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Soil carbon stratification affected by long-term tillage and cropping systems in southern Brazil

Ademir de Oliveira Ferreira [a], Telmo Jorge Carneiro Amado [a,*], Rodrigo da Silveira Nicoloso [b], João Carlos de Moraes Sá [c], Jackson Ernani Fiorin [d], Dâmaris Sulzbach Santos Hansel [a], Dorothy Menefee [e]

[a] Soil Department, Federal University of Santa Maria (UFSM), Av. Roraima, 1000, CEP 97105-900 Santa Maria, RS, Brazil
[b] Embrapa Swine and Poultry, BR 153, Km 110, CEP 89700-000 Concórdia, SC, Brazil
[c] Soil and Agrilcultural Engineering Department, State University of Ponta Grossa (UEPG), Av. Carlos Cavancanti, 4748, CEP 84030-900 Ponta Grossa, PR, Brazil
[d] CCGL-TEC, Rod. RS 342, Km 149, CEP 98005-970 Cruz Alta, RS, Brazil
[e] Department of Agronomy, Kansas State University, United States

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ABSTRACT

Continuous residue inputs when associated with minimum soil disturbance gradually promote the stratification of soil organic carbon (SOC) in the soil profile. In temperate soils, this characteristic has been used as an indicator of quality of soil management. However, few studies have been conducted with this indicator in tropical and subtropical climates or with the main soil orders in these areas. To fill this gap, this study was carried out in a subtropical climate with two of the major Brazilian soil orders, Oxisol and Alfisol, that together account for 63% of Brazilian agricultural soils. This study tested the hypothesis that the CSR is affected by soil order and climate type. The main treatments were soil tillage and different cropping systems in two long-term experiments carried out in the State of Rio Grande do Sul, Brazil. The first experiment, established in 1985, was conducted over a clayey Hapludox (Oxisol) soil. The main plots were treated with one of two tillage systems (conventional tillage – CT; and no-tillage – NT). The subplots were treated with one of three cropping systems: (a) continuous crop succession (R0) – wheat (*Triticum aestivum* L.)/soybean (*Glycine max* L. Merrill); (b) winter crop rotation (R1)–wheat/soybean/black oat (*Avena strigosa* Schreber)/soybean; (c) summer and winter crop rotation (R2) – wheat/soybean/black oat/soybean/black oat + common vetch (*Vicia sativa* L. Walp)/maize (*Zea mays* L.)/forage radish (*Raphanus sativus* var. *oleiferus* Metzg.). The second experiment was established in 1991 over a sandy loam distrophic Paleudalf (Alfisol) soil. Five cropping systems were analyzed under no-till: (a) maize + jack beans (*Canavalia ensiformis* DC)/soybean (M/JB); (b) maize/fallow/soybean (M/F); (c) maize/ryegrass (*Lolium multiflorum* Lam.) + common vetch/soybean (M/R); (d) maize + velvet beans (*Stizolobium cinereum* Piper and Tracy)/soybean (M/VB); and (e) maize/radish oil/soybean (M/FR). The carbon stratification ratio (CSR) was assessed in the 19th and 22nd experimental years for Oxisol and in the 10th and 17th years for Alfisol. This index was calculated through the ratio of SOC stocks in the 0–0.05 and 0.05–0.15 m soil layers. The CPI was determined through the ratio of SOC stocks in the 0–0.15 m soil layer in a given treatment compared with native vegetation. Regardless of the soil order, SOC was influenced by C input and the tillage system; there was a positive linear relationship between CSR and CPI. The relationship between the CSR and the carbon pool index (CPI) was used to infer the quality of soil management. Higher CSR and CPI indices were found under treatments with minimum soil disturbance and intensive crop rotation. Lower CSR and CPI values were associated with frequent mobilization and lower crop diversity. These CSR indices sensitively distinguished the intensity of tillage (NT replacing CT) and cropping systems (cover crops replacing winter fallow or crop succession). The CSR values in subtropical soils investigated were lower than those reported for temperate soils. The soil order affected the critical CSR value being lower in the Oxisol than in the Alfisol. Our findings recommend accept our hypothesis that the CSR is affected by climate and soil order.

* Corresponding author. Tel.: +55 55 3220 8916; fax: +55 55 3220 8108.
E-mail addresses: florestatel@hotmail.com, tamado@smail.ufsm.br (T. Jorge Carneiro Amado).

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1. Introduction

The topsoil layer of croplands mediates energy flux, water partition and nutrient cycling; concentrates most biological activity; and regulates gas exchange between the soil and the atmosphere. Therefore, the topsoil layer plays a crucial role in ecosystem productivity and environmental quality (Franzluebbers, 2002; Sá and Lal, 2009). These processes are regulated by the concentration of SOC in the shallow topsoil, which is one of the most important indicators of soil quality in the agroecosystem (Doran and Parkin, 1994; Islam and Weil, 2000; Conceição et al., 2005). Yet, concentration of SOC in the shallow topsoil improves crucial hydraulic properties, such as water infiltration, soil water storage capacity and pore stability; besides related properties as soil aggregation, and resistance to soil compaction (Franzluebbers, 2002; Conceição et al., 2005; Moreno et al., 2006; Causarano et al., 2008; Tivet et al., 2013).

In natural ecosystems, the concentration of soil organic carbon (SOC) generally decreases from the topsoil to subsoil layers. This process is related to the continuous aboveground carbon (C) input by crop residues and animal excrement and the lack of soil disturbance (Prescott et al., 1995). In these ecosystems, the movement of C in the soil profile is promoted by bioturbation (Gabet et al., 2003; Jimenez and Lal, 2006; White and Rice, 2009), leaching of dissolved C (Neff and Asner, 2001), and direct C input by root systems (Santos et al., 2011). Long-term no-till (NT) systems also gradually promote SOC stratification between the topsoil and subsoil soil layers (Franzluebbers, 2002; Sá and Lal, 2009; Ferreira et al., 2012). In contrast, conventional tillage (CT) promotes the frequent inversion of soil layers and a more uniform C distribution through the soil profile (Angers et al., 1995; Hernanz et al., 2002). Some studies have noted an increase in SOC stocks in subsoil layers where crop residues were mechanically mixed in relation to NT (Baker et al., 2006; Blanco-Canqui and Lal, 2008; Olchin et al., 2008).

NT is a C-conservative system because it reduces biological SOC oxidation, decreases soil temperature, increases water content of soil, slows the turnover of macroaggregates and prevents erosion (Golchin et al., 1994; Jastrow et al., 1996; Six et al., 2000; Pes et al., 2011). The continued deposition of organic residues on the soil surface combined with minimum soil disturbance enhances biological activities that stimulate bio-physico-chemical C stabilization. This enhancement explains partially the SOC gains under NT in comparison with CT (Golchin et al., 1994; Six et al., 1998; Amado et al., 2006; Razafimbelo et al., 2008; Stewart et al., 2009).

Several indicators have been proposed for the evaluation of soil quality (Doran and Parkin, 1994; Karlen et al., 1994; Blair et al., 1995; Vezzani & Mielniczuk, 2009). Among them, the carbon pool index (CPI) relates the SOC stock in a soil under agricultural practices to the stock from a reference usually under natural vegetation (Blair et al., 1995). This index is also an efficient indicator quality of soil management in tropical climates (Vieira et al., 2007; Bayer et al., 2009; Campos et al., 2011) and temperate climates (Blair et al., 1995; Shang and Tiessen, 1997).

The carbon stratification ratio (CSR) is the ratio between the SOC stocks from two distinct soil layers. Usually, the first layer is the topsoil, which is strongly influenced by quality of soil management (tillage and cropping system). The second is a subsoil layer, which is less affected by these farming operations (Franzluebbers, 2002). Higher CSR values indicate that soil management adopted enhance soil quality (Franzluebbers, 2002, 2010; Sá and Lal, 2009; Ferreira et al., 2012).

The time of adoption of soil management practices also affects the CSR. A study carried out in Southeast USA showed that the CSR increased from 2.4 to 3.1 after 5 years of conversion from CT to NT; the CSR reached 3.6 after 12 years (Franzluebbers, 2010). Several studies note that a CSR value of 2.0 is critical for maintaining soil quality in temperate climates (Franzluebbers, 2002).

Long-term studies addressing the CSR and its relation to soil quality in tropical and subtropical soils are scarce. This study tested the hypothesis that CSR is affected by soil order and climate type. The CPI index could be an efficient tool to establish the critical CSR value. We predict that critical CSR values for temperate soils cannot be directly applied to tropical and subtropical soils.

2. Materials and methods

2.1. Description of the experimental areas

This study consisted of two long-term experiments in southern Brazil. The first experiment was established in 1985 in Cruz Alta in the State of Rio Grande do Sul, Brazil (28°33′ S 53°40′ W, 409 m of altitude). The local climate is subtropical humid (Cfa 2a according to Koppen's classification) with an mean annual rainfall and an annual temperature of 1774 mm and 19.2 °C, respectively. The highest mean monthly temperature (30.0 °C) is recorded in January, and the lowest mean monthly temperature (8.5 °C) is recorded in June (Maluf, 2000). The soil is distroferric Hapludox (referred in this text as Oxisol) with a slope of 4.7% and a predominance of kaolinite and iron oxides (63.5 g kg^{-1}) (Campos et al., 2011).

The second experiment was established in 1991 in Santa Maria, Rio Grande do Sul, Brazil (29°43′ S 53°42′ W, 86 m of altitude). The local climate is subtropical (Cfa in the Koppen's classification) with a mean annual rainfall and an annual temperature of 1769 mm and 19.3 °C, respectively (Maluf, 2000). The highest mean monthly temperature (30.4 °C) is recorded in January, and the lowest mean monthly temperature (9.3 °C) is recorded in June (Maluf, 2000). The soil is distrophic Paluedalf (referred in this text as Alfisol) with a slope of 5.5%, a moderate A horizon, and a clay loam texture. Further soil characteristics are presented in Table 1.

The long-term experiment at the Oxisol site had a split-plot design with two tillage systems in the main plots (i.e., CT and NT) and three cropping systems in subplots without replications. These subplot treatments were as follows: (a) continuous crop succession (R0) – wheat/soybean; (b) winter crop rotation (R1) – wheat/soybean/black oat/soybean; c) summer and winter crop rotation (R2) – wheat/soybean/black oat/soybean/black oat + common vetch/maize/forage radish. Detailed information regarding the temporal cropping system is shown in Fig. 1. Table 2 shows the cultivars used in this study. The CT system consisted of a disk plow with 5 disks of 38.1 cm working at a 0.20 m depth and a disk tandem with 20 disks of 30.5 cm working at a 0.15 m depth. The CT system was tilled twice a year, in the autumn and spring seasons.

Table 1
Main soil characteristics by the establishment of the experiments.

Location	Soil	Layer	C[a]	pH	Phosphorus	Potassium	Sand	Silt	Clay
		m	g kg^{-1}	H_2O	mg dm^{-3}		g kg^{-1}		
Cruz Alta, RS, Brazil	Oxisol	0–0.20	19.0	4.5	19	82	310	120	570
Santa Maria, RS, Brazil	Alfisol	0–0.20	14.2	4.5	1.8	33	660	253	87

[a] *Source*: Adapted from Campos (2006); Amado et al. (2006) and Lanzanova et al. (2010). C = Carbon.