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

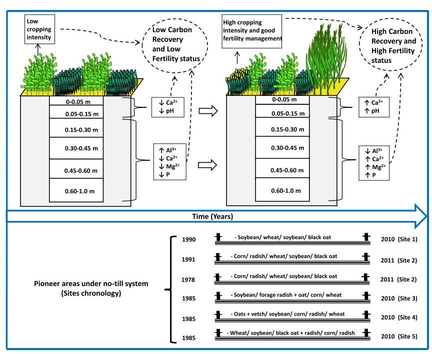
Ademir de Oliveira Ferreira [a,*], Telmo Jorge Carneiro Amado [b], Charles W. Rice [c], Dorivar A. Ruiz Diaz [c], Clever Briedis [d], Thiago Massao Inagaki [e], Daniel Ruiz Potma Gonçalves [a]

[a] Soil Organic Matter Laboratory (Labmos), State University of Ponta Grossa, Carlos Cavalcanti Av. 4748, 84010-330 Ponta Grossa, PR, Brazil
[b] Soil Science Department, Federal University of Santa Maria, Santa Maria, Brazil
[c] Dep. of Agronomy, Kansas State University, Manhattan, KS 66506, USA
[d] Embrapa Instrumentação, XV de novembro st. 1452, 13560-970 São Carlos, SP, Brazil
[e] Technical University of Munich, Chair of Soil Science, Emil-Ramann Str. 2, 85354 Freising, Bayern, Germany

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



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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.

* Corresponding author.
E-mail address: ademir.ferreira@kroton.com.br (A. de Oliveira Ferreira).

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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