Science of the Total Environment 622–623 (2018) 735–742

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Driving factors of soil carbon accumulation in Oxisols in long-term no-till systems of South Brazil

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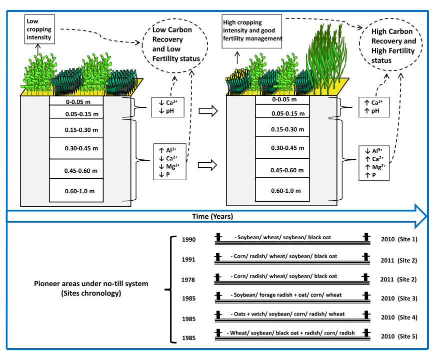
HIGHLIGHTS

- The factors that drive C recovery in long-term no-till are proper nutrient management associated with high residue C input.
- The sites with less C recovery were associated with high Al^{3+} and low Mg^{2+} and P.
- The sites with greater C recovery were associated with low Al^{3+} and high bases saturation.
- The subsoil C recovery showed close association with Ca^{2+} content.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 May 2017
Received in revised form 3 December 2017
Accepted 3 December 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Conservation agriculture
Crop rotation
Deep carbon
Soil fertility

ABSTRACT

In a climate change scenario, it is important to understand the factors that lead to changes in a soil carbon (C) sink. It is recognized that such process is highly dependent on climate, soil properties, topography, and vegetation. However, few studies demonstrate how these mechanisms operate in highly weathered Oxisols. Therefore, this study evaluated the driving factors for C recovery and accumulation and its relations with fertility attributes in the soil profile (0 to 1 m depth) in no-till (NT) croplands of south Brazil. The adoption of NT in the studied fields started between 1978 (pioneer areas) and 1990 and represent a range of textural and mineralogical characteristics South Brazil main croplands. Soil samples were collected in paired fields of native vegetation and NT (NV vs. long-term NT) to a depth of 1 m. The studied NT areas of Rio Grande do Sul State were managed according to the principles of conservation agriculture (minimum soil disturbance, permanent soil cover and diverse crop rotation). The processes that drove SOC recovery in the studied sites were soil fertility management allied with high C input through intense crop rotation. The C recovery was were for areas with the predominance of soybean in the cropping system, higher levels of Al^{3+} and lower levels of Mg^{2+} and P. Sites with medium/high cropping intensity, lower levels of Al^{3+} and higher levels of P, Ca^{2+}, Mg^{2+}, and K^{+} resulted in higher C recovery.

Abbreviations: C, carbon; NT, no-till; SOC, soil organic carbon; CA, conservation agriculture; TOC, total organic carbon; V%, base saturation; Al, aluminum; NV, natural vegetation; PCA, principal component analysis; $CEC_{effective}$, cation exchange capacity; Mg^{2+}, magnesium; K^{+}, potassium; P, phosphorus; Ca^{2+}, calcium.

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https://doi.org/10.1016/j.scitotenv.2017.12.019

1. Introduction

Soil is essential to sustain terrestrial and human basic needs such as food, clean water, clean air, and biodiversity (Keesstra et al., 2016). However, soil is a finite resource and vulnerable to degradation by mismanagement (Lal, 2015; Karlen and Rice, 2015). The Global Assessment of Soil Degradation study estimated that nearly 2 billion ha (22.5%) of agricultural land, pasture, forest, and woodland has been degraded since the 20th century, of which 140 million ha (7%) are in Brazil (IPEVS, 2017). In this region, the continuous use of conventional soil management practices with intensive tillage (plowing) leads to depletion of soil organic carbon (SOC), decline of soil quality and reduction of the provision of essential environmental services (Lal, 2004; De Oliveira Ferreira et al., 2013; Sá et al., 2015).

Climate-smart soil management contributes to the net removal of carbon (C) from the atmosphere (Paustian et al., 2016), restoration of SOC (De Oliveira Ferreira et al., 2017), improvement of soil quality and an increase of agronomic productivity (Sá et al., 2015). Several practices are efficient strategies to climate smart principles such as improved crop rotations, organic amendments, nutrient management, reforestation, improvement of soil fertility, C addition as plant residue and reduce soil disturbance. The degree of SOC depletion and restoration depend on many factors including soil texture, mineralogy, climate, cropping systems, biomass carbon input, plant root systems, tillage, and chemical attributes.

Topsoil chemical characteristics significantly affect C accumulation rates. Recent studies demonstrated the effect of base saturation (V%) and the Al^{+3} contents on C accumulation at surface layers (Briedis et al., 2012). According to the authors, the enhancement of surface C (0–0.20 m) is related mainly to the increase of base saturation and the reduction of aluminum saturation. Likewise, Inagaki et al. (2016) found a strong relationship between the Ca^{+2} and SOC content in a highly weathered soil under no-till. The soil C increase in response to the Ca^{+2} content also provides an important environmental service, since it provides significant benefits for topsoil layers that act as sinks of atmospheric CO_2.

The C accumulation in subsoil horizons of well-drained deep soils has received attention in the last years in temperate (Chabbi et al., 2009; Rumpel and Kogel-Knabner, 2011) and more recently on subtropical ecosystems (Boddey et al., 2010; Dick et al., 2013). Although the C content is lower compared to the shallow layers, the subsoil horizons contribute >50% of the total SOC stocks in temperate ecosystems (Rumpel and Kogel-Knabner, 2011) and >70% in subtropical ecosystems (Dick et al., 2013).

For climate change, it is important to understand the driver factors that lead to the transfer of C from the surface horizons to the subsoil. It is recognized that such process are highly dependent on time, climate, soil characteristics, topography and vegetation type (Davy and Koen, 2014; McLeod et al., 2014). The environmental conditions, texture and chemical properties on the subsoil can be different from the soil surface, and the C content may be affected by several factors (Lutzow et al., 2006).

In an incubation experiment, Briedis et al. (2016) demonstrated that the nutrient scarcity (Ca^{2+}, Mg^{2+} and P) leads to a low efficiency for C accumulation in the subsoil. The authors also noted that the improvement of nutrient availability on deeper layers is an efficient strategy to preserve the C stocks, providing a high C sequestration potential and consequently increasing productivity in highly weathered soils.

The factors that drive C recovery and accumulation in deep and surface soil layers and its relations to the improvement of soil fertility in areas under long-term conservation agriculture (CA) still need to be better understood, especially with climate change. In Brazil, the occurrence of dry periods during summer has becoming common in recent seasons and losses due to drought events of 2003/2004 and 2014/2015 were estimated in US$46.6 billion (Fuganti-Pagliarini et al., 2017). In southern Brazil (Rio Grande do Sul state), in the 2012 crop season about 10 million tons (72% of the municipalities were affected) were lost; soybean yields were 36% and corn 54% (Sousa Junior et al., 2012) of average production. Therefore, this study aimed to evaluate the driving factors for C recovery and accumulation and its relations with fertility attributes in the soil profile (0 to 1 m depth) in pioneers no-till croplands of south Brazil.

2. Materials and methods

2.1. Sites description

The studied areas were selected from pioneer sites of NT system adoption located in five municipalities of Rio Grande do Sul state, Brazil (Site 1 - Santa Rosa; Site 2 - Palmeira das Missões; Site 3 - Lagoa Vermelha; Site 4 - Cruz Alta and Site 5 - Fortaleza dos Valos).

In general, the clay content ranged from 570 to 720 g kg^{-1} for all locations and it is composed of variable charge minerals, primarily kaolinite, iron oxides, and gibbsite. According to the Köppen climate classification, the climate was humid subtropical (Peel et al., 2007). For comparison, we collected soil samples in the natural vegetation (NV) nearby each agricultural site with the same soil texture and landscape position.

2.1.1. Site 1 - Santa Rosa (27°52′S–54°28′W)

The average altitude was 330 m above sea level. The average minimum and maximum temperatures were 15.5 and 26.1 °C, respectively, and the annual precipitation was approximately 1725 mm. The soil was classified as Oxisol (Brazilian classification) equivalent to a Rhodic Hapludox (Soil Survey, 2014), with 720 g kg^{-1} of clay.

2.1.2. Site 2 - Palmeira das Missões (27°53′S–53°18′W)

The average altitude was 639 m above sea level. The average minimum and maximum temperatures were 3.0 and 39.7 °C, respectively, and the annual precipitation was approximately 1625 mm. The soil was classified as Oxisol (Brazilian classification) equivalent to a Rhodic Hapludox (Soil Survey, 2014), with 600 g kg^{-1} of clay.

2.1.3. Site 3 - Lagoa Vermelha (28°22′S–51°50′W)

The average altitude was 840 m above sea level. The average minimum and maximum temperatures were 12.4 and 22.7 °C, respectively, and the annual precipitation was approximately 1725 mm. The soil was classified as Oxisol (Brazilian classification) equivalent to a Rhodic Hapludox (Soil Survey, 2014), with 700 g kg^{-1} of clay.

2.1.4. Site 4 - Cruz Alta (28°38′S–53°36′W)

The average altitude was 452 m above sea level. The average minimum and maximum temperatures were 12.8 and 21.5 °C, respectively, and the annual precipitation was approximately 1729 mm. The soil was classified as Oxisol (Brazilian classification) equivalent to a Rhodic Hapludox (Soil Survey, 2014), with 570 g kg^{-1} of clay.

2.1.5. Site 5 - Fortaleza dos Valos (28°47′S–53°13′W)

The average altitude was 406 m above sea level. The average minimum and maximum temperatures were 8.6 and 30.0 °C, respectively, and the annual precipitation was approximately 1727 mm. The soil was classified as Oxisol (Brazilian classification) equivalent to a Rhodic Hapludox (Soil Survey, 2014), with 600 g kg^{-1} of clay. Additional detailed information on the sites had been provided by De Oliveira Ferreira et al. (2016).

No-till sites evaluated in the study were categorized by cropping intensity as low, medium, and high. The low cropping intensity generated approximately 6–8 Mg ha^{-1} $year^{-1}$ of aboveground biomass with a frequency of 3/1 soybean (*Glycine* max L. Merril)/maize (*Zea mays* L.); the medium cropping intensity was 8–10 Mg ha^{-1} $year^{-1}$ of aboveground biomass with a frequency of 2/1 soybean/maize; and the high cropping intensity was 10–12 Mg ha^{-1} $year^{-1}$ of aboveground biomass with a frequency of 1/1 soybean/maize. Cover crops used in winter were: black oat (*Avena strigosa Schieb*) (Low cropping intensity); black oat + radish oil (*Raphanus sativus* L.) (medium cropping intensity) and forage radish (overseeded) + oat/corn/wheat (*Triticum aestivum* L.) or oats + vetch (*Vicia sativa* L.)/soybean/corn/radish/wheat (high cropping intensity). The soil use chronology and soil management systems are summarized in Fig. 1.

2.2. Historical land use and management

In southern Brazil, the grain crop production systems started in the colonial period (subsistence) agriculture (between 1900 and 1965), with soil plowing primarily by animal traction and slash-burn of native vegetation. The main activities were livestock, cultivation of maize, wheat (*Triticum aestivum* L.), beans (*Phaseolus vulgaris* L.), lentils (*Lens culinaris* Medik), cassava (*Manihot esculenta* Crantz) and after 1956 soybean. The agriculture was based on the natural fertility from the forest and native prairie, which were converted to croplands. After 1965, mechanized agriculture began with intense soil plowing and harrowing (conventional tillage, CT), use of chemical fertilizers and wheat/soybean crop rotations, besides the burning of wheat residues, as a phytosanitary procedure, caused soil physical degradation and water erosion. Between 1981 and 1990, farmers started to adopt conservation agriculture practices, such as the use of chisel plow and disc harrow (reduced tillage). After an initial period, farmers stopped burning wheat residues and started introducing black oats as a cover crop. In 1990, NT was largely adopted, and since then it has been used in most crop fields. In 2000, the transgenic adoption was fast and crop systems were specialized with consequent loss of diversity.

2.3. Characterization and description of native vegetation

The NV in the sampled areas were classified as steppes, and grassy woody without gallery forest (IBGE, 2010), equivalent to subtropical prairies. The dry mass production (DM) during the warm season of the year ranges from 2 to 3.4 Mg ha^{-1} of DM (Pillar et al., 2009).

2.4. Soil sampling, soil bulk density, and total organic C content

Soil samples were collected in paired areas of native vegetation and long-term no-till system opening 10 pits with dimensions of 0.3 × 0.3 × 1 m in each site (i.e. five in NT and five in NV). Samples were collected with a spatula on the pit face at the following depths: 0–0.05; 0.05–0.15; 0.15–0.30; 0.30–0.45; 0.45–0.60 and 0.60–1.0 m. Samples were air-dried and passed through a 2-mm sieve removing roots and plant residues. The samples were ground with a mortar and pestle. Total organic C (TOC) was determined by wet combustion by the method of Mebius modified in the digestion block (Nelson and Sommers, 1996; Rheinheimer et al., 2008).

To determine soil bulk density (BD), we collected undisturbed samples at depths of 0.05–0.15; 0.15–0.30; 0.30–0.45; 0.45–0.60 and 0.60–1.0 m using steel rings with dimensions of 0.05 m of diameter by 0.04 m height. Bulk density was used to calculate the SOC stocks. All the SOC stocks and recovery rates are reported in De Oliveira Ferreira et al. (2016).

The soil fertility attributes were analyzed according to the methods described by Pavan et al. (1992). Soil pH was analyzed in 0.01 M $CaCl_2$ suspension. Exchangeable Ca, Mg, and Al were extracted with a 1 M KCl solution. Exchangeable K and $H_2PO_4^-$ contents were extracted with a Mehlich-1 solution (0.025 N H_2SO_4 + 0.05 N HCl). All the elements were determined by atomic absorption spectroscopy (Model AA240Z - Varian).

2.5. Statistical analysis

A paired *t*-test ($p < 0.05$) was used to compare native vegetation (undisturbed field) vs. long-term no-till system (>20 yrs. under continuous NT) at the different sampling depths in the soil profiles (0–1.0 m)

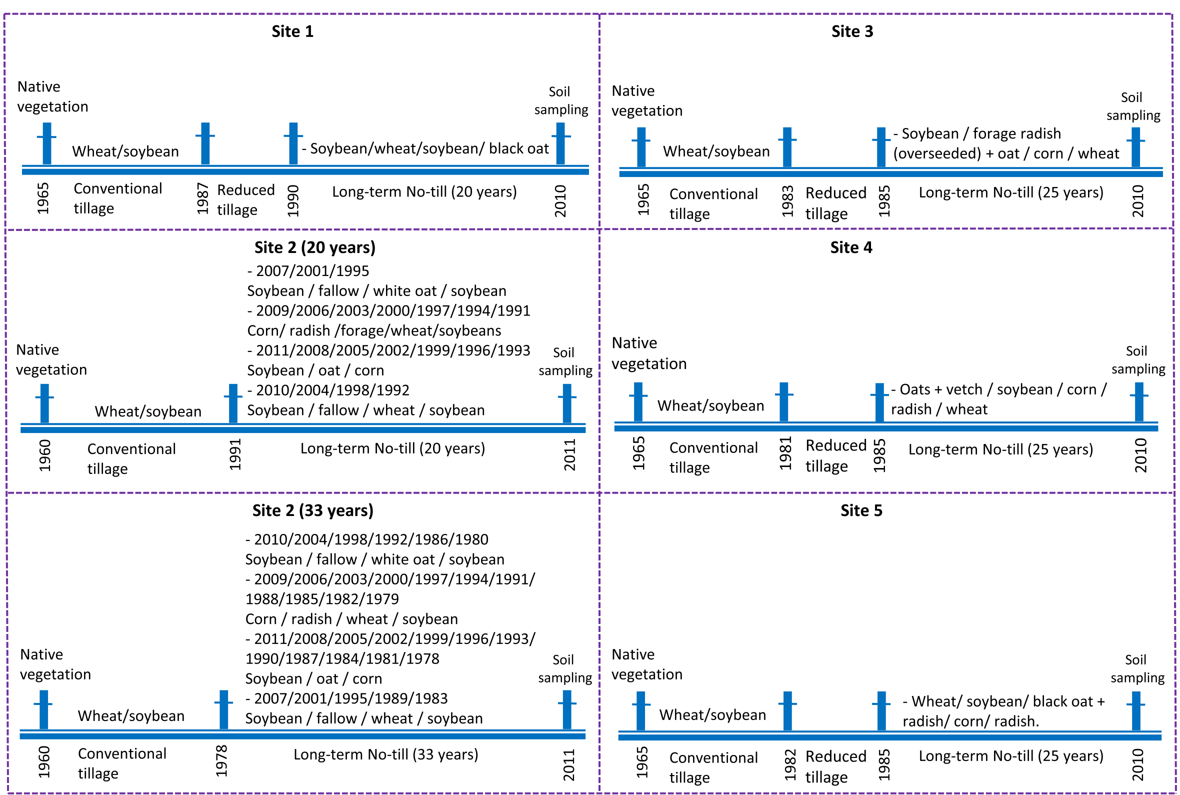

Fig. 1. Chronology of soil use and management at the pioneer areas under no-till system. Site 1 - Santa Rosa; Site 2 - Palmeira das Missões; Site 3 - Lagoa Vermelha; Site 4 - Cruz Alta and Site 5 - Fortaleza dos Valos.

of the five sampled sites (Santa Rosa, Palmeira das Missões, Lagoa Vermelha, Cruz Alta, and Fortaleza dos Valos). We also performed Bivariate Pearson correlations and a Principal Component Analysis (PCA) to evaluate the relationship between soil fertility attributes, SOC stocks, carbon recovery and crop intensity. In addition, we performed multiple linear regressions fitting C recovery in function of all variables on depths 0–15 and 60–100 cm using stepwise (both directions) procedure. This analyse aimed to generate models to understand the driving factors of SOC accumulation in surface and deep layers. All statistical analysis were made using R v. 3.4.1 (Team, 2014).

3. Results

3.1. Main chemical attributes in different soil layers of Oxisols under pioneer no-till croplands and native vegetation

Overall, the pH_{H2O} in NT ranged, on average, from 4.87 ($\pm$0.2) to 5.7 ($\pm$0.3) and from 4.68 ($\pm$0.1) to 5.34 ($\pm$0.4) for the soil layers of 0–0.05 and 0.6–1.0 m, respectively (Table 1). For the NV, these values ranged from 4.46 ($\pm$0.1) to 5.45 ($\pm$0.1) and from 4.42 ($\pm$0.1) to 5.30 ($\pm$0.1), respectively (Table 1). The Al^{+3} content in NT varied, on average, from 0.04 ($\pm$0.1) to 0.64 ($\pm$0.2) cmolc dm^{-3} and from 0.28 ($\pm$0.1) to 1.69 ($\pm$0.4) cmolc dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. In NV areas, these values ranged from 0.35 ($\pm$0.2) to 2.75 ($\pm$0.7) cmolc dm^{-3} and from 0.45 ($\pm$0.2) to 3.85 ($\pm$0.4) cmolc dm^{-3}, respectively.

The P content in NT ranged, on average, from 20.52 ($\pm$0.8) to 43.85 ($\pm$4.0) mg dm^{-3} and from 0.71 ($\pm$0.5) to 1.53 ($\pm$1.2) mg dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For the NV, these values ranged from 0.40 ($\pm$0.4) to 3.87 ($\pm$0.8) mg dm^{-3} and from 0.28 ($\pm$0.1) to 0.63 ($\pm$0.4) mg dm^{-3}, respectively. The K^{+} content in NT ranged, on average, from 0.40 ($\pm$0.1) to 1.10 ($\pm$0.2) cmolc dm^{-3} and from 0.04 ($\pm$0.0) to 0.09 ($\pm$0.1) cmolc dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For the NV, these values ranged from 0.01 ($\pm$0.0) to 0.77 ($\pm$0.1) cmolc dm^{-3} and from 0.01 ($\pm$0.0) to 0.19 ($\pm$0.1) cmolc dm^{-3}, respectively.

The Ca^{+2} content in NT ranged, on average, from 7.51 ($\pm$0.7) to 9.34 ($\pm$1.5) cmolc dm^{-3} and from 2.00 ($\pm$0.7) to 4.28 ($\pm$0.3) cmolc dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For the NV, these values ranged from 0.69 ($\pm$0.1) to 7.11 ($\pm$1.0) cmolc dm^{-3} and from 0.49 ($\pm$0.1) to 6.80 ($\pm$0.6) cmolc dm^{-3}, respectively. The Mg^{+2} content in NT ranged, on average, from 3.44 ($\pm$0.3) to 5.08 ($\pm$0.4) cmolc dm^{-3} and from 1.73 ($\pm$0.2) to 3.31 ($\pm$0.5) cmolc dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For the NV, these variations were from 1.07 ($\pm$0.2) to 5.78 ($\pm$0.2) cmolc dm^{-3} and from 0.06 ($\pm$0.0) to 2.69 ($\pm$0.2) cmolc dm^{-3}, respectively.

Finally, the cation exchange capacity ($CEC_{effective}$) in NT ranged, on average, from 11.83 ($\pm$0.6) to 14.69 ($\pm$2.4) cmolc dm^{-3} and from 5.93 ($\pm$0.6) to 8.0 ($\pm$0.4) cmolc dm^{-3}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For the NV, these values ranged from 4.54 ($\pm$0.4) to 12.88 ($\pm$0.4) cmolc dm^{-3} and from 1.98 ($\pm$0.2) to 9.93 ($\pm$0.6) cmolc dm^{-3}, respectively.

3.2. Pearson correlation between carbon recovery and soybean frequency

The Pearson correlation coefficients indicated high and significant correlation among the carbon recovery, soybean frequency in cropping system and soil fertility attributes (Table 1. Supplementary material). The highest Person coefficients found for relative C recovery were with altitude, temperature, Mg^{+2} content, effective cation exchange capacity (CEC effective), and amount of aboveground crop residues input. For deeper layers (0.45–0.60 and 0.60 to 1 m) the Al^{+3} content affected C recovery.

3.3. Principal component analysis

The analysis of principal components was successful at identifying the different sampling sites within each depth (Fig. 2). The sites were arranged in three groups as follow: 1) Lagoa Vermelha (site 3); 2) Fortaleza dos Valos (site 5), Cruz Alta (site 4) and Palmeira das Missões (site 2); and 3) Santa Rosa (site 1). The group 1 was characterized by a more diverse crop rotation (less frequency of soybean) and high plant biomass input. This group showed the highest C recovery in the subsoil. The group 2 represented intermediate levels of crop intensity and C recovery, but higher soil fertility attributes and clay content throughout the soil profile. A higher soybean frequency mainly characterized the group 3 with lower plant biomass input and lower C recovery.

For the shallow layer (0–0.15 m) of weathered distrophic Oxisols, the soil fertility attributes of Ca^{+2} and pH_{H20} composed the first principal component, which explained 37.6% of variance. On the other hand, factors related to the relative C recovery, as altitude and C input composed the second principal component, which explained 24.4% of the variance. For the subsoil layer (0.6–1.0 m), the soil fertility attributes of Ca^{+2}, base saturation, Al^{+3}, pH_{H20} and clay content composed the first principal component, which explained 41.6% of the variance. On the other hand, factors related to the relative C recovery composed the second principal component, which explained 26.9% of the variance.

Overall, the soil fertility attributes of Ca^{+2}, Al^{+3}, base saturation and pH_{H20} composed the first principal component, which explained in average 39.6% of the variance throughout the 1-m soil profile (37.6, 34.1, 45.7, 39.1 and 41.6% for the layers 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60 and 0.60–1.0 m, respectively). On the other hand, factors related to the SOC stocks such as relative C recovery and C input composed the second principal component, which explained in average 24.5% of the variation throughout the 1-m soil profile (24.4, 22.8, 20.8, 27.4, 26.9% for layers 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60 and 0.60–1.0 m, respectively).

4. Discussion

4.1. Soil fertility attributes as a driving factor of C recovery in Oxisols under long term no-till system

All of the NT sites represented SOC stocks significantly different from the NV in at least 6 layers (Table 1). The surface layers of sites 2, 3 and 4 presented higher SOC stocks compared to native vegetation. These results indicate higher SOC recovery compared to Sá et al. (2014), that did not overcome SOC stocks of NV even after 29 years, showing that long term no-till allied with fertilization management can result in a new equilibrium state that can overcome NV stocks. The Site 1 had the lowest SOC stocks ranging between 72 and 49.5% of the NV which had higher levels of Al^{3+} and the lowest level of Mg^{2+} and P. The other sites that had SOC stocks closer to the NV had lower levels of Al^{3+} and higher levels of P, Ca^{2+}, Mg^{2+} and K^{+}, reflecting the CEC (Table 1. Supplementary material). The complexation of Al^{3+} with organic compounds (Caires et al., 2008) and the increase of CEC (Sparks, 2003) can explain the increase of SOC stocks.

These results indicate that nutrient management plays an important role in SOC recovery in long-term no-till systems as it provides conditions for sustained crop production, that add crop residues to the soil. In addition, some authors explored the role of nutrient stoichiometry on SOC stabilization. Kirkby et al. (2013) reported that the fine fraction of SOC has the stoichiometry C:N:P:S = 10000:833:200:143, indicating that the fertility management is directly related to the increase of SOC stocks.

The elevation and temperature also significantly affected the SOC recovery (Table 1. Supplementary material), which allied with crop rotation and soybean frequency may be influencing crop residue input to the soil. A possible explanation is that corn has higher yields in the

Table 1
Variation of pH, aluminum, phosphorus, potassium, calcium, magnesium, and cation exchange capacity in different soil layers of the sampled areas under no-till and native vegetation.

Soil depth (m)	Site 1 - Santa Rosa		Site 2 - Palmeira das Missões			Site 3 - Lagoa Vermelha		Site 4 - Cruz Alta		Site 5 - Fortaleza dos Valos	
	NV[†]	NT[††]	NV	NT[*]	NT[**]	NV	NT	NV	NT	NV	NT
						pH_{H2O}					
0–0.05	5.45 ±0.1 a	5.45 ±0.4 a	4.63 ±0.1 c	5.70 ±0.3 a	5.21 ±0.3 b	5.08 ±0.1 a	4.87 ±0.2 b	4.46 ±0.1 b	5.22 ±0.3 a	4.46 ±0.1 b	5.49 ±0.2 a
0.05–0.15	5.28 ±0.1 a	4.96 ±0.2 b	4.43 ±0.1 b	5.21 ±0.2 a	5.53 ±0.2 a	4.89 ±0.1 a	4.87 ±0.1 a	4.42 ±0.1 a	4.89 ±0.2 a	4.42 ±0.2 a	5.29 ±0.5 a
0.15–0.30	5.25 ±0.0 a	4.97 ±0.1 b	4.49 ±0.1 b	5.37 ±0.3 a	5.59 ±0.2 a	4.79 ±0.1 b	5.23 ±0.2 a	4.39 ±0.0 a	4.94 ±0.2 a	4.39 ±0.2 a	5.04 ±0.5 a
0.30–0.45	5.25 ±0.1 a	4.99 ±0.2 b	4.51 ±0.1 b	5.14 ±0.4 a	5.44 ±0.2 a	4.93 ±0.1 a	5.01 ±0.1 a	4.41 ±0.1 a	4.94 ±0.1 a	4.41 ±0.1 a	4.80 ±0.4 a
0.45–0.60	5.26 ±0.1 a	4.92 ±0.1 b	4.59 ±0.1 b	4.96 ±0.3 b	5.38 ±0.3 a	4.99 ±0.1 a	4.57 ±0.1 b	4.35 ±0.1 a	4.98 ±0.1 a	4.35 ±0.1 a	4.72 ±0.2 a
0.60–1.0	5.30 ±0.1 a	4.89 ±0.1 b	4.58 ±0.1 b	4.77 ±0.4 b	5.34 ±0.4 a	4.99 ±0.1 a	4.55 ±0.1 b	4.42 ±0.1 a	5.01 ±0.1 a	4.42 ±0.1 a	4.68 ±0.1 a
						Aluminum (cmolc dm^{-3})					
0–0.05	0.35 ±0.2 a	0.04 ±0.1 b	2.75 ±0.7 a	0.07 ±0.2 b	0.26 ±0.2 b	0.82 ±0.2 a	0.64 ±0.2 a	2.66 ±0.3 a	0.16 ±0.2 b	2.66 ±0.2 a	0.07 ±0.2 b
0.05–0.15	0.45 ±0.1 a	0.34 ±0.2 a	1.66 ±0.8 a	0.65 ±0.2 b	0.12 ±0.1 b	0.99 ±0.4 a	1.10 ±0.2 a	3.25 ±0.3 a	0.60 ±0.5 b	3.25 ±0.5 a	0.31 ±0.2 b
0.15–0.30	0.41 ±0.0 a	0.44 ±0.2 a	0.94 ±0.3 a	0.48 ±0.4 ab	0.14 ±0.1 b	0.35 ±0.2 b	1.51 ±0.3 a	3.49 ±0.3 a	0.74 ±0.5 b	3.49 ±0.5 a	0.98 ±0.4 b
0.30–0.45	0.44 ±0.0 a	0.46 ±0.2 a	0.75 ±0.8 a	0.60 ±0.3 a	0.17 ±0.1 b	1.04 ±0.9 b	1.69 ±0.4 a	3.65 ±0.4 a	0.90 ±0.4 b	3.65 ±0.4 a	1.28 ±0.4 b
0.45–0.60	0.43 ±0.1 b	0.72 ±0.4 a	1.36 ±0.9 a	0.34 ±0.2 b	0.28 ±0.2 b	3.22 ±0.3 a	1.70 ±0.4 b	3.40 ±1.2 a	0.68 ±0.1 b	3.40 ±0.1 a	1.60 ±0.2 b
0.60–1.0	0.45 ±0.2 b	0.64 ±0.2 a	1.70 ±0.7 a	0.28 ±0.1 b	0.34 ±0.3 b	3.30 ±0.5 a	1.69 ±0.4 b	3.85 ±0.4 a	0.69 ±0.1 b	3.85 ±0.1 a	1.42 ±0.2 b
						Phosphorus (mg dm^{-3})					
0–0.05	3.87 ±0.8 b	43.85 ±4.0 a	2.75 ±0.7 c	35.03 ±1.9 a	27.32 ±2.2 b	0.40 ±0.4 b	32.72 ±3.0 a	3.37 ±2.3 b	20.52 ±0.8 a	3.37 ±0.8 b	32.50 ±0.3 a
0.05–0.15	1.74 ±0.2 b	17.15 ±4.6 a	1.66 ±0.8 b	10.48 ±2.5 a	10.53 ±2.3 a	0.36 ±0.4 b	36.05 ±5.7 a	1.98 ±0.3 b	5.31 ±0.6 a	1.98 ±0.6 b	18.26 ±1.4 a
0.15–0.30	0.76 ±0.8 a	2.65 ±1.5 a	0.94 ±0.3 b	2.34 ±1.2 b	4.32 ±2.8 a	0.07 ±0.0 b	6.56 ±0.8 a	0.60 ±0.3 a	2.55 ±0.4 a	0.60 ±0.3 a	2.38 ±1.0 a
0.30–0.45	0.69 ±0.8 a	1.76 ±1.5 a	0.60 ±0.3 b	1.45 ±0.8 a	1.73 ±0.7 a	0.07 ±0.0 b	1.74 ±0.3 a	0.42 ±0.4 a	2.24 ±0.9 a	0.42 ±0.4 a	1.11 ±0.3 a
0.45–0.60	0.36 ±0.2 a	0.89 ±0.5 a	0.34 ±0.2 b	0.76 ±0.4 b	1.33 ±0.6 a	0.99 ±0.7 a	1.15 ±0.2 a	0.44 ±0.3 a	1.97 ±1.7 a	0.44 ±0.3 a	1.18 ±0.3 a
0.60–1.0	0.63 ±0.4 a	0.98 ±0.2 a	0.28 ±0.1 b	0.73 ±0.4 a	0.71 ±0.5 a	0.53 ±0.4 a	0.99 ±0.1 a	0.35 ±0.3 a	1.53 ±1.2 a	0.35 ±0.3 a	1.29 ±0.4 a
						Potassium (cmolc dm^{-3})					
0–0.05	0.77 ±0.1 a	0.79 ±0.1 a	0.01 ±0.0 c	0.40 ±0.1 b	0.54 ±0.1 a	0.23 ±0.2 b	1.10 ±0.2 a	0.11 ±0.0 b	0.40 ±0.1 a	0.11 ±0.0 b	0.62 ±0.2 a
0.05–0.15	0.58 ±0.1 a	0.46 ±0.1 a	0.01 ±0.0 b	0.20 ±0.1 a	0.25 ±0.1 a	0.17 ±0.1 b	0.67 ±0.1 a	0.07 ±0.0 b	0.11 ±0.0 a	0.07 ±0.0 a	0.11 ±0.0 a
0.15–0.30	0.36 ±0.2 a	0.26 ±0.2 a	0.01 ±0.0 b	0.12 ±0.1 a	0.14 ±0.1 a	0.10 ±0.1 b	0.44 ±0.2 a	0.04 ±0.0 a	0.06 ±0.0 a	0.04 ±0.0 a	0.07 ±0.0 a
0.30–0.45	0.30 ±0.2 a	0.13 ±0.1 b	0.01 ±0.0 b	0.08 ±0.1 a	0.08 ±0.0 a	0.07 ±0.0 b	0.26 ±0.1 a	0.03 ±0.0 a	0.05 ±0.0 a	0.03 ±0.0 a	0.06 ±0.0 a
0.45–0.60	0.24 ±0.1 a	0.14 ±0.2 a	0.01 ±0.0 b	0.06 ±0.0 a	0.06 ±0.0 a	0.16 ±0.1 a	0.12 ±0.1 a	0.03 ±0.0 a	0.04 ±0.0 a	0.03 ±0.0 a	0.06 ±0.0 a
0.60–1.0	0.19 ±0.1 a	0.06 ±0.0 b	0.01 ±0.0 b	0.05 ±0.0 a	0.05 ±0.0 a	0.11 ±0.1 a	0.09 ±0.0 a	0.02 ±0.0 a	0.04 ±0.0 a	0.02 ±0.0 a	0.06 ±0.0 a
						Calcium (cmolc dm^{-3})					
0–0.05	7.11 ±1.0 b	9.34 ±1.5 a	2.14 ±0.4 c	8.90 ±0.8a	7.59 ±0.4 b	6.23 ±0.4 b	7.51 ±0.7 a	0.69 ±0.1 b	8.10 ±1.9 a	0.69 ±0.1 b	8.08 ±0.6 a
0.05–0.15	6.66 ±0.5 a	6.78 ±1.0 a	1.18 ±0.2 b	5.90 ±1.1 a	7.08 ±0.9 a	4.91 ±0.8 b	7.63 ±0.6 a	0.51 ±0.1 b	5.70 ±1.7 a	0.51 ±0.1 b	6.37 ±1.8 a
0.15–0.30	6.64 ±0.3 a	5.74 ±0.6 a	1.02 ±0.1 b	5.06 ±1.0 a	6.14 ±0.9 a	3.82 ±0.7 b	8.27 ±0.5 a	0.47 ±0.1 b	5.06 ±1.1 a	0.47 ±0.1 b	4.31 ±1.1 a
0.30–0.45	7.47 ±1.1 a	5.23 ±0.6 b	0.98 ±0.1 b	3.52 ±1.5 a	4.69 ±1.0 a	2.98 ±0.5 b	5.46 ±1.4 a	0.43 ±0.1 b	4.67 ±0.3 a	0.43 ±0.1 b	2.99 ±0.4 a
0.45–0.60	7.78 ±0.9 a	4.77 ±0.3 b	0.99 ±0.1 b	2.62 ±1.4 a	3.69 ±0.8 a	2.41 ±0.3 a	2.58 ±0.4 a	0.53 ±0.1 b	4.05 ±0.3 a	0.53 ±0.1 b	3.00 ±0.2 a
0.60–1.0	6.80 ±0.6 a	4.28 ±0.3 b	0.89 ±0.1 b	2.00 ±0.7 ab	3.06 ±0.8 a	2,12 ±0.2 a	3.07 ±2.5 a	0.49 ±0.1 b	4.16 ±0.7 a	0.49 ±0.1 b	3.03 ±0.3 a
						Magnesium (cmolc dm^{-3})					
0–0.05	3.52 ±1.2 b	4.52 ±0.9 a	2.95 ±0.6 b	5.08 ±0.4 a	3.44 ±0.3 b	5.78 ±0.2 a	4.65 ±0.2 b	1.07 ±0.2 b	4.73 ±1.0 a	1.07 ±0.2 b	4.39 ±0.3 a
0.05–0.15	3.25 ±0.5 a	3.18 ±0.6 a	1.55 ±0.3 b	3.18 ±0.5 a	3.75 ±0.4 a	4.61 ±0.2 a	4.38 ±0.2 a	0.40 ±0.1 b	3.54 ±0.9 a	0.40 ±0.1 b	3.69 ±0.8 a
0.15–0.30	2.62 ±0.5 a	2.51 ±0.3 a	0.99 ±0.2 c	2.96 ±0.5 b	3.72 ±0.3 a	2.94 ±1.2 b	4.70 ±1.2 a	0.30 ±0.2 b	2.99 ±0.8 a	0.30 ±0.2 b	3.14 ±0.8 a
0.30–0.45	2.27 ±0.5 a	2.16 ±0.3 a	0.75 ±0.2 c	2.48 ±0.7 b	3.43 ±0.4 a	2.18 ±0.9 b	4.60 ±0.9 a	0.07 ±0.1 b	3.00 ±0.6 a	0.07 ±0.1 b	2.48 ±0.5 a
0.45–0.60	2.22 ±0.5 a	1.80 ±0.3 a	0.80 ±0.1 c	2.20 ±0.5 b	3.32 ±0.4 a	1.99 ±0.3 a	2.59 ±0.3 a	0.08 ±0.1 b	2.67 ±0.3 a	0.08 ±0.1 b	2.28 ±0.4 a
0.60–1.0	2.48 ±0.3 a	1.73 ±0.2 a	0.80 ±0.1 c	2.19 ±0.6 b	3.31 ±0.5 a	2.69 ±0.2 a	2.48 ±0.2 a	0.06 ±0.0 b	2.76 ±0.5 a	0.06 ±0.0 b	2.25 ±0.3 a
						Cation exchange capacity - $CEC_{effective}$ (cmolc dm^{-3})					
0–0.05	11.75 ±1.7 b	14.69 ±2.4 a	7.84 ±0.9 c	14.45 ±1.1 a	11.83 ±0.6 b	12.88 ±0.4 a	14.08 ±0.8 a	4.54 ±0.4 b	13.39 ±2.6 a	4.54 ±0.4 b	13.17 ±0.8 a
0.05–0.15	10.94 ±0.8 a	10.77 ±1.3 a	4.39 ±0.9 b	9.94 ±1.4 a	11.20 ±1.2 a	10.78 ±1.2 b	13.67 ±0.9 a	4.22 ±0.4 b	9.95 ±2.1 a	4.22 ±0.4 b	10.49 ±1.3 a
0.15–0.30	10.02 ±0.9 a	8.96 ±0.6 a	2.95 ±0.5 c	8.62 ±1.2 b	10.13 ±1.0 a	8.37 ±1.1 b	13.76 ±1.8 a	4.30 ±0.2 b	8.85 ±1.4 a	4.30 ±0.2 b	8.50 ±1.1 a
0.30–0.45	10.48 ±1.8 a	7.97 ±0.6 b	2.33 ±0.2 c	6.83 ±1.6 b	8.36 ±1.1 a	6.91 ±0.7 b	11.36 ±1.5 a	4.18 ±0.4 b	8.63 ±0.9 a	4.18 ±0.4 b	6.81 ±0.9 a
0.45–0.60	10.66 ±1.3 a	7.42 ±0.1 b	2.13 ±0.1 b	6.24 ±1.3 a	7.35 ±0.9 a	6.43 ±0.7 a	8.35 ±0.4 a	4.03 ±1.1 b	7.44 ±0.4 a	4.03 ±1.1 b	6.94 ±0.5 a
0.60–1.0	9.93 ±0.6 a	6.72 ±0.2 b	1.98 ±0.2 b	5.93 ±0.6 a	6.75 ±1.0 a	7.56 ±1.0 a	8.00 ±0.4 a	4.41 ±0.4 b	7.65 ±1.1 a	4.41 ±0.4 b	6.76 ±0.4 a

Means followed by the same letter between rows for each location are not statistically different by the paired *t*-test at $p < 0.05$. (Comparison made among management systems (NV × NT) at the same depth and site).
[†] NV = native vegetation.
[††] NT = no-till system.
[*] 20 years no-till system.
[**] 33 years no-till system.

region with cold nights due to the reduction of respiration and extension of maturation period (Jen-Hu, 1981).

In the analysis of principal components (APC), we observed three distinct groups. The site Lagoa Vermelha (LV) stands out as the location with the highest SOC stocks mainly due to the high biomass input from the crop rotation, as discussed in our previous study (de Oliveira Ferreira et al., 2016). The increases of SOC stocks were also related to improvements in soil fertility attributes. The higher C recovery observed in De Oliveira Ferreira et al. (2016) either of surface layers or of subsoil layers indicates that other effects besides the cropping diversity affect SOC recovery. Thus, the same crop rotation under different soil fertility conditions can produce different SOC recoveries. One possible explanation is the fact that crop residue input is dependent on plant nutrition and yield achieved that is linked to other factors to soil fertility. Paradelo et al. (2015) recently reviewed 30 sites and postulated that the increase SOC contents occurs, based on two main pathways: (1) in response to improved soil structure and (2) as a consequence of higher biomass-C input through enhanced crop yields from improved soil fertility. Dalla Nora et al. (2014) found out that the amelioration of soil fertility on the subsurface layers of an Oxisol (i.e. reduction of Al saturation

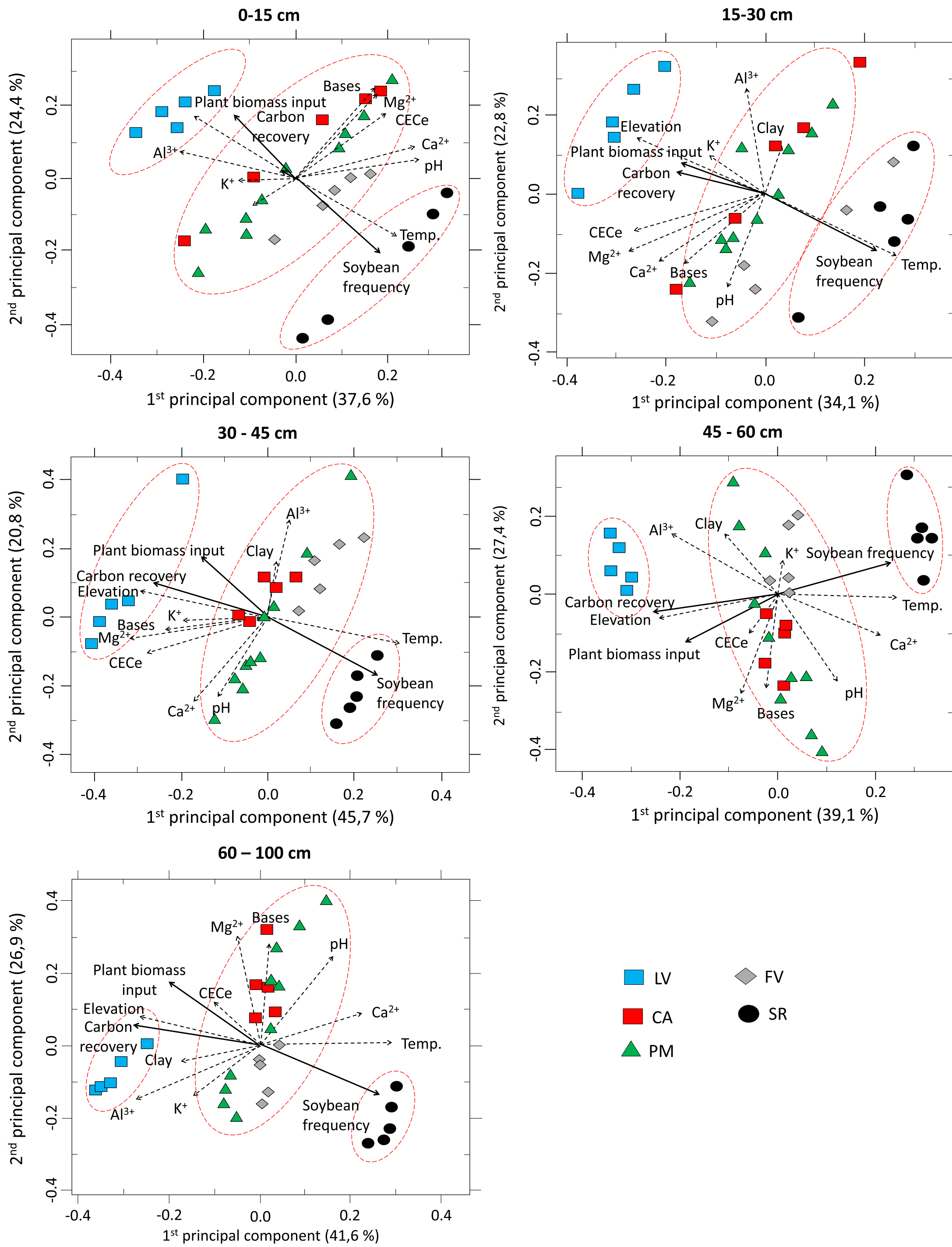

Fig. 2. Principal component analysis (PCA) involving crop intensity, carbon recovery and soil fertility attributes in Oxisols under long-term no-till from different locations in Rio Grande do Sul State. LV = Lagoa Vermelha; CA = Cruz Alta; PM = Palmeira das Missões; FV = Fortaleza dos Valos; SR = Santa Rosa. Soybean frequency = 3/1 soybean/corn, 2/1 soybean/corn and 1/1 soybean/corn; Carbon recovery = percentage of carbon stock recovered by the use of long-term no-till system from the native vegetation stocks; plant biomass input = 6–8, 8–10 and 10–12 Mg ha^{-1} year^{-1} of plant biomass input.

and increase of Ca content and base saturation) resulted in increases of 9 and 11% for corn and soybean crop yield, respectively.

Considering the entire soil profile (0–1.0 m), the Ca^{+2} content increased in no-till in comparison to the nearby native vegetation for the sites Palmeira das Missões, Lagoa Vermelha, Cruz Alta and Fortaleza dos Valos and was a key factor for C recovery (Group 1 and 2 PCA). In addition, significant correlations were found between Ca^{+2} and SOC recovery mainly at the layers of 15–30 and 45–60 cm. These results support the findings of Briedis et al. (2012b) and Inagaki et al. (2017) who indicated a strong correlation between the Ca^{+2} and C accumulation,. The Ca^{+2} is important for root (Sumner, 1994) and the decrease of the Al/Ca ratio is important to decrease the Al toxicity to plants (Caires et al., 2006a).

The elevated relative C recovery on the surface and subsoil layers suggest a response from soil fertility on the deeper layers of the Oxisols (Lagoa Vermelha, Cruz Alta, Fortaleza dos Valos – Group 1 and 2 PCA). Therefore, the soils represented adequate levels of nutrients (Table 1. Supplementary material). Caires et al. (2015) observed increases in the movement of Ca^{2+} (12 to 34%) and Mg^{2+} (7 to 41%) below a depth of 0.6 m in an experiment (2004–2012) under continuous no-till. The authors suggested that the complex Ca-fulvic acid promoted the transport of Ca^{2+} into the subsoil. This transport alleviates the effects of soil acidity in deeper layers, resulting in a greater root development. In this way, such increase of roots may provide a direct increase of C in deep layers (Jobbágy and Jackson, 2000).

In highly weathered soils such as the studied Oxisols, the C accumulation in the deeper layers can be even higher (Briedis et al., 2016) because the anion exchange capacity that Fe and Al oxides present at the pH of the studied soils favors the biding and stabilization of high molecular weight carbonatic compounds (Gonçalves et al., 2017). The high Fe and Al oxides content in the Oxisols (Lagoa Vermelha, Cruz Alta, Fortaleza dos Valos) associated with the higher elevation and low temperatures promoted a prone condition to the C protection (Table 1. Supplementary material). Other studies conducted in subtropical soils also indicate that the C accumulation in subsoil layers are primarily mediated by Fe and Al oxides (Dieckow et al., 2005; Zinn et al., 2007; Rumpel and Kogel-Knabner, 2011; Reis et al., 2014).

Agreeing with our study, Caires et al. (2006b) observed that the amelioration of soil fertility in subsoil layers has been mostly observed in long-term no-till soils. In order to promote the increase of soil fertility in Oxisol's deeper layers as in our study, it is necessary to fulfill certain requirements. Among them: a) the buildup of a surface layer rich in basic cations, which will work as an eluviation layer. For this, high amounts and frequency of Ca-based soil amendments are necessary to saturate this layer with Ca. b) the precipitation level needs to be high enough to provide water for cation transport along the soil profile. c) The K content on the surface layer needs to be elevated to avoid imbalance of bases. d) The presence of continuous pores associated with a high biological activity is essential to provide water infiltration. e) It is necessary to use a crop rotation system with high biomass-C input and plants with a deep root system in order to form a soil layer rich in SOC (Nora and Amado, 2013). These actions associated with a minimum soil disturbance allow cation leaching, neutralization of toxic Al in subsurface layers, deep root system development and the resulting increase of SOC. These processes are supported by the linear models adjusted for the surface (0–15 cm) and subsurface (60–100 cm) soil layers (Fig. 1. Supplementary material). The models highlighted the importance of increasing soil pH keeping nutrient availability to plants aligned with high plant biomass input for support C recovery in surface layers. In the subsoil layers, Ca^{2+} availability is an important driver for SOC recovery.

Therefore, the main factors associated with C recovery were crop inputs, crop diversity with a lower frequency of soybean, increased soil fertility and alleviate of soil acidity in deep soil layers, besides the absence of soil disturbance.

4.2. The role of pioneer no-till areas of Southern Brazil to mitigate greenhouse gases emissions and improve agriculture sustainability

Currently, Brazil have 35 million ha under NT, corresponding to 60% of total croplands (Febrapdp, 2015). The Rio Grande do Sul and Paraná states have 90% dry croplands under NT (Derpsch and Friedrich, 2009). However, the C recovery and accumulation in croplands need to be tracked to document the environmental benefits of NT for farmers and society. The studied croplands were selected from representative grain production regions and represent together 271,000 ha of soybean, 29,500 ha of maize and 83,000 ha of wheat (Emater, 2014).

In the Brazilian croplands census "Rally da safra 2015" that considered 308 municipalities (1388 farms), 51% of maize and soybeans áreas were analyzed (Pessôa, 2015).The states of Rio Grande do Sul, Paraná and Santa Catarina (Area 1) represented the highest percentage of covered soil where 68% of croplands achieved 40–100% of covered area associated with high crop residues. However, in the last years the reduction of maize frequency in croplands has led to a reduction in covered soils in croplands. In área 1, the croplands with high residue cover represented in 76% of the farms, however this number has reduced to 36% in 2015.

Recently, De Oliveira Ferreira et al. (2012) reported a minimum amount of biomass input of 3.21 Mg C ha^{-1} $year^{-1}$ (7.13 Mg ha^{-1} $year^{-1}$ of plant biomass). Sá et al. (2015) reported a biomass-C input of 4.15 Mg ha^{-1} $year^{-1}$ (9.23 Mg ha^{-1} $year^{-1}$ of plant biomass) under a long-term (20 yr) NT system to maintain the steady state of SOC stocks. In the current study, the minimum amount of biomass (medium crop intensity 8–10 Mg ha^{-1} $year^{-1}$ of plant biomass)/high cropping intensity (10–12 Mg ha^{-1} $year^{-1}$ of plant biomass), promoted C sequestration. Although an economical analysis was not performed, the costs of cover crops were partially balanced by the higher crop yields.

Some studies have reported that the large scale adoption of no-till system can be an important tool for mitigate greenhouse gases. Minasny et al. (2017) introduced the SOC four per mille concept in which the authors recommended that an increase SOC of 0.04% per year during 20 years would lead to a mitigation of 2–3 Gt of C $year^{-1}$, offsetting 20–35% of global anthropogenic emissions. This strategy would save time for the development of new technologies that aim to contribute for reduce atmospheric CO_2 levels. Sá et al. (2017) also reported that the no-till system on the South American continent has the potential to offset 2.01 Pg of C over the next 30 years.

5. Conclusions

The processes that drove SOC recovery in the studied sites were the soil fertility management allied with high C input trough intense crop rotation. The studied sites with medium(8–10 Mg ha^{-1} $year^{-1}$ of plant biomass) and high cropping intensity (10–12 Mg ha^{-1} $year^{-1}$ of plant biomass) and good fertility management can promote SOC.

For areas with the predominance of soybean in the cropping system, higher levels of Al^{3+} and lowest of Mg^{2+} and P, the C recovery was smaller. In the other hand, the other sites with medium/high cropping intensity, lower levels of Al^{3+} and higher levels of P, Ca^{2+}, $Mg^{2+\cdot}$ and K^{+} reflected in larger C recovery. The same pattern was observed in surface and deep layers, supporting that improvements of no-till systems are not restricted to the surface layer, but are transferred to deeper layer creating a stratified environment in well managed long term systems.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.019.

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