Soil Quality Indicators in Conventional and Conservation Tillage Systems in the Brazilian Cerrado

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Abstract

Conventional and conservation tillage systems can alter soil aggregation and total and labile soil organic matter (SOM) contents. This study aimed to determine the degree of soil aggregation, quantify total carbon (TC), permanganate oxidizable carbon (POXC), light organic matter (LOM), and potentially mineralizable carbon (CO$_2$-C) contents in soils aggregates, and assess soil quality indices at sites under conventional and conservation tillage in the Cerrado region of Minas Gerais State, Brazil. Four experimental areas were analyzed: a area under conventional tillage for 20 years, a area under no-till for 6 years, a area under no-till for 18 years, and a reference area of undisturbed Cerrado vegetation. Soil aggregates retained on 8.0 to 4.0 mm sieves were evaluated for size class distribution and mean weight diameter. TC, POXC, LOM, daily and total CO$_2$-C emissions were also analyzed. These data were used to calculate the C/N ratio and sensitivity, carbon pool, and lability indices. The results of SOM compartments were in agreement with those obtained for the soil aggregation status. Environmental conditions at no-till areas promoted macroaggregate formation and preserved TC and LOM contents, resulting in a high degree of aggregate stability. Soil quality indices were sensitive to identify changes between the reference area and managed areas. Soil aggregates from no-till areas had higher CO$_2$-C emissions and accumulations than those from the conventional tillage area.

Introduction

Conservation management is essential for maintaining and enhancing agricultural production and soil quality. Soil preparation is a key factor in conservation management, as it can alter soil physical, chemical, and biological attributes as well as biogeochemical cycles (Somasundaram et al. 2018). Conventional management or conventional tillage (CT) can be defined as any system in which < 15 % of crop residues are left on the soil surface for subsequent crops (Ramnarine et al. 2015). The practices and inputs used in conventional systems may negatively affect soil attributes, thereby compromising crop yield and system sustainability.

Conservation agriculture (or conservation management) emerges as a strategy to mitigate the negative effects of conventional management by adopting a sustainable approach to enhancing agricultural production and profitability (Somasundaram et al. 2018). No-tillage (NT) has been the main practice or system adopted intensively and in extensive areas of food production in the world. In Brazil, widespread adoption of NT practices began in the 1970s. From 2006 to 2017, there was an increase of about 85 % in the area of annual crops under NT, increasing from 17.9 to 33.0 million ha in 2018 (Briedis et al. 2020; Fuentes-Llanillo et al. 2021).

Conversion from CT to NT may improve soil quality. Soil indicators, such as aggregation and soil organic matter (SOM) contents, have proven effective in assessing the quality of anthropized environments, especially when analyzed together because of the strong interaction between factors (Bronick and Lal 2005). SOM contents may vary according to the environment, be it agricultural or forest production systems, pastures, or less impacted areas, such as forests at different stages of succession. Organic
matter ‘hotspots’ may form in soil aggregates, in which the more labile forms of SOM are more abundant (Jiang et al. 2011).

The study of total, labile, and recalcitrant compartments of SOM can be made by separating chemical (e.g., total carbon and labile organic carbon), physical (e.g., light organic matter), and biochemical (e.g., potentially mineralizable carbon) fractions. Such analyses can expand the scientific knowledge about the different mechanisms of carbon stabilization in soil, provide a better understanding of the impact of management practices, and help identify strategies to increase soil carbon sequestration and mitigate the effects of anthropogenic CO$_2$ emissions (Briedis et al. 2018).

Soil quality indices have been proposed to evaluate the effects of different management systems and environmental conditions on soil parameters (Duval et al. 2018). Indices are commonly compared with those of a reference site without anthropogenic disturbances. The sensitivity index (SI) is used to assess soil aggregation, an important physical parameter (Bolinder et al. 1999). For SOM fractions, carbon indices are adopted, such as the carbon management index, carbon pool index (CPI), and lability index (LI) (Blair et al. 1995).

In this study, we hypothesized that management systems (conventional and conservation) can promote changes in aggregation and the total and labile compartments of SOM associated with soil aggregates. Thus, this study aimed to (i) determine soil aggregation status, (ii) quantify total carbon, labile organic carbon, light organic matter, and potentially mineralizable carbon of SOM in soil aggregates, (iii) determine soil quality indices, and (iv) apply multivariate analyses to investigate the dissimilarity between CT, NT, and an undisturbed reference area (Cerrado vegetation).

Material And Methods

Location, climate, and soil of experimental areas

Soil samples were collected at experimental areas (19°39′10.17″ S and 47°58′15.65″ W, 790–819 m elevation) of the Federal Institute of Triângulo Mineiro (IFTM), Uberaba, Minas Gerais State, Brazil. The climate is warm tropical (Köppen classification: Aw), with wet summers and dry and cold winters, mean annual rainfall of 1600 mm, and an average temperature of 22.6°C. The soil at the experimental areas was classified as *Latossolo Vermelho Distróico típico*, according to Santos et al. (2018), which corresponds to Typic Hapludox in the USA Soil Taxonomy (Soil Survey Staff 2006) and Haplic Ferralsol in the FAO classification system (IUSS Working Group WRB 2006).

Land use history of study areas

Four experimental areas were analyzed in the study: a area under CT for the past 20 years (CT), a area under NT for the past 6 years (6NT), a area under NT for the past 18 years (18NT), and a reference area of undisturbed Cerrado vegetation (CA). Soil chemical properties in the 0.00–0.10 m layer are summarized in Table 1.
At 6NT and 18NT, cover crops (millet, *Brachiaria*, and *Crotalaria*) are rotated with annual crops (maize and soybean or common bean); both areas are managed similarly, differing only in duration of NT adoption. At CT, in general, two tillage operations are performed per year (plowing and land leveling), always before planting the annual crop (maize and soybean or common bean). At CT, 6NT, and 18NT, the annual crop at the time of sample collection was soybean (*Glycine max* L.).

### Table 1

Soil chemical properties in the 0.00–0.10 m layer at four experimental areas in Minas Gerais State, Brazil.

| Areas | pH | Ca$^{2+}$ | Mg$^{2+}$ | H + Al | SB  | T    | K$^+$ | P    | BS  |
|-------|----|-----------|-----------|--------|-----|------|-------|------|-----|
| H$_2$O | 5.37 | 1.12 | 0.84 | 3.68 | 2.14 | 5.46 | 56 | 42 | 35 |
| CT    | 5.42 | 1.00 | 0.83 | 3.53 | 2.00 | 5.54 | 43 | 12 | 35 |
| 6NT   | 5.23 | 0.97 | 0.75 | 3.98 | 1.81 | 5.78 | 42 | 10 | 31 |
| 18NT  | 5.40 | 0.37 | 0.88  | 7.12 | 1.11 | 8.23 | 91 | 3 | 14 |

SB, sum of bases; T, cation-exchange capacity at pH 7.0; BS, base saturation; CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area).

Annual crops are fertilized according to the recommendations of Ribeiro et al. (1999). For maize, 400 kg ha$^{-1}$ NPK (08-28-16) fertilizer is applied at the time of planting (basal fertilization), followed by surface application of 140 kg ha$^{-1}$ N and 80 kg ha$^{-1}$ K, split between 20 and 40 days after planting. For soybean, fertilization consists of 200 kg ha$^{-1}$ NPK (00-20-15) + 2.5% Zn + 2.5% Mn (equivalent to 40 kg ha$^{-1}$ P$_2$O$_5$, 60 kg ha$^{-1}$ K$_2$O, 5 kg ha$^{-1}$ Zn, and 5 kg ha$^{-1}$ Mn) applied in-furrow. Common bean receives a basal application of 350 kg ha$^{-1}$ NPK (08-28-16) + 0.5% Zn.

### Soil sampling and aggregate separation

Sampling was carried out in January 2019. Five pseudoreplicates (soil clods) were collected from the 0.00–0.05 and 0.05–0.10 m layers at each area. After collection, samples were air-dried and sieved through a set of 9.7, 8.0, and 4.0 mm mesh sieves. Aggregates in the range of 8.0 to 4.0 mm were used for analysis.

### Soil aggregation status

Soil aggregates (25 g) were weighed and evaluated for stability by wet sieving through a set of sieves with decreasing mesh sizes (2.0, 1.0, 0.50, 0.25, and 0.105 mm) for 15 min on a Yoder sieve shaker. The
material retained on each sieve was transferred to Petri dishes and oven-dried at 105°C to constant weight (Teixeira et al. 2017). Weight data were used to calculate the mean weight diameter (MWD) and size class distribution (%) of water-stable aggregates (A₁, 8.0 > Ø ≥ 2.0 mm; A₂, 2.0 > Ø ≥ 1.0 mm; A₃, 1.0 > Ø ≥ 0.50 mm; A₄, 0.50 > Ø ≥ 0.25 mm; A₅, 0.25 > Ø ≥ 0.105 mm; and A₆, Ø < 0.105 mm) (Teixeira et al. 2017). Samples were also classified according to size into macroaggregates (8.0 > Ø ≥ 2.0 mm), mesoaggregates (2.0 > Ø ≥ 0.25 mm), and microaggregates (0.25 > Ø ≥ 0.053 mm) (Costa Junior et al. 2012).

**Analysis of total and labile SOM fractions in soil aggregates**

For determination of TC and carbon/nitrogen (C/N) ratio, aggregates collected from the 0.00–0.05 and 0.05–0.10 m layers were analyzed by the dry combustion method using a PerkinElmer 2400 CHN elemental analyzer. Labile organic carbon (permanganate oxidizable carbon, POXC) was quantified by oxidation with 0.02 mol L⁻¹ KMnO₄ solution (Weil et al. 2003; Culman et al. 2012). Light organic matter (LOM) was separated by flotation in aqueous medium (Anderson and Ingram 1989).

Soil aggregates from the 0.00–0.05 m layer were used for determination of potentially mineralizable carbon (CO₂-C). First, samples were re-moistened by spraying with water twice a day for two weeks to reactivate soil organisms (Gonçalves et al. 2002). Field capacity was determined by using the funnel method (Loss et al. 2013). CO₂-C evolution was assessed at 25°C (refrigeration temperature) in the laboratory according to the method developed by Mendonça and Matos (2005), with four replications per study area. Measurements were performed from September to October 2020 at 24 h intervals during the first 7 days, then at 48 h intervals between days 8 and 17, and finally at 96 h intervals between days 18 and 29. Daily emissions are presented in mg CO₂-C 50 g⁻¹ sample. Total CO₂-C production was calculated as the sum of daily emissions during the 29-day incubation period.

**Soil quality indices**

The following soil quality indices were used to compare managed areas with the reference area: sensitivity index for MWD (SI_{MWD}) (Bolinder et al. 1999), carbon pool index for TC (CPI_{TC}), and lability indices for POXC and LOM (LI_{POXC} and LI_{LOM}, respectively) (Blair et al. 1995).

**Statistical analysis**

For each layer, data were analyzed for normality and homoscedasticity by Shapiro–Wilk and Bartlett's tests, respectively. Variables that did not meet the test assumptions (LOM and LI_{LOM}) were Box–Cox transformed. Subsequently, data were analyzed in a completely randomized design and subjected to analysis of variance, F-test, and Tukey's test at the 5% significance level for comparison of means using R statistical software version 3.3.1 (R Development Core Team 2015) and the ExpDes.pt. package (Ferreira et al. 2013). Principal component analysis (PCA) and hierarchical cluster analysis (single-linkage clustering with the Gower similarity coefficient) were performed using PAST software. Pearson correlation analysis was carried out using Microsoft Excel.
Results

Aggregate distribution and stability

Soil aggregation status was assessed by determining the MWD distribution of aggregates. Differences were observed between management systems, particularly in the 0.00–0.05 m layer (Table 2).

Table 2
Size class distribution and mean weight diameter (MWD) of soil aggregates from Cerrado areas under conventional and conservation tillage in Minas Gerais State, Brazil.

| Areas  | A₁ | A₂ | A₃ | A₄ | A₅ | A₆ | MWD |
|-------|----|----|----|----|----|----|-----|
| CT    | 18.90 B | 7.80 A | 10.60 A | 22.70 A | 22.70 A | 17.30 A | 1.20 B |
| 6NT   | 73.70 A | 2.80 B | 3.60 B | 6.50 B | 5.60 B | 7.80 B | 3.80 A |
| 18NT  | 64.40 A | 3.10 B | 4.70 AB | 9.50 B | 7.70 B | 10.60 B | 3.40 A |
| CV%   | 13.7 | 25.8 | 25.1 | 11.2 | 18.5 | 15.0 | 11.4 |
| CA    | 78.80 | 1.00 | 0.80 | 1.10 | 2.30 | 16.00 | 3.97 |
|       |       |       |       |       |       |       |      |
| CT    | 18.30 B | 6.20 A | 10.50 A | 27.40 A | 24.00 A | 13.60 A | 1.24 B |
| 6NT   | 52.10 A | 6.30 A | 9.50 A | 14.60 A | 8.70 B | 8.80 B | 2.90 A |
| 18NT  | 42.80 A | 5.60 A | 11.80 A | 19.00 A | 11.70 B | 9.10 B | 2.30 A |
| CV%   | 33.8 | 58.6 | 33.7 | 31.1 | 36.0 | 12.8 | 20.6 |
| CA    | 78.40 | 1.10 | 0.70 | 1.10 | 2.40 | 16.30 | 3.96 |

Means within columns followed by the same letter do not differ significantly by Tukey’s test (p < 0.05).

A₁, 8.0 > Ø ≥ 2.0 mm; A₂, 2.0 > Ø ≥ 1.0 mm; A₃, 1.0 > Ø ≥ 0.50 mm; A₄, 0.50 > Ø ≥ 0.25 mm; A₅, 0.25 > Ø ≥ 0.105 mm; A₆, Ø < 0.105 mm; CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CV, coefficient of variation; CA, undisturbed Cerrado vegetation (reference area).

6NT and 18NT had a higher proportion of A₁ aggregates (macroaggregates) and higher MWD values than CT in both layers (Table 2). For other classes of aggregates, CT had the highest proportions of A₂,
A₃, and A₄ (mesoaggregates) at 0.00–0.05 m depth and A₅ and A₆ (microaggregates) at 0.00–0.10 m depth. Proportionally the MWD values under CT were reduced by 68, 64, 57 and 46 % compared to NT’s.

**Total C, C/N ratio, POXCl, and LOM**

The results of SOM compartments were similar to those of aggregation status (Tables 2 and 3). Differences were mainly observed in TC and LOM contents (Table 3). At 0.00–0.05 m depth, TC and LOM contents were highest in 6NT and 18NT aggregates (Table 3). In 0.05–0.10 m depth soil, LOM values were 41 and 82 % higher in 18NT and 6NT, respectively, than in CT. 6NT and 18NT aggregates exhibited higher C/N ratios in the 0.05–0.10 m layer. Management systems did not differ in POXCl content.

### Table 3
Total carbon (TC), carbon/nitrogen ratio (C/N), permanganate oxidizable carbon (POXCl), and light organic matter (LOM) in soil aggregates at Cerrado areas under conventional and conservation tillage in Minas Gerais State, Brazil.

| Areas   | TC  | C/N  | POXCl | LOM  |
|---------|-----|------|-------|------|
|         | g kg⁻¹ |      | mg kg⁻¹ | g kg⁻¹ |
| **0.00–0.05 m** | | | | |
| CT      | 12.30  | 12.60 | 210  | 1.80  |
| 6NT     | 13.70  | 13.50 | 297  | 5.00  |
| 18NT    | 14.90  | 13.80 | 307  | 3.80  |
| CV%     | 6.6   | 6.2   | 26.9 | 28.3  |
| CA      | 29.30 | 19.70 | 453  | 5.70  |
| **0.05–0.10 m** | | | | |
| CT      | 11.45  | 12.46 | 343  | 1.60  |
| 6NT     | 12.55  | 14.83 | 295  | 2.92  |
| 18NT    | 12.36  | 14.56 | 279  | 2.26  |
| CV%     | 8.6   | 9.4   | 19.7 | 41.9  |
| CA      | 24.20 | 18.30 | 410  | 2.64  |

|       |       |       |       |       |

*Means within columns followed by the same letter do not differ significantly by Tukey’s test (*p* < 0.05).*

CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CV, coefficient of variation; CA, undisturbed Cerrado vegetation (reference area).
Soil quality indices

Comparison of managed sites with the reference area showed that only 6NT exhibited an $LI_{LOM}$ greater than 1.00 (1.14) in the 0.05–0.10 m layer (Table 4). $SI_{MWD}$ and $LI_{LOM}$ values were close to (1.0), demonstrating similarity with the reference area. In the 0–0.05 m layer, 6NT had an $SI_{MWD}$ of 0.96 and an $LI_{LOM}$ of 0.93. In comparing the soil indices of managed areas, we found a similar pattern to that observed for $A_{1}$, MWD, TC, and LOM (Tables 3 and 4). In 6NT and 18NT, higher $SI_{MWD}$ values were observed in the 0.00–0.10 m layer and higher $CPI_{TC}$ and $LI_{LOM}$ values were found in the 0.00–0.05 m layer (Table 4).

| Areas | $SI_{MWD}$ | $CPI_{TC}$ | $LI_{POXC}$ | $LI_{LOM}$ |
|-------|------------|------------|-------------|------------|
|       | 0.00–0.05 m |            |             |            |
| CT    | 0.31 B     | 0.42 B     | 0.50 A      | 0.36 B     |
| 6NT   | 0.96 A     | 0.47 A     | 0.66 A      | 0.93 A     |
| 18NT  | 0.85 A     | 0.51 A     | 0.70 A      | 0.77 A     |
| CV%   | 12.2       | 10.0       | 25.3        | 81.7       |
| CA    | 1.00       | 1.00       | 1.00        | 1.00       |
|       | 0.05–0.10 m |            |             |            |
| CT    | 0.31 B     | 0.47 A     | 0.84 A      | 0.67 A     |
| 6NT   | 0.73 A     | 0.52 A     | 0.71 A      | 1.14 A     |
| 18NT  | 0.58 A     | 0.51 A     | 0.68 A      | 0.85 A     |
| CV%   | 21.2       | 11.6       | 19.8        | 51.5       |
| CA    | 1.00       | 1.00       | 1.00        | 1.00       |

$^{A,B}$ Means within columns followed by the same letter do not differ significantly by Tukey’s test ($p < 0.05$).

CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CV, coefficient of variation; CA, undisturbed Cerrado vegetation (reference area).
Potentially mineralizable carbon

The daily evolution of CO$_2$-C in soil aggregates is shown in Fig. 1. Over the 29 days of incubation, CO$_2$-C emission differed on days 3, 6, 9, 11, 13, 15, and 17, especially for CA, 6NT, and 18NT aggregates. The lowest values of CO$_2$-C were observed in CT aggregates, ranging from 1.2 to 11.1 mg CO$_2$ 50 g$^{-1}$.

Shortly after incubation (day 1), CO$_2$-C values were highest in 18NT aggregates (13.1 mg CO$_2$ 50 g$^{-1}$), followed by 6NT aggregates (9.0 mg CO$_2$ 50 g$^{-1}$). On the same day, CA and CT aggregates showed the lowest CO$_2$-C values (6.5 and 5.0 mg CO$_2$ 50 g$^{-1}$, respectively). Variations in daily CO$_2$-C emissions were observed: values increased and then decreased shortly after the beginning of incubation until about day 15 (Fig. 1). Between days 7 and 13, a significant increase in carbon consumption was observed, causing peaks of CO$_2$-C evolution, mainly in CA, 6NT, and 18NT aggregates (28.0, 21.5, and 19.2 mg CO$_2$ 50 g$^{-1}$, respectively) (Fig. 1). From day 15 onward, there was a tendency toward stabilization of microbial respiration, with values ranging from 1.1 to 7.4 mg CO$_2$ 50 g$^{-1}$.

CA, 6NT, and 18NT aggregates had the largest CO$_2$-C accumulation at the end of the incubation period. Total CO$_2$-C results agree with those of A$_1$, MWD, TC, and LOM in 6NT and 18NT (Tables 2 and 3). CO$_2$ accumulation was 76, 67, and 61 % higher in 6NT, 18NT, and CA, respectively, than in CT (Table 5).

| Soil layer (m) | Total CO$_2$-C (mg CO$_2$ 50 g$^{-1}$) |
|---------------|----------------------------------|
|               | CT                               | 6NT  | 18NT  | CA    |
| 0.00–0.05     | 76$^B$                           | 134$^A$ | 127$^A$ | 123$^A$ |
| CV%            | 9.2                              |

Values are the mean of four replications.

$^A,B$ Means within columns followed by the same letter do not differ significantly by Tukey’s test ($p < 0.05$).

CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area); CV, coefficient of variation.

Multivariate analyses
PCA revealed two PCs, which together explained 82 and 75 % of the total variance in the dataset for the 0.00–0.05 m and 0.05–0.10 m layers, respectively. Figs. 2 and 3 show the formation of three distinct groups (CA, NT areas, and CT) for the 0.00–0.05 m layer and three groups (CA, 6NT, and CT) for the 0.05–0.10 m layer.

On the basis of 0.00–0.05 m depth data, CA, 6NT, and 18NT were plotted far from CT along the PC1 axis (accounting for 64 % of the data variance). The following variables were discriminatory, given their strong correlation with PC1 (−0.7 ≥ r ≥ 0.7): TC, POXC, C/N ratio, CPI_{TC}, and LLI_{POXC} for CA; A_1, MWD, LOM, total CO_2–C, SL_{MWD}, and LLI_{LOM} for 6NT and 18NT; and A_2, A_3, A_4, and A_5 for CT (Fig. 2 and Table 6).

For the 0.05–0.10 m layer, the variables that most contributed to the separation of CA and 6NT from CT were TC and CPI_{TC} (CA); A_1, MWD, C/N ratio, and SL_{MWD} (6NT); and A_4 and A_5 (CT). These variables were strongly correlated with PC1 (± 58 %) (Fig. 3 and Table 6). A_6 had a strong correlation (> 17.0 %) with CT and CA along the PC2 axis in both layers (Figs. 2 and 3).

Hierarchical cluster analysis (Fig. 4) corroborated the results of PCAs (Figs. 2 and 3). The dendrograms of Fig. 4 demonstrate the dissimilarities between management systems and the reference area. For both soil layers (Fig. 4a and b), three dissimilar groups were formed; the first was composed of 6NT and 18NT (homogeneous), the second was composed of CA (heterogeneous), and the third was composed of CT (heterogeneous).

As depicted in Fig. 4a, CT was plotted far from 6NT and 18NT, with a dissimilarity of ± 56 %. However, for the 0.05–0.10 m layer (Fig. 4b), the dissimilarity between managed systems decreased to ± 40 %. An inverse pattern was observed for CA compared with NT areas: the distance between areas was about 40 % in the 0.00–0.05 m layer and 60 % in the 0.05–0.10 m layer (Fig. 4a and b).
Table 6
Principal component analysis matrix for soil attributes in the 0.00–0.05 and 0.05–0.10 m layers. Relative contributions refer to Pearson's correlation coefficients ($r$) between principal components (PC) and the analyzed variables.

| Variable          | 0.00–0.05 m | 0.05–0.10 m |
|-------------------|-------------|-------------|
|                   | PC1         | PC2         | PC1         | PC2         |
| MWD               | 0.94        | −0.30       | 0.95        | −0.23       |
| $A_1$             | 0.95        | −0.28       | 0.95        | −0.19       |
| $A_2$             | −0.83       | 0.14        | −0.66       | −0.11       |
| $A_3$             | −0.78       | 0.12        | −0.86       | −0.25       |
| $A_4$             | −0.92       | 0.07        | −0.95       | 0.05        |
| $A_5$             | −0.94       | 0.19        | −0.82       | 0.35        |
| $A_6$             | 0.27        | 0.85        | 0.47        | 0.75        |
| TC                | 0.75        | 0.63        | 0.91        | 0.27        |
| POXC              | 0.73        | 0.38        | 0.53        | 0.54        |
| LOM               | 0.83        | −0.06       | 0.31        | −0.63       |
| Total CO$_2$-C    | 0.80        | −0.51       | −           | −           |
| SI$_{MWD}$        | 0.94        | −0.29       | 0.95        | −0.23       |
| CPI$_{TC}$        | 0.74        | 0.64        | 0.91        | 0.29        |
| C/N               | 0.77        | 0.59        | 0.83        | −0.08       |
| LI$_{POXC}$       | 0.71        | 0.44        | 0.51        | 0.65        |
| LI$_{LOM}$        | 0.67        | −0.04       | 0.23        | −0.56       |

MWD, mean weight diameter; $A_1$, 8.0 > $\varnothing$ ≥ 2.0 mm; $A_2$, 2.0 > $\varnothing$ ≥ 1.0 mm; $A_3$, 1.0 > $\varnothing$ ≥ 0.50 mm; $A_4$, 0.50 > $\varnothing$ ≥ 0.25 mm; $A_5$, 0.25 > $\varnothing$ ≥ 0.105 mm; $A_6$, $\varnothing$ < 0.105 mm; TC, total carbon; POXC, permanganate oxidizable carbon; LOM, light organic matter; SI$_{MWD}$, sensitivity index for mean weight diameter; CPI$_{TC}$, carbon pool index; C/N, carbon/nitrogen ratio; LI$_{POXC}$, lability index for permanganate oxidizable carbon; LI$_{LOM}$, lability index for light organic matter; Total CO$_2$-C, total accumulation.

Discussion
Soil aggregation status under conventional and conservation management

Several studies on agricultural production in different countries (Brazil, China, India, Canada, Argentina, and the United States of America) have shown that conservation management, in particular, NT practices, may positively influence soil quality. Factors such as time since system adoption, continuous input of organic matter (plant residues), beneficial action of plant root residues, and protection provided by cover crops are associated with the increase in soil quality (Andrade et al. 2018).

In Paraná State, Brazil, Loss et al. (2014) observed higher MWD values in Rhodic Paleudalfs (Red Nitosol, *Nitossolo Vermelho*) under NT and pasture than in soil under CT. The authors attributed the results to the high organic carbon contents stemming from the well-developed root systems of *Axonopus compressus* in pasture and ryegrass in NT. Sales et al. (2016), in evaluating the structural quality of a Hapludox (Red-Yellow Latosol, *Latossolo Vermelho-Amarelo*) in Minas Gerais, Brazil, also observed higher MWD values and macroaggregate proportions at NT areas than at CT areas, both of which were planted with maize, sorghum, and sunflower. The authors argued that NT contributes to soil aggregation, especially in fields planted with grasses.

In a Typic Hapludoll in Northeast China, Zheng et al. (2018) found that long-term adoption of conservation management significantly increased macroaggregate proportion and MWD values compared with conventional management. According to the authors, aggregate stability is associated with the ability of soil to resist exogenous action and remain stable when exposed to changes in the external environment. In a Ferralsol (Yellow Latosol, *Latossolo Amarelo*) in Piauí, Brazil, Silva et al. (2018) found that soil aggregation was highest in an old NT system, followed by pasture and forest (eucalyptus). However, at a CT site, aggregate stability was low.

The results of macroaggregate proportion and MWD in the 0.00–0.10 m layer of 6NT and 18NT might be related to the lower soil mobilization associated with organic carbon content and fractions. The results also suggest that the use of cover crops (millet, *Brachiaria*, and *Crotalaria*) in rotation with maize/soybean or common bean (annual crops) favored the formation of larger aggregates; macroaggregate proportion and MWD values were higher in NT systems than in CT (Table 2). The higher proportions of meso- (*A*_2, *A*_3, and *A*_4) and microaggregates (*A*_5 and *A*_6) in CT further confirmed that conventional practices decreased the proportion of macroaggregates (*A*_1) compared with NT (Table 2).

In Central India, Somasundaram et al. (2018) found higher proportions of meso- and microaggregates and lower MWD values in CT than in NT and reduced tillage systems. Similar results were reported by Comin et al. (2018) in a Humic Dystrudept (Humic Cambisol, *Cambissolo Húmico*) in Santa Catarina State, Brazil. According to the authors, the negative effects of management on soil quality were associated with reductions in aggregate stability, especially with the decrease in macroaggregate proportion.
The higher proportions of meso- and microaggregates in the 0.00–0.10 m layer of CT may be attributed to intense tillage practices (plowing and leveling) and lack of soil cover and plant diversity. Such factors contribute to reducing macroaggregate formation and stabilization and increasing the proportion of meso- and microaggregates in surface/subsurface layers. Thus, it can be inferred that macro-, meso-, and microaggregate proportions were directly related to the low MWD values in CT (Table 2). Another negative effect of conventional management on soil aggregation status is the decrease in hierarchization process. Higher proportions of soil meso- and microaggregates in detriment to macroaggregates indicate that hierarchization is at the early-to-mid stage (Somasundaram et al. 2018). Thus, the high macroaggregate proportions and MWD values in NT indicate an advanced stage of hierarchization process (Table 2).

**Effect of management systems on SOM compartments**

The effects of management practices on soil carbon dynamics may vary depending on the quantity and quality of organic waste deposited on the soil surface. During soil preparation, SOM may be redistributed in the environment. Given this, small variations in organic carbon content and fractions can significantly affect aggregate stability (Somasundaram et al. 2018). SOM exerts a decisive influence on the formation and stabilization of aggregates because of its diverse molecular structure and the differences in decomposition rates of SOM fractions in soil (Schiller et al. 2018).

Regarding total SOM contents, Loss et al. (2014) observed higher carbon contents in the 0.00–0.05 m layer of NT soil and lower carbon contents in the 0.00–0.10 m layer of CT soil. Sales et al. (2016) found that NT accumulated more soil carbon than CT in the 0.00–0.05 m layer in all cropping systems. Silva et al. (2018) found that carbon contents were lower in an 8-year-old CT system and a 6-year-old forest than in the other systems evaluated. Somasundaram et al. (2018) observed that management practices had a significant effect on the contents of carbon associated with soil aggregates, especially macroaggregates. The authors argued that higher carbon values favored the formation of macro- and mesoaggregates in conservation systems compared with conventional ones.

In Santa Catarina, Brazil, Comin et al. (2018) found that the use of grasses in succession or rotation with other crops under NT increased carbon contents in the surface layer, particularly when in rotation with maize and winter grasses. In Northeast China, Zheng et al. (2018) observed that the contents of carbon associated with soil aggregates in conservation management systems were higher than in conventional systems. The findings were related to the large amount of SOM and good soil structure of the conservation system. In a Hapludox (Red-Yellow Latosol, *Latossolo Vermelho-Amarelo*) in Mato Grosso, Brazil, 9 years of NT led to higher carbon contents at 0.00–0.05 m depth than CT (Souza et al. 2018). The authors attributed this effect to the increased protection of SOM against rapid microbial decomposition in NT soil. Through the interaction of the organic fraction with soil structure, SOM is protected from oxidation, maximizing the formation of more recalcitrant and stable carbon fractions (Blanco-Canqui and Lal 2004).

Crop rotation, used in NT systems, also contributes to carbon sequestration and maintenance. This practice increases the diversity of substrates and exudates released by plant roots and during above-
ground organic matter decomposition. Crop residues and root biomass stimulate microbial communities, especially that of mycorrhizal fungi in soil aggregates, positively influencing carbon and aggregation dynamics (Zhang et al. 2012). Ramalho et al. (2019), in studying an Umbric Ferralsol (Latossolo Bruno) in Paraná State, Brazil, found that a 9-year-old NT system promoted greater carbon accumulation in the 0.00–0.20 m layer than CT. This finding underscored the potential of NT in improving soil quality and increasing SOM. In the same region, Assunção et al. (2019) found that a Ferritic Ferralsol (Red Latosol, Latossolo Vermelho) under NT showed higher carbon contents at 0.00–0.10 m depth than soil under pasture or CT. According to the authors, NT is one of the most efficient agricultural practices for sequestering and accumulating carbon in soil.

From the above, it is possible to infer that the potential of NT in maintaining or increasing carbon contents in tropical soils depends on the quantity and quality of organic residues added to the soil surface as well as the magnitude of anthropogenic disturbances (Souza et al. 2018). The results of Sales et al. (2016), Silva et al. (2018), Somasundaram et al. (2018), Comin et al. (2018), Zheng et al. (2018), Souza et al. (2018), Ramalho et al. (2019), and Assunção et al. (2019) agree with our findings for TC (Table 3).

The lower TC contents in the 0.00–0.05 m layer of CT soil (Table 3) can be attributed to disaggregation caused by soil tillage (Balesdent et al. 2000; Comin et al. 2018). Aggregate fragmentation is intensified with the use of agricultural implements and irrigation/drying cycles (Comin et al. 2018). Soil disaggregation was evidenced by the higher proportion of meso- and microaggregates and the lower MWD values in CT (Table 2).

Previous studies have also investigated more labile SOM fractions. Assunção et al. (2019) observed higher values of POXC in soil (0.00–0.05 m depth) under native forest (1130 mg kg\(^{-1}\)) as a function of increasing organic matter input, although values did not differ significantly from those in NT and pasture systems (980 and 900 mg kg\(^{-1}\), respectively). POXC contents are mainly influenced by management practices that contribute to SOM accumulation or stabilization (long-term carbon sequestration) (Hurisson et al. 2016). In quantifying POXC and LOM contents, Santos et al. (2020) did not observe differences in POXC contents but found significant variations in LOM between sites with Inceptisol (Haplic Cambisol, Cambissolo Háplico) under sugarcane in southeastern Brazil, in agreement with the results of the current study. The results indicate that the more labile chemical fraction (POXC) was less sensitive to management practices than the more labile physical fraction (LOM) of SOM (Table 3).

Loss et al. (2014) observed higher LOM contents at NT, pasture, and forest sites and associated LOM results with MWD values. In assessing a 6-year-old NT site and a CT site of a Typic Hapludalf in Canada, Ramnarine et al. (2015) observed that light fraction weight and organic carbon content were higher at the NT area. The authors argued that NT provides better protection of this SOM fraction, at least in the short term. As noted by Briedis et al. (2018), such an increase in the carbon contents of labile and stabilized fractions of SOM at NT areas may result in carbon sequestration in the long term.
Briedis et al. (2018) investigated SOM dynamics at NT, CT, and native vegetation areas in tropical and subtropical regions of Brazil. The authors found higher contents of coarse particulate organic carbon (cPOC) at NT and native vegetation areas. In a Haplic Kastanozem in Argentina, Duval et al. (2018) found that cPOC contents were 58 % higher at NT areas than at CT areas. cPOC and LOM are labile SOM fractions with similar diameters (2.0 > Ø ≥ 0.25 mm); these parameters are efficient indicators of soil quality. According to Duval et al. (2018), cPOC can be used as an initial indicator of changes in soil quality resulting from soil management practices.

Following physical protection via encapsulation within macroaggregates, labile SOM fractions (e.g, LOM, cPOC, or light fraction) become a substrate for soil microfauna. These fractions also act as a nucleation site for the formation of microaggregates within macroaggregates, contributing to hierarchization process (Six et al. 2000; Briedis et al. 2018). Also noteworthy is the intrinsic relationship between litterfall/crop residues and LOM. Incorporation of plant material in soil can be carried out directly, using soil preparation techniques, or indirectly, through biological homogenization. Biological homogenization is more efficient in NT than in CT systems (Buurman and Roscoe 2011). The environmental conditions of NT sites favor biological activity, especially that of soil invertebrates. These individuals are responsible for various ecosystem functions and services, including SOM fragmentation and decomposition, aggregate formation, and stabilization and accumulation of organic carbon (Lavelle et al. 2006; Brown et al. 2018).

The higher LOM contents in 6NT and 18NT soils (Table 3) are likely associated with their higher macroaggregate proportion, MWD, and TC (Tables 2 and 3). In CT soil, the low LOM contents (Table 3) can be attributed to the destructive effect of tillage on soil macroaggregates, as tillage exposes physically protected LOM to microbial attack in a more oxidizing environment (Cambardella and Elliott 1993; Briedis et al. 2018). This hypothesis is supported by the aggregation status of CT soil (Table 2).

**Soil quality indices under native vegetation**

Soil quality indices were lowest in CA, except for LI_{LOM} at 0.05–0.10 m depth, which was lower in 6NT (Table 4). The increase in soil carbon content is a slow process because of the complexity of stable organic fractions. Such fractions depend on the quantity and quality of deposited organic waste and on the prevailing climatic conditions, which directly affect decomposing microorganisms (Torres et al. 2019). These factors help explain the results of carbon indices (CPI_{TC}, LI_{POXC}, and LI_{LOM}) in NT systems compared with the reference area.

6NT and 18NT clearly influenced soil quality indices, particularly SI\_{MWD}, CPI_{TC}, and LI\_{LOM} (Table 4). In the 0.00–0.05 m layer, Sales et al. (2016) found that the aggregation status of NT was similar to that of native forest (SI\_{MWD} ≥ 1.0); CT, by contrast, had lower soil aggregation (SI\_{MWD} < 1.0) and carbon accumulation. Rosset et al. (2019) observed an increase in CPI_{TC} as a function of time since NT implementation, with values of 0.64, 0.67, and 0.76 at NT areas aged 6, 14, and 22 years, respectively; significant differences were observed between NT areas aged 6 and 22 years. According to the authors, this pattern is related to the slow and gradual increase of TC contents in soil under NT.
Ramalho et al. (2019) reported that NT sites had higher LI values than CT, reinforcing the hypothesis that conservation management can enhance soil quality. High LI values were also recorded by Rosset et al. (2019) at NT areas, especially after 22 years of system implementation. In the 0.00–0.20 m layer, Duval et al. (2018) found that CPI and LI were higher in NT than in CT systems. According to the authors, soil carbon indices were more sensitive to management practices than total organic carbon.

**Effect of management practices on CO$_2$-C contents**

Changes in SOM quantity and quality in response to management practices directly influence microbial activity and, consequently, CO$_2$-C emission from aggregates during incubation. This fraction is best associated with environmental practices and conditions that promote rapid SOM mineralization (Hurisson et al. 2016; Wade et al. 2018). The greater release of CO$_2$-C by NT aggregates (Fig. 1) can be attributed to practices such as crop rotation (maize/soybean or common bean), use of cover crops (millet, Brachiaria, and Crotalaria), and minimal soil disturbance.

The lower CO$_2$-C values of CT aggregates throughout incubation (Fig. 1) can be related to the negative effects of conventional management practices on soil structure, as discussed above. A similar finding was obtained by Loss et al. (2014). The authors attributed their results to the detrimental effect of CT on soil aggregates, which increase SOM mineralization rates, culminating in low aggregation and low LOM contents. Low availability of the most labile physical fraction (e.g., LOM) for soil biota might have resulted in the low CO$_2$-C in CT samples.

Variations in the evolution of CO$_2$-C during the first 15 days of incubation (Fig. 1) might have been caused by the consumption of SOM by soil microbiota. These microorganisms release CO$_2$-C when decomposing available SOM, resulting in peaks of CO$_2$-C emission. CO$_2$-C emission occurs until the substrate ends, after which the microorganisms die and CO$_2$-C values decrease. Dead microfauna then become a source of energy for resistant microorganisms, which multiply and generate new peaks of CO$_2$-C emission (Carvalho et al. 2008; Pinto et al. 2018). Such a pattern explains the peaks in CO$_2$-C observed between days 7 and 13 of incubation, as also reported by Loss et al. (2013; 2014) and Rosset et al. (2019). In the present study, microbial activity stabilized from the 15th day onward (Fig. 1).

Total CO$_2$-C values were highest at areas with the highest macroaggregate proportion, MWD values (Table 2), and TC and LOM contents (Table 3). Such findings agree with those of Loss et al. (2013; 2014), Wade et al. (2018), and Rosset et al. (2019). Total CO$_2$-C values of CA, 6NT, and 18NT samples (Fig. 1) suggest that there is a direct relationship between LOM contents and CO$_2$-C accumulation. According to Loss et al. (2014), greater LOM availability in aggregates contributes to microbial activity, leading to greater CO$_2$-C accumulation.

Several studies have investigated the relationship between CO$_2$-C and POXC under different soil and environmental conditions (Hurisson et al. 2016; Wade et al. 2018). Culman et al. (2013) analyzed a Typic Hapludalf cropped with maize and managed under different systems in the United States and observed
that POXC was mostly influenced by amendment with organic matter (manure). On the other hand, CO$_2$-C was more influenced by rotation of annual crops with cover crops. These results help explain the lack of differences in POXC contents as well as the significant variations in total CO$_2$-C between management systems (Tables 3 and 5).

**Dissimilarity between evaluated areas**

Multivariate techniques were used to identify similarity patterns for the analyzed data. Such techniques have been applied in previous research (Silva et al. 2018; Rosset et al. 2019; Assunção et al. 2019; Briedis et al. 2020), contributing to understanding the patterns of variations between areas in association with statistical tests. Duval et al. (2018) used PCA to investigate associations between management systems and fertilizer applications; the authors observed that soil attributes had low sensitivity to management practices compared with soil quality indices.

PCA showed that aggregation status, more labile SOM compartments (LOM and total CO$_2$-C), and SI$_{MWD}$ and LI indices were directly related to the management practices adopted in CT and NT. Total SOM compartment (TC), POXC values, and their respective indices were more associated with CA (more stable and balanced environment). The variables that contributed most to discriminating areas in the 0.00–0.10 m layer were aggregate classes ($A_1$–$A_6$), MWD, TC, C/N ratio, SI$_{MWD}$, and CPI$_{TC}$ (Figs. 2 and 3). Such findings highlight the importance of assessing aggregation and SOM compartmentalization to determine the quality of anthropized environments.

The reduction in dissimilarity between CT and NT areas with depth (from ± 56 to ± 40 %), as shown by hierarchical cluster analysis (Fig. 4), suggests that CT management practices exert stronger effects on the surface layer (0.00–0.05 m), resulting in greater dissimilarity to NT systems, mainly in surface.

**Conclusions**

Conventional and conservation management practices influenced aggregation and SOM compartmentalization in soil aggregates in different manners. Environmental conditions at NT areas favored the formation of macroaggregates while maintaining TC and LOM contents, which consequently increased degree aggregate stability. CT significantly decreased macroaggregation and increased the proportion of small aggregates in soil.

Soil quality indices allowed to identify differences between the reference Cerrado area and managed area. Aggregates from NT systems showed higher CO$_2$-C emission and accumulation than aggregates from the CT area, in agreement with the higher aggregation status and organic matter contents in total and labile fractions. Aggregate distribution and stability, TC, C/N ratio, SI, and CPI contributed the most to the discrimination of evaluated areas in the 0.00–0.10 m layer.

**Declarations**
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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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Figures

![Figure 1](image)

Figure 1

Daily evolution of CO2-C emissions from soil aggregates (0.00–0.05 m layer) during 29 days of incubation. Values are the mean of four replications. * Significant by Tukey’s test (p < 0.05). ns Not significant. CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area).
Figure 2

Principal component analysis of the soil aggregation status, labile and total compartments of soil organic matter, and soil quality indices in the 0.00–0.05 m layer at Cerrado areas under conventional and conservation tillage. CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area); MWD, mean weight diameter; A1, 8.0 > Ø ≥ 2.0 mm; A2, 2.0 > Ø ≥ 1.0 mm; A3, 1.0 > Ø ≥ 0.50 mm; A4, 0.50 > Ø ≥ 0.25 mm; A5, 0.25 > Ø ≥ 0.105 mm; A6, Ø < 0.105 mm; TC, total carbon; POXC, permanganate oxidizable carbon; LOM, light organic matter; SIMWD, sensitivity index for mean weight diameter; CPITC, carbon pool index; C/N, carbon/nitrogen ratio; LIPOXC, lability index for permanganate oxidizable carbon; LILOM, lability index for light organic matter; Tot-CO2-C, total accumulation.
Figure 3

Principal component analysis of the soil aggregation status, labile and total compartments of soil organic matter, and soil quality indices in the 0.05–0.10 m layer at Cerrado areas under conventional and conservation tillage. CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area); MWD, mean weight diameter; A1, 8.0 > Ø ≥ 2.0 mm; A2, 2.0 > Ø ≥ 1.0 mm; A3, 1.0 > Ø ≥ 0.50 mm; A4, 0.50 > Ø ≥ 0.25 mm; A5, 0.25 > Ø ≥ 0.105 mm; A6, Ø < 0.105 mm; TC, total carbon; POXC, permanganate oxidizable carbon; LOM, light organic matter; SIMWD, sensitivity index for mean weight diameter; CPITC, carbon pool index; C/N, carbon/nitrogen ratio; LIPOXC, lability index for permanganate oxidizable carbon; LILOM, lability index for light organic matter.
Hierarchical cluster analysis of the soil aggregation status, labile and total compartments of soil organic matter, and soil quality indices in the (a) 0.00–0.05 and (b) 0.05–0.10 m layers at Cerrado areas under conventional and conservation tillage. CT, area managed under conventional tillage for the past 20 years; 6NT, area under no-till for the past 6 years; 18NT, area under no-till for the past 18 years; CA, undisturbed Cerrado vegetation (reference area).