Soil organic carbon in an integrated crop-livestock system under different grazing intensities

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ABSTRACT: An integrated crop-livestock system (ICLS) under no-till may be an effective tool to promote soil organic carbon (SOC) accumulation. However, it is not yet clear how pasture management affects SOC accumulation. In this study, we assessed the effect of grazing intensity (10, 20, 30, and 40 cm of sward height and no grazing) on SOC and coefficients of soil organic matter dynamics and used them in a simulation of SOC sequestration in a 0-20 cm soil layer. The overall study was conducted on a subtropical rhodic hapludox from southern Brazil managed as a no-till integrated soybean-beef cattle system for 13 yr. SOC sequestration rates ranged from 0.097 Mg ha^{-1} yr^{-1} with a pasture sward height of 10 cm to 0.308 Mg ha^{-1} yr^{-1} with one of 40 cm. Simulations revealed a higher potential of the soil for C sequestration with a moderate (30 cm) or low (40 cm) grazing intensity. Although the ICLS under no-till led to a positive carbon balance irrespective of grazing intensity, the simulation of temporal evolution of SOC stocks over time revealed a higher potential for SOC accumulation with the less intensive grazing treatments than with the more intensive ones.

Key words: carbon balance; carbon sequestration rate; no-till; pasture sward height; soil organic matter

Carbono orgânico do solo em um sistema integrado de produção agropecuária sob diferentes intensidades de pastejo

RESUMO: Os sistemas integrados de produção agropecuária (SIPA) sob plantio direto podem sem uma ferramenta efetiva para promover o acúmulo de carbono orgânico do solo (CO). No entanto, ainda não está claro como o manejo da pastagem afeta o acúmulo de CO. Nesse trabalho, avaliamos o efeito de intensidades de pastejo (10, 20, 30 e 40 cm de altura de pasto e sem pastejo) no CO e nos coeficientes da dinâmica da matéria orgânica e usá-los na simulação do sequestro de CO na camada de solo de 0-20 cm. O estudo foi conduzido em um Latossolo Vermelho Distroférrico típico no sul do Brasil manejado em um sistema integrado de produção de soja-bovinos de corte, em plantio direto, durante 13 anos. As taxas de sequestro de CO variaram entre 0,097 na altura de manejo de pasto de 10 cm até 0,308 Mg ha^{-1} ano^{-1} na de 40 cm, respectivamente. As simulações revelam um maior potencial de sequestrar C no solo com intensidade de pastejo moderada (30 cm) ou baixa (40 cm). Enquanto os SIPA em plantio direto levam a um balanço positivo de carbono independentemente da intensidade de pastejo, a simulação da evolução temporal dos estoques de COT revela um maior potencial de acumular CO nos tratamentos com as menores intensidades de pastejo do que nos mais intensivos.

Palavras-chave: balanço de carbono; taxa de sequestro de carbono; plantio direto; altura de manejo de pasto; matéria orgânica do solo

Introduction

In Brazil, no-till (NT) land covers an area of 32 million hectares, located mainly on oxisols (FEBRAPDP, 2017). Although this management system is widely recognized as one of the most effective strategies for soil conservation, crop rotations or cover crops are only used in some parts of the NT-managed area. In southern Brazil, cultivated land amounts to 15.4 Mha in the summer but drops to only about 20% in winter, where the remaining 80% is left fallow or sown with a cover crop (CONAB, 2017). In fact, the high climatic risks of the winter season (Del Ponte et al., 2015) have led to large areas of land being left fallow, which reduces the potential of NT for improving soil quality.

In these circumstances, farm diversification through the introduction of animals during the winter can reduce the risks associated with agricultural activity and increase safety and profits. In fact, the alternate use of crops and livestock during the year, as part of the integrated system diversity inherent in NT, can result in economic and environmental gains. Thus, animals are the catalyst for some processes that modify the soil system (Moraes et al., 2014). Including forage plants in a crop rotation allows an integrated crop-livestock system (ICLS) to increase the input of residues from grazing, and hence soil organic matter (SOM), in NT systems (Roscoe et al., 2006). Also, ICLS at a moderate grazing intensity can increase the carbon sequestration rate (CSR) of soil (Salton et al., 2011). An appropriate grazing regime helps maintain leaf photosynthetic activity to some extent, affording adequate growth and renovation of the root system in relation to intensive grazing or no grazing (NG) (Assmann et al., 2014).

However, the impact of land use and soil management on soil organic carbon (SOC) stocks varies widely among soil types, clayey oxisols being more resilient than sandy loam soils under conservative management (Bavoso et al., 2012). SOM in clayey soils is highly stabilized by interaction with surfaces of iron and aluminum oxides, and its decomposition rate is less markedly influenced by soil disturbance than in sandy soils (Bayer, 1996; Campos et al., 2011). Large SOC stocks resulting from organic stabilization can be further increased with high C inputs (Blanco-Moure et al., 2016). It is therefore interesting to estimate the coefficients of SOM dynamics in order to simulate SOC stocks in clayey oxisols under different management systems and extrapolate experimental periods.

In a soil profile where C has not reached saturation, the linear relationship between photosynthetic C input and SOC stocks can be used to estimate coefficients K_1 (coefficient of SOM humification) and K_2 (coefficient of SOM loss) for SOM in terms of the initial SOC stocks (Bayer et al., 2006a; Vieira et al., 2009). These coefficients allow one to predict the future evolution of SOC stocks until they reach a steady state (C_s) and also the C inputs needed to maintain the stocks. Bayer et al. (2006a) studied a sandy clay loam acrisol under NT and conventional tillage (CT) and found the estimated decomposition rate to be higher under CT (0.040 yr^{-1}) than under NT (0.019 yr^{-1}). Coefficient K_2 in NT soil is mainly related to physical protection of SOM by soil aggregates (Boeni et al., 2014), which provide stability through interaction with mineral surfaces over extended periods. The difference in annual decomposition rate between the CT and NT soil in the study by Bayer et al. (2006a) led to a difference in the C input needed to maintain their SOM content: 8.5 Mg ha^{-1} yr^{-1} under CT and 4.4 Mg ha^{-1} yr^{-1} under NT.

On the basis of the foregoing, we hypothesized that introducing animals at a moderate grazing intensity in winter pasture might result in C accumulating in soil to an extent similar to that in NG land and even greater than in high-grazing areas. In order to test our hypothesis, we used a highly weathered soil from southern Brazil under a soybean-beef cattle ICLS to (i) assess the effect of grazing intensity on SOC stocks and (ii) estimate the coefficients of SOM dynamics to simulate the temporal evolution of SOC stocks.

Material and Methods

The study was based on an experimental protocol established in 2001 at São Miguel das Missões County, Rio Grande do Sul State. The study area is in a subtropical region of Brazil (29°03'10"S, 53°50'44"W, 465 m a.s.l.) with a warm humid summer (Cfa) climate according to the Köppen classification. The annual average temperature in the region is 19 °C, and annual precipitation is 1850 mm. The studied soil was classified as a clayey rhodic hapludox and contained 540, 270, and 190 g kg^{-1} clay, silt, and sand, respectively, in the 0-20 cm layer. It was highly weathered and exhibited a prevalence of kaolinite, quartz, and rutile in the iron-free clay fraction and goethite, hematite, maghemite, rutile, and quartz in the concentrated iron oxide fraction (Cecagno et al., 2016).

The experiment was established on a total area of 22 ha, the land having previously been conventionally tilled with plow and disking twice a year from the 1970s to 1993 and then placed under NT until the summer of 2000/2001. The experiment was started in May 2001 with the introduction of black oat (*Avena strigosa* Schreb.) + Italian ryegrass (*Lolium multiflorum* Lam.) pasture. The grazing season lasted from July to November, when young neutered male steers weighing approximately 200 kg each where introduced into the pasture system. During the grazing cycle, the cattle foraged naturally and were supplied a supplement of mineral salt. A continuous grazing system was adopted, and grazing was started when the pasture sward height was approximately 20 cm (around 1.5 Mg ha^{-1} of dry matter). The grazing period was followed by cultivation of NT soybean [*Glycine max* (L.) Merr.] in summer. This annual succession was repeated the following years.

Treatments differed in grazing intensity during the winter, adjusted through pasture sward height: 10, 20, 30, and 40 cm (treatments G10, G20, G30, and G40, respectively). A control treatment with NG was also used. The experimental plots ranged from 0.8 to 3.6 ha in size and were arranged in a

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Table 1. Estimation of the carbon addition rate at different grazing intensities in a long-term, no-till, integrated crop-livestock system (produced from data of Assmann et al., 2014).

Grazing intensity sward height	Pasture shoot	Pasture root	Manure + urine	Soybean shoot	Soybean root	Total
Plant and animal residues (Mg ha^{-1} yr^{-1})						
10 cm	1.40	1.40	1.22	2.38	1.72	8.12
20 cm	2.98	1.30	0.81	2.28	1.91	9.28
30 cm	4.74	1.20	0.61	2.83	1.70	11.07
40 cm	5.80	1.00	0.46	2.02	1.69	10.97
No grazing	5.50	0.70	...	2.40	2.22	10.82
Carbon input (Mg ha^{-1} yr^{-1})						
10 cm	0.63	0.63	0.55	1.07	0.77	3.65
20 cm	1.34	0.59	0.36	1.03	0.86	4.18
30 cm	2.13	0.54	0.27	1.27	0.77	4.98
40 cm	2.61	0.45	0.21	0.91	0.76	4.94
No grazing	2.48	0.32	...	1.08	1.00	4.87

randomized block design with three replicates. The average C inputs of pasture and soybean are shown in Table 1.

Soil was sampled from the 0-5, 5-10, 10-15, and 15-20 cm soil layers after soybean was harvested in May 2014. An area of native forest (NF) adjacent to the experimental site was also sampled as a reference for natural SOC stocks. Soil samples were dried at 40 °C. Roots and residues were removed, and soil was ground in a mortar. The milled samples were analyzed and C content quantified by dry combustion on a Fisher Scientific Flash 2000 instrument.

SOC stocks were calculated using the soil equivalent mass method (Ellert & Bettany, 1995) at an NG soil bulk density of 1.28 and 1.35 kg dm^{-3} for the 0-5 and 5-20 cm layer, respectively (Souza et al., 2009).

The coefficients of SOM dynamics were estimated from the linear relationship between annual C input and changes in SOC stocks in soils with no C saturation (Hénin & Dupuis, 1945), using the procedure devised by Bayer et al. (2006a) and Vieira et al. (2009). Briefly, on the basis of the SOC stock at the beginning of the experiment (SOC$_0$ = 51 Mg ha^{-1}) (Souza et al., 2009), coefficient K$_2$ was calculated from "a" in the equation y = a + bx, which was obtained by using linear regression to fit the variation of SOC stocks (*y*-axis) with the annual C input (*x*-axis) at time t = 13 yr (the duration of the experiment):

$$K_2 = \frac{(\ln SOC_0 - \ln a)}{t} \quad (1)$$

Likewise, coefficient K$_1$ was estimated from K$_2$ and coefficient "b" in the linear equation—which represents annual changes in SOC stocks per unit of C input by above- and below-ground crop biomass (pasture + soybean):

$$K_1 = \frac{K_2 b}{\left(1 - e^{-K_2 t}\right)} \quad (2)$$

The annual CSR of atmospheric C in soil was calculated as the ratio of the difference between current SOC stocks for the different treatments and SOC$_0$ to the duration of the experiment, t:

$$CSR = \frac{(SOC_t - SOC_0)}{t} \quad (3)$$

SOC stocks were simulated using the following equation with SOC$_0$ and the previously estimated K$_1$ and K$_2$ values, and A being the annual C input:

$$C_t = \frac{SOC_0 e^{-K_2 t} + K_1 A}{K_2 \left(1 - e^{-K_2 t}\right)} \quad (4)$$

The first term on the right-hand side of the equation represents the carbon loss from the soil prior to the experiment and the second SOC accumulation by effect of plant and animal inputs during the experiment. As can be seen, C$_t$ equals SOC$_0$ at t = 0 and C$_s$ at t = ∞.

The amount of C to be added to the soil each year in order to maintain SOC$_0$, C$_a$ (Mg ha^{-1} yr^{-1}), was calculated from the following equation, where "a" and "b" are the abovementioned coefficients of the linear regression equation between C input and SOC stock:

$$C_a = \frac{(SOC_0 - a)}{b} \quad (5)$$

Prior to analysis, data were checked for normality with the Kolmogorov-Smirnov test and homoscedasticity of variances with test. This was followed by analysis of variance (ANOVA) and, when differences between means were significant ($p < 0.05$), by comparison with Tukey's test at $p < 0.05$. The effects of the treatments on SOC were assessed using a MIXED procedure with treatment as the fixed factor and block as the random variable. All analyses were done with the software SAS® v. 9.4 (Statistical Analysis System Institute, Cary, North Carolina, USA). SOC values for the 0-20 cm soil layer were subjected to ANOVA using the statistical model Y$_{ij}$ = μ + B$_i$ + T$_j$ + Error (ij), where μ denotes the general mean

of the experiment, B block (i = 1, 2, 3), T treatment (grazing intensity, j = 1, 2, 3, 4, 5), and Error experimental error.

Results

There was a linear relationship (R^2 = 0.98) between C input by plants and animals and SOC stocks (Figure 1). C input peaked at the G30 grazing intensity (Table 1). An estimated 44.1 Mg C ha^{-1} in the 0-20 cm layer must have come from the original C remaining in the soil after 13 years, and 2.18 Mg ha^{-1} from for each Mg ha^{-1} yr^{-1} of C added to it (Figure 1). SOC stocks in the 0-20 cm soil layer with ICLS ranged from 52 to 55 Mg ha^{-1} and were not significantly affected (p > 0.05) by grazing intensity (Table 2). Stocks amounted to 72.0 Mg ha^{-1} in NF and averaged 54.0 Mg ha^{-1} (75% of SOC stocks in the reference area) with the grazing treatments.

C_S for G30, G40, and NG was even higher than that for NF (the reference), for which the value was 72.0 Mg ha^{-1} (Table 2). By contrast, C_S for G10 was 59.0 Mg ha^{-1}, only 73% of the amount in the 0-20 cm layer for G30 (Table 2). Clearly, the G10 and G20 treatments led to a reduction in steady state SOC stocks to less than that for NF, and G10 conditions resulted in an increase of only 7 Mg ha^{-1} (Table 2). In the

accumulation stage, G30, G40, and NG produced very similar stocks (ca. 79.7 Mg ha^{-1}), surpassing those for NF.

All grazing intensities in ICLS increased the initial SOC stock (SOC$_0$ = 51 Mg ha^{-1}), the increase ranging from 1.08 to 3.98 Mg ha^{-1} (Table 2). Maintaining the initial SOC stock would have required adding 3.15 Mg C ha^{-1} yr^{-1}. All treatments produced amounts of C greater than this. Although the differences among SOC stocks were not significant (Table 2), CSR was three times greater with G40 (0.308 Mg ha^{-1} yr^{-1}) than it was with G10 (0.097 Mg ha^{-1} yr^{-1}) (Table 2). On the other hand, CSR was significantly smaller with G10 and G20 than it was with G30, G40, and NG. Despite these mean values, CSR increased logarithmically, with higher values at baseline that declined over time (Figure 2).

Regarding SOM dynamic coefficients, K_1 was estimated to be 0.180 yr^{-1} (Table 2), meaning that 18.0% of the amount of carbon added each year was humified and contributed to increasing SOM. Also, K_2 was 0.011 yr^{-1} (Table 2), indicating that 1.1% of SOM in the 0-20 cm layer decomposed within 1 year.

Discussion

The reduced SOC stocks found under grazing relative to NF were the result of 20 years of CT before NT began in
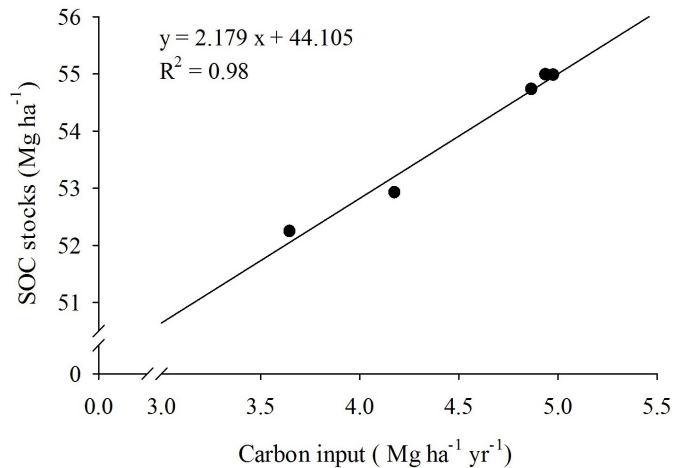

Figure 1. Relationship between soil organic carbon (SOC) stocks and annual carbon input to soil in a long-term, no-till, integrated crop-livestock system under different grazing intensities.
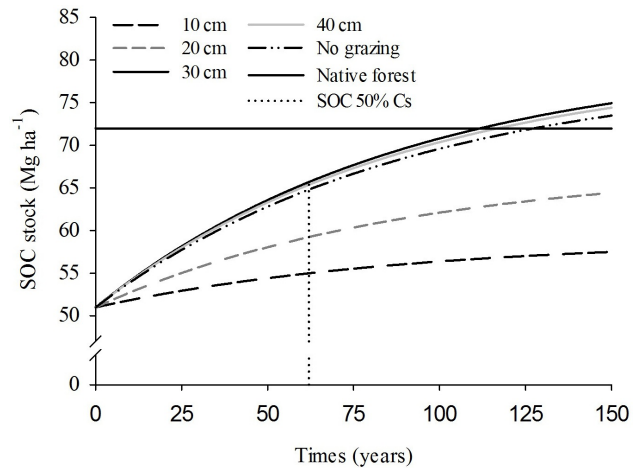

Figure 2. Simulations of soil organic carbon accumulation (SOC, 0-20 cm layer) with one-compartment model in a long-term, no-till, integrated crop-livestock system under different grazing intensities.

Table 2. Coefficients of dynamics and prediction of soil organic matter accumulation with a one-compartment model in a long-term, no-till, integrated crop-livestock system under different grazing intensities.

Grazing intensity (Sward height)	K_1 [1]	K_2 [2]	Current SOC [3]	SOC$_{50\% C_S}$ [4]	C_S [5]	CSR[6]
	yr^{-1}			Mg ha^{-1}		Mg ha^{-1} yr^{-1}
10 cm			52.1 ns	55.0	59.0	0.097 b
20 cm			53.2	59.3	67.6	0.149 b
30 cm	0.180	0.011	55.0	65.7	80.5	0.307 a
40 cm			54.9	65.4	79.8	0.308 a
No grazing			54.7	64.8	78.7	0.288 a
Native forest	...	...	72.0	...	...	...

[1] Coefficient of soil organic matter humification; [2] Coefficient of soil organic matter loss; [3] Soil organic carbon as fitted by linear regression; [4] 50% of SOC stock change between experiment establishment and C_S; [5] Soil organic carbon at steady state. [6] Carbon sequestration rate. ns No significant difference within a column (Tukey's test, p > 0.05). Values followed by the same letter in each column were not significantly different as per Tukey's test at p > 0.05.

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1993. If the experimental area were still being tilled, SOC stocks would possibly have continued to decline and to fall below the level of 2001: 51 Mg ha^{-1} (Souza et al., 2009). The similarities of SOC stocks in experimental areas having different pasture heights were probably due to compensatory mechanisms. Although G10 had the lowest input of residues (Table 1), the expected difference was offset by root growth (Souza et al., 2008), which led to SOC stocks similar to those of the other treatments (Table 2). The root system of crops is the individual attribute best correlating with SOC stocks (Albuquerque et al., 2015), possibly as a result of its coefficient of C humification being 2.3 times higher than that of shoots (Kätterer et al., 2011), and of roots accounting for 80% of the increase in labile SOC fraction (Mazzilli et al., 2015). Even though G10 produced smaller amounts of shoot residues, it was the individual treatment receiving the largest amounts of manure (Table 1), which, along with the abovementioned root effects, explains the similarities of SOC stock across pasture heights.

The CSR found in this study varied between 0.097 and 0.308, with all ICLS sequestering C and with the greatest potential occurring in systems with the less intensive grazing treatments. Zanatta & Salton (2010) found a greater increase in CSR with ICLS than with NT and NG. In tropical regions, CSR can reach 1.0 Mg ha^{-1} yr^{-1} (Sá, 2001), higher than the levels found in this study (Table 2). Bayer et al. (2006b) estimated an average CSR for the tropics and subtropics of 0.35 and 0.48 Mg ha^{-1} yr^{-1}, respectively. However, their reference values were SOC stocks for CT, and their mathematical model only held for the first 10-20 years under NT. As can be seen in Figure 2, our CSR values increased logarithmically, with higher values at baseline that declined over time. In a meta-analysis of 115 studies, Conant et al. (2001) found increased CSRs during the first 40 years of NT. Therefore, the experimental areas in our study still have the potential to accumulate SOC.

The C sequestration potential was quite low with G30 and even smaller with G10. More than 20 Mg C ha^{-1} will not be sequestered from the 0-20 cm soil layer—and an even greater amount from the deeper layers (Harper & Tibbett, 2013). Also, possibly, the soil under G10 conditions was very close to its C sequestration potential.

K$_2$ value (0.011 yr^{-1}) is similar to those found in oxisols under NT by Bayer (1996), 0.012 yr^{-1}, and Campos et al. (2011), 0.011 yr^{-1}. This value is low for a typical soybean and pasture system under NT, which can be ascribed to decreased microbial oxidation of SOM in this soil class. In addition, the clayey soil provided greater physical protection for SOM and stability of organo-mineral complexes, thereby further contributing to the low value for K$_2$ (Marques et al., 2015).

K$_1$ depends on the residence time of residues in soil. Our K$_1$ value (0.180 yr^{-1}) falls within the ranges reported by Bolinder et al. (1999) and Gregorich et al. (1995), 0.077-0.23 yr^{-1}, but above those found under NT in southern Brazil: 0.146 yr^{-1} (Bayer et al., 2006a) and 0.096 yr^{-1} (Vieira et al.,

2009). Our relatively high K$_1$ value can be ascribed to slower cycling of particulate organic matter (Gregorich et al., 1995). Also, some intrinsic properties of residues, such as origin and composition, have a direct effect on their residence time in soil.

According to Bolinder et al. (1999) and Gregorich et al. (1995), K$_1$ differs between shoots (0.122 yr^{-1}) and roots (0.211 yr^{-1}). This is a result of a substantial portion of roots being protected by soil aggregates, and with microbial access (and organic matter decomposition) being hindered as a result (Golchin et al., 1994), the net outcome is longer residence times in soil. Moreover, there are indications that the residence time of residues plays no crucial role in humification (Cotrufo et al., 2013). Thus, legumes have lower C:N ratios—and hence shorter residence times—than grasses, but undergo more marked humification (Martins & Angers, 2015).

Nicoloso et al. (2008) assessed the effect of grazing frequency and found soil to be a C sink only in the absence of grazing or with a grazing frequency of 28 days or more (i.e., with moderate grazing). The smallest amount of C to be added in our experiment, 3.15 Mg ha^{-1} yr^{-1}, was influenced by NT and the succession of cropping systems (grasses and legumes). The amount was small owing to the low K$_2$ value and high K$_1$ value—which, however, are similar to those reported by Lovato et al. (2004) and Vieira et al. (2009). Bayer et al. (2006a) emphasized the importance of adding at least 3.9 Mg C ha^{-1} yr^{-1} to soil under NT.

As can be seen in Figure 2, the logarithmic increase in SOC stocks tended to a maximum. The increase in labile SOM with time alters the rate of organic matter loss because this fraction is decomposed especially rapidly (Krull et al., 2003). Also, soil aggregation, which is one of the protective mechanisms for SOM, increases with time (Boeni et al., 2014). Particular caution is thus needed in interpreting the predictions of one-compartment models because they use average values only and SOM compartments have turnovers ranging from a few months to thousands of years.

Conclusions

Carbon balance in a subtropical clayey oxisol under an integrated NT soybean-beef cattle system was positive. No effect of grazing intensity on the SOC stock was observed over 13 years. Simulating the temporal evolution of SOC stocks over time with provision for humification and decomposition revealed a higher potential for accumulation of organic C in soil with the less intensive grazing treatments (viz., a pasture sward height of 30 or 40 cm) than with the more intensive ones (10 or 20 cm).

Acknowledgments

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