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Soil carbon fractions in response to mineral and organic fertilizer types and rates

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ABSTRACT: The use of organic fertilizers from pig slurry and poultry litter can increase soil organic carbon and crop productivity. This study aimed to evaluate soil organic carbon fractions and corn yield after applying organic and mineral fertilizers. The experiment was conducted in the western region of Santa Catarina State, southern Brazil on a *Nitossolo Vermelho Eutroférrico típico* (Rhodic Kandiudox). The production system was an integrated crop-livestock using corn and soybean in the summer and black oat and rye with grazing by sheep in the winter. The experimental design was randomized blocks, with treatments in factorial 5 × 3 + 1, with four replications, five sources of fertilizers, three rates and the control with no fertilization. The treatments were three organic fertilizers: poultry litter, pig slurry and compost from pig slurry and two minerals fertilizer (M1 and M2). Mineral fertilizers were formulated from pig slurry (M1) and poultry litter (M2), with the application of three rates, which represent 75, 100 and 150 % of the recommendation for the crop, based on the element that is most demanding by the plant (K for soybeans and N for corn). Soil samples were collected at the layers of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m in which fractions of total soil organic carbon (TOC), namely particulate (POC) and mineral-associated organic carbon (MAC) were determined. Corn yield was evaluated in the 2018/2019 and 2019/2020 seasons. The results were analyzed through analysis of variance to compare sources and polynomial regression analysis for fertilizer rates. The MAC fraction has a higher proportion of TOC and its contents were higher with increasing rates of organic and mineral fertilizers, mainly in the surface layer. Poultry litter and compost fertilizers increased TOC's particulate fraction (POC), showing the highest levels at the highest fertilization recommendation rate. Organic and mineral fertilizers positively increase corn yield, and animal-derived fertilizers show that they can be an alternative for high crop yields.

Keywords: total organic carbon, organic fertilization, and corn productivity.

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INTRODUCTION

Soil stores around 1580 Gt of carbon (C), playing an important role in the C conservation and protection processes (Schimel, 1995; Li et al., 2017). Managements prioritizing the increase in C concentrations are important, mainly to maintain crop productivity and soil quality. Production systems such as integrated crop-livestock (ICL) become a sustainable alternative for productivity, as they increase soil C as well as benefit the soil physical, chemical and microbiological properties, in addition to being a conservationist option to the current model of agriculture, which is characterized by low plant diversity and high use of soluble inputs (Moojen et al., 2022; Silva et al., 2022).

Soil organic matter (SOM), which has 58 % C and other macro and micro-nutrients, is an important component of soil fertility and productivity, that can be improved through better SOM management using efficient agronomic practices such as no-tillage, liming and fertilization, crop rotation and minimum tillage. To achieve this objective, a better understanding of the forms and amount of total organic carbon (TOC) is necessary, as its fractions can change according to the management adopted and the characteristics of soil and climate (Abdalla et al., 2018; He et al., 2018a).

The granulometric fractionation method of the TOC into particulate organic carbon (COP) and carbon associated with minerals (MAC) is used to evaluate soil quality. The former has a higher carbohydrate content and the latter contains aliphatic or aromatic materials and these fractions can be differently affected by management practices (Cambardella and Elliott, 1992; Six et al., 1999; Midwood et al., 2021; Mustafa et al., 2021). Thus, the use of pig slurry and poultry litter rates in agricultural areas can affect soil carbon fractions, as they can improve soil properties as well as increase nutrient cycling and productivity of agricultural crops (Oliveira et al., 2017; Soares et al., 2020).

The rates of organic fertilizers can increase soil carbon inputs due to the high amount of organic residue applied. Ashraf et al. (2020) observed that the increase in C contents and its fractions was associated with the application of higher rates of animal organic residues, compared to the balanced application of organic fertilizer; however, this relationship may be affected due to the well-balanced soil texture as chemical composition of fertilizers. These fractions provide a better understanding of TOC stabilization and turnover. In this sense, through the knowledge of the fractions of C and the characteristics of soil and fertilizers, it is possible to adjust fertilization rates according to the soil types, aiming to maximize crop responses and reduce the polluting potential of organic residues (Mafra et al., 2015; Midwood et al., 2021).

Therefore, understanding the relationship of TOC fractions in response to the application of organic and mineral fertilizers allows a better understanding of the protection and stability of C. Long-term organic fertilization in the soil may increase TOC fractions, while mineral fertilization may show opposite results (Shah et al., 2021; Waqas et al., 2020). These results can be attributed to the types and amounts of fertilizers which, in turn, affect the chemical composition of the TOC. Furthermore, applying organic fertilizers from animal waste may result in an increased concentration of TOC fractions (Sarma et al., 2017; Qaswar et al., 2020).

High rates of organic and mineral fertilizers can improve C fractions in two ways, the organic residue contains high amounts of C and, therefore, directly adds C to the soil, mineral fertilizers can improve the physical properties of the soil, due to the increase in productivity of crops that have higher biomass, which can also add C through plant residues in the soil which can benefit soil structure as well as increase aggregation and improve TOC storage (He et al., 2018b; Mustafa et al., 2021). The objective of this study was to evaluate the fractions of soil organic carbon and corn yield due to forms and rates of organic and mineral fertilizers applied in an integrated crop-livestock system.

MATERIALS AND METHODS

The experiment was carried out in southern Brazil, in the municipality of Concórdia (27° 12′ 0.08″ S and 52° 4′ 58.22″ W), west of Santa Catarina State, since June 2011. The production system was an integrated crop-livestock, implemented in a no-tillage system with corn (cv. Syngenta Celeron LT) intercropping with *Brachiaria brizantha* cv. Xaraés in the summer and rye (*Secale cereale* L.) in the winter.

Two lime rates of 5 Mg ha^{-1} (dolomitic limestone) were applied, and pig slurry rates of 50 m^3 ha^{-1} were annually spread according to the normative instruction of the Santa Catarina Environmental Institute (IMA-IN11) in November of each year and mineral fertilization according to the crop demand, based on soil analysis and grain yield estimation by CQFS-RS/SC (2016). Before sowing the winter pasture, the soil was chiseled to loosen the surface layer of the area. 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 in the area was classified according to the Brazilian Soil Classification System as a *Nitossolo Vermelho Eutroférrico típico*, corresponding to a Rhodic Kandiudox (IUSS Working Group WRB, 2015). The chemical and physical properties of the soil are shown in table 1. The regional climate is humid subtropical (Cfa), according to the Köppen classification system, with mean temperatures around 15 °C in winter months (June and July) and mean annual temperature of 23 °C. The rains are regular and well distributed, with no hydrological deficit and total annual rainfall of 1.500 mm. The predominant relief is undulating to gently undulating and altitude of 569 m above sea level (Hentz et al., 2016). Temperature and precipitation data were measured at the *Embrapa Suínos e Aves* weather station (Figure 1).

Table 1. Initial characterization of the *Nitossolo Vermelho Eutroférrico típico* (Rhodic Kandiudox) in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers

Properties	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

Soil analyses were 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. Clay content was determined according to Claessen (1997).

The production system adopted was integrated crop-livestock with summer crops of corn (*Zea mays*) and soybean (*Glycine max*) and black oat (*Avena sativa* Schreb) and rye (*Secale cereale* L.) during winter with sheep grazing, using 20 females per ha in a rotational use. The grazing cycles were carried out five to six times between autumn and winter and its duration was adjusted according to pasture development, considering a initial pasture height of 0.35 and 0.40 m and residual height of 0.15 and 0.20 m.

The experimental design was in randomized blocks with four replications, and treatments consisted of a 5×3+1 factorial, with five sources and three rates of fertilizer recommendation for summer crops and a control treatment with no fertilization.

There are three treatments with organic fertilizers: poultry litter; pig slurry; and a compost from pig slurry and two minerals M1 (formulated according to the composition of the pig slurry) and M2 (it was adjusted according to the composition of poultry litter), the formulations being adjusted for each crop, according to the composition of the organic fertilizers used in each period, combined with three rates, equivalent to 75, 100 and 150 % of the recommendation for the cash crop, based on the element with higher demand for the crop (K for soybean and N for corn) (CQFS-RS/SC, 2016).

The control treatment did not receive fertilization. The experimental units consisted of 5 × 5 m (25 m^2) plots, 2.5 m apart between blocks, with no space between plots in the same block. Fertilizers were broadcast manually applied on the surface in summer and winter crops.

The pig slurry organic fertilizer was obtained through the complete breeding cycle system of the Federal Institute of Santa Catarina (IFC - Concórdia), where animals were raised on a compact floor system from birth to slaughter with an average live weight of 120 kg and mean age of 145 days.

Compost organic fertilizer was formulated based on pig slurry; its constitution was through the use of 8 to 12 liters of waste (4 to 6 % of dry matter) for every 1 kg of substrate

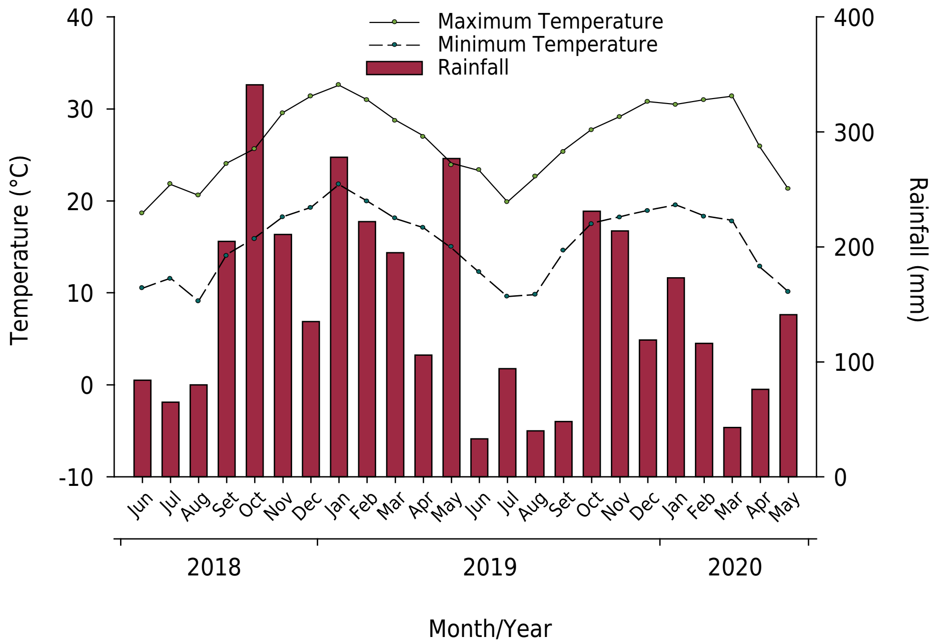

Figure 1. Precipitation (mm), maximum and minimum temperature (°C), registered during the experiment in the 2018-2020, crop seasons, Concórdia, Santa Catarina, Brazil.

formed by the mixture of shavings and sawdust, in a windrow of 1 m high, 3 m wide and 20 m long. The impregnation process in the wood shavings was carried out every week, with turning only in case of temperature rise inside the windrow above 60 °C. This operation was performed automatically until temperature stabilization, when the compost maturation process began until its application in the field.

Poultry litter was produced at IFC Concordia, where broiler birds were raised. Poultry litter used came from 5 to 6 lots of broilers. The chemical composition of organic fertilizers for each crop during the experiment and the C contribution were analyzed based on the official methodology (AOAC, 2000; APHA, 2012) and for the determination of N, P, and K (Table 2).

According to the results on the contents of N, P and K of organic fertilizers, formulations for mineral fertilizers were made. The N source was urea, for P it was triple superphosphate, and for K, potassium chloride was used; in the M1 treatment, the same amounts of these nutrients were added, as in the M2 treatment. The formulations of organic and mineral fertilizers were adjusted for each season based on their compositions applied in each period.

The corn crop (*Zea mays*) used in the evaluation period of the study was the cultivar Celeron TL Syngenta, simple hybrid, super early. For planting corn, sowing was carried out with 8-9 seeds per linear meter, with a spacing of 0.80 m between rows. Soybean (BRS 523) was planted with 18 seeds per linear meter, spaced 0.45 m between rows. The crops were sowed 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.

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 crop 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 crop 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 crop 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 the American Public Health Association – APHA (2012).

In the winter period, black oat (*Avena sativa* Schreb), common cultivar, was sown as a replacement for rye, with a density of 50 kg ha^{-1} of seeds, approximately 80 seeds per linear meter, spaced 0.20 m between rows.

Fractionation of total organic carbon

To determine the soil organic carbon, samples were collected in the layers of 0.00-0.05, 0.05-0.10 and 0.10-0.20 m; ten sub-samples in each depth and treatment were randomly taken with the aid of a mechanized auger. The fractions of total organic carbon, particulate organic carbon (POC) and mineral-associated organic carbon (MAC) were determined.

Samples were ground in a porcelain grate and the determination of TOC fractions was carried out by dry combustion in an elemental TOC analyzer VCSH Shimadzu. The POC was fractionated from a mixture of 20 g of soil and 60 mL of sodium hexametaphosphate (5 g L^{-1}) (soil chemical dispersion), with horizontal agitation for 16 h and sieving in a 53 µm mesh, the correction was made for the mass of sand in the POC contents (Cambardella and Elliott, 1992). After separation, the particulate fraction was dried in an oven at 50 °C, and determined in an elemental analyzer. Mineral-associated organic carbon was calculated by the difference between COT and POC, respectively.

Corn crop productivity

The harvest of corn grains was manual, collecting the ears contained in 2 rows with 2 m in length and 0.8 m in width between rows. Then, manual threshing, weighing and drying were performed, determining the mass of the harvested grains to calculate the grain yield per hectare with 13 % moisture (wet basis). Plant population was determined by counting the number of plants contained in the useful area of the plot, at the harvest. Due to the pandemic limitation, data from the dry matter evaluation of the above-ground biomass were harmed and will not be presented for study.

Statistical analysis

The 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 used were fertilizer, rates, and organic carbon fractions; 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

Total organic carbon fractions

The MAC was the most representative fraction of the TOC for all rates and layers evaluated; the organic fertilizer presented the highest fractions of POC in all rates of the fertilization recommendation in the surface layer (Figure 2a).

Poultry litter organic fertilizer presented higher MAC content (75), pig slurry (100) and M2 (100 and 150) increased the soil MAC fractions for the same layer. With increasing depth, the TOC fractions decreased, the fertilizers M2 (100 and 150) and compost (75) had the highest concentrations of POC, while for MAC the highest concentrations were for pig slurry, M1 (75) and M2 (75, 100 and 150) in the 0.05-0.010 m layer (Figure 2b).

In the layer of 0.10-0.20 m, poultry litter (75 and 100) and pig slurry (100), M1 (75, 100 and 150) presented higher content of the POC fraction, for the MAC fraction compost (75), M1 (75, 100) and M2 (150) showed significant results for this fraction of the TOC (Figure 2c).

In response to the increasing rates of fertilizer recommendation, poultry litter, pig slurry and compost increased the POC fractions at the highest rates, a different result was found for mineral fertilizers, that is, there was a decrease in the 0.00-0.05 m layer (Figure 3a). For the MAC fraction of the TOC, only poultry litter, M2 and compost showed significant adjustments; poultry litter presented its highest increase up to 100 %, then decreasing with the increase of the highest rate, with inverse result for M2 and compost fertilizers (Figure 3b).

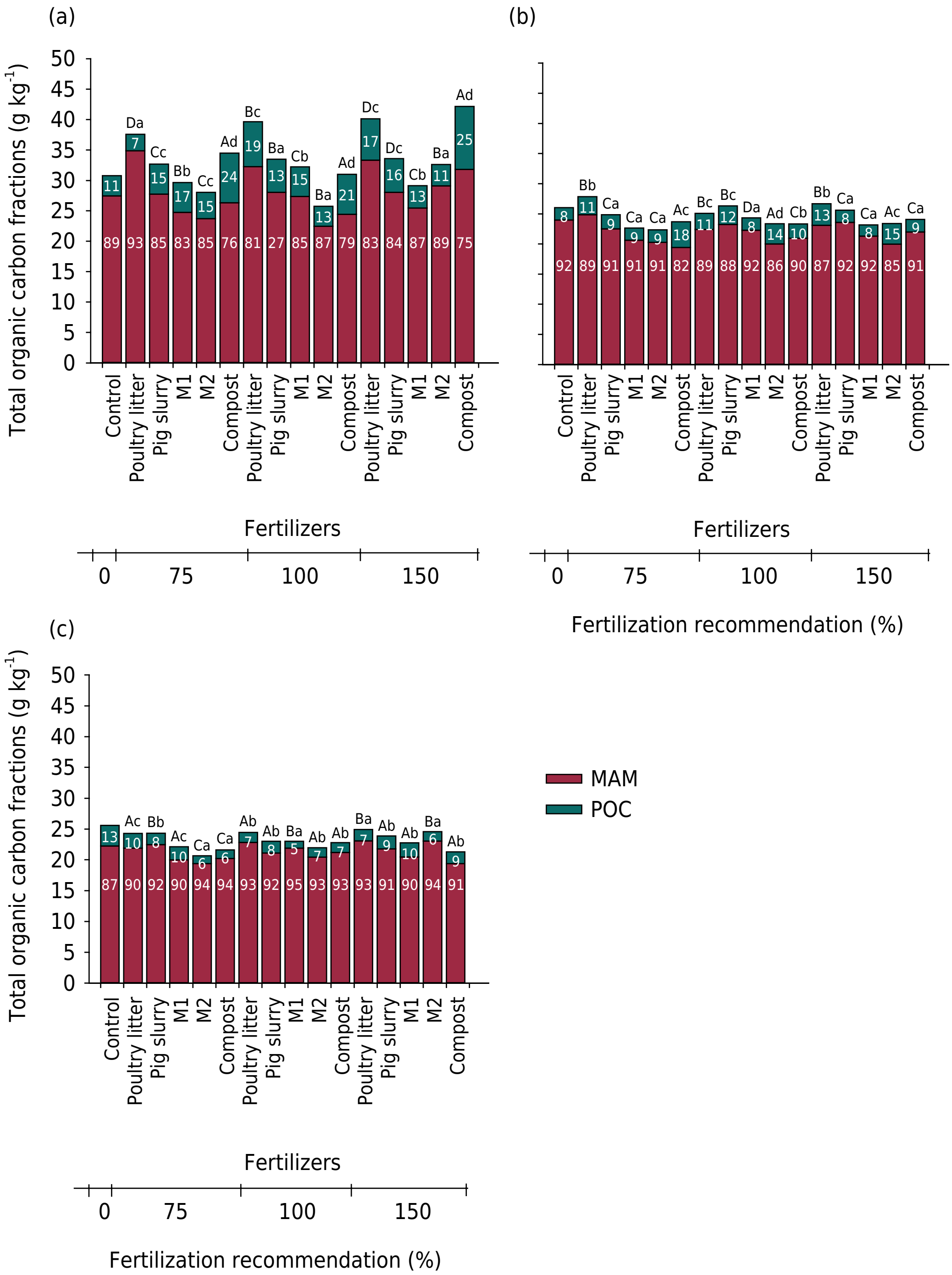

Figure 2. Proportion of total organic carbon fractions (g kg^{-1}) in response to application of organic and mineral fertilizers from Rhodic Kandiudox. a: 0.00-0.05; b: 0.05-0.10; and c: 0.10-0.20 m. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter. Uppercase letters compare the POC fractions and lowercase letters compare the MAC fractions. Mean values are not different through the Tukey (p<0.05).

In the 0.05-0.10 m layer, poultry litter and M2 increased POC fraction, and pig slurry and compost fertilizers increased this fraction at the rate of 75 % (Figure 3c). The MAC fraction increased in response to fertilization rates for M1 and compost, with a better response for rate 150 % (Figure 3d). In the 0.10-0.20 m layer, all fertilizers showed significant adjustments for COP fraction in response to applied rates (Figure 3e). The MAC fraction increased in the M2 treatment according to fertilization recommendation rates (Figure 3f).

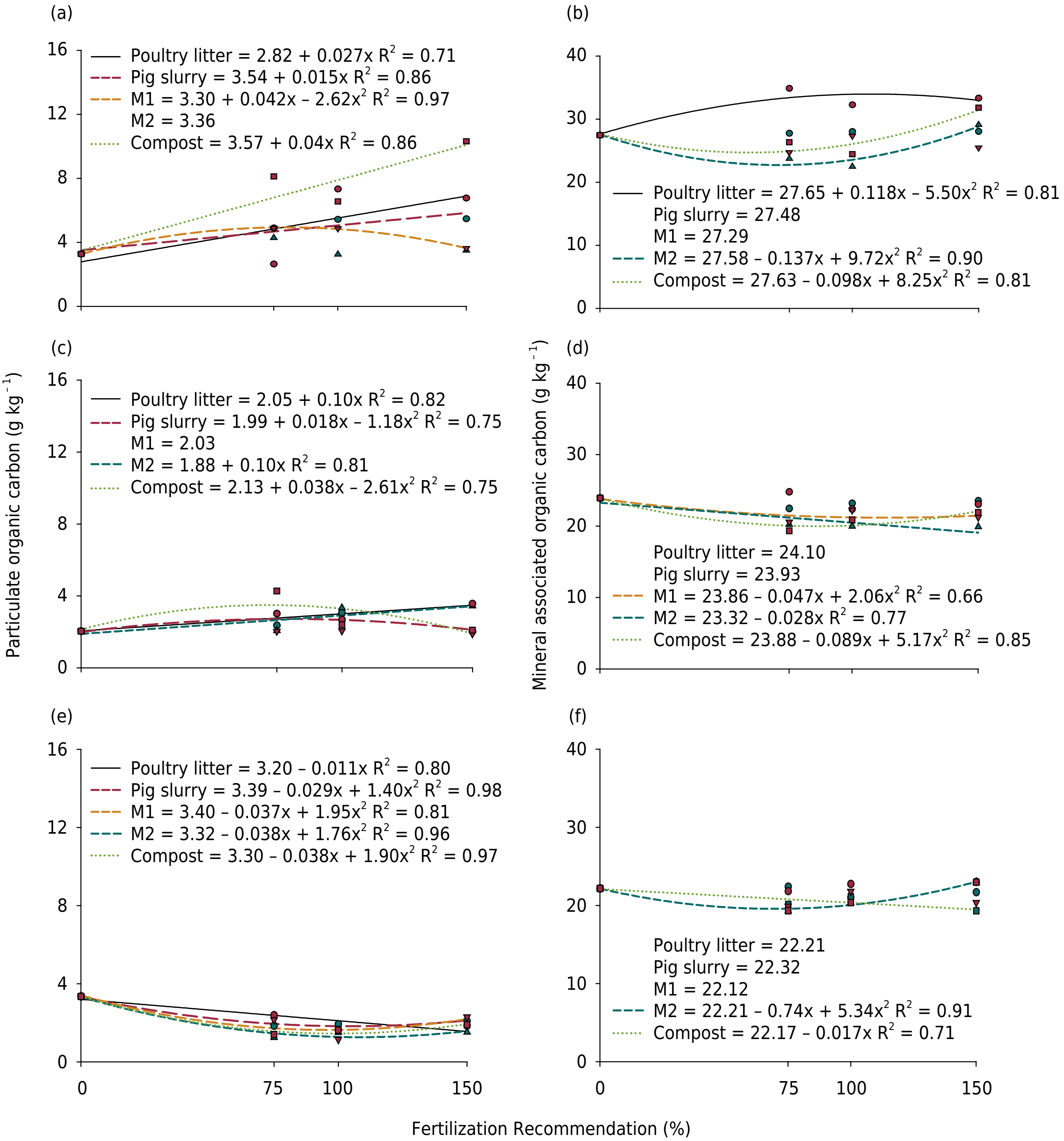

Figure 3. Total organic carbon fractions (TOC) (g kg^{-1}) of a Rhodic Kandiudox. a/b: 0.00-0.05: c/d: 0.05-0.10; and e/f: 0.10-0.20 m. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

Corn productivity

Corn grain productivity increased in response to the application of organic and mineral fertilizers and due to the increase in rates in both agricultural seasons. In 2018/2019 corn yield increased due to organic and mineral fertilizers. Poultry litter, pig slurry, and M2 increased corn yield at the highest fertilization rate, while M1 fertilizers decreased to a higher rate and compost increased at a rate 75 (Figure 4).

In the 2019/2020 crop year, corn productivity positively responded to increasing fertilization recommendation rates. All fertilizers increased productivity for the evaluated crop. Poultry litter, pig slurry and M1 showed an increase in productivity for the highest rate of fertilization recommendation, the mineral fertilizer M2 and compost increased productivity from the rate 100, thus the productivity was higher at the highest rates. Productivity was higher in the 2019/2020 crop compared to 2018/2019, which can be explained by the lower amount of rain in this period (Figure 1).

DISCUSSION

Proportion of total organic carbon fractions

Application of organic fertilizers increases organic carbon concentrations in the soil. These animal manures present C in their composition and can improve soil physical, chemical and biological properties, which can increase crop biomass, and result in higher C addition as crop residues in the soil (Mustafa et al., 2022a).

The increase in TOC fractions in response to organic fertilizer application in the surface layer can be justified by the carbon input and the release of nutrients to the plants. In addition, the inorganic composition of mineral fertilizers may explain the difference in the contents of the TOC fractions, which assigns an important role in the application of organics to the studied soil (Li et al., 2017). These results indicate that the TOC content of the soil increased in the surface layer in response to rates of organic and mineral fertilizers.

Contents of TOC fractions positively responded to rates of poultry litter and compost in the superficial layer. The contribution of carbon to the soil with the application of organic and mineral fertilizers increased the levels of TOC fractions in the 0.00-0.05 m

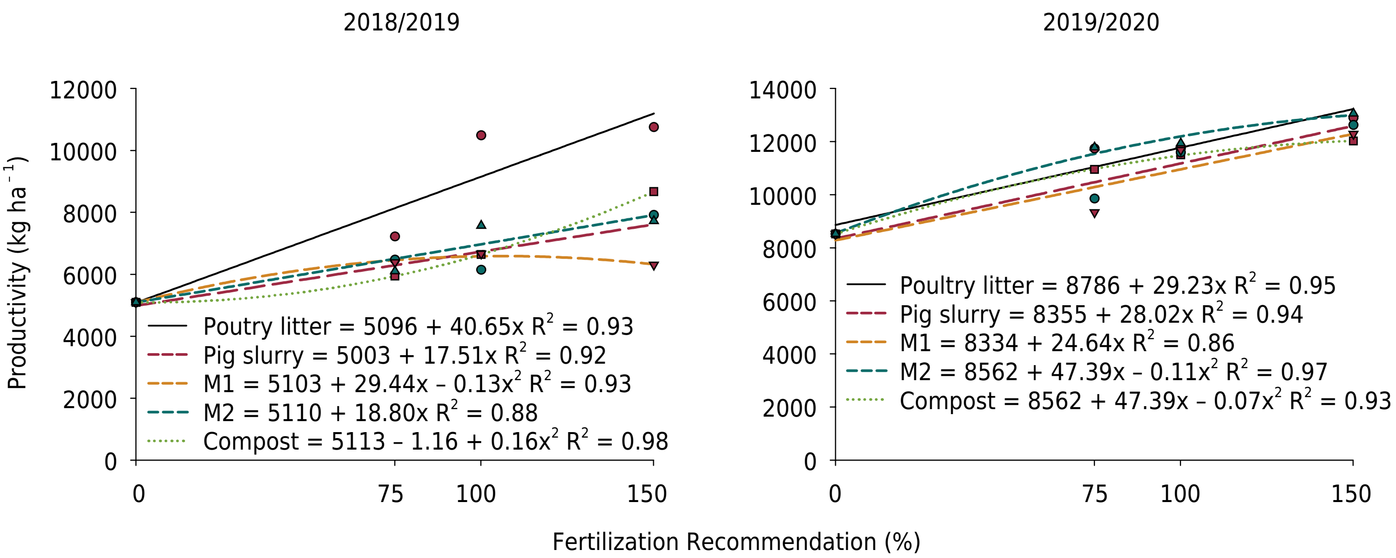

Figure 4. Corn grain yield (kg ha^{-1}) in response to the application of increasing rates of organic and mineral fertilizers in a Rhodic Kandiudox. M1: mineral fertilizer 1, equivalent to pig slurry; M2: mineral fertilizer 2, equivalent to poultry litter.

layer, mainly at 100 and 150 % rates. A similar result was found by Mustafa et al. (2022b) in a study evaluating the long-term effect of organic and mineral fertilizers, increasing soil organic carbon concentrations in response to rates of organic fertilizers. This result was associated with the addition of C via organic fertilizers. In another study that evaluated the role of organic and mineral fertilization, organic carbon contents increased due to the application of animal manure rates, compared to mineral fertilizers. Thus, the associated use of organic and mineral fertilizers would be a viable option to improve nutrient availability to crops and store carbon in the soil (Ashraf et al., 2020).

The stabilized MAC was the predominant TOC fraction, which can be associated with the inherent clayey and Fe rich soil condition and can occur despite the application of organic fertilizers (Mi et al., 2019). Clay soils increase the stability of organic substrates and microbial biosynthesis, thus, clay soils protect carbon and can raise its levels, this occurs by the formation of organomineral complexes, which results in the accumulation of organic matter with the increase in clay content (Conceição et al., 2008; Silva et al., 2014). The MAC is associated with the silt and clay fractions of the soil and is characterized as the fraction of SOM that interacts with the surface of mineral particles, forming organomineral complexes, and being protected by the colloidal protection mechanism (Loss et al., 2009). In this way, the organic compounds of fertilizers of animal origin can be chemically protected in connection with clay and form more stabilized carbon fractions, due to their relationship with the more humified fraction of soil organic matter, which is linked with greater chemical stability, by the strong interaction with the mineral fraction of the soil (Courtier-Murias et al., 2013; Pinheiro Junior et al., 2021). Furthermore, it is a fraction of C that is more resistant to biodegradation, caused mainly by the organomineral complexes that are generated by the mineralogical composition of the soil, these complexes are responsible for increasing the protection of more recalcitrant functional groups in the long term, with this there is greater protection and preservation of MAC in the soil thus increasing soil carbon sequestration (Li et al., 2017).

The POC fraction presented its highest content in the surface layer of the soil, this type of TOC fraction is a labile fraction and can be linked to root activity, crop residues and fungal hyphae. These components depend on soil type, fertilizer use and management practices, and can be considered a sensitive indicator of soil quality (Li et al., 2017; Ge et al., 2021). Thus, long-term applications of organic or mineral fertilizers can increase soil organic C in several ways, with a variable influence on labile or recalcitrant forms, and then defining a more stable carbon or not (Tong et al., 2014).

The study of the relationship between organic and mineral fertilizers for carbon sequestration is essential, since the application of organic fertilizer in soils is an important agricultural practice to increase the contents and fractions of organic carbon in the soil, also showing the important role of the physical fractionation of carbon to obtain results that help decision-making in the productive areas.

Corn productivity

Organic and mineral fertilizers increased corn productivity, especially poultry litter and compost fertilizers in the 2019/2020 crop season when the rainfall distribution was irregular. Rigo et al. (2019) also found that the application of organic fertilizers poultry litter, pig slurry and mineral M1 increased corn productivity due to the suitable nutrient availability. The long-term use of organic fertilizers has positive effects on corn yield and can additionally improve soil structure and bacterial diversity. The animal manures increase nutrient availability in the soil, with better corn yield, when compared to mineral fertilizers (Mei et al., 2021).

Application of organic and mineral fertilizers is a soil management practice that increases the accumulation of organic carbon in the soil and collaborates in the nutrient cycling. In this way, organic fertilizers can increase soil TOC and crop yields. In addition, long-term applications of organic and mineral fertilizers are factors that contribute positively to corn production, as observed in the present study. Mustafa et al. (2021) evaluated corn yield response to fertilizers for 28 years, and animal organic fertilizers increased corn grain and biomass production in relation to mineral sources, associated with a higher nutrient supply to the crop. The results obtained for corn productivity in the 2018/2019 and 2019/2020 crop years, in the iCL conservation system, showed that organic and mineral fertilizers were important for increasing productivity.

CONCLUSIONS

Mineral-associated organic carbon (MAC) fraction has a higher proportion of total organic carbon (TOC) and its contents increase with increasing rates of organic and mineral fertilizers, mainly in the surface layer. Poultry litter and compost fertilizers increased the particulate fraction particulate organic carbon (POC) of TOC, showing the highest levels at the highest fertilization recommendation rate. Application of organic and mineral fertilizers increases TOC levels in the layer of 0.00-0.05 m. Organic and mineral fertilizers increase corn yield and animal-derived fertilizers can be an efficient source for high crop yields.

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