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Can no-till grain production restore soil organic carbon to levels natural grass in a subtropical Oxisol?

Ademir de Oliveira Ferreira[a,*], Telmo Amado[b], Charles W. Rice[c], Dorivar A. Ruiz Diaz[c], Cristiano Keller[b], Thiago Massao Inagaki[a]

[a] Soil Organic Matter Laboratory (Labmos), Ponta Grossa State University, Av. Carlos Cavalcanti 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, E.U.A., KS 66506, United States

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ABSTRACT

The conversion of native vegetation (NV) to agricultural systems, especially with intensive tillage and low carbon (C) input, decreases soil organic carbon (SOC) stocks. However the adoption of conservation agriculture (CA) may partially restore SOC stocks. However, the magnitude of this restoration is dependent on the cropping system, quality and quantity of C input, soil, and climate. In this study, we assessed the redistribution and recovery of SOC stocks in six no-till (NT) fields (> 20 years) in the small grain production area of southern Brazil. The adoption of NT in the fields investigated started between 1978 and 1990 and represent a range of textural and mineralogical characteristics. Soil samples were collected in paired fields (NV vs. long-term NT) to a depth of 1 m. The pioneer NT areas of Rio Grande do Sul State investigated in this study were managed according to the principles of CA (minimum soil disturbance, permanent soil cover and diverse crop rotation). The sites had recovered to 92–100% of the original SOC stocks. The sites which represented medium cropping intensity recovered 79.5 and 85.4%, of NV SOC stocks. The sites representative of high cropping intensity had recovered 84.9–116.5% of NV SOC stocks. The lowest recovery of SOC stock (60.6%) had higher frequency of soybean (*Glycine max* L. Merril) in the crop rotation. Therefore, NT following the principles of CA was an efficient system to restore SOC stock lost due to land-use change, performing a crucial role in the system productivity and soil quality.

1. Introduction

Land-use change is one of the main driving factors affecting soil organic carbon (SOC) stocks and its distribution in the soil profile. Tillage disturbs the soil structure and aggregates (Tivet et al., 2013a), induces drastic environmental changes in soil (temperature, moisture and oxygen content), reduces medium/long term biological activity and diversity (Babujia et al., 2010), increases C-CO_2 emission (Elliott, 1986; Powlson et al., 1987), increases soil loss (Lal, 2004) and depletes SOC stocks. These processes are accelerated under humid tropical and subtropical climates. The depletion of SOC is associated with decline in soil quality (De Oliveira Ferreira et al., 2013; Da Silva et al., 2014) and impairs important environmental services provided by soil (Lal, 2015).

Conservation agriculture (CA) has been proposed as an alternative to restore SOC stock and improve soil quality in grain production systems (Amado et al., 2006; Derpsch and Friedrich, 2009; Derpsch et al., 2014). However, few studies were able to show complete restoration of SOC stocks when deep soil layers are taken into account (Baker et al., 2007; Blanco-Canqui and Lal, 2008). Many factors such as soil texture, climate, cropping systems, SOC input, plant root systems, soil aggregation, tillage, and chemical attributes affect the degree of SOC depletion and restoration under CA. The time of adoption of CA and the soil layer analyzed are critical to understand SOC dynamics. Recent studies in temperate soils have shown important C accumulation in deep soil layers (Chabbi and Rumpel, 2009), but there is a lack of studies to confirm this process in tropical and subtropical soils. In the main grain production region in southern Brazil (Santa Rosa, Palmeira das Missões, Cruz Alta, and Lagoa Vermelha), the conversion to no-till systems (NT) was increased by adverse environmental impacts caused by conventional tillage, such as soil

* Corresponding author.
E-mail addresses: aoferreira1@yahoo.com.br (A. de Oliveira Ferreira), proftelmoamado@gmail.com (T. Amado), cwrice@ksu.edu (C.W. Rice), ruizdiaz@ksu.edu (D.A. R. Diaz), cristianokeller89@hotmail.com (C. Keller), thiago811@yahoo.com.br (T.M. Inagaki).

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degradation by erosion, high production costs due the use of the plow, yield loss associated with short drought and reduction in SOC levels (Mielniczuk et al., 2003; Bayer et al., 2006). In reaction to this scenario, NT has been widely adopted to minimize the risks of soil degradation, to sustain the productivity of agroecosystems (Mielniczuk et al., 2003; Sá et al., 2014), and to maintain/improve soil structure and quality (Vezzani and Mielniczuk, 2011).

Currently, Brazil has 32 million hectares under NT, corresponding to around 75% of total grain production (Gassen, 2012). The state of Rio Grande do Sul and Paraná were the pioneers in NT adoption in the early 70s but the system was only adopted on a large scale in the 90s. Currently, these states have 90% of the cultivated area with dryland crops under NT (Derpsch and Friedrich, 2009). Several studies recognize the role of soil as a sink of atmospheric CO_2 (Lal, 2004) and there is a growing interest in the adoption of NT as a strategy to mitigate greenhouse gases and recover the SOC stocks lost by the conversion from native vegetation (NV) to agroecosystems. Long-term NT (>20 years) following CA principles may achieve SOC stock recovery because it is characterized by high and diverse crop biomass input, minimal soil disturbance, high cation exchange capacity (CEC) and nutrient cycling (Sá et al., 2004).

Most Brazilian studies of changes in SOC stocks were performed in experimental trials. Studies on commercial fields under long-term NT system are scarce. Scaling up of results from experimental trials to large areas is a challenge. The change in SOC stock in farmer's fields needs to be tracked to determine the environmental benefits of NT for the farmers and society.

Another important factor analyzing changes on SOC stocks induced by management systems is sampling to adequate depth. Many studies have contributed to better comprehension of the effects of SOC redistribution on soil profile (Zhang et al., 2006; Mueller and Koegel-Knabner, 2009; Boddey et al., 2010; Harrison et al., 2011; Piva et al., 2012; Reis, 2012). Osher et al. (2003) and Don et al. (2009) reported that they would had overestimated SOC losses after long-term management systems if they had not considered the subsurface horizons. Studies considering deeper layers are necessary to understand the relationship between SOC redistribution and its dynamics on soil under different management systems.

The objective of this study was to assess the recovery and redistribution of SOC stocks in agricultural areas under NT grain production systems (>20 years) that followed the principles of CA in southern Brazil.

2. Materials and methods

2.1. Areas description

The fields in this study were selected from pioneer regions in the adoption of NT systems that are representative of the grain production regions in Rio Grande do Sul, Brazil. The fields were located in the six different counties: Site 1—Santa Rosa (18,000 ha of soybean, 6940 ha of maize and 10,000 ha of wheat); Site 2—Manoel Viana (25,000 ha of soybean, 3000 ha of maize and 4300 ha of wheat); Site 3—Palmeira das Missões (93.500 ha of soybean, 12,000 ha de maize and 30,000 ha of wheat); Site 4—Lagoa Vermelha (37,000 ha of soybean, 8700 ha of maize and 6.000 ha of wheat); Site 5—Cruz Alta (90,000 ha of soybean and 30,000 ha of wheat); and Site 6—Fortaleza dos Valos (32,5000 ha of soybean, 1830 ha of maize and 7000 ha of wheat) (EMATER, 2014).

The clay content ranged from 90 to 720 g kg^{-1}. This clay fraction is composed of variable charge minerals, primarily kaolinite, iron oxides, and gibbsite. According to the Köppen climate classification, the climate is humid subtropical (Peel et al., 2007). The climate of the areas and a summary of no-till systems is summarized in Table 1. For comparison, we collected soil samples in the natural vegetation (NV) nearby each agricultural site with the same soil texture and slope position.

Sites evaluated in the study were categorized by cropping intensity in low, medium, and high. The low cropping intensity generate approximately 6–8 Mg ha^{-1} $year^{-1}$ of plant biomass input with frequency of 3/1 soybean/corn; the medium cropping intensity 8–10 Mg ha−1 $year^{-1}$ of plant biomass input with frequency of 2/1 soybean/corn; and the high cropping intensity 10–12 Mg ha^{-1} $year^{-1}$ of plant biomass input with frequency of 1/1 soybean/corn.

2.2. Historical land use and management

In southern Brazil, the beginning of agriculture was a period of colonial (subsistence) agriculture (between 1900 and 1965), with soil plowing primarily by animal traction. The main activities were livestock, cultivation of corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), beans (*Phaseolus vulgaris* L.), lentils (*Lens culinaris* Medik), cassava (*Manihot esculenta* Crantz) and after 1956 soybeans (*Glycine max* L. Merril). The agriculture was based on the natural fertility from forest and natural vegetation which were converted to agriculture fields. After 1965, mechanized agriculture began, with intense soil plowing and harrowing (conventional tillage, CT), use of chemical fertilizers, wheat and soybean crop rotations, besides the burning of wheat residues that caused soil physical degradation. Between 1981 and 1990, farmers started to adopt conservation agriculture practices (CA), such as use of chisel plow and disc harrow (reduced tillage). Burning of wheat residues stopped and the introduction of black oats as cover crop, which was rotated with wheat. In 1990, NT was largely adopted for soybean cultivation, and since then it has been used in most crop fields.

2.3. Characterization and description of native vegetation

The NV in the most parts of the areas sampled in Rio Grande do Sul were classified as steppes, and grassy woody without gallery forest (IBGE, 2010). Regarding the dry mass production (DM) at the warm season of the year, we observed rates from 2 to 3.4 Mg ha^{-1} of DM under native pasture (Pillar et al., 2009).

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

The samples were collected in paired areas of native vegetation vs. long-term no-till system opening 10 trenches with dimensions of $0.3 \times 0.3 \times 1$ m in each site (i.e. five in NT and five in NV). Samples were collected with a spatula on the trench 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 diameter by 0.04 m height (Solos, 1997). Bulk density was used to calculate the SOC stocks.

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 a soil profile (0–

Table 1
Description of study locations, soil type, clay content, parent material, climate, soil use (management system), time of no-till use and sampling depth.

Description	Site 1—Santa Rosa	Site 2—Manoel Viana	Site 3—Palmeira das Missões		Site 4—Lagoa Vermelha	Site 5—Cruz Alta	Site 6— Fortaleza dos Valos
Geographic coordinates	27°52′S–54°28′W	29°35′S–55°28′W	27°53′S–53°18′W		28°22′S– 51°50′W	28°38′S–53°36′W	28°47′S– 53°13′W
Elevation	330 m	113 m	639 m		840 m	452 m	406 m
Soil Classification δ	Rhodic Hapludox	Typic Quartzipsamment	Rhodic Hapludox		Rhodic Hapludox	Rhodic Hapludox	Rhodic Hapludox
Clay content ($g\,kg^{-1}$)	720	90	600		700	570	600
Parent Material	Basalt	Sandstone-basaltic	Basalt		Basalt	Sandstone	Sandstone
Mineralogy – iron oxides ($g\,kg^{-1}$)	246 (extracted by H_2SO_4)‡	18 (extracted by H_2SO_4) ‡	234 (extracted by H_2SO_4) ‡		222 (extracted by H_2SO_4) ‡	63,5 (extracted by DCB) ‡‡	64 (extracted by DCB) ‡
Climate	Cfa	Cfa	Cfa		Cfa	Cfa	Cfa
Annual mean temperature	20.8 °C†	20.3 °C†	19.6 °C‡‡‡		16.8 °C†	17.2 °C†	19.3 °C
Maximum temperature	26.1 °C†	25 °C†	39.7 °C‡‡‡		22.7 °C†	21.5 °C†	30.0 °C‡‡‡
Minimum temperature	15.5 °C†	13.4 °C†	3 °C‡‡‡		12.4 °C†	12.8 °C†	8.6 °C‡‡‡
Annual mean precipitation (mm)	1725†	1662†	1625‡‡‡		1735†	1729†	1727‡‡‡
Relative humidity (%)	74.9†	73.8†	74.1†		75.2†	77.9†	70.0†
Crop rotation	soybean/wheat/soybean/black oat	wheat/soybean/oat + radish/soybean	Corn/radish/wheat/soybean/black oat		soybean/radish* + oat/corn/wheat	Oats + vetch/soybean/corn/radish/wheat	wheat/soybean/black oat + radish/corn/radish
Relation soybean/corn adopted (years)	3/1	2/1	2/1		1/1	1/1	2/1
Cropping intensity	Low	Medium	High		High	High	Medium
NT duration (years)	20	23	20	33	25	25	25
Area conversion	1965	1970	1960	1960	1965	1965	1965
Conventional tillage	1985–1987§	1970–1987§§	1960–1991§	1960–1978§	1965–1983§	1965–1981§	1965–1982§
Long-term No-till	1990–2010[I]	1987–2010[II]	1991–2011[VI]	1978–2011[V]	1985–2010[III]	1985–2010[VI]	1985–2010[VII]
Reduced tillage	1987–1990	–	–		1983–1985	1981–1985	1982–1985
Plant biomass input ($Mg\,ha^{-1}\,year^{-1}$)	6–8	8–10	10–12		10–12	>12	8–10
Sampling depth (m)	0–0.05; 0.05–0.15; 0.15–0.30; 0.30–0.45; 0.45–0.60 e 0.60–1.0	Same as Site 1	Same as Site 1		Same as Site 1	Same as Site 1	Same as Site 1

δ Soil Survey Staff (2010); ‡ Brasil (1973); ‡‡ Campos (2006); ‡‡‡ Moreno (1961); † average in the period from 1976 to 2005. Data Source: Climatic atlas from Rio Grande do Sul (available at www.cemet.rs.gov.br).
*Forage radish was over seeded by plane when soybean was in the stage of falling leaves; § = Wheat/Soybean; §§ = Wheat/Soybean + Livestock; [I] = Soybean/wheat/soybean/black oat; [II] = Wheat/soybean/oat/soybean; [III] = Soybean/forage radish (overseeded) + oat/corn/wheat; [VI] = 1991/1994/1997/2000/2003/2006//2009 (corn, turnips, forage, wheat, soybeans); 1992/1998/2004/2010 (soybean/fallow/wheat/soybean); 1993/1996/1999/2002/2005/2008/2011 (soybean/oat/corn); 1995/2001/2007 (Soybean/fallow/white oat/soybean); [V] = 1978/1981/1984/1987/1990/1993/1996/1999/2002/2005/2008/2011 (soybean/oat/corn); 1980/1986/1992/1998/2004/2010 (soybean/fallow/white oat/soybean); 1979/1982/1985/1988/1991/1994/1997/2000/2003/2006/2009 (Corn/radish/wheat/soybean); 1983/1989/1995/2001/2007 (Soybean/fallow/wheat/soybean); [VI] = Oats + vetch/soybean/corn/radish/wheat; [VII] = wheat/soybean/black oat + radish/corn/radish.

1.0 m) of the six sampled sites (Santa Rosa, Manoel Viana, Palmeira das Missões, Lagoa Vermelha, Cruz Alta, and Fortaleza dos Valos). All statistical analyses were carried out using R software (Team, 2014).

3. Results

3.1. Soil bulk density

In all the consolidated no-till (NT) fields, a nearby native vegetation (NV) area was selected, which was used as a reference of non-disturbed environment in the same soil type, climate and drainage to assess the changes in soil bulk density (BD) due the land-use change. In all of the fields we found an increase of BD in long-term NT compared with NV (Table 2). In general, under NT system, the averaged depth BD ranged from 0.99 (site 4, 0–0.05 m) to 1.78 $Mg\,m^{-3}$ (site 2, 0–0.5–0.15, 0.15–0.30 m), while in NV it ranged from 0.87 to 1.64 $Mg\,m^{-3}$.

Considering critical BD ranges from 1.3 to 1.4 $Mg\,m^{-3}$ in clayey soils (Reichert et al., 2003), sites 1 and 3 had a compacted layer at 0.05–0.15 m depth, with BD of 1.44 (±0.08) and 1.56 (±0.03) $Mg\,m^{-3}$ D. This BD value was an increase of 21% and 25% relative to NV, respectively. At site 6, the compacted layer occurred at 0.05–0.30 m depth with 1.59 (±0.05) and 1.43 (±0.8) $Mg\,m^{-3}$ for 0.05–0.15 and 0.15–0.30, respectively. This increase in BD represented an increase, for the same depth, of 27% and 16% relative to NV, respectively. At site 1, higher BD values for the whole soil profile were noted relative to NV. For this site, the BD of NT ranged from 1.28 to 1.44 $Mg\,m^{-3}$, while in NV BD ranged from 1.09 to 1.24 $Mg\,m^{-3}$.

3.2. Soil carbon concentration

The SOC ($g\,kg^{-1}$), decreased with soil depth, regardless of land-use, although the distribution of SOC in the soil profile varied according to soil management systems. In general, the SOC concentration in NT varied on average from 11.2 (± 1.1) to 45.7 (± 2.4) $g\,kg^{-1}$, and from 4.6 (±1.4) to 15.1 (±1.0) for the soil layers of 0–0.05 and 0.6–1.0 m respectively. F or NV, this variation was from 7.8 (±1.4) to 44.1 (±1.8) $g\,kg^{-1}$ and from 4.0 (±1.6) to 10.8 (±0.8) $g\,kg^{-1}$, at the same layers, respectively (Table 2). These

Table 2
Variation of soil bulk density ($Mg\,m^{-3}$), soil carbon concentration ($g\,kg^{-1}$), carbon stock ($Mg\,ha^{-1}$) and carbon stocks recovery (%) in different soil layers of the sampled areas under no-till and native vegetation.

Soil depth (m)	Site 1		Site 2		Site 3			Site 4		Site 5		Site 6	
	NV†	NT††	NV	NT	NV	NT*	NT**	NV	NT	NV‡	NT	NV‡	NT
Soil bulk density ($mg\,m^{-3}$)													
0–0.05	1.1 ± 0.12	1.3 ± 0.11	1.5 ± 0.06	1.6 ± 0.08	1.1 ± 0.17	1.3 ± 0.22	1.3 ± 0.03	0.9 ± 0.09	1.0 ± 0.06	1.3 ± 0.20	1.2 ± 0.07	1.3 ± 0.20	1.3 ± 0.11
0.05–0.15	1.2 ± 0.16	1.4 ± 0.08	1.6 ± 0.07	1.8 ± 0.03	1.2 ± 0.05	1.6 ± 0.03	1.5 ± 0.01	1.0 ± 0.07	1.2 ± 0.05	1.2 ± 0.07	1.4 ± 0.03	1.2 ± 0.07	1.6 ± 0.05
0.15–0.30	1.2 ± 0.07	1.4 ± 0.05	1.6 ± 0.09	1.8 ± 0.08	1.2 ± 0.02	1.4 ±0.07	1.4 ± 0.05	1.1 ± 0.04	1.1 ± 0.05	1.2 ± 0.03	1.4 ± 0.05	1.2 ± 0.03	1.4 ± 0.08
0.30–0.45	1.2 ± 0.10	1.4 ± 0.02	1.6 ± 0.09	1.7 ± 0.12	1.2 ± 0.07	1.3 ± 0.04	1.3 ± 0.01	1.1 ± 0.04	1.1 ± 0.01	1.2 ± 0.13	1.3 ± 0.06	1.2 ± 0.13	1.3 ± 0.07
0.45–0.60	1.1 ± 0.03	1.3 ± 0.05	1.6 ± 0.13	1.6 ± 0.09	1.2 ± 0.07	1.2 ± 0.07	1.2 ± 0.04	1.1 ± 0.01	1.1 ± 0.02	1.2 ± 0.10	1.3 ± 0.06	1.2 ± 0.10	1.3 ± 0.07
0.60–1.0	1.2 ± 0.06	1.3 ± 0.08	1.5 ± 0.09	1.5 ± 0.11	1.1 ± 0.09	1.2 ± 0.06	1.2 ± 0.03	1.1 ± 0.01	1.1 ± 0.06	1.1 ± 0.04	1.3 ± 0.06	1.1 ± 0.04	1.2 ± 0.03
Soil carbon concentration ($g\,kg^{-1}$)													
0–0.05	33.7 ± 2.7 a	22.4 ±3.3b	7.8 ±1.4 b	11.2 ±1.1a	22.9 ± 0.9 b	27.6 ±2.9 a	28.6 ±1.0 a	44.1 ±1.8 a	45.7 ±2.4 a	25.8 ± 0.7 b	30.2 ±2.0 a	25.8 ± 0.7 a	22.8 ±2.4 b
0.05–0.15	23.7 ±1.5 a	14.9 ±1.7 b	6.8 ±2.0 a	5.6 ±1.6 a	17.7 ± 0.5 a	14.8 b ±0.6	15.7 ± 0.2 b	33.2 ±2.1 a	27.9 ±2.2 b	21.0 ± 0.5 a	18.3 ±1.2 b	21.0 ± 0.5 a	14.9 ±1.3 b
0.15–0.30	16.4 ±1.2 a	11.2 ±1.7 b	5.5 ±2.4 a	5.2 ±1.0 a	16.4 ± 0.6 a	12.9 ±1.0 b	13.1 ± 0.6 b	25.3 ±2.5 a	25.4 ±1.7 a	18.0 ± 0.3 a	16.6 ±0.8 b	18.0 ± 0.3 a	12.2 ±1.2 b
0.30–0.45	13.3 ±1.7 a	8.2 ± 0.6 b	4.9 ±2.5a	6.0 ±1.6 a	14.9 ±1.2 a	11.9 ± 0.9 b	12.5 ± 0.3 b	17.4 ±1.0 b	23.4 ±2.3 a	16.0 ± 0.2 a	13.7 ± 0.6 b	16.0 ± 0.2 a	10.9 ±1.6 b
0.45–0.60	11.5 ±0.5 a	5.6 ±0.1 b	4.3 ±1.7 a	5.0 ±1.2 a	12.8 ± 0.8 a	10.5 ± 0.8 b	10.7 ± 0.7 b	14.3 ±1.3 b	19.0 ±2.2 a	13.0 ± 0.5 a	11.9 ± 0.8 b	13.0 ± 0.5 a	9.9 ±1.4 b
0.60–1.0	9.1 ±2.0 a	4.7 ± 0.3 b	4.0 ±1.6 a	4.6 ±1.4 a	10.8 ± 0.8 a	9.1 ± 0.5 b	9.3 ± 0.1 b	9.3 ±1.6 b	15.1 a ±1.0	9.0 b ±0.6	10.5 a ±0.8	9.0 a ±0.6	8.7 a ±0.9
Carbon stock ($Mg\,ha^{-1}$)													
0–0.05	18.5 ± 3.2 a	12.3 ± 2.1 b	5.9 ± 0.9 b	8.5 ± 0.9 a	12.1 ± 1.6 b	14.8 ± 3.2 ab	15.3 ± 2.8 a	19.9 ± 3.2 a	19.9 ± 2.2 a	16.6 ± 3.6 b	19.5 ± 1.3 a	16.6 ± 3.6 a	14.7 ± 1.5 a
0.05–0.15	28.3 ± 2.4 a	18.3 ± 2.1 b	12.4 ± 1.5 a	9.3 ± 2.5 b	22.2 ± 0.6 a	18.6 ± 1.4 b	19.7 ± 0.7 ab	34.7 ± 2.9 a	29.2 ± 3.1 b	26.2 ± 2.3 a	22.8 ± 1.5 b	26.2 ± 2.3 a	18.7 ± 2.8 b
0.15–0.30	29.2 ± 2.7 a	21.0 ± 3.8 b	14.8 ± 2.8 a	12.5 ± 2.1 a	30.4 ± 1.3 a	24.0 ± 1.8 b	24.3 ± 1.4 b	41.6 ± 3.2 a	40.8 ± 3.8 a	33.2 ± 1.5 a	30.7 ± 1.5 b	33.2 ± 1.5 a	22.4 ± 2.2 b
0.30–0.45	23.7 ± 3.9 a	14.8 ± 1.0 b	13.0 ± 2.8 a	13.0 ± 2.8 a	27.2 ± 2.2 a	21.6 ± 0.6 b	22.8 ± 1.7 b	30.0 ± 1.3 b	37.6 ± 1.1 a	28.8 ± 1.7 a	24.7 ± 1.1 b	28.8 ± 1.7 a	19.8 ± 2.8 b
0.45–0.60	20.1 ± 1.3 a	9.9 ± 0.4 b	13. ± 1.7 a	12.1 ± 2.7 a	23.4 ± 1.5 a	19.2 ± 2.2 b	19.5 ± 1.3 b	24.5 ± 2.9 b	31.7 ± 3.9 a	23.2 ± 2.4 a	21.3 ± 1.6 b	23.2 ± 2.4 a	17.8 ± 2.6 b
0.60–1.0	45.0 ± 2.5 a	23.4 ± 1.9 b	32.4 ± 2.2 a	22.9 ± 2.5 b	49.0 ± 0.6 a	41.2 ± 3.7 b	41.8 ± 3.2 b	42.7 ± 1.8 b	66.2 ± 1.1 a	39.2 ± 5.2 b	45.9 ± 3.5 a	39.2 ± 5.2 a	39.6 ± 1.3 a
0–0.15	46.8 ± 6.7 a	30.7 ± 4.9 b	18.3 ± 1.5 a	17.7 ± 3.4 a	34.3 ± 1.1 a	33.4 ± 1.4 a	34.9 ± 1.7 a	54.6 ± 10.4 a	49.2 ± 6.5 a	42.9 ± 0.6 a	42.3 ± 1.7 a	42.9 ± 0.6 a	33.4 ± 3.9 b
0–0.30	76.0 ± 6.4 a	51.7 ± 4.4 b	33.1 ± 2.2 a	30.3 ± 5.9 a	64.7 ± 1.2 a	57.4 ± 1.8 b	59.2 ± 1.7 b	96.2 ± 11.1 a	90.0 ± 11.0 a	76.1 ± 0.9 a	73.0 ± 2.8 a	76.1 ± 0.9 a	55.9 ± 5.0 b
0–0.45	99.7 ± 5.2 a	66.5 ± 3.9 b	46.1 ± 2.4 a	43.3 ± 8.8 a	91.9 ± 1.4 a	79.1 ± 0.6 b	82.0 ± 1.6 b	126.2 ± 9.1 a	127.5 ± 10.2 a	104.9 ± 1.9 a	97.8 ± 3.9 b	104.9 ± 1.9 a	75.6 ± 7.7 b
0–0.60	119.8 ± 4.9 a	76.5 ± 4.6 b	59.3 ± 3.6 a	55.4 ± 9.3 a	115.3 ± 1.5 a	98.2 ± 2.2 b	101.5 ± 1.6 b	150.7 ± 8.5 b	159.2 ± 8.9 a	128.1 ± 1.7 a	119.1 ± 5.3 b	128.1 ± 1.7 a	93.5 ± 10.3 b
0–1.0	164.8 ± 8.1 a	99.8 ± 5.2 b	91.7 ± 5.7 a	78.3 ± 4.6 b	164.3 ± 1.3 a	139.5 ± 3.7 b	143.3 ± 1.9 b	193.4 ± 9.2 b	225.4 ± 18.2 a	167.3 ± 4.0 a	165.0 ± 7.7 a	167.3 ± 4.0 a	133.0 ± 10.8 b
Carbon Recovery§ (%)													
0–0.05		66.7		144.4		121.8	125.6		100.7		117.0		88.5
0–0.15		65.5		96.9		97.4	101.9		90.1		98.7		78.0
0–0.30		68.0		91.6		88.8	91.6		93.5		96.0		73.4
0–0.45		66.7		93.9		86.0	89.2		101.0		93.2		72.1
0–0.60		63.8		93.4		85.2	88.0		105.6		93.0		73.0
0–1.0		60.6		85.4		84.9	87.3		116.5		98.6		79.5

† NV = Native vegetation; †† NT = No-till system; * 20 years No-till system; ** 33 years No-till system. ‡ Data adapted from Jantalia et al. (2006). Means followed by the same letter between rows for each location are not statistically different by the pairedt test at $p < 0.05$ (Comparison made among management systems (NV × NT) at the same depth and site).
§ Carbon recovery = Percentage of carbon stock recovered by the use of long-term no-till system from the native vegetation stocks.

concentrations were highly stratified within the soil profile for both NT and NV.

Considering the clayey Oxisols sampled (Sites 1, 3, 4, 5 and 6), the mean SOC concentration in NT varied from 22.4 (±3.3) to 45.7 (±2.4) g kg^{-1}, and from 4.7 (±0.3) to 15.1 (±1.0) g kg^{-1} for the soil layers of 0–0.05 and 0.6–1.0 m respectively. For NV, these variations ranged from 22.9 (±0.9) to 44.1 (±1.8) g kg^{-1}, and from 9.0 (±0.6) to 10.8 (±0.8) g kg^{-1}, at the same layers, respectively.

3.3. SOC stocks and recovery under consolidated No-till system

In general, the SOC stocks in NT varied, on average, from 8.5 (±0.9) to 19.9 (±2.2) Mg ha^{-1} and from 22.9 (±2.5) to 66.2 (±1.1) Mg C ha^{-1}, for the soil layers of 0-0.05 and 0.6–1.0 m, respectively. In NV areas, these variations were from 5.9 (±0.9) to 19.9 (±3.2) Mg C ha^{-1} and from 32.4 (± 2.2) to 49.0 (±0.6) Mg C ha^{-1}, respectively. The accumulated SOC stocks in the soil layers of 0-0.3 and 0–1.0 m in NT varied, in average, from 30.3 (±5,9) to 90.0 (±11.0) Mg C ha^{-1} and from 78.3 (± 4.6) to 225.4 (±18.2) Mg C ha^{-1}, respectively. For NV, these variations were from 33.1 (±2.2) to 96.2 (±11.1) Mg C ha^{-1}, and from 91.7 (±5.7) to 193.4 (±9.1) Mg C ha^{-1} respectively.

Considering the different crop rotations adopted along more than 20 years (Table 1), the SOC stocks under NT with low cropping intensity were in average 12.3 (±2.1) and 23.4 (±1.9) Mg ha^{-1}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For NV, SOC stocks ranged from 18.5 (±3.2) and 45.0 (±2.5) Mg ha^{-1}, respectively. At the layers of 0-0.3 and 0–1.0 m, the SOC stocks in NT were 51.7 (±4.4) and 99.8 (±5.2) Mg C ha^{-1}, respectively. For NV, these C stocks were 76.0 (±6.4) and 164.8 (±8.1) Mg C ha^{-1} respectively (Table 2).

The SOC stocks in areas with medium cropping intensity varied from 8.5 (±0.9) to 14.7 (±1.5) Mg C ha^{-1} and from 22.9 (±2.5) to 39.0 (±1.3) Mg C ha^{-1} for the soil layers of 0–0.05 and 0.6–1.0 m, respectively. For NV these variations were 5.9 (±0.9) to 16.6 (±3.65) Mg C ha^{-1}, and from 32.4 (±2.2) to 39.2 (±5.2) Mg C ha^{-1}, respectively. At the soil layers of 0-0.3 and 0–1.0 m the accumulated stocks in NT varied from 30.3 (±5.9) to 55.9 (±5.0) Mg C ha^{-1} and from 78.3 (±4.6) to 133.0 (±10.8) Mg C ha^{-1} respectively. In NV areas, these accumulated stocks varied from 33.1 (±2.2) to 76.1 (±0.9) Mg C ha^{-1} and from 91.7 (±5.7) to 167.3 (±4.0) Mg C ha^{-1}, respectively.

Finally, under high cropping intensity the SOC stocks varied from 14.8 (±3.2) to 19.9 (±2.2) Mg C ha^{-1}, and from 41.2 (±3.7) to 66.2 (±1.1) Mg C ha^{-1}, for the soil layers of 0–0.05 and 0.6–1.0 m, respectively (Table 2). In NV areas, these variations were from 12.1 (±1.6) to 19.9 (±3.2) Mg C ha^{-1}, and from 39.2 (±1.6) to 49.0 (±0.6) Mg C ha^{-1}, respectively. The accumulated SOC stocks at the layers of 0–0.3 and 0–1.0 m in NT areas varied from 57.4 (±1.8) to 90.0 (±11.0) Mg ha^{-1}, and from 139.5 (±3.7) to 225.4 (±18.2) Mg ha^{-1}, respectively. In NV areas, these accumulated SOC stocks varied from 64.7 (± 1.1) to 96.1 (± 11.1) Mg C ha^{-1}, and from 164.3 (± 1.3) to 193.4 (± 9.1) Mg C ha^{-1}, respectively.

Considering NV as a reference, the recovery percentages of SOC in NT (> 20 years) for the layers of 0–0.05, 0–0.30 and 0–1.0 m varied from 66.7 to 144.3%, 68.0 to 95.9% and 60.6 to 116.5% respectively. However, in the clayey Oxisols (sites 1, 3, 4, 5 and 6), the percentages of SOC recovery in NT areas at the surface layer of 0-0.05 m were in average 66.7, 88.5 and 116.2% for crop systems with low, medium and high cropping intensity, respectively. At the layer of 0-0.3 m these recoveries were 68.0, 73.4 and 92.5% respectively. At the layer of 0–1.0 m the recoveries were 60.6, 79.5 and 96.8% respectively (Fig. 1).

4. Discussion

4.1. Soil bulk density

For all fields investigated (Table 2) BD was higher under long-term NT relative to NV. It is likely the pressure from the heavy machinery use in NT increased bulk density. The replacement of natural grass with a well-developed root system, by a small grain crop with shallow root system also may had affected the BD. The soils with clayey texture, as in the most of the fields studied, had a greater increase in BD (Vieira and Muzilli, 1984; Corrêa, 1985).

The greater impact of land-use change in BD in relation to NV was verified in the shallow depths (0.05-0.15 m) while in the deepest layer we found a slight difference. The increase in BD was associated with traffic of heavy machinery, disk and plow

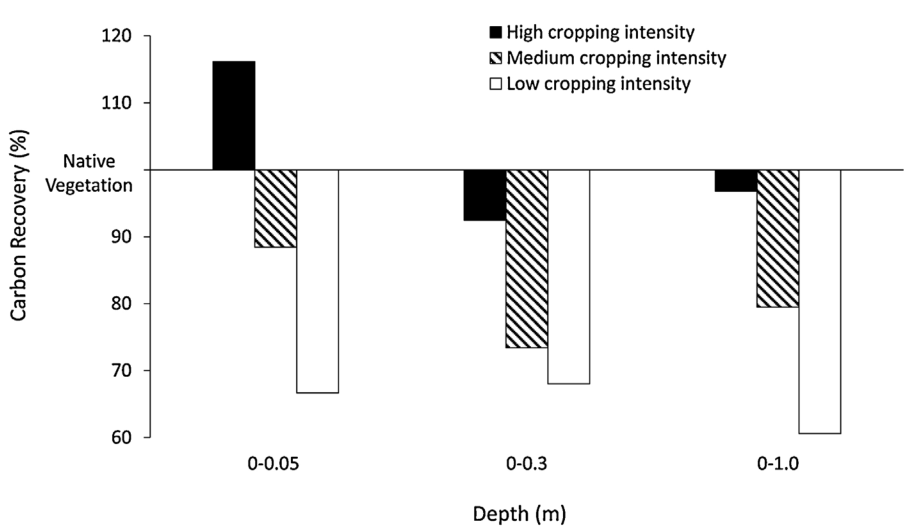

Fig. 1. Carbon recovery as affected by crop cultivation intensity for different soil layers.
† Mean carbon recovery under long term no-till in Oxisols (Santa Rosa, Palmeira das Missões, Lagoa Vermelha, Cruz Alta and Fortaleza dos Valos sites) at the 0–0.05, 0–0.3 and 0–1.0 m soil depth.
Low cropping intensity = 6-8 Mg ha^{-1} $year^{-1}$ of plant biomass input with frequency of 3/1 soybean/corn.
Medium cropping intensity = 8-10 Mg ha^{-1} $year^{-1}$ of plant biomass input with frequency of 2/1 soybean/corn.
High cropping intensity = 10-12 Mg ha^{-1} $year^{-1}$ of plant biomass input with frequency of 1/1 soybean/corn.

operations during the conventional tillage period before the adoption of NT.

4.2. SOC stocks and recovery under consolidated no-till system

In general, the SOC levels in NT were higher than the NV at the surface layer of 0–0.05 m, and similar at the layers of 0-0.3 and 0–1.0 m. Increasing SOC stocks in the topsoil has been reported as an important factor for soil quality, especially increases in cation exchange capacity, nutrient availability, and biological activity. Improvement in soil structure positively effects gas exchange, water infiltration, soil porosity and aggregate stability (Franzluebbers, 2002; Sá and Lal, 2009; Tivet et al., 2013a). The higher SOC stocks found in NV in most part of the sites can be explained in part by the deeper plant root system (Jobbágy and Jackson, 2000). In addition, SOC stocks of NV areas were under a steady state, where the C inputs and losses were at equilibrium (Sá et al., 2001; Vezzani and Mielniczuk, 2011).

In general, considering NV as reference, the recovery percentages of SOC in all NT areas were 109.2, 86.1 and 87.5% for the soil layers of 0–0.05, 0–0.30 and 0–1.0 m respectively. Therefore, the SOC stock was fully recovered at the surface layer of 0-0.05 m and >86% if we consider the deeper layers (0–0.3 and 0–1.0 m). Higher SOC stocks in NT following CA principles were also observed by Lopes et al. (2013), Sá et al. (2001), Tivet et al. (2013b) and Sá et al. (2015).

Therefore, the historical management of each NT area of this study influenced the rate of SOC stocks recover, and was directly related to cropping intensities (Table 1). The area with low cropping intensity (Site 1), characterized by continuous soybean had the lowest SOC recovery percentages (60.6–68.0%) for all layers sampled when compared with the other NT areas.

These results reflect the trend in South Brazil of higher soybean frequency and lower use of corn throughout the years. Similar results were found by Amado et al. (2006), Campos et al. (2011) and Ferreira et al. (2012) who reported that with less corn cultivation in relation to soybean in the crop rotation system SOC stock will be more depleted. The same authors observed that corn when associated with leguminous cover crops, increase its potential to accumulate SOC. Similar results were also reported by Bayer et al. (2011), who reported a SOC depletion rate of 0.27 Mg C ha^{-1} y^{-1} when soybean was continuously cultivated.

The clayey Oxisols (sites 3, 4 and 5), managed with high cropping intensity for more than 20 yrs achieved the highest recovery percentages of SOC stocks, fully recovering the original SOC stock on the soil surface (0–0.05 m) and > 92% considering deeper layers (0–0.3 and 0–1.0 m) (Fig. 1). Sá et al. (2015) found a linear increase of SOC stocks with the increase of plant biomass input in a tropical Oxisol. The results of this study indicate that after an initial depletion of SOC stock with the conversion of the native vegetation to cropland, it is possible to recover partially or totally the original SOC stock, through the use of crop rotations with high cropping intensity associated to NT systems (Fig. 1). According to De Oliveira Ferreira et al. (2013), when the high cropping intensity was associated with reductions of soil disturbance, NT achieve high indexes of soil quality, performing a crucial role for crop productivity and environmental sustainability.

The high recovery of SOC stock in the deeper layers of the areas managed with high cropping intensity may be related to the inclusion of oilseed radish (*Raphanus sativus*) in the crop rotation. Oilseed radish has the capacity of opening biopores creating favorable conditions for root growth of subsequent crops (Amado et al., 2007). The biopores formed by the oilseed radish roots have high stability, and after its decomposition, act as preferential path for water infiltration (Williams and Weil, 2004). These experimental results emphasize the importance of using plant species with deep root systemsto increase the SOC stocks. Wright et al. (2007) suggested that the translocation of soluble SOC may be an important mechanism of SOC accumulation in deeper layers. In addition, the use of long-term NT with minimum soil disturbance helps maintain root channels, facilitating crop root development (Boddey et al., 2010).

In our study, 89% of the SOC stock was concentrated in the 0.15–1.0 m layers, and 75% at the soil layer of 0.3–1.0 m. These results agree with Dick et al. (2013), who stated that more than 70% of the SOC stocks were concentrated in the 0.2–1.0 m layer in subtropical environment. The increment of SOC stocks in deeper layers is important, since they contribute for a higher residence time compared with surface layers (Fontaine et al., 2007).

In summary, the pioneer areas under NT of Rio Grande do Sul state investigated in this study managed according to the principles of CA (minimum soil disturbance, diverse crop rotation and permanent soil cover) were able to recover > 92% of the original SOC stocks. However for areas with the predominance of soybean in the rotation, recovery SOC stock was only 60% and the SOC gain restricted to shallow soil layers.

4.3. SOC gains and losses according to the management system

The adoption of conventional tillage for 25 years decreased SOC stocks to 19.3% of the original value to a depth of 1.0 m. (Fig. 2). During this period the rate of SOC decomposition was higher than SOC input resulting in a depletion of SOC (Bayer et al., 2000; Dieckow et al., 2005). In addition, between the period of 1970 and 1980, it was common to burn the wheat residues, which resulted in further decreased C inputs (Lopes et al., 2013).

The phase of SOC decrease, associated with adoption of conventional/reduced tillage and with low cropping intensity was also described in other regions simulated by the Century model for Rio Grande do Sul (Bortolon, 2008; Tornquist et al., 2009; Lopes et al., 2013). The recovery of SOC stocks with the adoption of CA and the introduction of cropping systems with medium cropping intensity as in sites 2 and 6, the SOC recovery was 79.5 and 85.4%, respectively. With high cropping intensity (sites 3, 4 and 5) the SOC recovery ranged from 84.9 to 116.5% (Fig. 2). Sites 4 and 5 had the highest SOC recovery (>90%). At this sites, the average temperature was lower than other sites which would decrease soil organic matter decomposition. In addition, the soil characteristics are more favorable to SOC stabilization due the higher physical and chemical protection (Table 1). This sites had high plant biomass input and low soil disturbance throughout the use of cover crops.

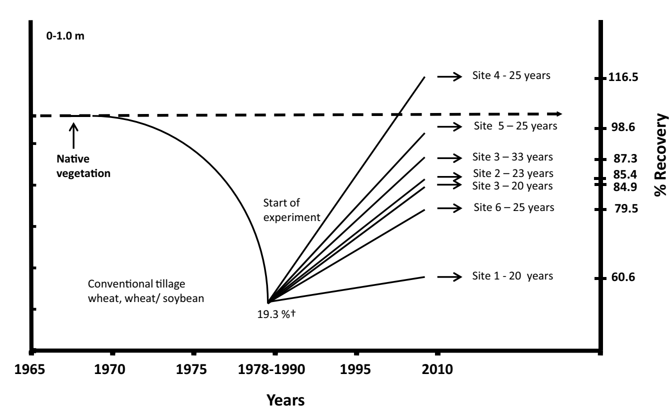

Fig. 2. Overall scenario of carbon gains and losses according to the management system over the years.
† Mean SOC stock depletion rate under long-term experiments in Rhodic Hapludox (Cruz Alta, Santo Angelo and Passo Fundo sites) at the 0–1.0 m soil depth.

5. Conclusions

The pioneer no-till areas in the State of Rio Grande do Sul that are mature (> 20 years) and have a diversified crop rotation were able to recover > 92% of SOC stocks relative to native vegetation. Lower recovery of SOC stock occurred where predominance of soybean in the crop rotation.

An increase of SOC in deeper layers was measure at two sites where the SOC stocks were higher in NT than in NV. The increase in SOC stocks in deeper layers was associated with intensity and diversity of crop rotation and the use long-term NT.

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