Comissão 2.4 - Química do solo

PARTICULATE SOIL ORGANIC CARBON AND STRATIFICATION RATIO INCREASES IN RESPONSE TO CROP RESIDUE DECOMPOSITION UNDER NO-TILL[1]

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SUMMARY

In soils under no-tillage (NT), the continuous crop residue input to the surface layer leads to carbon (C) accumulation. This study evaluated a soil under NT in Ponta Grossa (State of Paraná, Brazil) for: 1) the decomposition of black oat (*Avena strigosa* Schreb.) residues, 2) relation of the biomass decomposition effect with the soil organic carbon (SOC) content, the particulate organic carbon (POC) content, and the soil carbon stratification ratio (SR) of an Inceptisol. The assessments were based on seven samplings (t_0 to t_6) in a period of 160 days of three transects with six sampling points each. The oat dry biomass was 5.02 Mg ha^{-1} at t_0, however, after 160 days, only 17.8 % of the initial dry biomass was left on the soil surface. The SOC in the 0-5 cm layer varied from 27.56 (t_0) to 30.07 g dm^{-3} (t_6). The SR increased from 1.33 to 1.43 in 160 days. There was also an increase in the POC pool in this period, from 8.1 to 10.7 Mg ha^{-1}. The increase in SOC in the 0-5 cm layer in the 160 days was mainly due to the increase of POC derived from oat residue decomposition. The linear relationship between SOC and POC showed that 21 % of SOC was due to the more labile fraction. The results indicated that the continuous input of residues could be intensified to increase the C pool and sequestration in soils under NT.

Index terms: black oat, carbon sequestration, dry matter decomposition, half-life.

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(1) Received for publication in August 8, 2011 and approved in June 26, 2012.

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RESUMO: *AUMENTO DO CARBONO PARTICULADO DO SOLO E DA RELAÇÃO DE ESTRATIFICAÇÃO EM RESPOSTA À DECOMPOSIÇÃO DE RESÍDUOS CULTURAIS EM PLANTIO DIRETO*

O aporte contínuo de resíduos na superfície do solo, conduzidos sob sistema plantio direto (SPD), leva ao acúmulo de carbono (C). Os objetivos deste estudo foram avaliar a decomposição dos resíduos de aveia-preta (Avena strigosa Schreb.) *e relacionar o efeito da decomposição sobre o carbono orgânico do solo (COS), o carbono orgânico particulado (COP) e a taxa de estratificação (TE) de C do solo em um Cambissolo Háplico sob SPD na região dos Campos Gerais - PR. As avaliações foram realizadas durante sete datas de coleta (t_0 a t_6) em 160 dias, em três transectos, com seis pontos de coleta para cada um. A produtividade inicial de biomassa de aveia foi de 5,02 Mg ha^{-1}, restando, após 160 dias, 17,8 % da matéria seca inicial. O conteúdo de COT foi superior (38 %) na camada de 0-5 cm em comparação à de 5-20 cm, variando, na primeira, de 27,56 a 30,07 g dm^{-3} (t_0 para t_6). A TE aumentou de 1,33 para 1,43 durante os 160 dias. Além disso, houve aumento do estoque de COP nesse período, o qual variou de 8,1 a 10,7 Mg ha^{-1}. O aumento de COS na camada de 0-5 cm, durante os 160 dias, ocorreu principalmente devido ao aumento do COP derivado da decomposição dos resíduos da aveia. A relação linear entre o COS e o COP mostrou que 21 % do primeiro teve contribuição da fração mais lábil. Os resultados são um indicativo de que a entrada contínua de resíduos pode ser intensificada, como forma de aumentar o estoque e sequestro de C em solos sob SPD.*

Termos de indexação: aveia-preta, decomposição de resíduos, meia-vida, sequestro de carbono.

INTRODUCTION

The total area used for no-tillage (NT) agriculture has expanded exponentially in Brazil in the last 10 years, reaching about 27.5 million hectares (Derpsch & Friedrich, 2009). A large part of this expansion must be ascribed to the benefits of the NT system, e.g., improvements in the soil chemical, physical and biological properties (Venzke Filho et al., 2008; Watts et al., 2010; Obalum & Obi, 2010), as well as a reduction in greenhouse gas emissions because of the minimum plowing and the biomass input by crop residues (Lal, 2008; Sá et al., 2009).

In addition, the continuous input of crop residues and their maintenance on the soil surface lead to carbon (C) accumulation, especially in the surface layers, promoting the stratification of C throughout the soil profile (Franzluebbers, 2002; Franzluebbers et al., 2007; Sá & Lal, 2009). As a result, the water infiltration rate and storage in soils increase (Olibone et al., 2010); microbial activity is intensified (Cheneby et al., 2010); nutrient contents in the surface layer increase (Sá et al., 2009; Teixeira et al., 2010; Murungu et al., 2011), and water erosion is markedly reduced (Silva et al., 2005; Bertol et al., 2010).

On the other hand, the input of dry biomass into soils under no-tillage also alters the quantity and quality of the particulate fraction of soil organic matter (SOM), because this fraction is directly linked to the residue supply from the above- and belowground plant biomass (Bayer et al., 2004; Dieckow et al., 2005; Sá & Lal, 2009; Salvo et al., 2010). The protection of particulate organic carbon (POC) within the soil aggregates under NT increases the time SOM remains in the soil, resulting in the accumulation and positive balance of C sequestration over time (Six et al., 1999; Sá & Lal, 2009; Jagadamma & Lal, 2010).

In Southern Brazil, particularly in the region of Campos Gerais (State of Paraná), NT was mainly adopted to introduce winter cover crops to improve the protection against erosion during the development of the summer crops. Black oat (*Avena strigosa* Schreb.) is one of the main species used for this purpose due to its high dry matter yield, robustness, tillering capacity, pest and disease resistance, and rapid formation of topsoil even in soils with low fertility (Calegari, 2001).

The study was conducted to test the hypothesis that oat residue decomposition increases the C flow, thus increasing the C pool as a function of the higher labile C. The specific objectives of this study were to: 1) assess the decomposition of black oat residues and relate the effect of biomass decomposition with the soil organic carbon (SOC) and the POC content and 2) assess the relationship between the increase of POC and the soil carbon stratification ratio (SR) as an indicator of C sequestration of an Inceptisol under NT in Ponta Grossa (Campos Gerais), Paraná, Brazil.

MATERIALS AND METHODS

This study was conducted in Ponta Grossa (region of Campos Gerais), state of Paraná, Brazil, at ~ 990 m asl (25° 05' S and 50° 03' W). The climate in the region was classified, according to the Köppen classification, as Cfb, i.e., a mesothermal, humid subtropical with mild summers, frequent severe frosts and no dry season. The average annual temperature is 18.2 °C and the average annual precipitation 1,554 mm (Figure 1). The soil of the experimental area is a Cambissolo Háplico (Embrapa, 2006), Inceptisol (Soil Survey Staff, 1999). Prior to the experiment, the chemical and particle size analyses of the 0-20 cm soil layer showed the following results: pH 5.0 (1:2.5 soil:solution, 0.01 mol L^{-1} $CaCl_2$); exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, and K^+ contents of 10, 27, 19, and 2.8 $mmol_c$ dm^{-3}, respectively. The total acidity at pH 7.0 (H+Al) was 57.5 $mmol_c$ dm^{-3}; P (Mehlich-1) 48 mg dm^{-3}; and the clay, silt, and sand contents were 140, 127, and 734 g kg^{-1}, respectively.

The crop rotation used in the entire study area (50 x 16 m) in the years prior to the experiment was as follows: common bean (*Phaseolus vulgaris*) in the summer of 2004 and 2005; wheat (*Triticum aestivum* L.) in the winter of 2005; soybean (*Glycine max* L.) in the summer of 2005 and 2006; black oat (*Avena strigosa* Schieb) in the winter of 2006; and soybean in the summer of 2006 and 2007.

The study was performed with the residues of black oat found to remain during the development of soybean (summer growing season of 2006 and 2007). Black oat was sown (80 kg ha^{-1} seeds) on June 14, 2006, and desiccated on October 19, 2006, with glyphosate herbicide (1,458 g ha^{-1} a.i.). After desiccation, the crop was cut. Soybean was sown on October 30, 2006, at a density of 16 seeds per meter. A 4-20-20 NPK fertilizer was applied at 300 kg ha^{-1} (e.g., 4 % N, 20 % P_2O_5 and 20 % K_2O).

The experiment was conducted on the entire study area (50 x 16 m), sampling 18 points along three transects, during soybean cultivation (Figure 2a). Samples were evaluated at t_0, i.e., the day of black oat desiccation, and t_1, t_2, t_3, t_4, t_5 and t_6, corresponding to 13, 42, 74, 107, 133, and 160 days after black oat desiccation, respectively (Figure 2b). Black oat dry matter was sampled from a 0.25 x 0.25 m square in the studied area. Disturbed soil was sampled from the layers 0-5 and 0-20 cm. Additionally, undisturbed soil samples were collected from the same layers with volumetric steel rings (diameter 5 cm x height 5 cm) to determine soil bulk density (Blake & Hartge, 1986) (Figure 2c). Because soil bulk density did not vary between the treatments within each sampled layer, the bulk density of the layers was used to calculate the C pool without an equivalent soil mass correction.

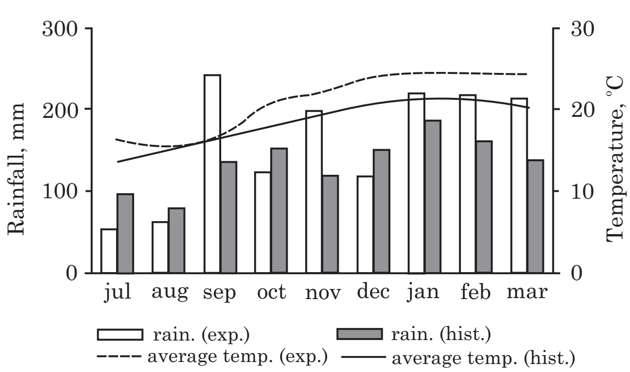

Figure 1. Temperature and rainfall distribution in this study (exp.), compared to the historical data (hist.) from 1954 - 2001.

To assess the decomposition rate of black oat residues, the samples were dried at 60 °C to constant weight (for approximately 72 h). To describe black oat decomposition, the data were fitted to an exponential mathematical model, previously described by Wieder & Lang (1982) and employed by Boer et al. (2008), using the following equation:

$$P = P_0\, exp^{(-kt)} \qquad (1)$$

where P is the dry biomass quantity at time t (in days), Po is the fraction of potentially decomposable dry biomass, and k is the constant for dry biomass decomposition.

The half-life ($t_{1/2}$), which is the time required for the decomposition of 50 % of the biomass left on the soil, was calculated according to Paul & Clark (1989), by the following equation:

$$t_{½} = 0.693 / k \qquad (2)$$

Soil organic matter (SOM) was physically fractionated by a wet sieving method (Sá et al., 2001) using air-dried soil samples that were gently crumbled and passed through a 2 mm sieve. Thereafter, 40 g of each sample were weighed and 100 mL H_2O + 0.75 g of hexametaphosphate (7.5 g L^{-1}) + three agata balls were filled in a 1 L plastic flask. After rapid and gentle manual shaking, the flasks were stored in a refrigerator for 16 h. Then, the flasks were shaken for 4 h in a horizontal shaker at 100 rpm and the soil suspension passed through a 53 mm sieve. The retained material was dried at 60 °C, resulting in a 53 to 2,000 mm fraction, corresponding to the POC.

The SOC in the POC fraction and in the entire soil sample was determined by oxidation with potassium dichromate in sulfuric acid medium and titration with ferrous ammonium sulfate, according to the modified method of Walkley & Black (1934), described by Nelson & Sommers (1996).

To calculate the SOC stock for each layer, the following expression was used: SOC_{stock} = (SOC x Ds x e)/10, where SOC_{stock} is the stock of total organic C at a certain depth (i.e., Mg ha^{-1}), SOC is the content of soil organic C (i.e., g kg^{-1}), Ds is the soil bulk density at each depth (i.e., Mg m^{-3}) and e is the thickness of each layer in cm. The SOC_{stock} (in Mg ha^{-1}) was not corrected for equivalent soil mass because all samplings were taken from the same soil layers under no-till among which the soil bulk densities did not differ statistically.

The SR of the SOC was calculated by dividing the carbon content in the 0-5 cm layer by that of the 0-20

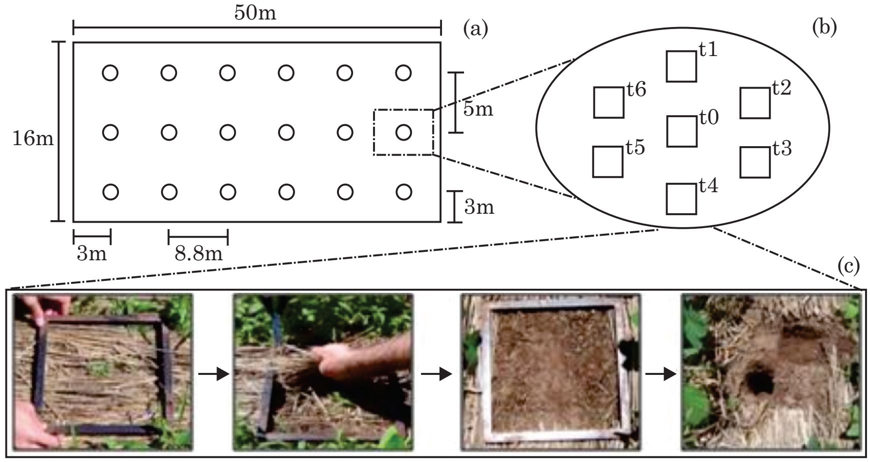

Figure 2. Diagram of the sampling procedure. (a) The experimental plot and collection points for each sampling time. (b) Alternate collection sites for each sampling time at the same sampling point. (c) Collection of crop residue and soil samples.

cm layer, according to Franzluebbers (2002) and Sá & Lal (2009). The change in the C stock (SOC stock; t_6 - t_0) and the change in the SR of SOC (SR t_6 - SR t_0) were also calculated.

A regression decay model with one exponential term was used to evaluate the curve of the oat residue decomposition over time. To regression significance level was calculated using Sigmaplot software (version 10.0; Jandel Scientific). To evaluate the difference between the mean values of the properties between the sampling times, the t-test was applied using Sisvar software (version 5.1) (Ferreira, 2008).

RESULTS AND DISCUSSION

Dry mass production, dry mass loss and half-life

At the first sampling (t_0), the black oat dry matter production was 5.02 Mg ha^{-1} (Figure 3), which was similar to values reported by Ferreira et al. (2009) and Wisniewski & Holtz (1997) in the same study region (5.16 and 4.2 Mg ha^{-1} dry matter, respectively). After 160 days, 82.2 % of the dry matter was lost, with an exponential decrease over time (Figure 3), and at the end of the study, the dry matter of the remaining crop residues was only 0.89 Mg ha^{-1}. Bertol et al. (1998) also reported a loss of black oat residue of 80 % after 180 days in Santa Catarina, Brazil. In addition, a loss of 91 % of black oat biomass was also detected after 179 days in Paraná (Campos Gerais region) by Wisniewski & Holtz (1997).

The half-life of 64 days of black oat residues in this study was considered short when compared to the half-life reported by Torres et al. (2008) of 110 days in an experiment with black oat in Uberaba, Minas Gerais, Brazil. As reported by Carneiro et al. (2008), in the state of Goiás, Brazil, the half-life of black oat residues was 72 days. This difference in the half-life values in this paper compared with those in other studies may be explained by the higher accumulated rainfall during the experiment, which reached about 1,000 mm (Fig. 1). In the experiments in Central Brazil (Cerrado region), residue decomposition was assessed in a period of low precipitation.

However, Aita & Giacomini (2003) reported a half-life of 51 days for oats in southern Brazil (State of Rio Grande do Sul).

Soil organic C (SOC) contents and stratification ratio (SR)

The SOC content varied between the t_0 and the t_6 sampling, and the highest SOC content was found in

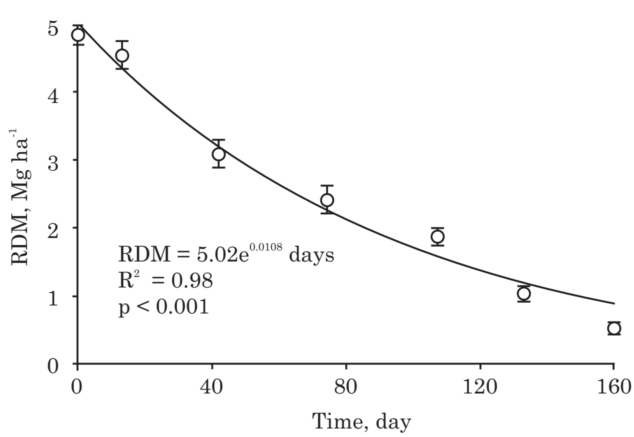

Figure 3. Remaining dry matter (RDM) from black oat residues over time (days) after desiccation. Vertical bars indicate the standard error of the mean.

the 0-5 cm surface layer (Table 1). The SOC content in the 0-5 cm layer varied from 27.56 (t_0) to 30.07 g kg^{-1} (t_6), representing a gain of 9.1 % in a period of 160 days. In contrast, no such increase was observed in the SOC content in the 0-20 cm layer (Table 1), indicating that the SOC in the 0-5 cm layer increased due to crop residue decomposition. However, the contribution of oat residue decomposition to C in the surface layer in a short period is a strong indication of an increase of the C pool in deeper layers over time, under continuous no-till. In long-term experiments (more than 15 years) in southern Brazil, Boddey et al. (2010) also reported that no-tillage promoted a greater accumulation of C than conventional tillage in the 0-1.0 m layer; this difference was greater than when only the surface layer 0-30 cm was considered.

The SR of C varied from 1.33 (t_0) to 1.43 (t_6), indicating carbon accumulation in the surface layer (Table 1). This increase was related to the crop residue input and persistence of these residues on the soil surface (Franzluebbers, 2002; Sá & Lal, 2009). In addition, Franzluebbers (2002) reported that the SR increase is high, indicating an increase in SOM quality of the surface soil layer, resulting in greater water infiltration, better development of macropores, more stable aggregates, greater supply of slow-release nutrients, and diversified food supply for the activity of soil organisms (Franzluebbers, 2002). Thus, the increase in the SR of C also indicates that soil acts as a C sink, thus promoting C accumulation (Sá & Lal, 2009).

Particulate organic carbon (POC)

The increase in SR and the accumulation of SOC in the surface layer in a short period of time was partly due to the increase in POC (Figure 4a). In addition, the POC increase in this period was due to oat residue decomposition (POC = 13.58 - 0.57 remaining dry matter; R^2 = 0.41; p = 0.17). Thus, the particulate fraction of SOM was the main indicator that the soil was acting as a drain and tended to sequester C. Moreover, the continuous inputs and maintenance of crop residues on the soil surface promote the conversion of the more labile into more stable C forms over time (Sá et al., 2008).

Table 1. Soil organic carbon (SOC) content and stock, stratification ratio (SR), and variation (t_6 - t_0) of SOC content, SOC stock and SR over time

Layer	Sampling periods		Δ (t_6 - t_0)
	t_0	t_6	
cm		SOC, g dm^{-3}	
0-5	27.56 Ab	30.07 Aa	2.50
0-20	20.72 Ba	21.03 Ba	0.31
SR (0-5:0-20)	1.33 b	1.43 a	0.10
		SOC, Mg ha^{-1}	
0-5	18.12 a	19.78 b	1.66
0-20	57.81 a	58.65 a	0.84

Means followed by the same capital letter in the columns and small-case letter in the lines are not different (t test, p < 0.05).

The close linear relationship between the period of oat residue decomposition (*x*, axis) and the POC stock (*y*, axis) for the 0-5 cm layer (POC $_{(Mg\ ha^{-1})}$ = 7.08 + 0.012 day; R^2 = 0.55; p = 0.090) demonstrated the contribution of black oat residues to C accumulation in this fraction, at a daily C accumulation rate of 12 kg ha^{-1} (Figure 4b). This relationship indicated that systems with a more intense crop rotation (a greater number of crops in a given period), promote the highest C input, mainly of particulate C, with the continuous residue supply.

Soil organic C and the relationship with particulate carbon (POC) and stratification ratio

The increase in the POC stock at the end of t_6 (160 days of oat residue decomposition) was reflected in the increase of total C stock from 18.12 to 19.78 Mg ha^{-1} in the 0-5 cm layer (Table 1). The linear relationship between SOC (*x*, axis) and POC (*y*, axis)

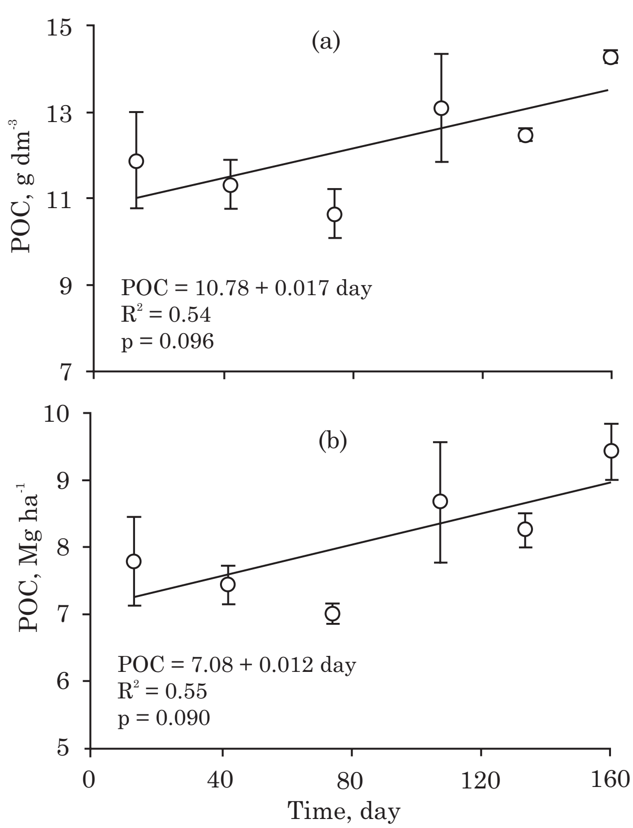

Figure 4. Particulate organic carbon (POC - fraction > 53 µm) content (a) and stock (b) in the 0-5 cm layer over time after black oat management. Vertical bars indicate the standard error of the mean.

in the 0-5 cm layer showed that 21 % of the total C was found in the particulate fraction (POC = 2.9 + 0.21_{SOC}; $R^2 = 0.84$; $p < 0.001$), which proved to be the main factor for the SOC increase. Bayer et al. (2004) also demonstrated that the greatest variation in the carbon content was associated with the particulate fraction (> 53 μm), which supports the results of our study.

The alteration in the C stock, representing the difference in the C stock between the last and the first sampling (t_6 to t_0), had a significant linear relationship (Figure 5) with the change in SR (0-5cm layer/0-20 cm layer). Thus, the increase in the SR of C shows that the soil is acting as a C sink and that it is closely related to the continuous input of crop residues. These results agree with those reported by Franzluebbers (2002) and Sá & Lal (2009), who demonstrated that SR is a good index to evaluate C sequestration in soil.

Thus, NT was important for CO_2 mitigation because it allowed the maintenance of permanent soil cover with crop residues, providing a slow and gradual decomposition and tending to accumulate SOC (Table 1) and POC (Figure 4).

Carbon converted from crop residues into soil

The SOC stock in the 0-20 cm layer was 57.81 Mg ha^{-1} (t_0), and increased to 58.65 Mg ha^{-1} (t_6) (Table 1). Moreover, the sequestration rate was 0.84 Mg ha^{-1} after 160 days of black oat decomposition. The input of 2.21 Mg ha^{-1} C (equivalent to 5.02 Mg ha^{-1} of oat residues) had an efficiency of 36.8 % of C conversion from the residues into soil C, and 63.2 % of the C was lost to the atmosphere in the form of CO_2. Based on a long-term study, Sá et al. (2001) reported a conversion rate of 26.5 % in the same region while Bayer et al. (2006), in another long-term study, reported a conversion rate of 14.6 % in a no-till system (state of

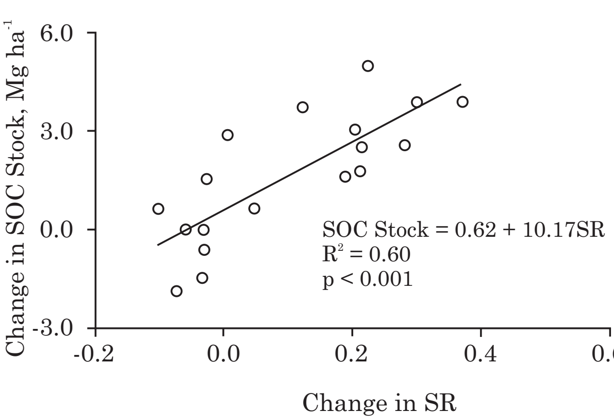

Figure 5. Relation between the change in the stratification ratio (SR) and the change in the SOC stock in the period of 160 days of oat residue decomposition.

Rio Grande do Sul). Moreover, considering only the 0-5 cm layer, the conversion rate of oats was 72.4 %. This high value can be explained by the high amount of oats left on the soil surface, increasing the C stock.

The high conversion rate found in this study could be explained by: 1) the input of a high amount of soybean prior to the input of black oat residues, contributing with a greater amount of N and stimulating greater biological activity; 2) the addition of high amounts of crop residues oat maintaining the soil cover until after soybean flowering, protecting the macroaggregates and ensuring a greater persistence of C in the system; and 3) favorable climatic conditions for decomposition, resulting in greater C cycling in the system through an increase in POC.

CONCLUSIONS

1. After 160 days, crop residue decomposition induced an increase in soil organic carbon and particulate organic carbon content in the 0-5 cm layer.

2. During the study period, the main factor for the increase of soil organic carbon was the particulate pool.

3. The C increase in the soil surface layer reflected in increased stratification of C and was significantly linearly correlated with the stratification ratio, and the higher the stratification ratio, the greater was C cycling, resulting in greater soil C sequestration

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