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Application of organic and mineral fertilizers increases carbon fractions in two classes of aggregates in an Integrated Crop-Livestock System

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ABSTRACT: Application of organic fertilizers of animal origin can increase organic carbon in the soil and increase its content in macroaggregates. This study aimed to evaluate carbon contents and fractions in two classes of soil aggregates in response to the application of organic and mineral fertilizers in an integrated crop-livestock system. The experiment was established in Concórdia, Santa Catarina State, in a *Nitossolo Vermelho Eutroférrico típico*, (Rhodic Kandiudox according to the WRB system) (0.00-0.05, 0.05-0.10, and 0.10-0.20 m), in an integrated crop-livestock, with corn and soybean in the summer, black oat and rye in the winter, shepherded by sheep. The design used was randomized blocks, with treatments in factorial design (5 × 3 + 1), with four replications, five sources of fertilizers, three rates and the control with no fertilization. Three organic fertilizers were applied: poultry litter, pig manure and compost; and two minerals fertilizers: M1 (formulated according to the composition of the pig slurry) and M2 (adjusted according to the composition of the poultry litter), combined with three applications rates, corresponding to 75, 100 and 150 % of the recommendation for the crop of interest, based on the element with greater demand. Total organic carbon (TOC), particulate (POC) and mineral-associated organic carbon (MAC) contents were determined in two classes of soil aggregates C1 (8.00 to 4.76 mm) and C2 (4.76 to 2.00 mm), in samples collected in the 2018/2020 crop season. Crop yields were determined in every season. The results were analyzed using analysis of variance to compare sources and polynomial regression analysis for fertilizer rates. The soil has high aggregate stability, even so, the use of organic and mineral fertilizers increased aggregation. The poultry litter organic fertilizer increases aggregation, forming largely aggregates with a size of 8.00-4.76 mm, and increases the contents of total fractions of soil organic carbon, providing the system with a more stabilized carbon. In the 0.00-0.05 m layer, organic fertilizers increased the content of total organic carbon. The stabilized fraction (MAC) showed a higher proportion of total soil organic carbon than particulate organic carbon (POC).

Keywords: conservation management, organic fertilization, soil structure.

INTRODUCTION

Imports of mineral fertilizers have increased over the years in Brazil. In 2021, the country purchased more than 29.1 million tons, an increase of 20 % compared to 2020. The significant cost to the trade balance stands out, in addition to the dependence on agribusiness, an activity responsible for 27 % of the gross domestic product (ANDA, 2021).

Options that minimize the high cost of fertilizer imports are important, since the country largely depends on agricultural activities. The use of organic fertilizers of animal origin in agriculture is a choice that can reduce these expenses, as they improve the physical, biological and chemical properties of the soil, nutrient cycling, increase the fractions of soil organic carbon (SOC) and agricultural production (Magalhães et al., 2018).

Conservationist production systems such as integrated crop-livestock (iCL) and the use of organic fertilizers can increase economic and environmental gains, as the diversity of the integrated system is enhanced (Anghinoni et al., 2011; Rigo et al., 2019). Integrated crop-livestock can accumulate carbon (C) and improve soil properties, with greater efficiency in the use of nutrients and an increase in the stock of C (Costa et al., 2015; Soares et al., 2020).

Applying organic fertilizers in iCL can modify physical properties such as soil aggregation, as it increases C inputs and can influence the formation pathways of soil aggregates (Ventura et al., 2018). The protection within the aggregates corresponds to the intermediate compartment, and the interaction with mineral and metallic ions is an important mechanism for maintaining C, since they physically protect against decomposition and microbial transformations, which improves the storage of total organic carbon (TOC) (Six et al., 2004; Von Lützow et al., 2008).

Aggregation is of great importance for the soil, since it influences the sequestration of C, soil microbial activity, airflow, water and infiltration. These characteristics affect the dynamics of soil organic matter (SOM) and nutrient cycling (Vezzani and Mielniczuk, 2011).

Determination of TOC fractions in the aggregates is based on the physical fractionation technique. The TOC is fractioned into particulate organic carbon (POC) and mineral-associated carbon (MAC). The POC represents the labile fraction of TOC, which is characterized as more easily decomposable, and MAC is formed by more recalcitrant compounds, with less degradation remaining longer in the soil (Pikul et al., 2007; Mikutta et al., 2019).

The application of organic and mineral fertilizers can affect density, porosity, aeration, water retention and infiltration capacity, and the soil productive capacity. In addition, the amount of C present in aggregates with a size of 8.00-2.00 mm is a result of management practices. Therefore, increasing the amount of C in these aggregates is a strategy that can increase and improve C sequestration (Guo et al., 2019).

Studies have shown that increases in C contents are directly linked to the application of adequate amounts of organic fertilizers in the form of animal manure and crop residues in the soil, and that change in SOC dynamics in agricultural soils is mainly determined by the balance between inputs of organic material and degradation rates of existing SOC and soil aggregates important for protecting the contents of C (Li et al., 2016).

Application of organic and mineral fertilizers affects the stability, size distribution of aggregates as well as regulates the amount of carbon within the soil aggregates. This is due to the formation of different aggregate sizes, texture and amounts of decomposing organic materials, as aggregates of different sizes respond differently to fertilizer applications (Rabbi et al., 2014). Sodhi et al. (2009) observed that organic and mineral fertilizers increased C in macroaggregates compared to microaggregates. In addition, C mineralization in macroaggregates is generally greater than in microaggregates, and C sequestration varies within different aggregate sizes, a fact that occurs as a function of soil types, texture, applied fertilizers and agricultural management (Koga, 2017).

Carbon preferentially accumulates in larger aggregates, especially the more labile (particulate) fraction. However, this relationship can vary depending on the physical protection mechanisms of the aggregates, application of organic and mineral fertilizers, soil texture and management system, which can increase the availability of stabilized carbon and present a better understanding of TOC gains (Six et al.,1999; Midwood et al., 2021; Mustafa et al., 2021).

Carbon sequestration can differ in different soils, and it will depend on their different fractions and compartments, and aggregate stability. A better understanding of how these aggregates respond to and protect C from microbial access under long-term fertilization practices is therefore important and would help sustainable management of agricultural production, thereby increasing C sequestration (Xie et al., 2017). Therefore, the use of organic fertilizers is relevant nowadays due to its potential to reduce production costs and minimize environmental impacts on agriculture. In addition, most studies that involve fertilization in the iCL system are focused on applying mineral fertilizers.

Studies to recommend fertilization involving organic residues in this system should be conducted, and it is important to determine the main fractions of TOC in soil aggregates, which can present a greater contribution to productivity and environmental quality. This study aimed to evaluate the carbon fractions in two classes of soil aggregates in response to the application of organic and mineral fertilizers in an integrated crop-livestock system.

MATERIALS AND METHODS

Study area is located in Concórdia, Santa Catarina, Brazil (27° 12’ 0.08” S and 52° 4’ 58.22” W). In the period from 1994 to 2011 was managed with corn cultivation (*Zea mays)* in the summer, and black oat (*Avena strigosa* Schreb) in the winter. Two liming (5 Mg ha^{-1}, with dolomitic limestone) and application of pig slurry organic fertilizer (50 m^3 ha^{-1} yr^{-1}) were carried out, based on the norms of the Santa Catarina Environment Institute in November of each year, and mineral fertilization according to the needs of the crop, based on soil analysis and grain yield by CQFS-RS/SC (2016).

In 2011, the experiment with the integrated crop-livestock (iCL) system was implemented in a no-tillage system with corn (cv. Syngenta Celeron LT) in intercropping with *Brachiaria brizantha* cv. Xaraés in the summer and rye (*Secale cereale* L.) in the winter. Before the implementation of the winter pasture, the soil was scarified to loosen the surface layer of the area, then there was desiccation with the use of glyphosate herbicide (2.160 g ha^{-1} of a.i.) soon after sowing was carried out (Hentz et al., 2016).

The soil of the experimental area is a Rhodic Kandiudox (WRB System), which corresponds to a *Nitossolo Vermelho Eutroférrico típico* according to the Brazilian Soil Classification System. Based on the results of soil analysis performed by Rigo et al. (2019), according to Tedesco et al. (1995) (Table 1), there was no need to perform liming.

Regional climate is humid subtropical (Cfa), according to the Köppen classification system. The coldest months (June and July) have average temperatures around 15 °C, and the annual mean temperature is 23 °C. The rains are regular and well distributed, without water deficit and with total annual rainfall of around 1.500 mm

Table 1. Initial characterization of the Rhodic Kandiudox (*Nitossolo Vermelho Distroférrico*) in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m soil layers. Concórdia, Santa Catarina, Brazil

Property [1]	Layer		
	0.00-0.05 m	0.05-0.10 m	0.10-0.20 m
Clay (g kg^{-1})	680	680	700
pH(H_2O)	5.8	5.6	5.5
TOC (g kg^{-1})	30	26	25
TN (g kg^{-1})	1.9	1.7	1.5
P (mg kg^{-1})	100	80	70
K^+ (mg kg^{-1})	590	406	346
Ca^{2+} (cmol$_c$ kg^{-1})	8.4	6.7	9.5
Mg^{2+} (cmol$_c$ kg^{-1})	4.8	4.0	4.2
H+Al (cmol$_c$ kg^{-1})	5.7	6.0	5.8
CEC (cmol$_c$ kg^{-1})	20.5	17.8	20.5
V (%)	72	66	72
Cu (mg kg^{-1})	4.7	5.5	4.4
Zn (mg kg^{-1})	5.1	4.4	3.6

[1] Soil analysis was determined according to Tedesco et al. (1995). pH(H_2O) at a ratio of 1:1 v/v; TOC: total organic carbon; TN: total nitrogen; P: phosphorus extracted by Mehlich-1; K^+: potassium extracted by Mehlich-1; Ca^{2+}: calcium extracted by KCl 1 mol L^{-1}; Mg^{2+}: magnesium extracted by KCl 1 mol L^{-1}; H+Al was extracted by a solution of calcium acetate 1.0 mol L^{-1}; CEC: cation exchange capacity; V: base saturation. The clay content was determined according to Claessen (1997).

and an altitude of 569 m above sea level. The predominant landform is sloped surfaces (Hentz et al., 2016). The experiment was evaluated from 2018 to 2020 in the field. The maximum and minimum temperatures and rainfall during the study period were measured at the weather station at the Embrapa Swine and Poultry Research Center (Figure 1). Experimental design was in randomized blocks with four replications, where the treatments consisted of a factorial design (5 × 3 + 1), with five sources of fertilizers, three rates of recommendation for culture and one control without fertilization. The production system adopted was iCL, and for the study period of evaluation, the cultures used were corn and soybean (*Glicine max*) in the summer and black oat (*Avena sativa* Schreb) and rye in the winter with grazing by sheep.

Experimental units are formed by 5 × 5 (25 m^2) plots, 2.5 m apart between blocks, with no space between plots in the same block. The treatments are three organics fertilizer, poultry litter, pig slurry and compost from pig slurry, and two minerals fertilizer (M1 and M2), combined with three rates equivalent to 75, 100 and 150 % of the recommendation. The rates were based on the element with the highest demand for the crop (K for soybean and N for corn) (CQFS-RS/SC, 2016). The control treatment received no fertilization.

Fertilizers application was carried out manually on the surface, next to the sowing line, in winter and summer crops. The fertilizer M1 was formulated according to the composition of the pig slurry, and the M2 was adjusted according to the composition of the poultry litter, the formulations being adjusted for each harvest, according to the composition of the organic fertilizers used in each period.

The pig slurry came from a full cycle breeding system at the Federal Institute of Santa Catarina (IFC - Concórdia), where the animals remain housed in a compact floor system from birth to slaughter with an average live weight of 120 kg and age average of 145 days. The compost fertilizer was produced from pig slurry, which was constituted

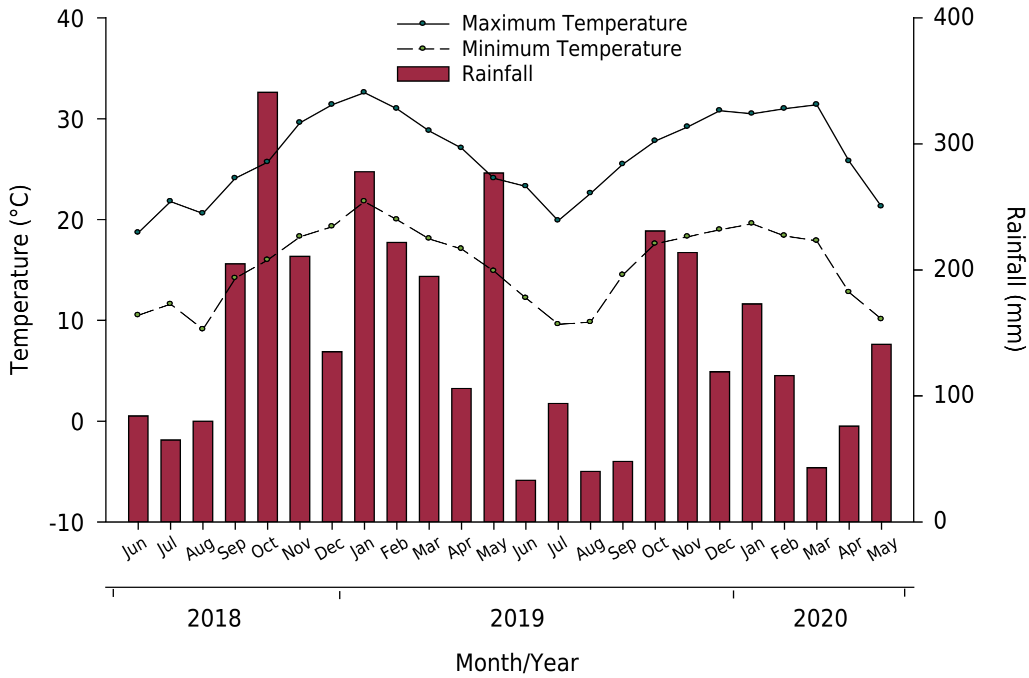

Figure 1. Precipitation (mm), maximum and minimum temperature (°C), registered during the experiment in the 2018-2020, crop seasons, Concórdia, Santa Catarina, Brazil.

from the application of 8 to 12 liters (with contents between 4 to 6 % of dry matter) for each 1 kg of substrate formed by the mixture of wood shavings and sawdust, in 1 m high, 3 m wide and 20 m long windrow. The poultry litter also came from IFC - Concórdia, where broiler birds are reared, which was used through 5 to 6 batches of broilers. The chemical composition of organic fertilizers for each crop during the experiment (2018-2020), as well as the C contribution, were analyzed based on the official methodology (AOAC, 2000; APHA, 2012) for the determination of N, P and K (Table 2). The chemical composition of fertilizers since the beginning of the experiment (2011-2017) is in Hentz et al. (2016) and Rigo et al. (2019).

From the concentration of N, P and K in organic fertilizers, formulations for mineral fertilizers were made, using urea as source for N, triple superphosphate for P and potassium chloride for K. In the M1 treatment the same amounts were added of these nutrients, as well as in the M2 treatment. The formulations were adjusted for each harvest, according to the composition of the organic fertilizers used in each period.

Corn (*Zea mays*) was of the cultivar Celeron TL Syngenta, simple hybrid, super early. Sowing was carried out with 8-9 seeds per linear meter, with row spacing of 0.80 m. Soybean (*Glicine max*) (BRS 523) was planted with 18 seeds per linear meter, spaced between rows of 0.45 m. The sowing of the crops was carried out with a no-tillage drag seeder, consisting of a frontal cutting disc and double lagged discs, with depth limiting wheels, furrower rod and “V” compactors with two rubber wheels. In the winter, black oat (*Avena sativa* Schreb), a common cultivar, was sown in place of rye, with a density of 50 kg ha^{-1} of seeds, approximately 80 seeds per linear meter in spacing between rows of 0.20 m.

Grazing was carried out by 20 sheep females, who entered the pasture when its height was between 0.35 and 0.40 m and left the pasture when its height was between 0.15 and 0.20 m. This cycle was carried out five to six times between autumn and winter. Grazing duration is adjusted according to pasture conditions, aiming to maintain the minimum height or minimum residual biomass after grazing, the history of crops used throughout the experiment period can be found in Rigo et al. (20'19).

Table 2. Nutritional report of organic fertilizers in integrated crop-livestock

Treatment	Content of nutrients in the fertilizer			100 % rate	% of recommendation		
	N	P	K		75	100	150
	g kg^{-1}			kg or L ha^{-1}	C contribution (kg ha^{-1})		
Corn cultivation 2017/2018							
Poultry litter	24.2	12.6	11.3	4132	987	1317	2013
Pig slurry	2.7	0.9	1.2	37037	116	219	329
Compost	5.1	5.5	5.1	15483	1314	1818	2568
Corn cultivation 2018/2019							
Poultry litter	16.2	5.3	12.8	6169	646	862	1181
Pig slurry	3.3	1.0	4.4	30303	113	147	230
Compost	6.2	6.4	5.4	17142	1313	2032	3045
Corn cultivation 2019/2020							
Poultry litter	22.1	10.6	16.6	6172	843	1112	1655
Pig slurry	3.5	0.9	0.9	33670	177	242	349
Compost	7.5	7.3	4.6	14607	1413	1938	2747
Sum of the contribution during the system conduction							
Poultry litter	–	–	–	–	2476	3291	4849
Pig slurry	–	–	–	–	406	608	908
Compost	–	–	–	–	4040	5788	8360

Chemical analyses were performed according to the Methodology of American Public Health Association – APHA (2012).

To determine the aggregation and carbon fractions in the soil aggregates, in June 2018 at IFC - Concórdia, soil with altered structure was collected (soil block weighing approximately 2.5 kg), in the layers of 0.00-0.05, 0.05-0.10, and 0.10-0.20 m, at three points between the lines of culture in each plot. These samples were used to determine the distribution of aggregates and the fractionation of soil organic carbon in the aggregates. The samples were at the point of friability of the soil and their manual separation was carried out in the range of sieves from 8 to 4.76 mm, by traction, without compressing the aggregates.

Aggregate stability analysis was performed by the standard wet method (Kemper and Chepil, 1965). The 4.76, 2.00, 1.00 and 0.25 mm mesh sieves were packed in descending order in the vertical oscillation apparatus. The aggregates (8 to 4.76 mm) were evenly distributed on the 4.76 mm sieve and were submerged in water for 10 min at rest for moistening. After the rest time, the agitation took place for 10 min, with 42 oscillations per minute. The aggregates percentage calculation was evaluated by the standard wet method by size class for the five classes and the geometric mean diameter (GMD) was determined. The GMD was calculated by equation 1:

$$\text{GMD (mm)} = \text{EXP} \sum_{i=1}^{n} \left[\frac{(mAgri - mi)*Ln.ci}{TAgr - miT} \right] \quad \text{Eq. 1}$$

in which: $mAgr_i$ is the mass of aggregates in each class (g); -*mi* is the mass of inert material in each class (g); -*TAgr* is the mass of aggregates from the initial sample (g); - *miT* is the mass of total inert material (of all classes) (g); -*ci* is the mean diameter of the aggregate class (mm); and -*Ln* is the natural logarithm.

The results were grouped into two size classes, the largest (C1), with a diameter of 8 to 4.76 mm and smallest (C2), with a diameter of 4.76 to 2.00 mm, as 97 % of the aggregates were retained in the two classes.

After laboratory determination, we observed that the aggregates were concentrated in the classes with diameter between 8-4.76 mm (C1) and 4.76-2 mm (C2), with a small amount in the smaller sieves. Thus, for the analysis total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated organic carbon (MAC), these two classes of aggregates were used.

The determination of soil carbon was carried out by dry combustion, in a TOC Shimadzu elemental analyzer, in ground samples and passed through a sieve with a diameter of 2 mm. The POC was fractionated according to Cambardella and Elliot (1992) and, after fractionation, the particulate fraction was dried in an oven at 50 °C, then ground in a porcelain grate. The MAC was calculated by the difference between TOC and POC.

Results were subjected to analysis of homogeneity and normality of variance, and there was no need to transform the data. ANOVA was used when there was a significant difference and the means were compared by the Tukey test at the level of 5 % error probability, protected by the significance of the global F test. The factors tested were fertilizer and rates. Correlation analysis was calculated to determine the relationship between variables affected by fertilizer application. For statistical analysis and graphing, SigmaPlot 12.5 software was used.

RESULTS

Aggregation

The GMD showed a small variation in response to increasing rates of fertilization recommendation. Poultry litter (100 and 150) and pig slurry (150) fertilizers increased the GMD in the 0.00-0.05 m layer, a different result for M1 mineral fertilizer. Only poultry litter fertilizer showed significant result in the 0.05-0.20 m layers. Thus, the equations indicated a reduction in the lower rates and an increase in the higher rates (Figure 2).

There were significant differences in the geometric mean diameter (GMD) in all evaluated layers. In the 0.00-0.05 m layer, the compost fertilizer (rate of 75 and 100) increased the aggregation, while the poultry litter increased the aggregate at rates 100 and 150 (Table 3). Only poultry litter (100 and 150) and compost (75 and 100) increased the aggregate stability, in the layer of 0.00-0.05 m, compared with control. For the layer of 0.05-0.10 m, the fertilizers compost (75, 100 and 150), poultry litter (100 and 150), M1 (75 and 100) and M2 (100) showed significant results for the GMD and in the 0.10-0.20 m only poultry litter (75 and 150) and compost (75 and 100).

In the 0.00-0.05 m layer, the highest percentage of C1 aggregates was observed in M1 at rate of 75, and compost at rates if 100 and 150. In the layers of 0.05-0.10 m and 0.10-0.20 m, higher percentages of aggregates were observed in the fertilizers poultry litter and pig slurry, and in one case in M2 (rate of 75 layer of 0.05-0.10 m) (Figure 3).

The distribution of soil aggregates from 8 to 4.76 mm in size (Class 1) varied for all evaluated layers, with a positive response to rates in most treatments. In the layer 0.00-0.05 m, the compost fertilizer increased the percentage of aggregates when compared with mineral fertilizers (M1, M2), poultry litter, and pig slurry at rates 100 and 150 % (Table 4). For the soil layer 0.05-0.10 m, pig slurry and M2 at 75 % rate showed greater aggregation; at 100 and 150 % rates, poultry litter and pig slurry

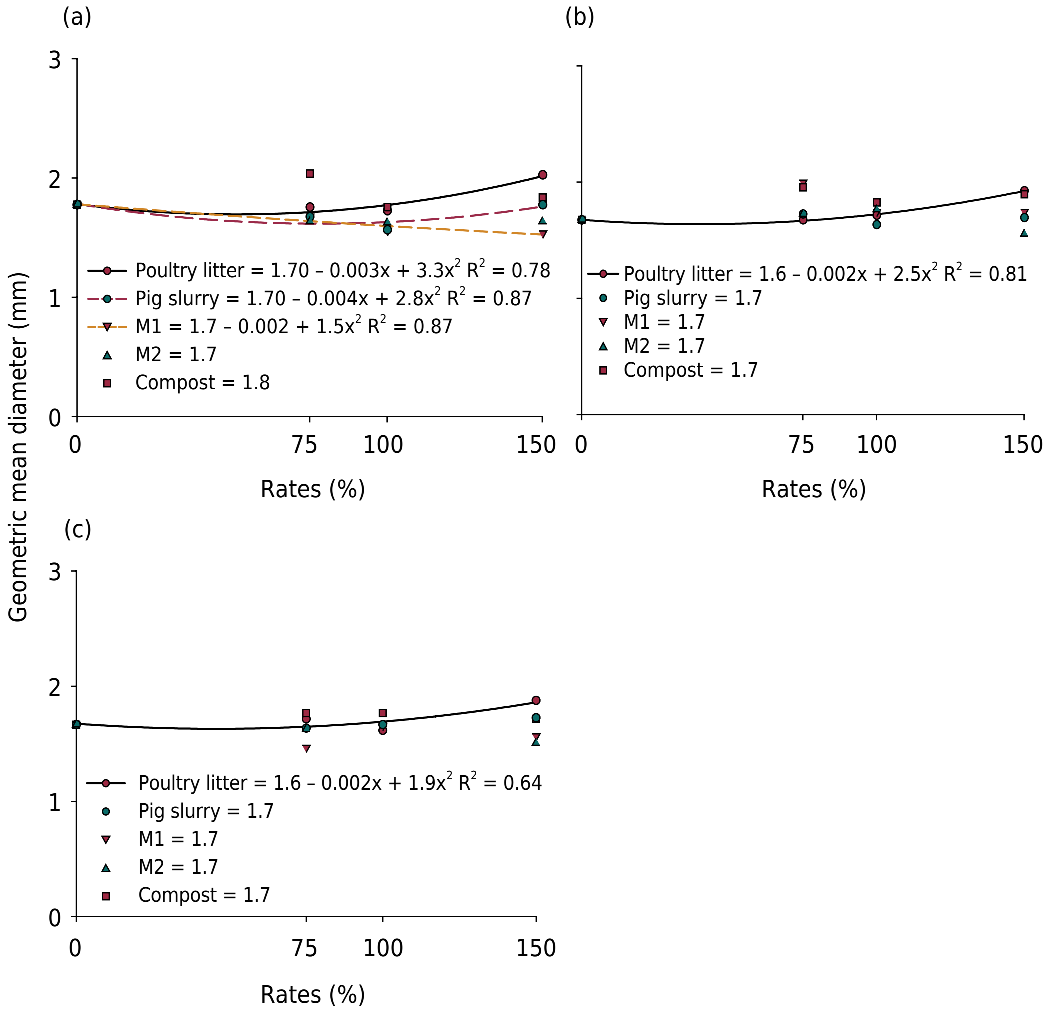

Figure 2. Geometric mean diameter (mm) of aggregates from a Rhodic Kandiudox, in the layers after seven years of different types and rates of organic and mineral fertilizers application. (a) 0.00-0.05 m soil layer; (b) 0.05-0.10 m soil layer; and (c) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

fertilizers increased aggregation, at greater depths, poultry litter and pig slurry increased aggregate stability at rates of 75, 100 and 150 % (Table 4).

In response to the increase in rates, fertilizer M1 (150) showed a higher percentage of aggregates in class C2 for the 0.00-0.05 m layer. In the 0.05-0.10 and 0.10- 0.20 m soil layer, the highest percentages of aggregates were observed in M1 fertilizers (100 and 150). The equations indicate a reduction in lower rates and an increase in higher rates, all showed a sharp drop in response to increased rates. For the deeper layer, M1 and compost showed a significant result for the increase in fertilization recommendation rates (Figure 4). Results for soil aggregates from 4.76 to 2.00 mm were statistically significant at all layers. In the 0.00-0.05 m layer, the treatment M1 and poultry litter obtained the lowest percentages of aggregates for a rate of 75 % of the fertilization recommendation, while the compost, pig slurry and M2 presented the highest percentage of these aggregates.

In the soil layer of 0.05-0.10 m, the mineral fertilizer M1 presented a significant result for all rates, and for the layer of 0.10-0.20 m, the M1 increased the distribution of aggregates at the rates of 75 and 150 % and the M2 to 100 % rate. The percentage of aggregates increased with the increase in fertilization recommendation rates for M1 (Table 5).

Table 3. Geometric mean diameter (mm) of aggregates from a Rhodic Kandiudox, in the layers of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m after seven years of application of types and rates (%) of organic and mineral fertilizers

Fertilizer	Rates			
	0	75	100	150
	%			
	0.00-0.05 m soil layer			
Poultry litter	1.7	1.8 B	1.8 A	2.0 A
Pig slurry	1.7	1.8 B	1.6 B	1.8 B
M1	1.7	1.8 B	1.6 B	1.5 C
M2	1.7	1.6 C	1.6 B	1.6 C
Compost	1.7	2.0 A	1.8 A	1.8 B
CV (%)	2			
	0.05-0.10 m soil layer			
Poultry litter	1.6	1.7 B	1.7 A	1.9 A
Pig slurry	1.6	1.7 B	1.6 B	1.7 B
M1	1.6	1.9 A	1.8 A	1.7 B
M2	1.6	1.7 B	1.8 A	1.5 C
Compost	1.6	1.9 A	1.8 A	1.9 A
CV (%)	4			
	0.10-0.20 m soil layer			
Poultry litter	1.6	1.7 A	1.62 B	1.9 A
Pig slurry	1.6	1.6 B	1.67 B	1.7 B
M1	1.6	1.4 C	1.65 B	1.5 C
M2	1.6	1.6 B	1.35 C	1.5 C
Compost	1.6	1.7 A	1.76 A	1.7 B
CV (%)	4			

Means followed by distinct capital letters in the column differ by Tukey's Test ($p \leq 0.05$). M1: mineral fertilizer 1, pig slurry mirror; M2: mineral fertilizer 2, poultry litter mirror.

Organic carbon in aggregate

In general, there was an increase in POC in the first layer in the C1 classes in the poultry litter and compost treatments. In the 0.05-0.10 m layer, for most treatments the POC increased in C2, however in M2, at the highest rates, the POC decreases in relation to rates 75 and 100. In the other layers the effects, although significant, were small. In the 0.10-0.20 m layer the M2 increased the POC in the C2 class (Figure 5).

In response to fertilization rates, there is a reduction in OC associated with minerals in the surface layer at rates 75 and 100 % and an increase at rate 150 in C1 (8.00-4.76 mm), in treatments M2 and Compost in C1 and poultry litter and M2 in C2 (4.76-2.00 mm) (Figure 6). In the 0.05-0.10 m layer, only the 8.00-4.76 mm aggregates showed significant results in response to the increase in fertilization rates. In the 0.10-0.20 m layer and the two classes of aggregates (C1 and C2), there is a reduction in the organic carbon associated with minerals in most treatments.

In the 0.05-0.10 m layer, only the 8.00-4.76 mm aggregates showed significant results in response to the increase in fertilization recommendation rates, pig slurry

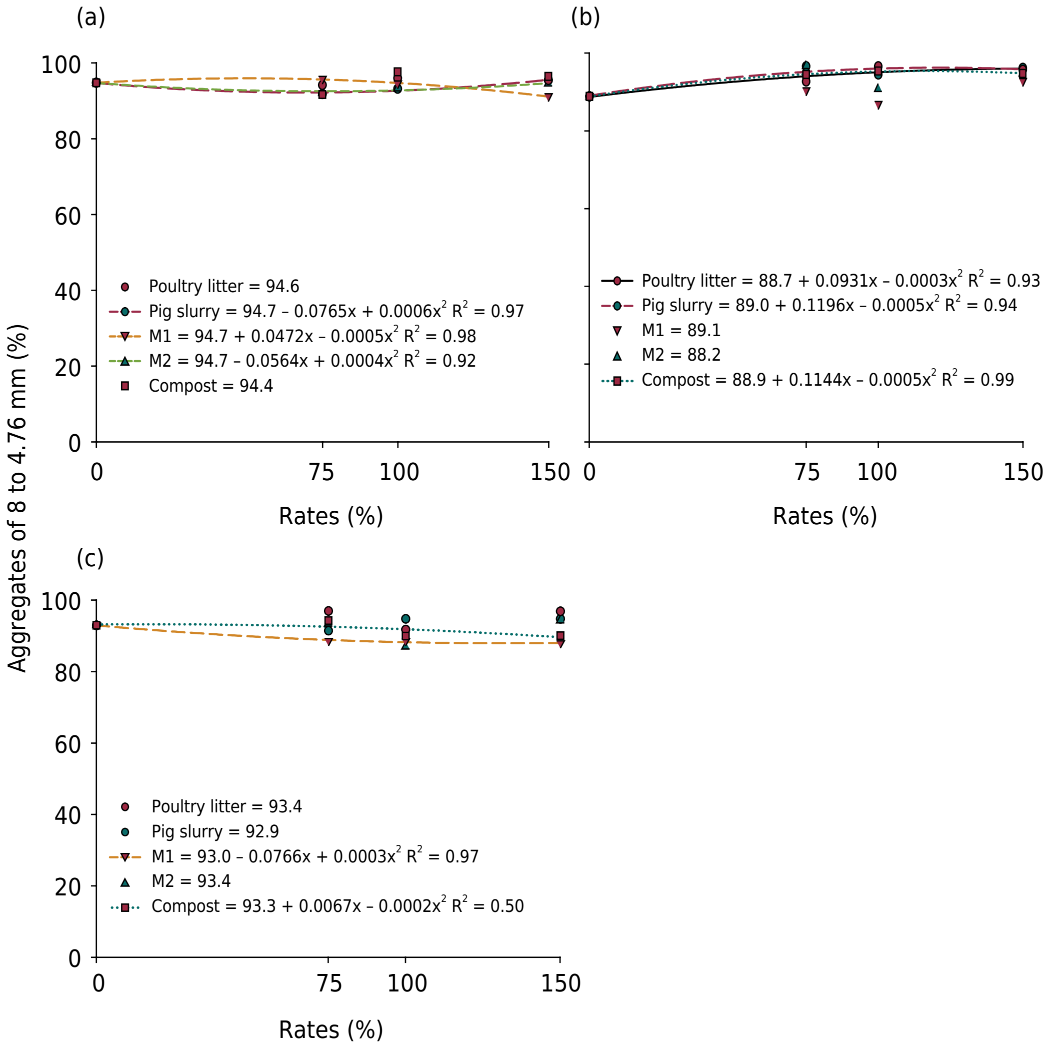

Figure 3. Aggregates of the class (C1 = 8 to 4.76 mm) in the Rhodic Kandiudox, in the layers after seven years of application of different types and rates (%) of organic and mineral fertilizers. (a) 0.00-0.05 m soil layer; (b) 0.05-0.10 m soil layer; and (c) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

increased MAC, a result observed in increasing rates, M1 and M2 decreased the fraction of C (Figure 6c).

For the last layer, an increase in poultry was observed only between the rate of 100 and 150. In the others, the percentage of MAC was reduced (Figure 6d), a different result for pig slurry and compost fertilizers that reduced C with increasing rates. In the aggregate class of 4.76-2.00 mm, it was possible to observe that poultry litter reduction in rates 75 and 100 and then increased at rate 150. The same behavior was not observed for M2 and compost fertilizers that had a decrease in MAC concentration in response to increasing rates of fertilization recommendation (Figure 6e).

The proportion of TOC fractions showed that MAC was predominant compared to POC in the two aggregate classes evaluated at all layers (Figure 7). In the 0.00-0.05 m layer in the 8.00-4.76 mm aggregates, compost, poultry litter and compost increased the TOC labile fraction (POC) content at rates 75, 100 and 150 %, while M1 and M2 increased the stabilized fraction (MAC) content at the 75 % rate, and M1 increased at the 100 and 150 % rates (Figure 7a).

In aggregates of 4.76-2.00 mm for the same layer (Figure 7b), pig slurry, M2, and compost increased the POC content at the rate of 75 and for 100 % poultry litter stood

Table 4. Percentage of aggregates of the class (C1 = 8 to 4.76 mm) from a Rhodic Kandiudox, in layers of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m after seven years of the application of different types and rates (%) of organic and mineral fertilizers

Fertilizer	Rates			
	0	75	100	150
	%			
	0.00-0.05 m soil layer			
Poultry litter	94.8	94.2 B	96.0 B	95.4 B
Pig slurry	94.8	91.7 C	93.0 D	95.8 B
M1	94.8	95.8 A	94.5 C	91.1 D
M2	94.8	92.1 C	93.2 D	94.4 C
Compost	94.8	91.7 C	97.7 A	96.5 A
CV (%)	2			
	0.05-0.10 m soil layer			
Poultry litter	88.8	92.5 C	96.6 A	95.6 B
Pig slurry	88.8	96.6 A	94.4 C	96.1 A
M1	88.8	90.3 D	86.8 E	92.7 D
M2	88.8	96.6 A	90.7 D	94.8 C
Compost	88.8	94.6 B	95.3 B	94.7 C
CV (%)	3			
	0.10-0.20 m soil layer			
Poultry litter	93.0	97.0 A	91.6 B	96.8 A
Pig slurry	93.0	91.3 C	94.7 A	94.8 B
M1	93.0	88.6 D	88.4 D	87.9 D
M2	93.0	93.3 B	86.8 E	94.3 B
Compost	93.0	94.2 B	89.9 C	90.0 C
CV (%)	4			

Means followed by distinct capital letters in the column differ by Tukey's Test ($p \leq 0.05$). M1: mineral fertilizer 1, pig slurry mirror; M2: mineral fertilizer 2, poultry litter mirror.

out for increasing the labile fraction of TOC, for a higher rate, pig slurry and compost incremented the POC fraction. Poultry litter increased MAC content at 75 % of the fertilization recommendation.

In the 0.05-0.10 m soil layer, the compost increased the POC content at rates of 75 and 150 % in the 8.00-4.76 mm aggregates (Figure 7c), for the MAC fraction, M2 and pig slurry were highlighted, which showed an increase in C in the rates 75 and 150 %. Compost increased the POC fraction in the 4.76-2.00 mm aggregates for the 75 % rate, while in the MAC fraction, M2 presented the highest content (Figure 7d).

For the 0.10-0.20 m layer, it was observed that pig slurry and compost showed an elevation of the POC fraction at a rate of 75 %, while for the MAC fraction, the highest content was found in poultry litter and M1 (Figure 7e). For aggregates of 4.76-2.00 mm for the three rates of fertilization recommendation in the POC fraction M1, pig slurry and M1 were the fertilizers that increased the content of the labile fraction. While for the MAC fraction, an increase was observed for the compost fertilizers at the 75 % rate, the pig slurry did not increase the MAC content at the 100 % rate.

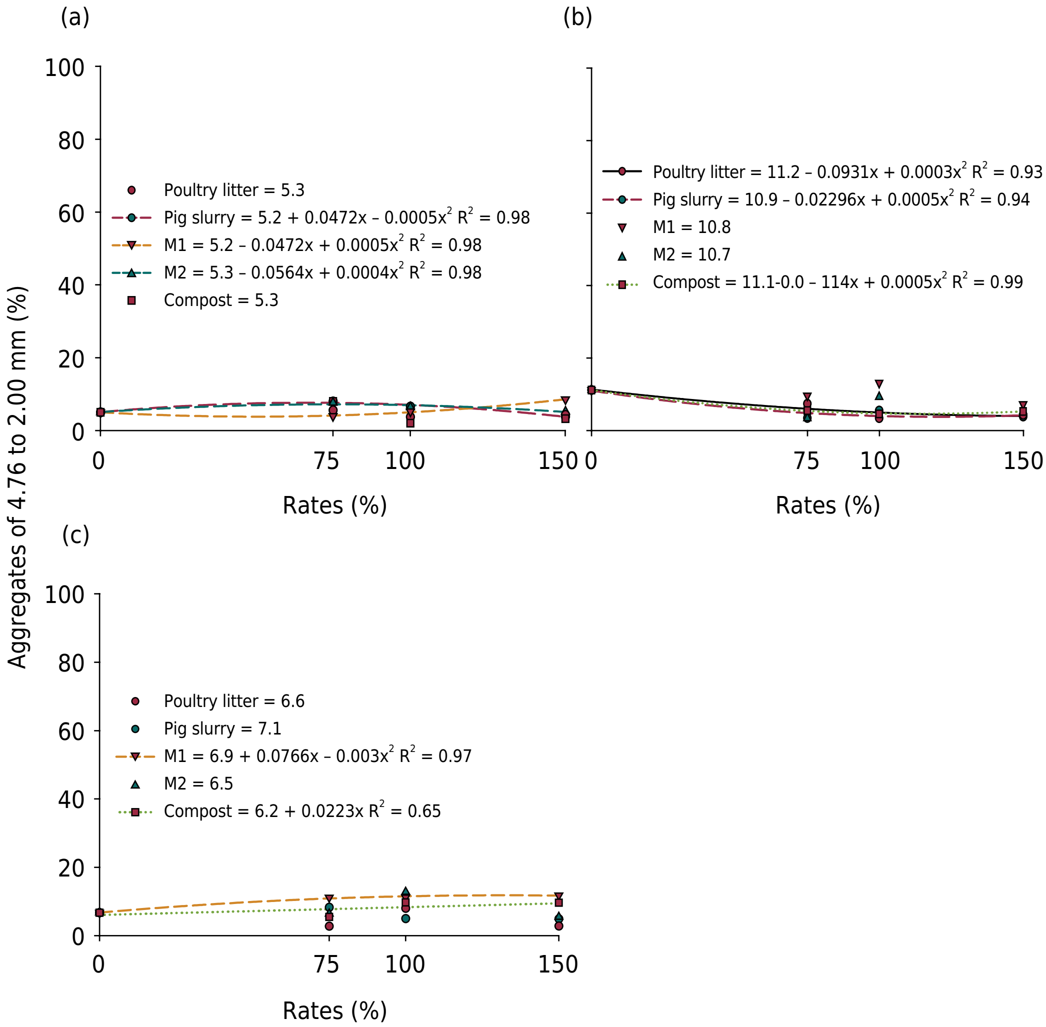

Figure 4. Percentage of aggregates of the class (C2 = 4.76 to 2.00 mm) in the Rhodic Kandiudox, in the layers after seven years of application of different types and rates (%) of organic and mineral fertilizers. (a) 0.00-0.05 m soil layer; (b) 0.05-0.10 m soil layer; and (c) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

DISCUSSION

Poultry litter fertilizer increased soil aggregation in all layers evaluated, performed well at the highest fertilization rates (100 and 150 %). Chen et al. (2020) found similar results when evaluated the effect of the application of different organic residues on the stability of aggregates for 9 years. They found an increase in aggregate formation above 2 mm by adding corn husk and organic fertilizers compared to minerals. The use of organic fertilizers for long periods can increase soil aggregation, especially for the formation of macroaggregates, because the addition of organic composts increases soil organic carbon, which favors the structuring and formation of aggregates, which improves the structural quality of the soil (Rauber et al., 2012; Mafra et al., 2014; Wang et al., 2017).

Each soil type can present a response to the use of organic fertilizers, which can be positive or negative, thus, the aggregation properties can present a significant response to the application of organic fertilizers (Troleis et al., 2017; Ribeiro et al., 2019). The studied soil has high stability, and the application of organic fertilizers contributed to the maintenance of aggregates of 8 to 2 mm.

The results of Zou et al. (2018) corroborate those of the present study. The authors found that the organic fertilizer increased the percentage of aggregates when compared to the

Table 5. Percentage of aggregates of the class (C2 4.76 to 2.00 mm) from a Rhodic Kandiudox, in layers of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m after seven years of application of types and rates (%) of organic and mineral fertilizers

Fertilizer	Rates			
	0	75	100	150
	%			
	0.00-0.05 m			
Poultry litter	4.3	5.8 B	3.9 C	4.5 C
Pig slurry	4.3	8.3 A	6.8 A	4.1 C
M1	4.3	4.2 C	5.4 B	8.8 A
M2	4.3	7.8 A	6.7 A	5.5 B
Compost	4.3	8.3 A	2.2 D	3.5 D
CV (%)	4			
	0.05-0.10 m			
Poultry litter	11.2	7.4 B	3.4 E	4.3 C
Pig slurry	11.2	3.3 D	5.5 C	3.9 D
M1	11.2	9.6 A	13.2 A	7.2 A
M2	11.2	3.4 D	9.3 B	5.2 B
Compost	11.2	5.5 C	4.6 D	5.3 B
CV (%)	5			
	0.10-0.20 m			
Poultry litter	7.01	3.0 D	8.2 D	3.1 D
Pig slurry	7.01	8.6 B	5.3 E	5.18 C
M1	7.01	11.4 A	11.5 B	12.1 A
M2	7.01	6.5 C	13.1 A	5.7 C
Compost	7.01	5.9 C	10.0 C	9.9 B
CV (%)	5			

Means followed by distinct capital letters in the column differ by Tukey's Test ($p \leq 0.05$). M1: mineral fertilizer 1, pig slurry mirror; M2: mineral fertilizer 2, poultry litter mirror.

soil without fertilization. In the present study, even the naturally structured soil, as can be seen through the treatment that did not receive fertilization in all evaluated layers, the organic and mineral fertilizers provided aggregation to the soil, signaling that the soil responded positively to the fertilization of organic residues, the which showed high structural quality after application in the conservation system.

The formation of larger and more stable aggregates in the 0.00-0.05 m layer may be related to the concentration of roots in this layer and to the implementation of a conservation system, which promotes the entry of plant residues through the use of pastures and other crops in the productive system (Costa et al., 2015). According to Almeida et al. (2014), the concentration of roots in the surface layer of the soil stimulates the activity of microorganisms, increasing the presence of cementing agents, and playing an important role in the formation and stabilization of soil aggregates. Rauber et al. (2012) found high aggregate stability in a Rhodic Kandiudox after the application of organic and mineral fertilizers and observed that crop root action and high soil clay content promote aggregation.

In a study evaluating the effect of continued application of organic and mineral fertilizers on water-stable aggregates, Ozlu and Kumar (2018) found that organic residue increased soil aggregation, providing the formation of aggregates larger than 2 mm, while the

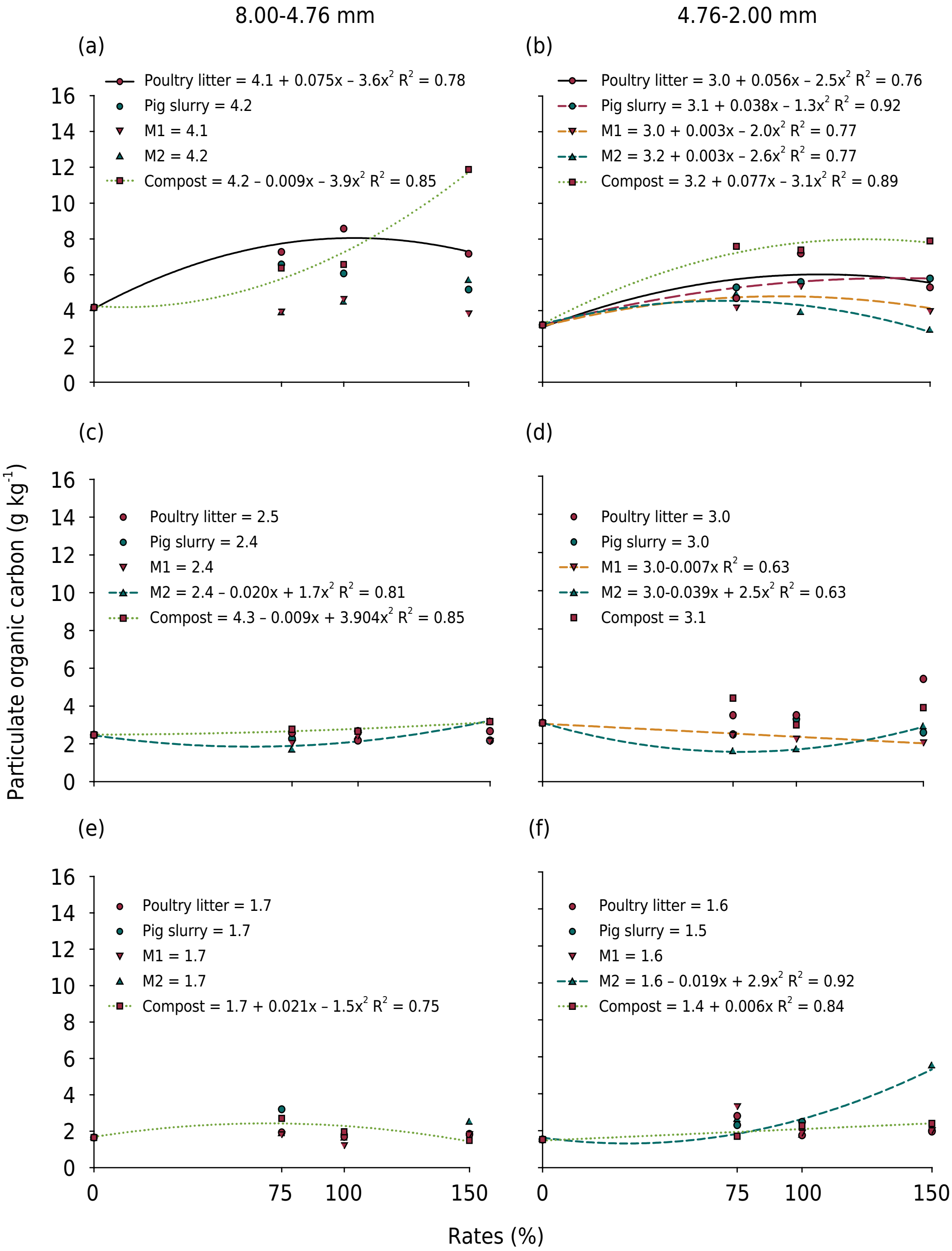

Figure 5. Particulate organic carbon (g kg^{-1}) from 8-4.76 and 4.76-2 mm aggregates in a Rhodic Kandiudox. (a,b) 0.00-0.05 m soil layer; (c,d) 0.05-0.10 m soil layer; and (e,f) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

mineral reduced this tendency, thus, the use of organic residue was an alternative to improve soil physical quality indicators.

Carbon fractions in soil aggregates

The high distribution of aggregates from 8 to 4.76 mm positively influenced the storage and availability of soil TOC fractions, as well as the use of different fertilization recommendation rates and types of organic and mineral fertilizers. In this study, it was observed that the clay content and mineralogy of the soil combined with the application of organic fertilizer increased the presence of larger aggregates and influenced the increase of TOC fractions in these aggregates. Soils with clayey textures tend to increase carbon levels, which

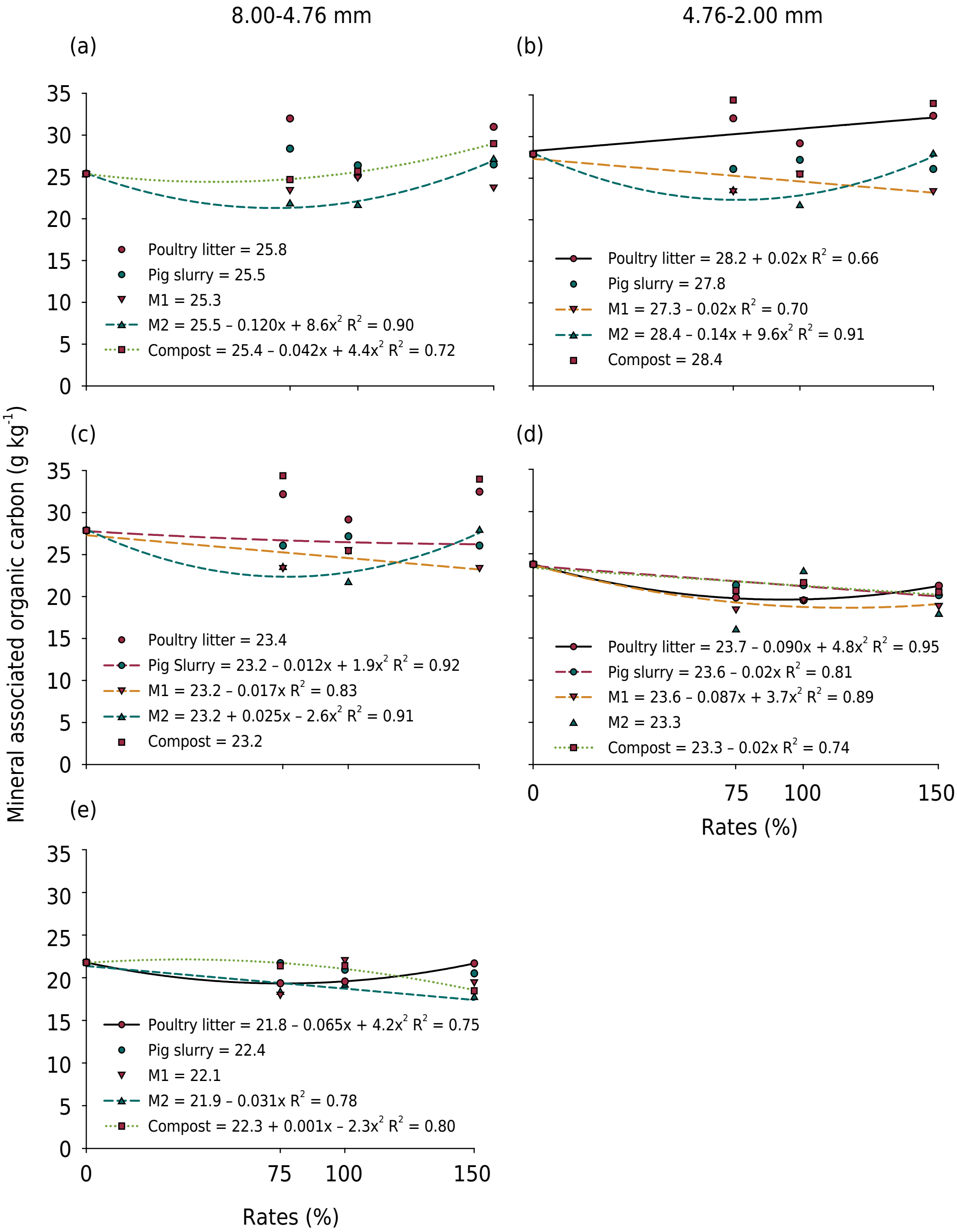

Figure 6. Mineral-associated organic carbon (g kg^{-1}) from 8-4.76 mm and 4.76-2 mm aggregates from Rhodic Kandiudox. (a,b) 0.00-0.05 m soil layer; (c,d) 0.05-0.10 m soil layer; and (e) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

interferes with the formation of aggregates and, consequently, with carbon protection (Degryze et al., 2004; Wang et al., 2021).

There is an important relationship between C and soil aggregation; when there is a greater input of organic material in the soil, the SOC contents and stock will soon increase, which favors the formation of aggregates (Baumgärtner et al., 2021). Therefore, the application of organic residues of animal origin in the soil, such as poultry litter and compost, becomes an alternative to improve the soil structure in the 0.00-0.05 m layer, as it can improve aggregation and increase the contents of organic carbon when compared to the control without fertilization (Fei et al., 2021).

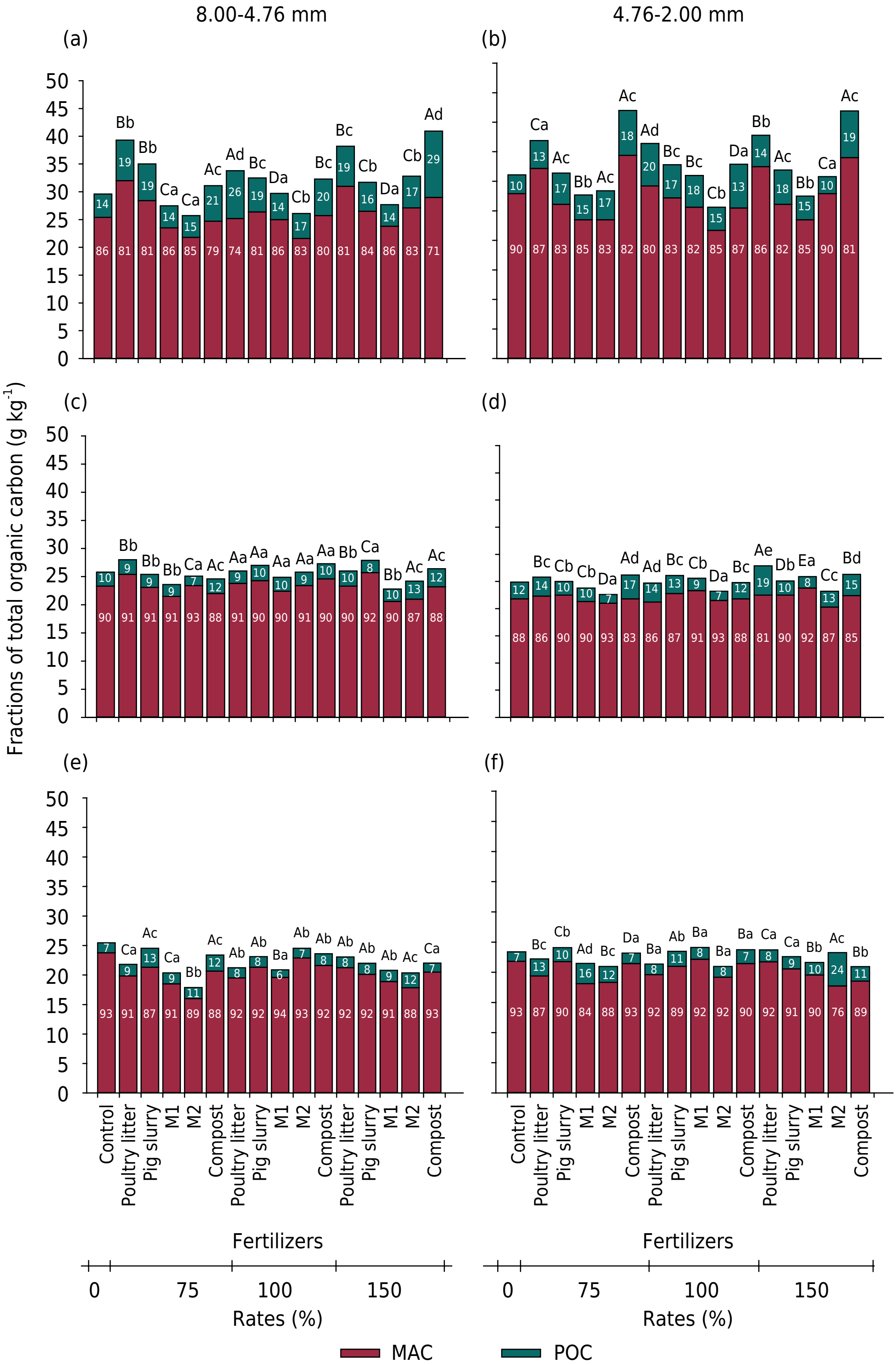

Figure 7. Proportion of fractions of total organic carbon (g kg^{-1}) (MAC in wine red and POC in grey) in the size aggregates of 8-4.76 mm and 4.76-2 mm in response to the application of organic and mineral fertilizers in a Rhodic Kandiudox. (a,b) 0.00-0.05 m soil layer; (c,d) 0.05-0.10 m soil layer; and (e,f) 0.10-0.20 m soil layer. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter. Uppercase letter compares the POC fractions and lowercase letter compare the MAC fractions. Through the Tukey ($p<0.05$).

The highest content of the POC fraction occurred in the surface layer 0.00-0.05 m in the different sizes of soil aggregates. In this way, it was possible to observe that the concentration of aggregates from 8 to 4.76 mm explains that the greater the size of these in this layer after the application of organic fertilizers, the increased storage and protection in the POC fractions (Six et al., 1999; Mustafa et al., 2021).

Soils that receive the application of organic fertilizers may improve their physical properties as in the case of aggregation. Physical properties such as texture are of paramount importance, since they influence the concentration of TOC fractions, a soil with a more clayey texture, as in the case of the present study, it tends to present a more stabilized fraction of the organic matter.

The presence of larger aggregates in the present study showed that the increasing rates of different types of organic and mineral fertilizers increased the fractions of total organic carbon in the soil, mainly the stabilized fraction, due to the physical protection mechanisms of C in these different aggregates. There is less access for microorganisms that degrade carbon, thus offering physical protection for the stabilization of soil organic matter, thus hindering the loss of C from the soil to the atmosphere (Barreto et al., 2009). These results further demonstrate the importance of high aggregate stability associated with the application of organic and mineral fertilizers that play an important role in the storage of carbon fractions.

Organic and mineral fertilizers showed significant results for the distribution of different sizes of aggregates, which demonstrated a positive effect for the addition of carbon to the soil and also as soil conditioning agents and protection of soil organic carbon fractions (Ferreira et al., 2021). In aggregates of 4.76-2.00 mm, the MAC fraction was lower for mineral fertilizer M1 (Figure 6b) compared to larger aggregates (8.00-4.76 mm). Which can be explained by the reason for these aggregates have higher organic matter content in relation to smaller aggregates, so the organic carbon content increases as the class of aggregates increases, a result that was observed with the increase in fertilization recommendation rates, and aggregate distribution.

The MAC fraction was predominant in the different sizes of soil aggregates and was influenced by the different rates of organic and mineral fertilizers. This fraction can be chemically protected in connection with clay and form more stabilized carbon fractions, due to the relationship with more humidified fraction of soil organic matter, which is linked with greater chemical stability, due to the strong interaction with the mineral fraction of the soil, and physical, by the protection inside the aggregates, evidencing the importance of the formation and distribution of aggregates (Courtier-Murias et al., 2013; Pinheiro Junior et al., 2021).

Application of organic fertilizers increases the concentrations of organic carbon in the soil. Animal residues present in their composition C, thus, the direct incorporation of C in the soil occurs. In addition, the use of organic fertilizers and minerals contributes to improving the physical, chemical and biological soil properties, which presents greater biomass for crops, thus improving the addition of C by plant residues in the soil (Mustafa et al., 2022).

The increase in TOC fractions in the surface layer can be explained by the direct application of the different types of organic fertilizers used, thus increasing the carbon input and the release of other nutrients to the plants. The inorganic composition of mineral fertilizers can explain the difference in the content of TOC in the soil, which shows the importance of applying organic fertilizers in conservation systems.

Another important factor for the increase in carbon in the surface layer may be related to the concentration of roots in this layer and the implementation of the iCL as it is a conservation system, which promotes the entry of plant residues through the use of pastures and other crops in the production system, showing important results for soil physical properties by including species with different root systems improving soil structure such as porosity, aeration and aggregate stability (Costa et al., 2015). According to Almeida et al. (2014), the concentration of roots in the surface layer of the soil stimulates the activity of microorganisms, increasing the presence of cementing agents in this layer, playing an important role in the formation and stabilization of soil aggregates and protection of soil organic carbon.

CONCLUSIONS

Poultry litter organic fertilizer increases aggregation, forming large aggregates with a size of 8.00-4.76 mm and increases the contents of total fractions of soil organic carbon, providing the system with a more stabilized carbon. Organic fertilizers increased the TOC content in the 0.00-0.05 m soil layer. The stabilized fraction (MAC) showed a higher proportion of total soil organic carbon than particulate organic carbon (POC).

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REFERENCES

Almeida RF, Machado HA, Martins FP, Queiroz ID, Teixeira WG, Mikhael JER, Borges EM. Correlação do tamanho e distribuição dos agregados em Latossolos Amarelo da região do triângulo mineiro em diferentes ambientes. Biosci J. 2014;30:1325-34.

American Public Health Association - APHA. Standard methods for the examination of water and wastewater. 22nd ed. Washington, DC: American Public Health Association; 2012.

Anghinoni I, Moraes A, Carvalho PCF, Souza ED, Conte O, Lang CR. Benefícios da integração lavoura-pecuária sobre a fertilidade do solo em sistema plantio direto. In: Fonseca AF, Caires EF, Barth G, editors. Fertilidade do solo e nutrição de plantas no sistema plantio direto. Ponta Grossa: Aeacg/Universidade Estadual de Ponta Grossa; 2011. p. 272-309.

Associação Nacional para Difusão de Adubos - ANDA. Estatística. São Paulo: ANDA; 2021. Available from: http://www.anda.org.br/estatistica/.

Association of Official Analytical Chemists International - AOAC. Official methods of analysis of AOAC international. 17th ed. Washington, DC: AOAC; 2000.

Barreto RC, Madari BE, Maddock JEL, Machado PLOA, Torres E, Franchini J, Costa AR. The impact of soil management on aggregation, carbon stabilization and carbon loss as CO_2 in the surface layer of a Rhodic Ferralsol in Southern Brazil. Agr Ecosyst Environ. 2009;132:243-51. https://doi.org/10.1016/j.agee.2009.04.008

Baumgärtner LN, Cordeiro RC, Rodrigues RAR, Magalhães CAS, Matos ES. Estoque e mecanismo de proteção física do carbono no solo em manejos agrícolas. Rev Bras Geogr. 2021;57:643-52. https://doi.org/10.26848/rbgf.v14.6.p3341-3354

Cambardella CA, Elliott ET. Particulate soil organic-matter chances across a grassland cultivation sequence. Soil Sci Soc Am J. 1992;56:777-83. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Chen K, Peng J, Li J, Yang Q. Stabilization of soil aggregate and organic matter under the application of three organic resources and biochar-based compound fertilizer. J Soils Sediments. 2020;20:3633-43. https://doi.org/10.1007/s11368-020-02693-1

Claessen MEC. Manual de métodos de análise de solo. 2. ed. Rio de Janeiro: Embrapa Solos; 1997.

Comissão de Química e Fertilidade do Solo - CQFS-RS/SC. Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina. 11. ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul; 2016.

Costa NR, Andreotti M, Lopes KSM, Yokobatake KL, Ferreira JP, Pariz CM, Bonini CSB, Longhini VZ. Atributos do solo e acúmulo de carbono na integração lavoura-pecuária em sistema plantio direto. Rev Bras Cienc Solo. 2015;39:852-63. https://doi.org/10.1590/01000683rbcs20140269

Courtier-Murias D, Simpson AJ, Marzadori C, Baldoni G, Ciavatta C, Fernandez JM, Sá EGL, Plaza C. Unraveling the long-term stabilization mechanisms of organic materials in soils by physical fractionation and NMR spectroscopy. Agr Ecosyst Environ. 2013;171:9-18. https://doi.org/10.1016/j.agee.2013.03.010

Degryze S, Six J, Paustian K, Morris SJ, Paul EA, Merckx R. Soil organic carbon pool changes following land-use conversions. Glob Change Biol. 2004;10:1120-32. https://doi.org/10.1111/j.1529-8817.2003.00786.x

Fei C, Zhang S, Li J, Liang B, Ding X. Partial substitution of rice husks for manure in greenhouse vegetable fields: Insight from soil carbon stock and aggregate stability. Land Degrad Dev. 2021;32:3962-72. https://doi.org/10.1002/ldr.4021

Ferreira GW, Benedet L, Trapp T, Andria PL, Muller Junior V, Loss A, Lourenzi CR, Comin JJ. Soil aggregation indexes and chemical and physical attributes of aggregates in a Typic Hapludult fertilized with swine manure and mineral fertilizer. Int J Rec Org W Agric. 2021;10:1-17. https://doi.org/10.30486/ijrowa.2021.1896960.1051

Guo Z, Zhang L, Yang L, Hua L, Cai C. Aggregate stability under long-term fertilization practices: The case of eroded Ultisols of south-central China. Sustainability. 2019;11:1169. https://doi.org/10.3390/su11041169

Hentz P, Correa JC, Fontaneli RS, Rebelatto A, Nicoloso RS, Semmelmann CEN. Poultry litter and pig slurry applications in an integrated crop-livestock system. Rev Bras Cienc Solo. 2016;40:e0150072. https://doi.org/10.1590/18069657rbcs20150072

Kemper WD, Chepil WS. Size distribution of aggregates. In: Black CA, Evans DD, White JL, Ensminger LE, Clarck FE, editors. Methods of soil analysis: Part 1 Physical and mineralogical properties, including statistics of measurement and sampling. Madison: American Society of Agronomy, Inc., Publisher; 1965. p. 499-510. https://doi.org/10.2134/agronmonogr9.1.c39

Koga N. Tillage, fertilizer type, and plant residue input impacts on soil carbon sequestration rates on a Japanese Andosol. Soil Sci Plant Nutr. 2017;63:396-404. https://doi.org/10.1080/00380768.2017.1355725

Li S, Li Y, Li X, Tian, X, Zhao A, Wang S, Wang S, Shi J. Effect of straw management on carbon sequestration and grain production in a maize-wheat cropping system in Anthrosol of the Guanzhong Plain. Soil Till Res. 2016;157:43-51. https://doi.org/10.1016/j.still.2015.11.002

Mafra MSH, Cassol PC, Albuquerque JA, Correa JC, Grohskopf MA, Panisson J. Acúmulo de carbono em Latossolo adubado com dejeto líquido de suínos e cultivado em plantio direto. Pesq Agropec Bras. 2014;49:630-8. https://doi.org/10.1590/S0100-204X2014000800007

Magalhães ACM, Blum J, Lopes FB, Tornquist CG. production components of the cowpea under different doses of organic fertiliser. J Exp Food Int. 2018;26:43558. https://doi.org/10.9734/JEAI/2018/43558

Midwood AJ, Hannam KD, Gebretsadikan T, Emde D, Jones MD. Storage of soil carbon as particulate and mineral associated organic matter in irrigated woody perennial crops. Geoderma. 2021;403:115185. https://doi.org/10.1016/j.geoderma.2021.115185

Mikutta R, Turner S, Schippers A, Gentsch N, Stüve SM, Condron LM, Peltzer DA, Richardson SJ, Eger A, Hempe G, Kaiser K, Klotzbücher T, Guggenberger G. Microbial and abiotic controls on mineral-associated organic matter in soil profiles along an ecosystem gradient. Sci Rep. 2019;9:10294. https://doi.org/10.1038/s41598-019-46501-4

Mustafa A, Frouz J, Naveed M, Zhu P, Nan S, M Xu, Núñez-Delgado A. Stability of soil organic carbon under long-term fertilization: Results from ^{13}C NMR analysis and laboratory incubation. Environ Res. 2022;76:11-24. https://doi.org/10.1016/j.envres.2021.112476

Mustafa A, Hu X, Abrar MM, Shah SAA, Nan S, Saeed Q, Kamran M, Naveed M, Conde-Cid M, Hongjun G, Ping Z, Minggang X. Long-term fertilization enhanced carbon mineralization and maize biomass through physical protection of organic carbon in fractions under continuous maize cropping. Appl Soil Ecol. 2021;165:103971. https://doi.org/10.1016/j.apsoil.2021.103971

Ozlu E, Kumar S. Response of soil organic carbon, pH, electrical conductivity, and water stable aggregates to long-term annual manure and inorganic fertilizer. Soil Sci Soc Am J. 2018;3:1243-51. https://doi.org/10.2136/sssaj2018.02.0082

Pikul JL, Osborne S, Ellsbury M, Riedell W. Particulate organic matter and water-stable aggregation of soil under contrasting management. Soil Sci Soc Am J. 2007;71:766-76. https://doi.org/10.2136/sssaj2005.0334

Pinheiro Junior CR, Pereira MG, Schultz N, Beutler SJ, Silva CF. Fertilidade do solo e dinâmica da matéria orgânica em áreas no perímetro irrigado Jaguaribe-Apodi, CE. ACSA. 2021;17:1-6. https://doi.org/10.30969/acsa.v17i1.1190

SMF, Wilson BR, Lockwood PV, Daniel H, Jovem IM. Soil organic carbon mineralization rates in aggregates under contrasting land uses. Geoderma. 2014;216:10-8. https://doi.org/10.1016/j.geoderma.2013.10.023

Rauber LP, Piccolla C, Andrade AP, Friederichs A, Mafra AL, Corrêa JC, Albuquerque JA. Physical properties and organic carbon content of a Rhodic Kandiudox fertilized with pig slurry and poultry litter. Rev Bras Cienc Solo. 2012;36:1323-32. https://doi.org/10.1590/S0100-06832012000400026

Ribeiro DO, Castoldi1 G, Silva HD, Calvacante TJ, Almeida Júnior JJ, Lima LIO, Carballal MR. Atributos físicos de um Latossolo após o uso de doses de cama de frango acrescidas à adubação mineral. Colloq Agr. 2019;15:9-17. https://doi.org/10.5747/ca2019.v15.n2.a280

Rigo AZ, Corrêa JC, Mafra AL, Hentz P, Grohskopf MA, Gatiboni LC, Bedendo G. Phosphorus fractions in soil with organic and mineral fertilization in a crop-livestock integration system. Rev Bras Cienc Solo. 2019;43:e0180130. https://doi.org/10.1590/18069657rbcs20180130

Six JA, Bossuytc H, Degryzed S, Denefb K. History of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Till Res. 2004;79:7-31. https://doi.org/10.1016/j.still.2004.03.008

Six J, Elliott ET, Paustian K. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci Soc Am J. 1999;63:5:1350-8. https://doi.org/10.2136/sssaj1999.6351350x

Soares MB, Freddi OS, Matos ES, Tavanti FRT, Wruck FJ, Lima JP, Marchioro V, Franchini JC. Integrated production systems: An alternative to soil chemical quality restoration in the Cerrado-Amazon ecotone. Catena. 2020;185:104-279. https://doi.org/10.1016/j.catena.2019.104279

Sodhi GPS, Beri V, Benbi DK. Soil aggregation and distribution of carbon and nitrogen in different fractions under long-term application of compost in rice-wheat system. Soil Till Res. 2009;103:412-8. https://doi.org/10.1016/j.still.2008.12.005

Tedesco MJ, Gianello C, Bissani CA, Bohnen H, Volkweiss SJ. Análises de solo, plantas e outros materiais. 2. ed. Porto Alegre: Universidade Federal do Rio Grande do Sul; 1995. (Boletim técnico, 5).

Troleis MJB, Roque CG, Borges MCR, Nogueira KB, Gouveia NA. Estabilidade de agregados e teor de matéria orgânica em um Latossolo Vermelho sob Urochloa Brizantha após a aplicação de cama de peru. J Neotrop Agr. 2017;4:1:83-7. https://doi.org/10.32404/rean.v4i1.1267

Ventura BS, Loss A, Giumbelli LD, Ferreira GW, Bueno AC, Lourenzi CR, Comin JJ, Brunetto G. Carbon, nitrogen and humic substances in biogenic and physicogenic aggregates of a soil with a 10- year history of successive applications of swine waste. Trop Subtrop Agroecosystems. 2018;21:329-43.

Vezzani FM, Mielniczuk J. Agregação e estoque de carbono em argissolo submetido a diferentes práticas de manejo agrícola. Rev Bras Cienc Solo. 2011;1:213-23. https://doi.org/10.1590/S0100-06832011000100020

Von Lützow M, Kögel-Knabner I, Ludwig B, Matzner E, Flessa H, Ekschmitt K, Guggenberger G, Marschner B, Kalbitz K. Stabilization mechanisms of organic matter in four temperate soils: Development and application of a conceptual model. J Plant Nutr Soil Sci. 2008;171:111-24. https://doi.org/10.1002/jpln.200700047

Wang RJ, Song JS, Feng YT, Zhou JX, Xie JY, Asif KCGX, Zhang SL, Yang XY. Changes in soil organic carbon pools following long-term fertilization under a rain-fed cropping system in the Loess Plateau, China. J Integr Agric. 2021;20:9:2512-25. https://doi.org/10.1016/S2095-3119(20)63482-7

Wang S, Li T, Zheng Z. Distribution of microbial biomass and activity within soil aggregates as affected by tea plantation age. Catena. 2017;153:1-8. https://doi.org/10.1016/j.catena.2017.01.029

Xie J, Hou M, Zhou Y, Wang R, Zhang S, Yang X, Sun B. Carbon sequestration and mineralization of aggregate-associated carbon in an intensively cultivated Anthrosol in north China as affected by long term fertilization. Geoderma. 2017;296:1-9. https://doi.org/10.1016/j.geoderma.2017.02.023

Zou C, Li Y, Huang W, Zhao G, Pu G, Su J, Coyne MS, Chen Y, Wang L, Hu X, Jin Y. Rotation and manure amendment increase soil macro-aggregates and associated carbon and nitrogen stocks in flue-cured tobacco production. Geoderma. 2018;325:49-58. https://doi.org/10.1016/j.geoderma.2018.03.017