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Organic matter and soil aggregation in agricultural systems with different adoption times

Matéria orgânica e agregação de solo em sistemas agrícolas com diferentes tempos de adoção

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Abstract

In conservation management systems, such as no-till (NT), it is important to analyze the pattern of changes in soil quality as a function of the time since adoption of the system. This study evaluated the physical fractions of organic matter and soil aggregation in management systems in areas cultivated with different times since implementation of NT: 6, 14, and 22 successive years of soybean and maize/wheat crops (NT_6, NT_{14}, and NT_{22}, respectively); 12 years of no-till with successive years of soybean and maize/wheat crops, and the last 4 years with integration of maize and ruzi grass (*Brachiaria ruziziensis*) - (NT+B); pasture; and forest. Physical fractionation of organic matter determined the total carbon (TC), particulate organic matter (POM), and mineral organic matter (MOM) by calculating the carbon management index (CMI) and variables related to soil structural stability. Forest and pasture areas showed the highest contents of TC, POM, and MOM, as well as higher stocks of POM and MOM. Among the cultivated areas, higher TC and particulate fractions of organic matter and the best CMI values were observed in the area of NT_{22}. There were changes in aggregation indices, depending on the time since implementation of NT. Areas of NT_{22}, pasture, and forest showed the greatest evolution in C-CO_2 indicating increased biological activity, with positive effects on soil structural stability.
Key words: Labile carbon. Carbon stocks. Conservation management.

Resumo

Em sistemas de manejo conservacionistas, como o plantio direto (PD), é importante analisar o padrão de mudanças na qualidade do solo em função do tempo desde a adoção do sistema. Este estudo avaliou as frações físicas de matéria orgânica e agregação do solo em sistemas de manejo em áreas cultivadas com diferentes épocas desde a implantação do PD: 6, 14 e 22 anos sucessivos de soja e milho/trigo (PD_6, PD_{14} e PD_{22}, respectivamente); 12 anos de plantio direto com anos sucessivos de lavouras de soja e milho/trigo, e os últimos 4 anos com integração de milho e braquiária ruziziensis (*Brachiaria ruziziensis*) - (PD+B); pastagem e floresta nativa. O fracionamento físico da matéria orgânica determinou o carbono

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total (CT), matéria orgânica particulada (MOP) e matéria orgânica mineral (MOM), calculando o índice de manejo do carbono (IMC) e variáveis relacionadas à estabilidade estrutural do solo. As áreas de floresta e pastagem apresentaram os maiores teores de TC, MOP e MOM, assim como maiores estoques de MOP e MOM. Entre as áreas cultivadas, maiores teores de CT, frações particuladas de matéria orgânica e os maiores valores de IMC foram observados na área de PD_{22}. Houve alterações nos índices de agregação, dependendo do tempo desde a implementação do PD. Áreas de PD_{22}, pastagem e floresta apresentaram a maior evolução em C-CO_2, indicando maior atividade biológica, com efeitos positivos na estabilidade estrutural do solo.

Palavras-chave: Carbono lábil. Estoques de carbono. Manejo conservacionista.

Introduction

Inadequate management of agricultural systems results in detrimental effects on the quality of soil (BAYER et al., 2004). This can be reversed through management practices, such as no-till (NT) and intercropping systems. Briedis et al. (2018) emphasized the importance of time of NT implementation for observing changes in accumulation of soil organic matter (SOM) and soil aggregation.

Changes in soil quality caused by management systems that contribute different amounts of plant biomass can be identified by the particulate fraction of SOM (particulate organic matter, POM) (MARRIOTT; WANDER, 2006). The POM fraction is considered one of the most sensitive to alterations (BATISTA et al., 2013; BRIEDIS et al., 2018). It is the labile fraction of C (CAMBARDELLA; ELLIOTT, 1992) and can be used as a tool to evaluate soil quality, especially in short periods (CONCEIÇÃO et al., 2005). This knowledge of the various C pools allows monitoring the quality of agricultural systems (BENBI et al., 2015). The SOM is considered the main agent for the formation and stabilization of aggregates (BAYER et al., 2004). Fractionation of aggregates, along with detailed knowledge of SOM dynamics, can facilitate the understanding of soil C dynamics (BANDYOPADHYAY; LAL, 2014). Aggregates protect the C inside (physical protection) against microbial processes and enzymatic reactions and are affected by different management systems (BRONICK; LAL, 2005).

Several studies reported the importance of adequate soil management with minimal disturbance with positive consequences for the increase total organic carbon (TOC) content (ANDRADE et al., 2010) soil biology (FERREIRA et al., 2019), POM (BENBI et al., 2015), and increased stability (BHATTACHARYYA et al., 2009) and size of aggregates (SIX; PAUSTIAN, 2014). Management systems that recommend less soil disturbance and increased TOC content, such as NT (BARRETO et al., 2009), intercropping systems, and pastures (LOSS et al., 2013) and/or adoption of pastures at certain periods of time (SALTON et al., 2008) are essential to increase the carrying capacity of agricultural areas (ARATANI et al., 2009). These systems especially improve soil properties over time (ANDRADE et al., 2010). Thus, the aim of this study was to evaluate the total carbon content, physical fractions of organic matter, and soil aggregation under different management systems and different times since adoption of these systems in the western region of the state of Paraná, Brazil.

Materials and Methods

Soil samples were obtained from commercial areas managed for different agricultural uses in the municipality of Guaíra in the western region of Paraná, Brazil (Figure 1). The climate is subtropical (Cfa), according to the Köppen classification system (CAVIGLIONE et al., 2000). According to a detailed soil survey of Paraná (EMBRAPA, 2007), soils from the study areas are classified as very clayey *Latossolo Vermelho Eutroférrico* in the Brazilian classification system (SANTOS et al., 2013). Their correspondence with the FAO is *Ferritic Ferralsols* (WRB, 2014), with particle size distribution of 121, 230, and 649 g kg^{-1} of sand, silt, and clay, respectively.

This study analyzed five areas under management and a reference site (native forest), comprising six different systems in a randomized design. The five areas included sites with different times since adoption of NT: 6 years, transition phase (NT_6); 14 years, consolidation phase (NT_{14}); and 22 years, maintenance phase (NT_{22}), with succession of soybean (summer) and maize/wheat (winter); 12 years of no-till with successive years of soybean and maize/wheat crops, and last 4 years with integration of maize and ruzi grass (*Brachiaria ruziziensis*) (consolidation phase) - (NT+B) (ANGHINONI, 2007); and permanent coast-cross pasture area (*Cynodon dactylon* (L.) Pers) (38 years), with a stocking rate of 3.5 animal unit - AU ha^{-1} and no visible signs of deterioration (Figure 2).

Figure 1. Location of the municipality of Guaíra, state of Paraná, Brazil.

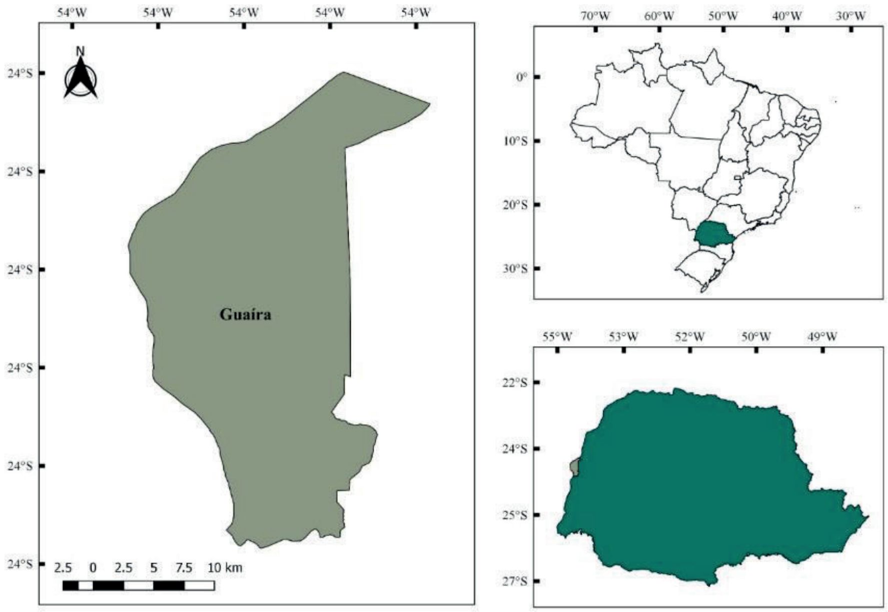
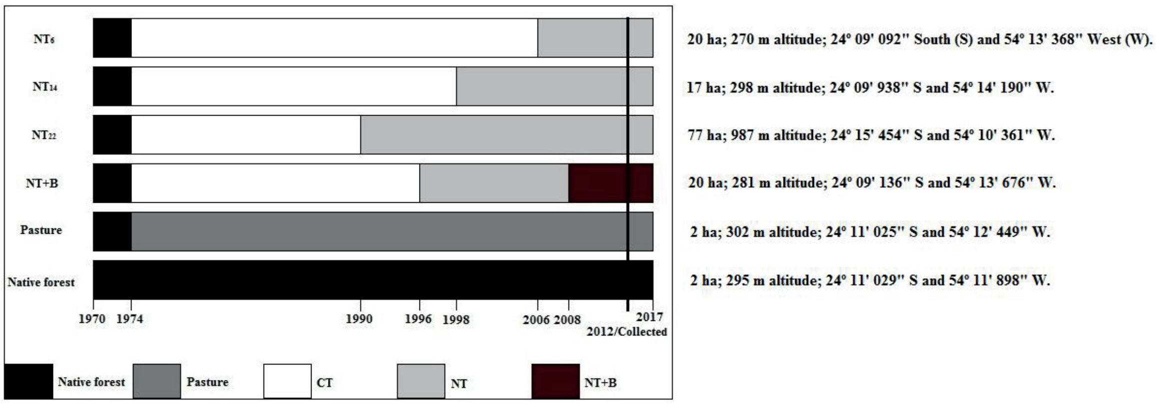


Figure 2. Land use and land use changes in the study areas, with their respective implementation dates in each management system: NT- no-till; CT - conventional tillage; NT+B - no-till intercropped with *Brachiaria*.



In all areas of NT, in the last 5 years of successive cultivation of soybean and maize/wheat crops, fertilization comprised 270 kg ha^{-1} 02-20-18 and inoculation with *Bradyrhizobium japonicum* and 270 kg ha^{-1} 10-15-15, respectively. In addition, lime was grown every 4 years at 1.7 Mg ha^{-1}, except in the NT_{14} area, which, after conversion of the sowing system (conventional tillage to NT in 1998), received no soil amendment. In the area cultivated with pasture, soil amendment or fertilization was not performed throughout the period in which the species was grown.

In each area, soil samples were collected in five 400 m^2 plots; each plot represented a replication. For physical fractionation and calculations of the carbon management index (CMI), samples were taken at five points (plots-replications) within six management systems, at soil layers of 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m, in which each composite sample was formed by 10 simple samples. Undisturbed soil cores were also collected using a 46.2 cm^3 volumetric ring, with five replications in all areas and layers. For aggregate analysis, undisturbed samples were collected by preserving the soil structure (monoliths of 0.20 × 0.20 × 0.05 m) in five replications in the 0.00-0.05 and 0.05-0.10 m layers.

Particle size fractionation of SOM was performed according to Cambardella and Elliott (1992) by separating the POM from organic matter associated with minerals (MOM); the carbon content (TC) was also analyzed. Total carbon and C-POM were determined by dry combustion in a CHNS analyzer (Elemental Analysensysteme GmbH, Hanau, Germany), and C-MOM was calculated by the difference between TC and POM. On determining the carbon content of POM and MOM, we calculated their respective stocks (ELLERT; BETTANY, 1995; SISTI et al., 2004). Subsequently, we calculated indices for assessing the quality of the soil organic fraction: carbon stock index (CSI), lability of SOM (Lab), lability index (LabI), and carbon management index (CMI) (BLAIR et al., 1995).

For aggregate stability analysis, the aggregate fraction retained in 8- and 4-mm sieves was subjected to sieving in water (KEMPER; CHEPIL, 1965) in a Yoder mechanical stirrer (YODER, 1936) using a set of sieves with 2.00, 1.00, 0.50, 0.25, and 0.125 mm mesh sizes. From the mass of aggregate fractions retained in the sieves, we calculated the mean weight diameter (MWD) (KIEHL, 1979) and the geometric mean diameter (GMD) (KEMPER; ROSENAU, 1986). After calculating the MWD, the sensitivity index (SI) was also determined (BOLINDER et al., 1999).

To assess the evolution of $C\text{-}CO_2$ (mineralizable carbon) in the laboratory, soil aggregates were manually separated until the entire sample passed through 8- and 4-mm sieves. Subsequently, aggregates were moistened by spraying with water (GONÇALVES et al., 2002). Field capacity was determined according to the funnel method. Then, $C\text{-}CO_2$ (MENDONÇA; MATOS, 2005) was evaluated with three replications per land use system and layer in a completely randomized design in the laboratory at 25 °C. Evaluations were made in 24-h intervals for the first 7 days, 48-h intervals between the 8th and 17th day, and 96-h intervals between the 18th and 49th day; the value of $C\text{-}CO_2$ evolved was expressed in mg $C\text{-}CO_2$ 100 cm^{-3} of soil (aggregates). Before incubation, total C and total N content in the aggregates were quantified using a CHNS analyzer (Elemental Analysensysteme GmbH, Hanau, Germany), and the C/N ratio was calculated.

Data were checked for assumptions of normality and homoscedasticity using the Lilliefors and Cochran and Bartlett tests, respectively. Next, in a completely randomized design, the results were subjected to analysis of variance using the F-test, and mean values were compared by the Tukey test at 5 % in the Genes software (CRUZ, 2006). Complementarily, canonical analysis was run with the variables of physical fractionation of SOM and CMI, which reduced the data set into linear combinations, generating scores for the first two canonical variables that attributed to more than 80 % of the total variation (CRUZ; REGAZZI, 1994). These scores were projected on two-dimensional plots. In addition to this technique, the modified Tocher clustering method was applied to distinguish the most similar treatments and group the different types of management practices from the Mahalanobis distance matrix using the Genes software (CRUZ, 2006).

Results and Discussion

The use of different management systems over the years has modified some of the analyzed variables such as TC content, C of the SOM size fractions, and CMI values (Table 1). TC values were higher in the 0.00-0.05 m layer, especially in the forest and pasture areas, 40.78 and 31.56 g kg^{-1}, respectively. Similarly, higher TC values in surface layers were also observed in areas under NT, indicating the influence of crop residues on soil surface in systems with soil disturbance in the plant row. This was also reported by Aratani et al. (2009) in an NT system for 5 to 12 years in the same soil type, by Guareschi et al. (2012) in 3, 15, and 20 years of chronosequence of NT, Benbi et al. (2015) in a system under maize/wheat succession for 10 years and Assunção et al. (2019) in the same region of this study.

Table 1. Total carbon (TC), particulate organic matter carbon (POM), mineral organic matter (MOM), carbon stock index (CSI), lability (Lab), lability index (LabI), and carbon management index (CMI) under different management systems in the western part of the state of Paraná, Brazil.

Management systems	TC	POM	MOM	CSI	Lab	LabI	CMI
	g kg^{-1}						
				0.00-0.05 m			
NT_6	18.78d	4.07d	14.71c	0.46d	0.28b	1.21b	55.14d
NT_{14}	20.94d	4.56c	16.38c	0.52d	0.28b	1.21b	61.37d
NT_{22}	24.02c	6.19b	17.83c	0.59c	0.35a	1.53a	89.15b
NT+B	18.96d	4.94c	14.02c	0.47d	0.36a	1.57a	71.49c
Pasture	31.56b	5.98b	25.58b	0.78b	0.24b	1.04c	79.09a
Forest	40.78a	7.98a	32.80a	1.00a	0.25b	1.00c	100.00a
CV (%)	4.9	3.5	11.6	5.6	7.8	6.1	6.6
				0.05-0.10 m			
NT_6	15.90d	3.09d	12.81b	0.61d	0.24b	0.74b	44.75d
NT_{14}	16.76cd	2.96d	13.80b	0.64cd	0.22b	0.65b	42.06d
NT_{22}	18.24bc	4.99b	13.25b	0.70bc	0.36a	1.08a	76.23b
NT+B	17.32cd	4.29c	13.03b	0.66cd	0.33a	1.01a	66.62c
Pasture	19.60b	4.79b	14.89ab	0.75b	0.33a	0.99a	74.14b
Forest	26.04a	6.45a	19.59a	1.00a	0.33a	1.00a	100.00a
CV (%)	4.9	4.4	16.6	4.2	7.5	6.0	5.0
				0.10-0.20 m			
NT_6	12.44c	2.83d	9.61b	0.84c	0.30b	0.84c	68.93e
NT_{14}	12.72c	2.53e	10.19b	0.85c	0.25b	0.70d	59.34f
NT_{22}	14.76bc	4.47a	10.29b	1.00b	0.47a	1.31a	124.54a
NT+B	15.82b	4.22b	11.60b	0.80c	0.37ab	1.05b	82.46d

continue

continuation

Pasture	19.82a	4.62a	15.20a	1.34a	0.30ab	0.85c	112.92b
Forest	14.94bc	3.93c	11.01b	1.00b	0.36ab	1.00b	100.00c
CV (%)	9.7	2.9	12.9	5.3	25.4	7.1	5.4
				0.20-0.40 m			
NT_6	9.82b	2.73c	7.08a	0.91b	0.39b	0.64d	58.15d
NT_{14}	10.42b	2.63c	7.79a	0.97b	0.36b	0.59d	54.85d
NT_{22}	9.90b	4.01a	5.89a	0.92b	0.69a	1.13a	103.92a
NT+B	10.64b	3.57b	7.07a	0.99b	0.52ab	0.87c	86.14c
Pasture	11.84a	3.94a	7.90a	1.10a	0.50ab	0.83c	92.17bc
Forest	10.78b	4.10a	6.68a	1.00b	0.61a	1.00b	100.00ab
CV (%)	4.9	3.5	20.6	4.5	19.8	6.7	6.3

Means followed by different letters in the same column are significantly different by the Tukey test ($p<0.05$). CV: coefficient of variation. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years. Methods - TC: combustion in a CHNS analyzer; POM and MOM: Cambardella and Elliott (1992); CSI, Lab, LabI and CMI: (BLAIR et al., 1995).

The TC content increased in accordance with the time of NT implementation, mainly in the 0.00-0.05 m layer, with differences only between NT_6 and NT_{22} (18.78 and 24.02 kg kg^{-1}, respectively; a difference of 5.24 g kg^{-1}). The content is equivalent to 0.33 g kg^{-1} per year. Thus, the soybean, maize/wheat succession system contributed to increased levels of TC, especially after reaching the maintenance phase (ANGHINONI, 2007). After the maintenance phase of the NT system was reached (ANGHINONI, 2007), non-disturbance of the system, allied with different strata of the root systems of soybean, maize, and wheat, as well as the potential for C accumulation in the root system of the grasses (NUNES et al., 2011; LOSS et al., 2013), increase the total carbon content. In addition, the difference in the total carbon content found in the 0.00-0.05 m layer between the area of 6 years and 22 years since adoption of the NT is due to the stratification of carbon accumulation, as well as the higher root growth of grass species, such as maize, in the uppermost layers of the soil, as also reported by Costa et al. (2009). This potential of soil carbon accumulation over time by different crop root systems was evidenced in the study by Gill and Jackson (2000) and, specifically, in soils for wheat, by Kuzyakov and Domanski (2000).

A greater accumulation of TC up to the 0.10 m layer was also found by Andrade et al. (2010) in NT after 12 years of crop rotation and succession in southern Brazil, but this pattern was not registered by Aratani et al. (2009) in the same type of soil in the state of São Paulo, Brazil. NT management is one of the most efficient agricultural practices for sequestration and accumulation of C in soil (BRIEDIS et al., 2018; ASSUNÇÃO et al., 2019). However, some contrasting results have been reported, depending on factors such as crop rotation, nitrogen fertilization (SISTI et al., 2004), weather, tillage intensity, and amount of residue left on the soil surface (MARRIOTT; WANDER, 2006).

In the last two layers, pasture area had higher levels of TC, thus demonstrating the contribution of the root system of grasses to accumulation of C in subsurface layers (GILL; JACKSON, 2000; SALTON et al., 2008). In the NT+B area, even after 4 years of intercropping, there was no significant increase in TC in the surface layers, compared to the no-tillage system areas. The lack of interference from intercropping in these layers may be due to rapid decomposition of straw on the soil surface under regional climatic conditions (CAVIGLIONE et al., 2000) and the succession of species grown in summer (SISTI et al., 2004). Divergent results are found in the literature regarding TC levels in intercropping systems (SALTON et al., 2005; ARATANI et al., 2009).

In the 0.00-0.05 and 0.05-0.10 m layers, higher levels of POM were found in forest areas, 7.98 and 6.45 g kg^{-1}, respectively. This was followed by NT_{22} areas and pasture, with 6.19 and 5.98 g kg^{-1} in the 0.00-0.05 m layer, and 4.99 and 4.79 g kg^{-1} in the 0.05-0.10 m layer, respectively. This represented 20, 26, and 19 % of TC in the 0.00-0.05 m layer and 25, 27, and 24 % in the 0.05-0.10 m layer, respectively (Table 1). These POM values in the surface layer reflect the accumulation of straw on the soil surface, associated with minimal disturbance to the system (CONCEIÇÃO et al., 2005). In general, the sensitivity of POM indicates differences between all layers evaluated in the management systems, and it can be used as a soil quality indicator (BRIEDIS et al., 2018; CONCEIÇÃO et al., 2005; DIEKOW et al., 2005; ROSSI et al., 2012). These results have also been reported in a maize/wheat succession system for 10 years (BENBI et al., 2015), and in long-term experiments in Acrisols in southern Brazil (CONCEIÇÃO et al., 2005) and Ferralsols in the *Cerrado* region (BATISTA et al., 2013).

POM replacement in the pasture area was not high, due to the lack of adequate management (replacement and maintenance fertilization), as well as intensive grazing. In areas under NT with the soybean, maize/wheat succession, especially for NT_{22}, the results obtained for POM showed the same TC increasing trend, with a slow and gradual rise according to the time since the adoption of NT. Under tropical and subtropical conditions in Brazil, which promote faster decomposition of plant residues, Briedis et al. (2018) observed significant increases in MOP levels and stocks in a no-tillage system in the same type of soil.

The mineral fraction of SOM (MOM) ranged from 59 to 83 %, with higher levels in the 0.00-0.05 m layer for the forest area, 32.80 g kg^{-1}, followed by pasture, 25.58 g kg^{-1}, with no difference among the management systems in the 0.20-0.40 m layer. The highest representation of this fraction compared to POM takes place in clayey soils (CAMBARDELLA; ELLIOTT, 1992), which is also related to stabilization of fractions, such as POM. This is because management systems with minimal or no tillage favor the processes of SOM stabilization (BATISTA et al., 2013), with consequent benefit in the medium and long term for the formation and stabilization of soil aggregates (improving structural quality), as proposed by Tisdall and Oades (1982).

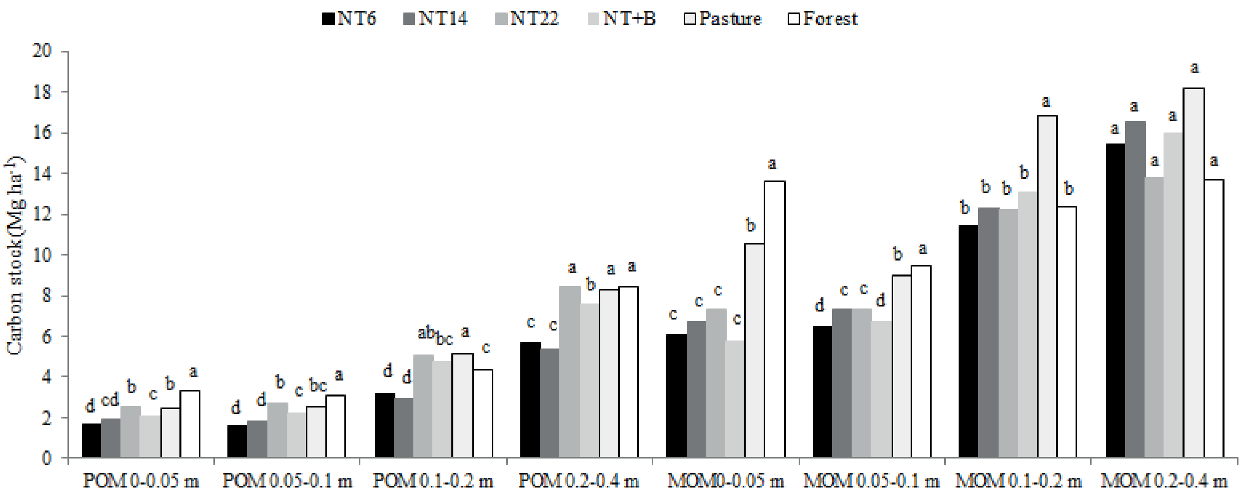
There was an increase in CSI in accordance with the time since the adoption of NT for the first three layers, with mean values of 0.64, 0.67, and 0.76 in areas of NT_6, NT_{14}, and NT_{22}, respectively, and also differences between NT_6 and NT_{22} (Table 1). This pattern confirms the gradual increase of soil TC in the soybean, maize/wheat succession. Benbi et al. (2015) reported CSI values of 0.65 for an NT area with crop successions for 10 years. For the CSI, potential C accumulation in the root system of pastures after long cultivation stands out, with higher values than those of forest areas in the last two layers, reaching 1.34 for the 0.10-0.20 m layer.

In relation to lability (Lab), values were below unity in all areas and layers (Table 1), confirming greater participation of MOM than that of POM. The lability of SOM is a good indicator of soil quality (BENBI et al., 2015) because it emphasizes the balance between labile and recalcitrant SOM (BLAIR et al., 1995), which is important for maintaining the quality of production systems (MAJUMDER; KUZYAKOV, 2010). The greater values of the lability index (LabI) in areas under an NT system for a longer time are also noteworthy, especially NT_{22}, which ranged from 1.08 to 1.53, higher than that for the forest area, except for the 0.05-0.10 m layer.

As for the CMI, the NT_{22} area showed values from 76.23 to 124.54, higher than those for the forest area in the 0.10-0.20 m layer (Table 1), with a mean value of 98.5 in the 0.00-0.40 m layer, close to the index value of 100 in the forest area, considered a reference site (BLAIR et al., 1995). This result demonstrates improvement in the quality of the organic fraction, which significantly affects properties such as water holding capacity, structural quality (aggregate stability), and biological activity (LOSS et al., 2013) after 20 years of using NT (maintenance phase) (ANGHINONI, 2007).

When evaluating the C stocks of the particle size classes of SOM (Figure 3), higher values of POM can be found in the forest area in the 0.00-0.05 and 0.05-0.10 m layers, 3.97 and 3.12 Mg ha^{-1}, respectively. Among the management systems in the soybean, maize/wheat succession, differences were detected for all layers only between NT_{22} and the others. Total values were 12.22, 12.05, and 18.75 Mg ha^{-1} in the 0.00-0.40 layer in the NT_6, NT_{14}, and NT_{22} areas, respectively. Deforestation took place in 1974, and the areas with a shorter time since adoption of NT produced lower levels (Table 1) and stocks (Figure 3) of POM and, hence, lower aggregation indices (Table 2) compared to the NT_{22} area. In the NT_6 and NT_{14} areas, soil aggregation processes are still evolving, because before the adoption of NT, the long period of soil disturbance under the conventional tillage system resulted in soil disaggregation and POM exposure (SIX et al., 2004). Areas with minimal soil disturbance, such as no-till system, generate larger structural units (TISDALL; OADES, 1982) and consequently provide greater protection to POM against oxidation by microorganisms inside the aggregates. This improvement in the structural quality of the soil is important for maintaining/increasing the production capacity of croplands, with beneficial consequences over the years for the economic and environmental aspects of the system (BRONICK; LAL, 2005).

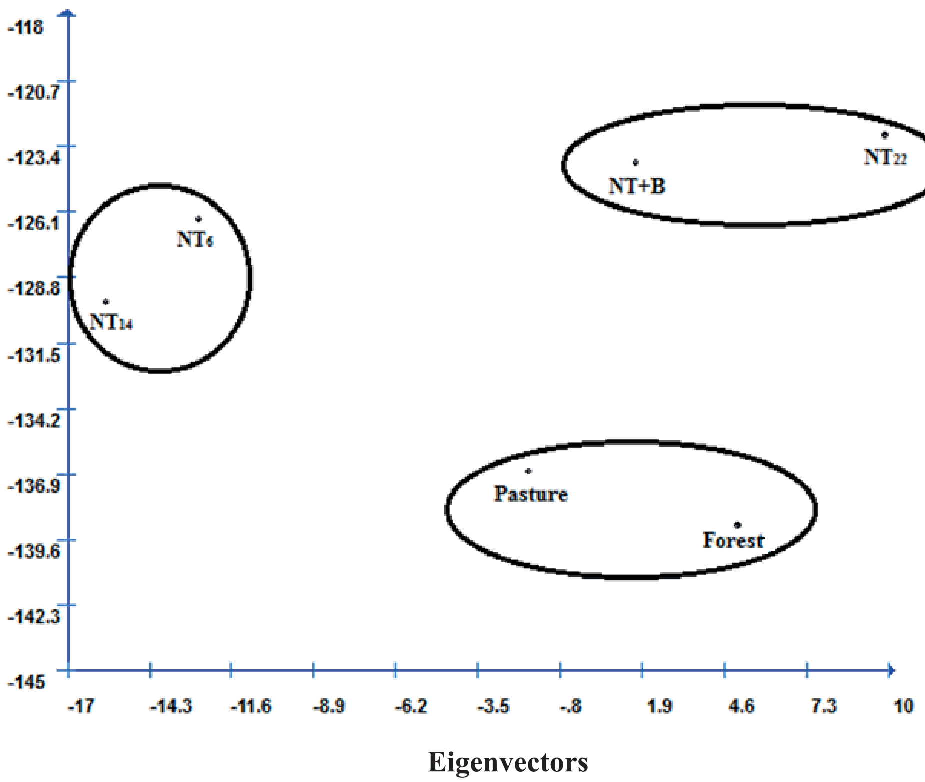
Figure 3. Particulate organic matter (POM) carbon stock and mineral organic matter (MOM) of soil under different management systems in the western part of the state of Paraná, Brazil. Means followed by different letters in the same layer are significantly different by the Tukey test ($p<0.05$). No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years.



The forest area had the greatest stocks of MOM in the 0.00-0.05 m layer (13.61 Mg ha^{-1}) and in the 0.05-0.10 m layer (9.49 Mg ha^{-1}), and in the pasture area in the 0.10-0.20 m layer (16.87 Mg ha^{-1}) (Figure 4). Greater stocks of MOM and POM influence the stabilization of micro- and macroaggregates (TISDALL; OADES, 1982).

In addition, regarding canonical analysis of properties of the physical fractions of SOM and CMI (Figure 4), the first and second canonical variable retained 68 and 30% of the variation, respectively, accounting for 98 % of the total variation. By using the modified Tocher clustering method, three groups were distinguished: one made up of NT_6 and NT_{14} areas, another of NT_{22} and NT+B areas, and a third cluster with pasture and forest areas. The variables that contributed most to this differentiation of areas were TC and POM, as well as the MOM stock. This pattern highlights the sensitivity of the physical fractions of SOM in detecting changes in management systems over time, as shown in other studies (LOSS et al., 2014; BENBI et al., 2015), especially with the most labile fraction of C (POM) (BATISTA et al., 2013; CONCEIÇÃO et al., 2005).

Figure 4. Dispersion of different systems of use and management by the modified Tocher clustering method of the first two canonical variables according to the physical fractions of soil organic matter in an Oxisol under different management systems in the western part of the state of Paraná, Brazil. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years.



The state of soil aggregation assessed by MWD and GMD indices and the percentage of aggregates retained in the sieves allowed identification of differences among the management systems (Table 2). Considering MWD and GMD and the percentage of aggregates larger than 2,00 mm, the forest and pasture areas showed higher values, reaching 4.86 and 4.67 mm for MWD and GMD, respectively, and 97 % of aggregates larger than 2,00 mm at the 0.05-0.10 m depth in the soil under forest. The lower disturbance of the soil and the higher content of C in the coarser fractions (Table 1) are responsible for stabilizing larger aggregates (SIX et al., 2004). This demonstrates the importance of management systems constantly enhancing carbon inputs, a pattern observed by Andrade et al. (2010) and Barreto et al. (2009) in southern Brazil.

The evolution of these properties over the time since adoption of NT, with the lowest values for NT_6, which were different from the other areas in the two layers for the percentage of aggregates larger than 2,00 mm, and similar to NT_{14} for MWD and GMD in the 0.05-0.1 m layer. This pattern is explained by the lower TC, POM, and MOM content (Table 1) and POM and MOM stocks (Figure 3), in which the rupture of the aggregates still in conventional system promoted loss of C, as these variables were associated with each other (SIX; PAUSTIAN, 2014). The use of cultivation systems with little soil disturbance that promote an increase in C over time (BARRETO et al., 2009), such as NT, can contribute to an increase in aggregate stability and gradually improve soil physical quality (BHATTACHARYYA et al., 2009).

Thus, NT contributes to improving the structural quality of the soil as a function of cultivation time, with significant results from the 14^{th} year on, similar to that observed in the NT_{22} and NT+B areas in the two layers. Improvements in soil properties as a result of human interference in management systems take time, while the formation and stability of aggregates is established (BARRETO et al., 2009; BRONICK; LAL, 2005). These benefits may be increased over time from the adoption of NT (ANGHINONI, 2007).

With regard to the sensitivity index (SI), only the pasture area showed values similar to those for the forest area, 1.02 and 0.95 in the 0.00-0.05 and 0.05-0.10 m layers, respectively (Figure 5). In general, among the NT areas, evolution in this index was observed over time from the time of implementation, from 0.56, 0.74, 0.79, and 0.81, in the 0.00-0.05 m layer, to 0.47, 0.59, 0.65, and 0.66 in the 0.05-0.10 m layer, in the NT_6, NT_{14}, NT_{22}, and NT+B areas, respectively. This trend was also verified by Aratani et al. (2009) as a function of time since the adoption of NT.

Table 2. Mean weight diameter (MWD), geometric mean diameter (GMD), and percentage of aggregates retained in 2, 1, 0.5, 0.25, and 0.125 mm sieves under different management systems in the western part of the state of Paraná, Brazil.

Management systems	MWD	GMD	2 mm	1 mm	0.5 mm	0.25 mm	0.125 mm
	—— mm ——		—— % ——				
				0.00-0.05 m			
NT_6	2.58c	1.58c	42.22c	15.17a	23.35a	13.92a	5.34a
NT_{14}	3.45b	2.47b	61.90b	15.05a	13.35b	6.28b	3.43b
NT_{22}	3.66b	2.79b	65.94b	19.06a	7.51c	3.98bc	3.51b
NT+B	3.73b	2.87b	67.88b	17.19a	7.23c	4.10bc	3.61ab
Pasture	4.72a	4.42a	93.08a	3.49b	1.57d	1.02c	0.84c
Forest	4.57a	4.33a	91.97a	3.25b	2.30cd	1.43c	1.05c
CV (%)	8.5	14.7	11.2	27.6	29.8	32.8	31.4
				0.05-0.10 m			
NT_6	2.29c	1.46c	32.72c	30.51a	19.92a	10.23a	6.62a
NT_{14}	2.85bc	1.93bc	46.79b	21.69bc	20.03a	8.18a	3.29c
NT_{22}	3.15b	2.24b	53.17b	25.00ab	11.87b	5.40b	4.55b
NT+B	3.19b	2.21b	55.56b	17.49c	15.68ab	7.83ab	3.53c
Pasture	4.62a	4.22a	90.64a	3.98d	3.04c	1.58c	0.76d
Forest	4.86a	4.67a	96.56a	1.18d	1.09c	0.68c	0.49d
CV (%)	8.3	10.4	11.4	21.3	22.8	23.0	16.8

Means followed by different letters in the same column for each layer are significantly different by the Tukey test ($p<0.05$). CV: coefficient of variation. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years. Methods - MWD: Kiehl (1979); GMD: Kemper and Rosenau (1986).

This increased structural stability, especially in the pasture and forest areas, for MWD, GMD, %2 mm, and IS (Table 2, Figure 5) is also due to the higher TC content of these aggregates (Table 3), especially in the 0.00-0.05 m layer, with values of 24.67 and 36.23 g kg^{-1}, respectively. The same pattern was also registered in a forest area and in NT under 12 years of a soybean-wheat succession on an Oxisol in southern Brazil by Barreto et al. (2009) and in the Central West region of Brazil by Loss et al. (2013).

Crop residues on the soil, especially in the forest area, had the highest concentration of N, 3.32 and 2.29 g kg^{-1} in the 0.00-0.05 and 0.05-0.10 m layers, respectively (Table 3). This pattern is related to the higher floristic heterogeneity of the residue deposited on the soil in this area, which was also reflected in the C/N ratio values. The soybean, maize/wheat succession system involves a single legume species and thus does not significantly contribute to an increase in aggregate N content. Differences were only found for NT_6, with effects including an increased C/N ratio between the NT_{14} and NT_{22} areas in the 0.00-0.05 m layer.

Figure 5. Sensitivity index (SI) of soil of areas under management compared with those at the reference site (forest). Means followed by different letters for each layer are significantly different by the Tukey test ($p<0.05$). No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years.

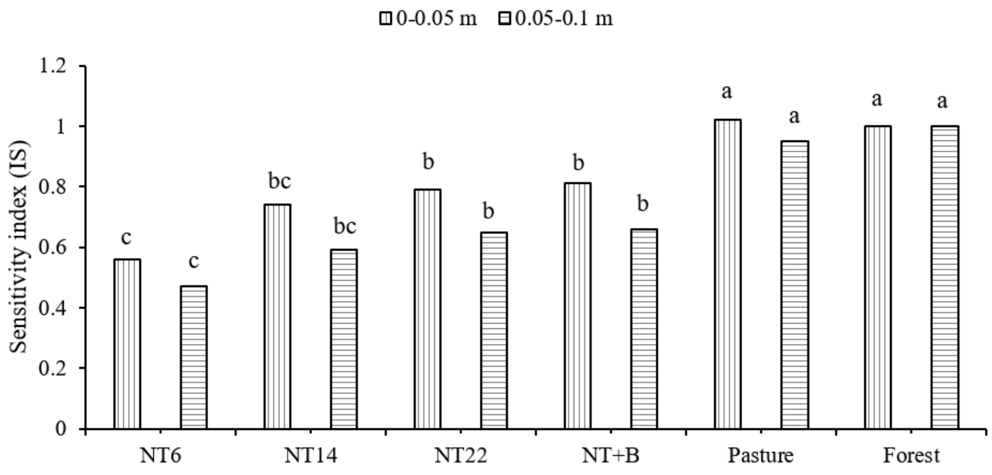


Table 3. Total carbon (TC), total nitrogen (N) and carbon/nitrogen ratio (C/N) of aggregates under different management systems in the western part of the state of Paraná, Brazil.

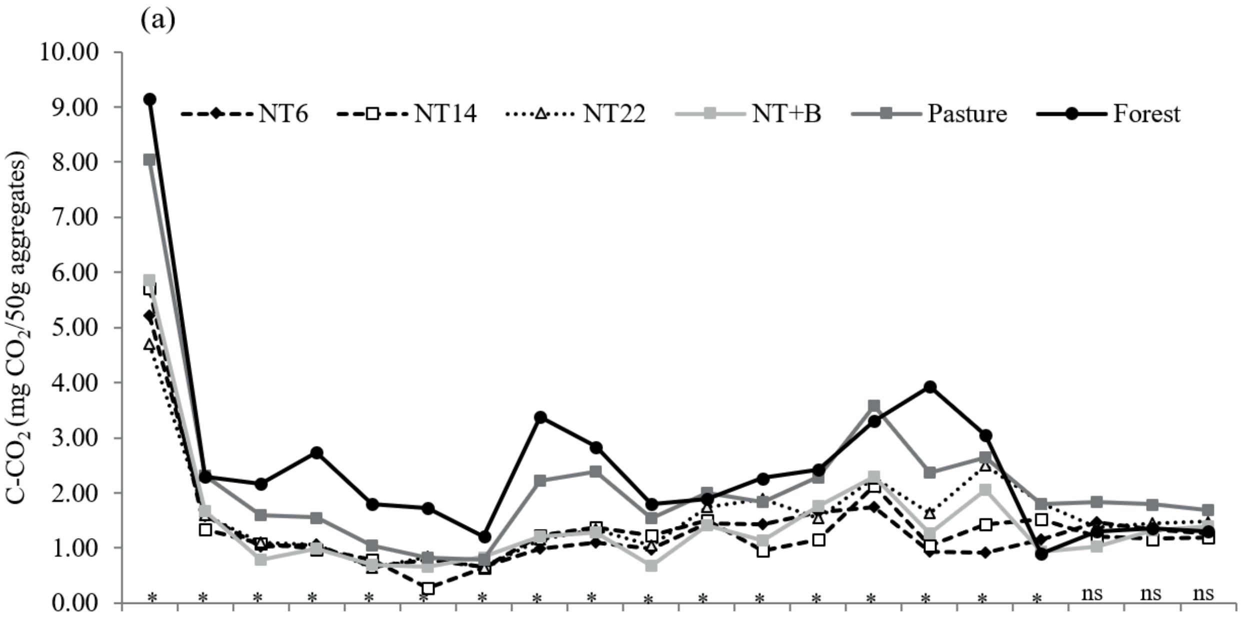
Depth	NT_6	NT_{14}	NT_{22}	NT+B	Pasture	Forest	CV
m							%
				COT (g kg^{-1})			
0.00-0.05	19.07c	19.97c	24.57b	20.00c	24.67b	36.23a	2.48
0.05-0.10	15.90d	16.13d	18.60c	18.10c	19.90b	24.23a	2.34
				N (g kg^{-1})			
0.00-0.05	1.55d	1.88c	1.96c	1.76cd	2.24b	3.32a	3.71
0.05-0.10	1.31c	1.67b	1.76b	1.77b	1.84b	2.29a	5.86
				C/N			
0.00-0.05	12.30a	10.62b	12.54a	11.36ab	11.01b	10.91b	4.12
0.05-0.10	12.14a	9.66b	10.56ab	10.23b	10.82ab	10.58ab	5.63

Means followed by different letters in the same row, in each layer, are significantly different by the Tukey test ($p<0.05$). CV: coefficient of variation. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last four years. Methods - TC and N: combustion in a CHNS analyzer.

The lower aggregate N content in the NT_6 area was due to lower soil structural stability (Table 2, Figure 5) owing to the soil being in a re-aggregation phase (6 years) following disturbances caused by conventional tillage. The greater the disturbance, the greater the breakdown of aggregates and, consequently, N exposure, which is lost by leaching and volatilization, since clusters of C and N are formed inside stable aggregates (ONWEREMADU et al., 2007). Another way to increase the N content in soil is the use of diversified crop systems over time, as reported by Sisti et al. (2004) under NT, in the same type of soil as that in the present study, in southern Brazil. Specifically, for the pasture area in the 0.00-0.05 m layer, cattle manure deposited on the soil over the grazing area contributes to the higher N content, 2.24 g kg^{-1}, than that in areas under NT, as also described by Salton et al. (2005).

With regard to the evolution of C-CO_2 following the incubation of aggregates, samples from forest and pasture areas had the highest C-CO_2 values after 24 hours of incubation in the two layers analyzed (Figure 6a and 6b), with values 94 and 71 % greater than those in NT_{22}, respectively. This was also reported by Bandyopadhyay and Lal (2014), Barreto et al. (2009), and Loss et al. (2013) in comparisons of soils from forest areas and those under long-duration NT. The greater release of C-CO_2 may have been influenced by the higher POM content of the soil (Table 2). The TC and N of the aggregates (Table 3) were more evident in the 0.00-0.05 m layer. This pattern is known as *priming* (KUZYAKOV et al., 2000), in which stimulation of microbial activity by the addition of readily decomposable organic matter favors accelerated decomposition of SOM.

Figure 6. Daily evolution of C-CO_2 in aggregate samples from the 0-0.05 m layer (a) and 0.05-0.10 m layer (b), incubated until 49 days of evaluation, under different management systems in the western part of the state of Paraná, Brazil. *: significant by the Tukey test at 5 %; ns: non-significant by the F-test at 5 %. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years.



From days 9-11 and 21-29 in the two layers, there were peaks of evolution in C-CO_2 (Figure 6a and 6b), particularly in areas with less anthropogenic interference and, consequently, with larger aggregates (forest and pasture) (Table 3). This pattern may be related to the death of certain microorganisms, because the evolution of C-CO_2 was gradually reduced to the levels observed in previous periods. The death of some microorganisms possibly provided nutrition for the remainder (GONÇALVES et al., 2002), leading to higher values of subsequent releases (peaks). In areas under NT for 16 years and in forest areas, Bandyopadhyay and Lal (2014) also reported higher evolution of C-CO_2 in larger aggregates. Stabilization of microbial respiration was observed from the 41st day for the 0.00-0.05 m layer (Figure 6a), and from the 49th day for samples from the 0.05-0.10 m layer (Figure 6b); this was later than the time on day 25 at which stabilization occurred in a study performed Loss et al. (2013) for the same type of soil.

The highest accumulation of C-CO_2 at the end of incubation for samples from the 0.00-0.05 m layer was observed for the forest area 50.79 mg CO_2 per 50 g aggregates followed by the pasture area (Table 4). In the same manner, Loss et al. (2013) analyzed the same type of soil in the *Cerrado* region and found higher values for C-CO_2 accumulation in samples of areas covered by native vegetation than in the NT system in the 0.00-0.05 and 0.05-0 10 m layers.

Table 4. Accumulation of C-CO_2 (mg CO_2 per 50 g aggregates) throughout the incubation of soil aggregates sampled from soil under different management systems in the western part of the state of Paraná, Brazil.

Depth m	NT_6	NT_{14}	NT_{22}	NT+B	Pasture	Forest	CV %
0.00-0.05	27.47d[(1)]	28.01d	31.77c	29.30cd	44.13b	50.79a	3.02
0.05-0.10	28.30c	29.72c	37.35b	30.11c	42.42a	42.34a	2.18

[(1)]Mean values of three replications. Different letters in the same row for each layer indicates significant differences by the Tukey test ($p<0.05$). CV: coefficient of variation. No-till for six years (NT_6), 14 years (NT_{14}) and 22 years (NT_{22}) with succession of soybean (summer) and maize/wheat (winter); NT+B: 12 years of no-till with successive years of soybean and maize/wheat crops, with integration of maize and ruzi grass (*Brachiaria ruziziensis*) in the last 4 years. Methods - C-CO_2 (mineralizable carbon): Mendonça and Matos (2005).

In both layers, on average, values for C-CO_2 accumulation were 34 % higher for samples from the forest area than for samples from NT_{22}; this was lower than that observed by Bandyopadhyay and Lal (2014), who drew comparisons between a forest area and an area under NT for 16 years. As the time since the adoption of NT increases, C-CO_2 accumulation increased, with that in the NT_{22} area differing from that in the other areas.

Conclusions

The highest values for total carbon, carbon stock, and content of the mineral and particulate fractions of soil organic matter, as well as better indexes of aggregation and biological activity in incubated aggregates, were found in forest and pasture areas.

The succession of crops in a no-till chronosequence, especially after 22 years since the adoption of no-till, slowly contributed to an increase in total organic carbon, particulate and mineral organic matter, and carbon management indexes.

Improvement in soil aggregation indexes and carbon stock in the soybean, maize/wheat succession system occurred 16 years following the adoption of the system.

The areas with the highest management history, NT_{22} and pasture, as well as the forest area showed higher evolution of C-CO_2, indicating greater biological activity, with positive effects on soil structural stability.

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