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Long-term effects of grazing intensities on soil aggregation and organic matter in a no-tilled integrated soybean-cattle system

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ABSTRACT

Grazing intensity in integrated crop-livestock systems (ICLS) can affect soil aggregation and C stabilization and, consequently, the soil condition and agricultural sustainability. This study evaluate the influence of 13 years of different grazing intensities on (i) soil aggregation, (ii) C content in different aggregate size, and (iii) C and N content in different fractions of soil organic matter (SOM), in a no-tilled with integrated soybean-beef production system on a subtropical Oxisol. Treatments consisted of four steers grazing intensities defined by sward height of 10, 20, 30 and 40 cm on mixed black oat and Italian ryegrass pasture in the winter under continuous stocking, plus an ungrazed treatment, in a randomized complete block design with three replicates. Soil aggregation was not affected by grazing intensities. There was no effect of the grazing intensities on organic C content in all aggregate-size fractions and in all soil layers evaluated, being lower in microaggregates than in large and small macroaggregates. The macroaggregates were predominant, representing 97% of the soil mass, of which 74% were large macroaggregates (>2 mm). The high macroaggregates stability contributed to the lack of difference in the C and N content on free light fraction and the light occlusal fraction of SOM. Most of C and N were observed heavy fraction of SOM (53–68%), with greater stock in the no grazing compared to the grazed treatments. Even with the animal trampling in the grazed systems, the soil maintained high stability of aggregates and consequently the labile forms of SOM.

1. Introduction

Soil aggregation is a hierarchical process of structure formation, originated from the interaction of physical, chemical and biological processes in the soil (Lavelle et al., 2020). Firstly, occurs the formation of microaggregates, by the approximation of clay particles linked by cations and organic compounds. After that, the aggregation process results in macroaggregates, which are less stable than microaggregates due to the binding nature and agents involved (Oades, 1984; Mondal and Chakraborty, 2022).

As a result of aggregates formation, the organic material is protected inside them, becoming less vulnerable to microbiological access and mineralization (Oades, 1984; Tisdall, 1996; Pinto et al., 2021). Consequently, soil aggregates play a key role as physical barriers preventing microorganisms to access organic substrate (Dieckow et al., 2004; Topa et al., 2021). Due to this physical protection, studies have shown a direct relationship between soil organic carbon (SOC) content and aggregate stability index (Salton et al., 2008; Ozly and Arriaga, 2021). Therefore, adequate soil management may increase soil aggregation and promote chemical, physical and biological changes that result in C accumulation on different soil organic matter (SOM) fractions.

Integrated crop-livestock systems (ICLS) have become an efficient alternative for agricultural land use, since they propose the diversification of plant species and the insertion of grazing animals in the production system (Nunes et al., 2021; Peterson et al., 2020; Carvalho et al., 2021). The benefits to the soil are increased when ICLS are conducted in no-tillage system (NTS), since the presence of crop residues on soil surface promote the formation and preservation of soil aggregates (Silva et al., 2018). The use of ICLS promote soil aggregation and SOC accumulation and can, consequently, improve soil quality (Souza et al.,

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2010; Loss et al., 2012; Neto et al., 2014).

Grazing can morphologically modify plant aerial structure and roots (Barros et al., 2017), playing an important role in aggregates genesis. Similarly, morphological changes in plants can cause nutrient cycling modifications by changing soil biotic and abiotic conditions (Anghinoni et al., 2011). The excreta of grazing animals also exert a strong influence on nutrient concentration (Carpinelli et al., 2020) and in microbial communities, resulting in changes on SOM decomposition process and N availability (Cao et al., 2019). Thus, promoting C and N cycling by crop residues and animal excreta can reduce the need of N fertilizers, recycling nutrients within the system and improving soil quality (Soussana and Lemaire, 2014). However, the influence of grazing intensity in soil aggregation and SOC accumulation is still unclear.

It is expected that a higher grazing intensity will result in lower C content and lower soil aggregation, due to the reduction of plant residues on soil surface and the destruction of soil aggregates caused by animal trampling. On the other hand, in moderate grazing, it is expected larger aggregates with potential to increase soil C contents, either due to the alteration in residue decomposition by the presence of grazing animals in areas with enough amount of biomass, or by the physical protection of SOM inside aggregates. Thus, the study of the influence of grazing intensity of ICLS on soil aggregation and C content in the soil and in different fractions of SOM is essential as it is directly linked to soil condition, aiming to find production systems that can have a role on climate change mitigation and indirectly on the soil capital (Morgan and McBratney, 2020), as it will influence the productivity of the agricultural system, ensuring food security while increasing the biodiversity of production systems.

The objective of this study was to evaluate the influence of 13 years of different grazing intensities on (i) soil aggregation, (ii) C content in different aggregate size fractions, and (iii) C and N content in different fractions of soil organic matter, in a no-tilled with integrated soybean-beef production system on a subtropical Oxisol.

2. Material and methods

2.1. Field experiment

This study was developed in a 13-year-old experiment at Fazenda do Espinilho, in Southern Brazil (29° 03′ 10″ S latitude, 53° 50′ 44″ W longitude and altitude of 465 m). The climate is classified as subtropical humid and warm (Cfa) according to the Köppen classification, with average annual temperature of 19 °C and average annual rainfall of 1673 mm. The soil was classified as Rhodic Hapludox (540, 270 and 190 g kg^{-1} of clay, silt and sand, respectively), with the predominance of kaolinite in the deferricated clay fraction and goethite, hematite and maghemite in the concentrated Fe oxides fraction (Cecagno et al., 2016). The area of 22 ha was cultivated in no-tillage system from 1993 to 2001, growing black oats (*Avena strigosa* Schreb) and ryegrass (*Lolium multiflorum* Lam.) in the autumn/winter as cover crops, and soybean (*Glycine* max L. Merril) in the spring/summer season.

The field experiment was established in June of 2001 with the same systems, but then with the pasture being grazed during autumn/winter. The treatments consisted of different grazing intensities during the winter period, regulated by pasture height management of 10, 20, 30 and 40 cm, and a treatment without grazing. The plots ranged from 0.8 to 3.6 hectares and grazing treatments were arranged in a randomized block design with three replications.

Continuous grazing method was adopted with animals entering when the pasture reaches an average accumulation of 1.5 Mg ha^{-1} of biomass and about 20 cm of sward height. The grazing cycle usually begins in the first half of July, and the pasture sward height was monitored every 14 days, using the Sward stick method (Bircham, 1981). Male, young, and castrated cattle were inserted in the experimental area weighing around 200 kg, simulating a system for rearing steers or finishing animals.

After the first grazing cycle and before cultivation of the first soybean cycle, 4.5 Mg ha^{-1} of limestone with effective neutralizing power of 62% were applied on the soil surface of the whole experimental area following official recommendations for liming in Southern Brazil (CQFS-RS/SC, 2004). The fertilization consists basically of the application of N in the winter pasture, and phosphorus (P) and potassium (K) in soybean, considering the soil analyzes, at rates needed to reach 7.0 Mg ha^{-1} dry matter of pasture and soybean yield of 4.0 Mg ha^{-1} following official recommendations for fertilization in Southern Brazil (CQFS-RS/SC, 2004). About 45 days after the sowing of the pasture, N was applied using urea (Table 1). The total amount of N, P_2O_5 and K_2O applied since the beginning of the experiment was 910, 840, and 840 kg ha^{-1}, respectively (Table 1). A summary of the fertilizer rates and nutrient sources used for each pasture and soybean cycle is presented in Table 1.

2.2. Main long-term productivity results

The main productivity results of herbage production, daily live weight animal gain, and soybean yield, are presented and discussed in detail in Kunrath et al. (2020) and Nunes et al. (2021). Although the soil sampling used in the present study was carried out in 2014, these studies above mentioned show that there is no significant temporal effect between treatments, and therefore, the average productivity of treatments for the period 2001 to 2016 is presented below. The average soybean yield was 2.9, 2.9, 2.8, 3.1, and 3.0 Mg ha^{-1} for the treatments with sward management height at 10, 20, 30, 40 cm, and the ungrazed treatment, respectively (Nunes et al., 2021). The average dry mass herbage production was 6.5, 7.5, 7.7, 8.1 and 6.9 Mg ha^{-1} for the treatments with sward management height at 10, 20, 30, 40 cm, and the ungrazed treatment, respectively (Nunes et al., 2021). The average live weight (LW) gain was 510, 428, 310, and 183 kg ha^{-1} for the treatments with sward management height at 10, 20, 30, and 40 cm, respectively (Nunes et al., 2021). Moreover, steers' average daily gains in the sward management heights of 20, 30 and 40 cm were similar with an average gain of LW of 1.08 kg animal^{-1} day^{-1} (Kunrath et al., 2020). However, the daily gain was lower in the highest grazing intensity (10 cm) compared to the other treatments, resulting in an increase in LW of 0.03 kg animal^{-1} day^{-1} for each cm of increase in sward height up to 19 cm

Table 1
History of nutrient applications over 13 years in the soybean and pasture phases in a Rhodic Hapludox with different grazing intensities in an integrated soybean-beef cattle system under in no-tillage in Southern Brazil.

Year	Soybean phase		Pasture phase		
	P_2O_5[a]	K_2O[b]	N[c]	P_2O_5	K_2O
	Nutrient rates (kg ha^{-1})				
2001/02	60	0	45	0	0
2002/03	60	90	45	60	0
2003/04	60	60	90	0	0
2004/05	60	90	45	0	0
2005/06	60	90	45	0	0
2006/07	60	90	45	0	0
2007/08	60	60	45	0	0
2008/09	60	60	45	0	0
2009/10	60	60	90	0	0
2010/11	60	60	45	0	0
2011/12	60	60	90	0	0
2012/13	0	0	140	60	60
2013/14	0	0	140	60	60
Total	660	720	910	180	120

[a] The source used was simple superphosphate in the first soybean season (2001/02) and the second forage season (2002); and in the other years triple superphosphate was applied.

[b] The source used was potassium chloride.

[c] The source used was urea. N rates above 45 kg ha^{-1} were separated in two applications at 30 and 60 days after forage establishment.

(Kunrath et al., 2020).

2.3. Soil sampling and aggregate stability

In April 2014, 13 years after the beginning of the experiment, trenches perpendicular to the soybean sowing line were opened in each plot with a cutting blade to permit the evaluation of the bulk density in the layers of 0–5, 5–10 and 10–20 cm, in duplicate, by the volumetric ring method (Black and Hartge, 1986). Undisturbed soil samples were also taken in the same trenches and soil layers. These undisturbed samples were manually ruptured at their weakness points until the entire sample could be passed through a 9.51-mm mesh and dried in the shade.

To determine the size distribution aggregates in water, 50 g samples of soil in duplicate were weighed and moistened by capillarity for 12 h on filter paper. Afterwards, they were transferred to 1000 mL plastic tubes containing 500 mL of distilled water and placed on a rotary shaker, following the procedure of by Kemper and Chepil (1965) modified by Tisdall et al. (1978) and Silva and Mielniczuk (1997). The samples were placed on a set of sieves with mesh sizes 4.76, 2.00, 0.50, 0.25 and 0.053 mm, and shaken in water at 42 oscillations per minute for 15 min, so the water at the lowest level reached the top of aggregates in the 4.76 mm sieve.

The mean weight diameter (MWD) of the aggregates was calculated with the values observed by the following Eq. (1).

$$MWD = \left[\sum (AGR_i x d_i) \Big/ \sum AGR\right]; \quad (1)$$

where d_i = mean of diameter of aggregate fraction *i*, obtained by [(thicker mesh + thinner mesh); AGR_i = [(mAGR*i* / ΣAGR) x 100], where AGR*i* = percentage of aggregate fraction *i*; and mAGR*i* = aggregate mass of aggregate fraction *i*; ΣAGR = total mass of aggregates.

The aggregates retained in the sieves of 4.76 and 2.00 mm were combined constituting the large macroaggregate class. The aggregates retained in the sieves 0.50 and 0.25 mm were also combined constituting the small macroaggregates. The aggregates passing the 0.25 mm sieve was considered the microaggregates class. In these three aggregates classes, the concentration of SOC and total nitrogen were determined by dry combustion in a Thermo elemental analyzer (Flash EA 1112, Thermo, Electron Corporation, Milan, Italy).

2.4. Physical fractioning of soil organic matter

The densimetric fractionation was performed only for the uppermost soil layer evaluated (0–5 cm) according methodology described by Tomazi et al. (2011). For this purpose, a representative soil sample of 10 g was placed in a tube (100 mL) containing 80 mL of sodium polytungstate (SPT) with density of 2.0 kg dm^{-3} (Conceição et al., 2007). The tube was slowly inverted five times and centrifuged at 2000 rpm for 90 min to isolate the free light fraction (FLF). The supernatant was poured into a vacuum filtration system with a fiber glass filter, previously weighed and dried in an oven (50 °C). The SPT solution that passed through the filter returned to the centrifuge tube containing a pellet, and sonicated with 743 J mL^{-1} energy. This level of energy was previously defined in a specific test and proven to be sufficient to disperse microaggregates >2.0 μm in order to obtain 99% of the total clay fraction. After sample dispersion, the suspension was centrifuged again, and the light occlusal fraction (LOF) was separated by following the same procedure as for FLF. The filters containing the FLF and LOF fractions were washed with 200 mL of distilled water, then with 100 mL of $CaCl_2$ solution (10 mmol L^{-1}), and again with 100 mL of distilled water. Each filter with the different fractions was dried at 50 °C for 24 h, weighed, ground in a mortar and pestle. Then, the content of organic C and total N was determined by dry combustion in a Flash EA 1112, Thermo, Electron Corporation, Milan, Italy. The heavy fraction (HF) was obtained by calculating the difference between SOC and C of the C-FLF and C-LOF.

Knowing the carbon and nitrogen concentration in the fractions (in g C kg^{-1} fraction and in g N kg^{-1} fraction) and the mass ratio of this fraction in the bulk soil sample (fraction mass: bulk soil mass) we calculated the carbon and nitrogen concentration of these fractions as C or N in g kg^{-1} soil, and then, converted to stock by using the data of soil bulk density. The soil bulk density of the 0–5, 5–10 and 10–20 cm layers were determined in duplicate by the volumetric ring method (Blake and Hartge, 1986).

2.5. Statistical analysis

After checking the data normality by means of Kolmogorov-Smirnov, the data were submitted to analysis of variance and, significant results ($p<0.05$) were compared using Tukey test ($p<0.05$). The MIXED procedure was used to compare the effects of grazing intensities (A) and soil aggregate classes (C) on the response variables.

All analyses were performed using the SAS statistical package v.9.4 (Statistical Analysis System Institute, Cary, North Carolina). The statistical model used in the analysis of variance to evaluate the results of organic C content in aggregate classes of each soil layer was:

$$Y_{ijk} = \mu + B_i + A_j + errora(i,j) + C_k + errorb(i,k) + AC_{jk} + errorc(i,j,k) \quad (2)$$

where B = blocks (i = 1, 2, 3); A = grazing intensities (j = 1, 2, 3, 4, 5); C = aggregates classes (k = 1, 2, 3). For the mean weight diameter of aggregates, stability of aggregates in water, and the fractions of soil organic matter, the variable aggregates classes and its associated errors were removed from the statistical model.

3. Results

3.1. Soil aggregates-size distribution

The mean weight diameter (MWD) was not affected by grazing intensities or soil layers, ranging from 4.39 to 4.67 mm (Table 2). These MWD values were similar to those found in native forest soil (4.78 mm), used as a reference. The proportion of aggregates-size fractions were also not influenced by grazing intensities (Fig. 1). More noticeable, the large macroaggregates (MaL) were the predominant class representing 74.2% of the soil mass, on average of the three soil layers, followed by small macroaggregates (MaS) with 23.2%, and microaggregate (Mic) with 2.6%.

3.2. Carbon content in different aggregate-size fractions

There was no effect of the different grazing intensities on organic C content in all aggregate-size fractions and in all soil layers evaluated (Table 3). Generally, organic C content was lower in microaggregates

Table 2
Mean weight diameter of aggregates in a Rhodic Hapludox after 13 years of different grazing intensities in an integrated soybean-beef cattle system under no-tillage in Southern Brazil.

Grazing intensity	Mean weight diameter of aggregates (mm)		
	0–5 cm	5–10 cm	10–20 cm
Pasture managed at 10 cm height	4.68 a	4.79 a	4.05 a
Pasture managed at 20 cm height	5.04 a	4.90 a	4.33 a
Pasture managed at 30 cm height	5.02 a	4.45 a	4.59 a
Pasture managed at 40 cm height	4.67 a	4.80 a	4.31 a
No grazing	4.66 a	4.44 a	4.25 a
Forest soil*	5.20	5.16	4.39

Means followed by the same lowercase letters in the column, comparing grazing intensity treatments within each soil layer, are not significantly different by Tukey test at $P < 0.05$.

* Forest soil was used as a reference and was not compared in the statistical analysis.

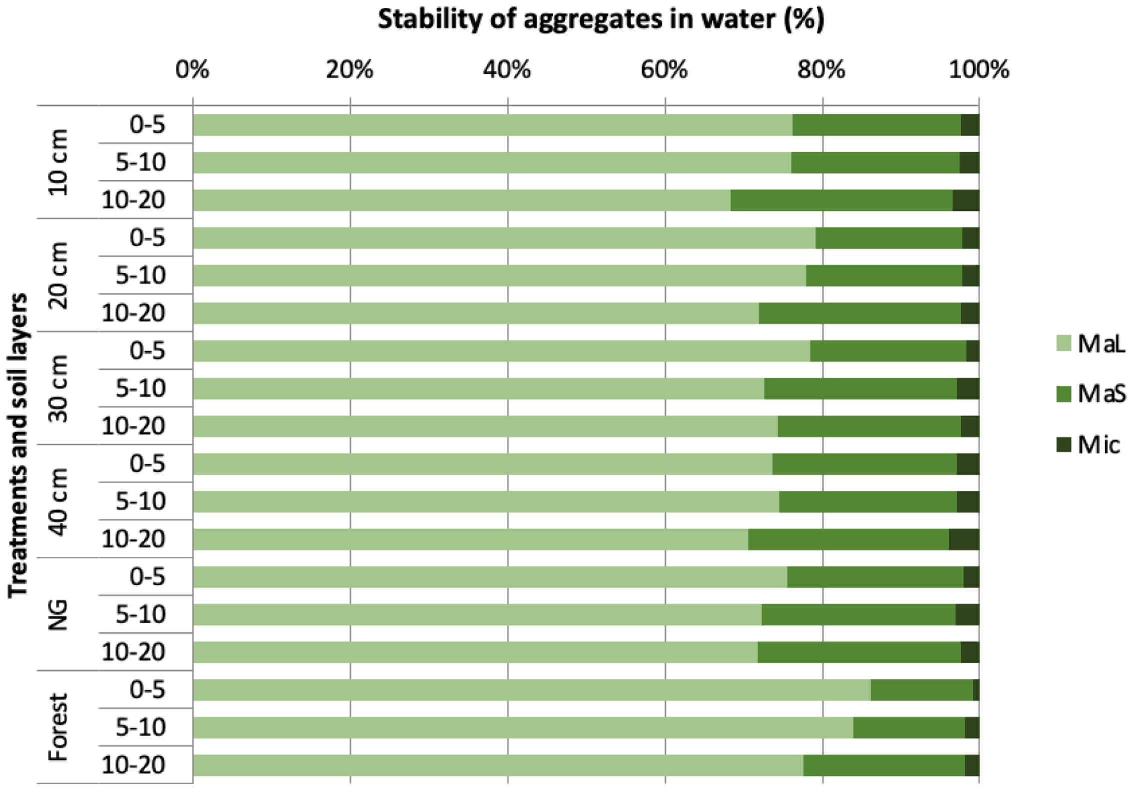

Fig. 1. Relative distribution of water-stable aggregates in different soil layers in a Rhodic Hapludox after 13 years of different grazing intensities in an integrated soybean-beef cattle system under in no-tillage in Southern Brazil. Treatments 10, 20, 30 and 40 cm correspond to the different pasture height treatments. NG, no grazing treatment. MaL = Large macroaggregates (> 2.00 mm); MaS = Small macroaggregates (0.25–2 mm); Mic = Microaggregates 0.053–0.25 mm).

than in large and small macroaggregates in all treatments and soil layers evaluated (Table 3). The exceptions were the treatment with pasture managed at 30 cm height in the 0–5, 5–10 and 10–20 cm soil layer, and the treatment with pasture managed at 40 cm height and no grazing treatment in the 5–10 10–20 cm soil layer (Table 3). The average organic C content in aggregate-size fractions was 26.8 g kg^{-1}, 28.6 g kg^{-1} and 22.7 g kg^{-1} in the large macroaggregates, small macroaggregates, and microaggregates, respectively (Table 3). Additionally, overall, organic C content decrease in-depth in all aggregate-size fractions and treatments (Table 3).

3.3. C and n in different fractions of soil organic matter

Accounting for a major part of the C and N stock, the heavy fraction had greater stocks of C (11.5 Mg ha^{-1}) and N (1.4 Mg ha^{-1}) in comparison to free light fraction (FLF) and light occlusal fraction (LOF) (Table 4).

Noticeably, regardless grazing intensities, no changes in labile fractions of organic matter were observed. More specifically, the stock of C was not affected by grazing in the LOF and FLF fraction (Table 4), and the stock of N was also not affected by grazing in the FLF fraction. However, no grazing presented higher C and N stock in the heavy fraction (14.1 and 1.56 Mg ha^{-1}, respectively) compared to grazed treatments.

N stock in LOF seemed to be more sensitive to variations in grazing intensities compared to C stock in the same fraction (Table 4). The lowest N stock in the LOF (0.18 Mg ha^{-1}) was observed in pasture managed at 10 cm height, while the other treatments stocked, on average, 0.25 Mg ha^{-1} of N in LOF (Table 4).

4. Discussion

After thirteen years of the beginning of the experiment in this Oxisol under no-tillage in Southern Brazil, different grazing intensities during the winter season did not affect the relative aggregate-size fraction distribution. Interestingly, the MWD values verified after 13 years of the beginning of the experiment (between 4.05 and 5.04 mm) were higher than those found by Souza et al. (2010) (between 3.20 and 3.80 mm) after 7 years. This can be consequence of the cumulative effect of no-tillage associated to winter crops, that have fasciculate roots contributing to improve the soil aggregation over time (Salton et al., 2008).

The higher proportion of large macroaggregates compared to small macroaggregates is a result of the long-term history of no-tillage in this area (21 years). As a consequence, the low disruption of macroaggregates by mechanical forces and the stabilization offered by the presence of organic compounds (Corrêa, 2002; Pinheiro et al., 2004) contributed to this great proportion of large macroaggregates. It is important to highlight that, even with the animal trampling in the grazed systems, the soil maintained high stability of soil aggregates. Moreover, the high clay content (540 g kg^{-1}) and iron oxides (hematite) also contribute to the stabilization of the soil aggregates (Darrel et al., 2006; Fernandez-Ugalde, 2013) of this Rhodic Hapludox. In kaolinitic and oxidic soils, such as the soil studied, kaolinite presents higher flocculation capacity and Fe and Al oxides play an important role in aggregates formation and stabilization by forming electrostatic bonds between primary and secondary soil particles (Muggler et al., 1999). The lack of influence of grazing intensities in the relative distribution of aggregates may be due to the similarity in soil organic C stocks and residue contribution (Cecagno et al., 2018) among non-grazing and grazing intensities.

Although some studies have shown that the labile soil organic matter can be rapidly altered by management systems and are considered as the most reactive fraction (Bayer et al., 2004; Conceição et al., 2008), our results show no effect of grazing intensities on the labile fraction of soil organic matter. Larger differences in this fraction are generally found

Table 3
Organic C contents in three aggregate-size fractions in a Rhodic Hapludox after 13 years of different grazing intensities in an integrated soybean-beef cattle system under no-tillage in Southern Brazil.

Grazing intensity	Organic C content (g kg^{-1})		
	Large macroaggregates (>2.0 mm)	Small macroaggregates (0.25–2.00 mm)	Microaggregates (0.053–0.25 mm)
	0–5 cm soil layer		
Pasture managed at 10 cm height	26.5 aA	27.0 aA	20.5 bA
Pasture managed at 20 cm height	27.4 aA	28.8 aA	22.0 bA
Pasture managed at 30 cm height	26.1 aA	27.5 aA	22.3 aA
Pasture managed at 40 cm height	27.6 aA	30.0 aA	22.6 bA
No grazing	26.6 abA	29.5 aA	25.9 bA
Forest soil*	33.3	37.3	38.1
	5–10 cm soil layer		
Pasture managed at 10 cm height	19.0 aA	18.3 aA	14.4 bA
Pasture managed at 20 cm height	19.9 aA	19.7 aA	16.0 bA
Pasture managed at 30 cm height	19.0 aA	18.7 aA	16.1 aA
Pasture managed at 40 cm height	19.7 aA	20.3 aA	14.9 aA
No grazing	18.8 aA	19.4 aA	18.0 aA
Forest soil*	22.7	22.9	22.6
	10–20 cm soil layer		
Pasture managed at 10 cm height	15.8 aA	15.7 aA	11.9 bA
Pasture managed at 20 cm height	15.2 aA	15.2 aA	12.4 bA
Pasture managed at 30 cm height	14.9 aA	14.8 aA	12.4 aA
Pasture managed at 40 cm height	15.8 aA	16.0 aA	11.8 bA
No grazing	15.0 aA	15.2 aA	12.3 bA
Forest soil*	18.6	19.2	19.3

Means followed by the same lowercase letters in the raw, comparing organic C content in different class of aggregates size within each grazing intensity treatment and within each soil layer are not different by Tukey test at $P < 0.05$. Means followed by the same uppercase letters in the column, comparing organic C content in different grazing intensity treatments within each soil layer and within each class of aggregates size, are not different by Tukey test at $P < 0.05$.

* Forest soil was used as a reference and was not compared in the statistical analysis.

Table 4
Stocks of organic C and total N in the free light fraction (FLF), the light occlusal fraction (LOF) and heavy fraction (HF) of the soil organic matter in the 0–5 cm soil layer in a Rhodic Hapludox after 13 years of different grazing intensities in an integrated soybean-beef cattle system under no-tillage in Southern Brazil.

Grazing intensity	Carbon (Mg ha^{-1})			Nitrogen (Mg ha^{-1})		
	FLF	LOF	HF	FLF	LOF	HF
Pasture managed at 10 cm height	1.14 a	4.85 a	11.60 ab	0.06 a	0.18 b	1.34 ab
Pasture managed at 20 cm height	0.99 a	5.92 a	10.73 b	0.06 a	0.27 a	1.36 ab
Pasture managed at 30 cm height	1.41 a	5.94 a	11.91 ab	0.08 a	0.25 ab	1.41 ab
Pasture managed at 40 cm height	2.23 a	5.76 a	9.33 b	0.11 a	0.24 ab	1.24 b
No grazing	2.10 a	4.86 a	14.14 a	0.13 a	0.22 ab	1.56 a

Means followed by the same lowercase letters in the column, comparing grazing intensity treatments within each fraction are not different by Tukey test at $P < 0.05$.

when no-till system is compared to conventional tillage (Veloso et al., 2019), once soil tillage causes aggregate disruption favoring the decomposition of labile organic matter by microorganisms. In our study, the similar content of labile fraction of soil organic matter among the treatments is due to the high stability of macroaggregates. As observed, the macroaggregates (large + small) were the predominant classes representing about 97% of the soil mass. Accordingly, many studies have shown the great contribution of macroaggregates physically protecting labile fractions of soil organic matter (Andruschkewitsch et al., 2014; Cates et al., 2016; Veloso et al., 2019).

The association of heavy fraction of soil organic matter with clay-minerals increase its stability and hampers the mineralization process. Therefore, this fraction often represents the largest fraction of the total soil organic C (Souza et al., 2008). Indeed, as observed in soil organic matter fractions, the largest stocks of C and N were found in heavy fraction, demonstrating the importance of organo-mineral interaction in soil organic matter protection in Oxisols. As all the grazing intensity treatments were under no-tillage system, with a high proportion of soil macroaggregates, it is expected a lower rate of macroaggregates renewal and soil organic matter may remain protected for a long time inside the aggregates, favoring the interactions between soil organic C and smaller soil particles such as clay and Fe and Al oxides (Chenu and Plante, 2006; Denef et al., 2007). The aggregates provide time for the occluded light fraction to become associated with the mineral soil matrix forming then the heavy fraction (Conceição et al., 2013). The formation of these complexes occurs through the adsorption of organic anions by electrostatic interactions with positively charged surface of oxides. For this reason, oxides play an important role in soil organic C accumulation and stabilization (Oades et al., 1989).

Despite the high stability, it is possible to have changes in the heavy fraction of the soil organic matter in long-term studies. Non-grazing treatment was slightly more effective on soil organic C stabilization in the heavy fraction (Table 3), that can be related to other physical and microbiological attributes, such as soil microporosity and the conversion of roots and shoots into soil organic matter. However, more studies are required to confirm this result.

The effect of grazing intensity on N stock was due to different pasture structure and the N input by animal excreta (Assmann et al., 2014). Light (pasture managed at 40 cm height) and moderate (pasture managed at 30 and 20 cm height) grazing intensities favored more N release by pasture residue and animal excreta, when compared to the intensive grazing (pasture managed at 10 cm height) (Assmann et al., 2014). Consequently, the pasture managed at 10 cm height favored a negative N balance compared to moderate grazing intensities which contributed to the lowest N stock in light occlusal fraction. Since the animal excreta have a great N content, this results can also explain the greater variation of N compared to C on stock in light occlusal fraction.

Although this study has shown little influence of grazing intensity on soil aggregation, C content in different aggregates sizes, and C and N content in different SOM fractions, the results have a great impact in soil security. The results obtained demonstrate that it is possible to intensify production systems in southern Brazil, increasing meat production up to 510 kg ha^{-1} for treatments with sward management height at 10 cm (Nunes et al., 2021), without compromising grain production in the same area and maintaining soil physical quality and soil C stocks. Therefore, ICLS can maintain soil condition and increase soil capital as it ensures food security while increasing the biodiversity of production systems (Morgan and McBratney, 2020).

5. Conclusions

Thirteen years of different grazing intensities during the winter season in an Oxisol under no-tillage in Southern Brazil do not affect the relative aggregate-size distribution in the soil. The macroaggregates were the predominant classes representing around 97% of the soil mass, indicating that even with the animal trampling in the grazed systems, the soil maintained high stability of soil aggregates. This high macroaggregate stability contributed to the lack of difference in the C and N content on free light fraction and the light occlusal fraction of soil organic matter. Most of C and N were observed heavy fraction of soil organic matter, with a tendency of greater stock in the no grazing compared to the grazed treatments. These results demonstrate that it is possible to intensify food production through integrated crop-livestock systems without compromising the soil physical quality and C stocks. However, more studies are necessary to confirm or not the observed tendency of decrease in C and N stocks in heavy fraction in grazed systems.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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