial biomass nitrogen was influenced by the time of use of direct seeding, in the following order: NT17>NT12=between the mounds≥top of mounds≥NT8. The adoption of soybean [*Glycine max* (L.) Merr.]/corn (*Zea mays* L.) succession cropping and of 17 years under no-tillage was sufficient to enhance these contents, which surpassed those of the native areas between the mounds and on top of the mounds (Table 4), possibly because of the high uptake of soluble nitrogen via fertilization. This microbial nitrogen recovery can generate more nitrogen recycling in the environment by the action of microbial biomass.

Regarding basal respiration and the metabolic quotient – both components of the biomass respiration rate and attributes related to the cycle of organic carbon –, high values were observed in NT8 and NT12, which only decreased in NT17 (Table 4). High respiration rates indicate ecosystems undergoing some stress or disturbance conditions, but the opposite is related to environments that are more stable or closer to their state of equilibrium (Silva et al., 2010). Therefore, the use of no-tillage for 17 years contributed to improve soil biological attributes, by reducing the amount of carbon respiration via CO_2 and, consequently, increasing the carbon contents stored in soil organic matter; this shows that, in the long term, the area can reach equilibrium as a production system.

The soil microbial quotient increased as the time of adoption of the no-tillage system increased, reaching 5.5% in NT17, whereas, in the native areas, this value was close to 3.5% (Table 4). These results are indicative that the adoption of no-tillage for a long time and the constant addition of organic matter with high nutritional quality contributed to increase microbial biomass and influenced its ability to use efficiently soil organic carbon. High values for the microbial quotient reflect an efficient conversion of recalcitrant carbon into microbial carbon, as well as the stabilization of organic carbon by the soil mineral fraction, expressing carbon accumulation in the soil (Sparling, 1992).

The different times of use of no-tillage caused an increase in S-POC between the mounds, compared with the top of the mounds (Table 2). This results in an improved soil management quality, which is indicated by the CMI, which can show the influence of the management system on the stocks of organic matter and the quality of soil management (Loss et al., 2011). The CMI increases with the increased use of no-tillage, which can reach 350%, compared with the top of the mounds (100%), evidencing recovery in soil management quality. Souza et al. (2016) also found higher CMI values in soils under no-tillage, compared

Table 4. Attributes used to indicate the quality of a Plintossolo Háplico of the Brazilian Cerrado, when evaluated under different management systems[(1)].

Soil quality attributes	Land management system				
	Between mounds	Top of mounds	NT8	NT12	NT17
MB-C (mg kg^{-1} C)	1,705.0a	1,491.0b	685.0c	645.0c	1,489.0b
MB-N (mg kg^{-1} N)	5.9b	4.5bc	3.5c	5.0b	8.9a
BR (mg CO_2 g h^{-1})	16.1a	6.1c	17.5a	14.3ab	11.9b
qCO_2 (mg CO_2 g h^{-1} mg C kg soil^{-1} x 10^{-3})	9.4b	4.1c	25.5a	22.2a	8.0b
qMIC (%)	3.5b	3.7b	3.2b	2.0c	5.5a
CMI (%)	220.0b	100.0e	126.0d	199.0c	350.0a
WMD1 (mm)	2.5a	2.4a	2.1b	2.3ab	2.6a
WMD2 (mm)	2.5ab	2.2ab	1.9b	2.1ab	2.7a

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's test, at 5% probability. MB-C, microbial biomass carbon; MB-N, microbial biomass nitrogen; BR, basal respiration; qCO_2, metabolic quotient; qMIC, microbial quotient; CMI, carbon management index; WMD1, weighted mean diameter at 0–5-cm depth; WMD2, weighted mean diameter at 5–10-cm depth; NT8, no-tillage during 8 years; NT12, no-tillage during 12 years; and NT17, no-tillage during 17 years.

with those on top of the mounds, and that there is an increased management quality, but without recovery of TOC stocks to the original values even after many years of adoption of the no-tillage system.

Soil aggregation values were similar to those for TOC and the CMI, with an improvement in WMD after 12 years of direct seeding, indicating a recovery of this attribute over time (Table 4) both at 0–5 and 5–10-cm depths. Direct seeding and crop residues maintained on the soil provide mucilage and compounds that are synthetized by roots and microorganisms acting as soil aggregation agents (Vezzani & Mielniczuk, 2011), which, associated with the time of land use, provide an aggregation similar to that of native areas. Carneiro et al. (2015), in the same area of the present study, observed an increase in soil aggregation as the time of use of no-tillage increased, but found a lower aggregation in the cropping lands, compared with the top of the mounds. This shows that the recovery of soil structure is slow under tillage, especially when there is a low diversity of plants in the system.

The multivariate analysis was used to define the main indicators of soil quality – 12 soil attributes that contributed the most to total data variation (Table 5). Of the assessed attributes, microbial biomass carbon (35.4%), the CMI (16.7%), and the microbial quotient (13.8%) accounted for 65.9% of total variation. Therefore, the use of these indicators is recommended in future soil quality assessments in areas that have similar features to the ones evaluated in the present study. Moreover, these results indicate the importance of these soil attributes in showing the effects of the land management system on soil quality, particularly of biological indicators, since the soil microbiota has a dynamic nature and high sensitivity to detect changes in ecosystems in general (Brookes et al., 2013).

Table 5. Relative and accumulated contribution of soil attributes to explain total data variation for a Plintossolo Háplico of the Brazilian Cerrado.

Variable[(1)]	Relative contribution (%)	Accumulated contribution (%)
MB-C	35.4	-
CMI	16.7	52.1
qMIC	13.8	65.9
S-POC	9.5	75.4
$q\text{CO}_2$	7.2	82.6
S-TN	5.2	87.8
S-TOC	3.5	91.3
BR	1.1	92.4
MB-N	0.9	93.3
S-PN	0.8	94.1
WMD	0.2	94.3
Other	5.7	100

[(1)]MB-C, microbial biomass carbon; CMI, carbon management index; qMIC, microbial quotient; S-POC, stock of particulate organic carbon; $q\text{CO}_2$, metabolic quotient; S-TN, stock of total nitrogen; S-TOC, stock of total organic carbon; BR, basal respiration; MB-N, microbial biomass nitrogen; S-PN, stock of particulate organic nitrogen; and WMD, weighted mean diameter.

A second group was formed by the stock of particulate carbon (9.5%), the metabolic quotient (7.2%), the stock of total nitrogen (5.2%), and total carbon (3.5%). The attributes that were less sensitive to changes in soil management were microbial biomass nitrogen (0.91%), the stock of particulate nitrogen (0.76%), and WMD (0.21%). According to Souza et al. (2014), the best attributes to indicate soil quality were microbial biomass carbon (14.3%), the stock of total carbon (12.7%), the stock of nitrogen in particulate organic matter (11%), WMD (9.8%), and the stock of particulate organic carbon (9.0%), whereas the less sensitive indicators were total nitrogen (0.8%), mineral-associated nitrogen (0.5%), and the stock of total organic nitrogen (0.5%).

After 17 years of the implementation of the no-tillage system, there was a recovery of almost all soil quality attributes. However, with the conversion to cropland, the areas suffered great losses in, for example, microbial diversity (Assis et al., 2014), plant diversity (Morais et al., 2014), and the fauna of the native lands. There were also losses in water resources, which will never return to the state of equilibrium of the native areas (Gomes Filho et al., 2011).

In converted lands, which, according to law, can be used for agriculture, conservation-based systems must be implemented in order to recover part of the ecosystems offered by these environments. Furthermore, as shown in the present study, over time, no-tillage has the ability to improve considerably soil quality attributes and its sustainability.

Conclusions

1. After 17 years of the implementation of the no-tillage system in "murundu" (mound) fields in the Brazilian Cerrado, there is an increase in organic carbon and nitrogen, as well as in their particulate

fractions compared with the reference area (top of the mounds).

2. The microbiological attributes reach higher values in the 17-year period of no-tillage compared with the reference area, while the other treatments under less no-tillage time show stress conditions in the soil microbiota.

3. For soil aggregation, 12 years of no-tillage use are sufficient to confirm an increase in this variable.

4. The main attributes to be used as soil quality indicators are microbial biomass carbon, the carbon management index, and the microbial quotient.

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