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Comparing on-farm and long-term research experiments on soil carbon recovery by conservation agriculture in Southern Brazil

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Abstract

Global studies, generally, and Brazilian studies, specifically, on soil organic carbon (SOC) in experimental research plots, support conservation agriculture (CA) as a tool to partially or totally restore SOC stocks depleted by conventional tillage agriculture. In response, the Brazilian Government implemented in 2010–2030 a "Low Carbon Agriculture Plan" (ABC Plan) program centered on large-scale CA adoption. However, the projections of SOC recovery based on long-term research trials may not adequately portray farm level high-yield operations. The objectives of this study were: (a) quantify and compare SOC stocks to a 1-m depth in long-term CA at the farm scale (>20 years) with paired native vegetation and nearest available long-term research experiments (>30 years) in Southern Brazil; (b) explore the role of oilseed radish (*Raphanus sativus* L.) as a cover crop to enhance SOC accumulation. In general, farm level CA systems restored SOC at an equal or higher level than the paired research plots. For the farm level CA systems, average SOC recovery was 92% (0–0.30 m) and 97% (0–1.0 m) in the soil profile relative to native vegetation. Moreover, compared to research scale CA, farm level CA average SOC recovery was 91 and 86%, for the same soil layers. Recovery of SOC in research scale CA can be scaled up to farm level systems in Southern Brazil. The main characteristics for SOC recovery (0–1.0 m) were high inputs of plant biomass, lack of soil disturbance, and diversification with oilseed radish cover crop.

KEYWORDS
conservation agriculture, crop rotation, farming systems, oilseed cover crop, Oxisol

1 | INTRODUCTION

Currently, Brazil has 36.8 million hectares under conservation agriculture (CA) (Sá et al., 2020; Sá & De Oliveira Ferreira, 2018), accounting for ~75% of the total grain production area. Two states of Southern Brazil (Paraná and Rio Grande do Sul) were the pioneers in the adoption of CA in the early 1970s, but the system was only scaled-up after the 1990s. In 1990, the area under CA was 0.9 million ha (M ha), with an annual adoption rate of 0.081 M ha per year, and in 2000, it was 14.0 M ha, with an annual adoption rate of 1.64 M ha per year. The CA area doubled in 2010 to 30.3 M ha, with an annual adoption rate of 1.51 M ha per year and in 2016/17 reached the area of our study (Sá et al., 2020; Sá & De Oliveira Ferreira, 2018), placing Brazil second in the world the adoption of CA (Kassam, 2020; Kassam et al., 2019).

Abbreviations: SOC, soil organic carbon; CA, conservation agriculture; ABC plan, low carbon agriculture.

Long-term experiments support the view that CA increases soil organic carbon (SOC) stocks in tropical and subtropical environments at varying rates according to biomass input, soil texture, temperature, rainfall distribution, and diversification of cropping systems (Amado et al., 2006; Bayer et al., 2009; De Oliveira Ferreira et al., 2016, 2021; De Oliveira Ferreiraet al., 2018; Dieckow et al., 2005; Hok et al., 2021; Mishra et al., 2010; Nicoloso & Rice, 2021; Sá et al., 2014, 2015; Tivet et al., 2013). De Oliveira Ferreira et al. (2018) evaluated five CA farms in southern Brazil and reported that SOC increased when the system was based on high crop carbon input and efficient use of nutrients balancing inputs and outputs with special attention to nitrogen. Tivet et al. (2013) reported high SOC associated with high biomass C input in the Southern and Mid-Western Brazilian regions.

Most global and Brazilian studies assess SOC stock changes based on experimental research plots (Boddey et al., 2010; Dick et al., 2013; Sá et al., 2015; Tivet et al., 2013; Veloso et al., 2018) with little data from farm-level CA systems (De Oliveira Ferreira et al., 2016; De Oliveira Ferreira et al., 2018; Gonçalves et al., 2017; Gonçalves et al., 2019; Sá et al., 2013). The scarcity of data regarding SOC from farm level CA systems creates uncertainness to scaling-up data from plot-level experiments (Gonçalves et al., 2019).

Some studies reported lower crop yields under CA compared with conventional tillage (Pittelkow et al., 2015), but in many cases associated with specific soil and weather conditions (cold and poorly drained soils), and failed to address the three principles of CA (permanent soil cover, minimum soil disturbance, and crop rotation). The level of SOC restoration in high-yielding commercial farms needs to be verified to support government programs such as the "Low Carbon Agriculture Plan" (ABC Plan) launched in 2010 to the agricultural C sink and reduce Brazilian's overall carbon footprint (Martins et al., 2018). We hypothesized that: (a) CA based on high-performance farming systems recover SOC at the same or even higher level than projected based on long-term experiments and (b) SOC recovery in farming systems is driven by high plant input coupled with the diversification of cropping system by cover crops with deep root system such as oilseed radish (*Raphanus sativus* L.).

The objectives of this study were to: (a) quantify and compare SOC stocks to a 1-m depth in long-term CA at the farm level (>20 years) with paired native vegetation and nearest available long-term research experiments (>30 years) in Southern Brazil; (b) explore the role of oilseed radish as a cover crop to enhance SOC accumulation.

2 | MATERIALS AND METHODS

2.1 | General description

The studied areas were selected from farm sites (ranging from 20 to 33 years under CA) located in representative municipalities of the grain production regions in Rio Grande do Sul, Brazil. *Site 1—Santa Rosa* (18,000 ha of soybean, 6940 ha of maize, and 10,000 ha of wheat)*; Site 2—Palmeira das Missões* (93,500 ha of soybean, 12,000 ha of maize and 30,000 ha of wheat)*; Site 3—Lagoa Vermelha* (37,000 ha of soybean, 8700 ha of maize and 6000 ha of wheat)*; Site 4—Cruz Alta* (90,000 ha of soybean and 30,000 ha of wheat) *and Site 5—Fortaleza dos Valos* (32,500 ha of soybean, 1830 ha of maize and 7000 ha of wheat) (EMATER, 2014). Long-term experiments under no-till (NT also termed zero tillage) (15–30 years) were selected in the same regions of Rio Grande do Sul State, Brazil (*Site 1—Santo Ângelo; Site 2—Cruz Alta/ FUNDACEP; Site 3—Passo Fundo/EMBRAPA Wheat Research Centre; Site 4—Eldorado do Sul/ UFRGS*) (Figure 1).

The clay content ranged from 220 to 720 g kg^{-1} for all sites investigated and was 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, soil was sampled in natural vegetation (NV) near each agricultural site with the same soil texture and landscape position to compose paired samples. Sites evaluated in the study were categorized by plant biomass input. The input levels were according to Figure 2.

2.2 | Historical land use and management—farming systems

In Southern Brazil, the grain crop production systems started in the colonial period, with subsistence agriculture between 1900 and 1965. Plowing was done primarily by animal traction and clearance was by slash-burn of the native vegetation - characterizing a subsistence agriculture system. The main economic activities were livestock, cultivation of maize, wheat (*Triticum aestivum* L.), beans (*Phaseolus vulgaris* L.), lentils (*Lens culinaris* Medik), cassava (*Manihot esculenta* Crantz), and soybean. Agriculture was based on the natural fertility from the forest and native prairie after conversion to croplands. After 1965, mechanized agriculture began with intense plowing and harrowing (conventional tillage: CT), long periods with bare soil, chemical fertilizers, and wheat/soybean rotation. Burning of wheat residues, as a phytosanitary procedure, expose the soil to heavy rainfall resulted in soil physical degradation and water erosion. In 1966, liming was promoted to correct soil acidity known as "Operação Tatu." Between 1981 and 1990, farmers adopted reduced tillage (chisel plow and disc harrow), moving toward CA. After this initial period, farmers were advised to stop the burning of wheat residues and implemented black oats (*Avena strigosa* Schreb.) as a winter cover crop. By the 1990's, CA was widely adopted by farmers (Bolliger et al., 2006). In 2000, the fast adoption of transgenic crops simplified the cropping systems and gave the farmer's false perception that chemical weed control was so efficient that cover crop weed suppression was not necessarily causing loss of diversity. The chronology of farming systems management is detailed (Table 1 and Figure 2). Plant biomass input (Mg ha^{-1}) for each site are shown in Figure 2 and Supplementary Table. Additional detailed information on the sites had been provided by De Oliveira Ferreira et al. (2016).

The NV in the paired sampled areas were classified as steppes and grassy woody without gallery forest (IBGE, 2010), equivalent to

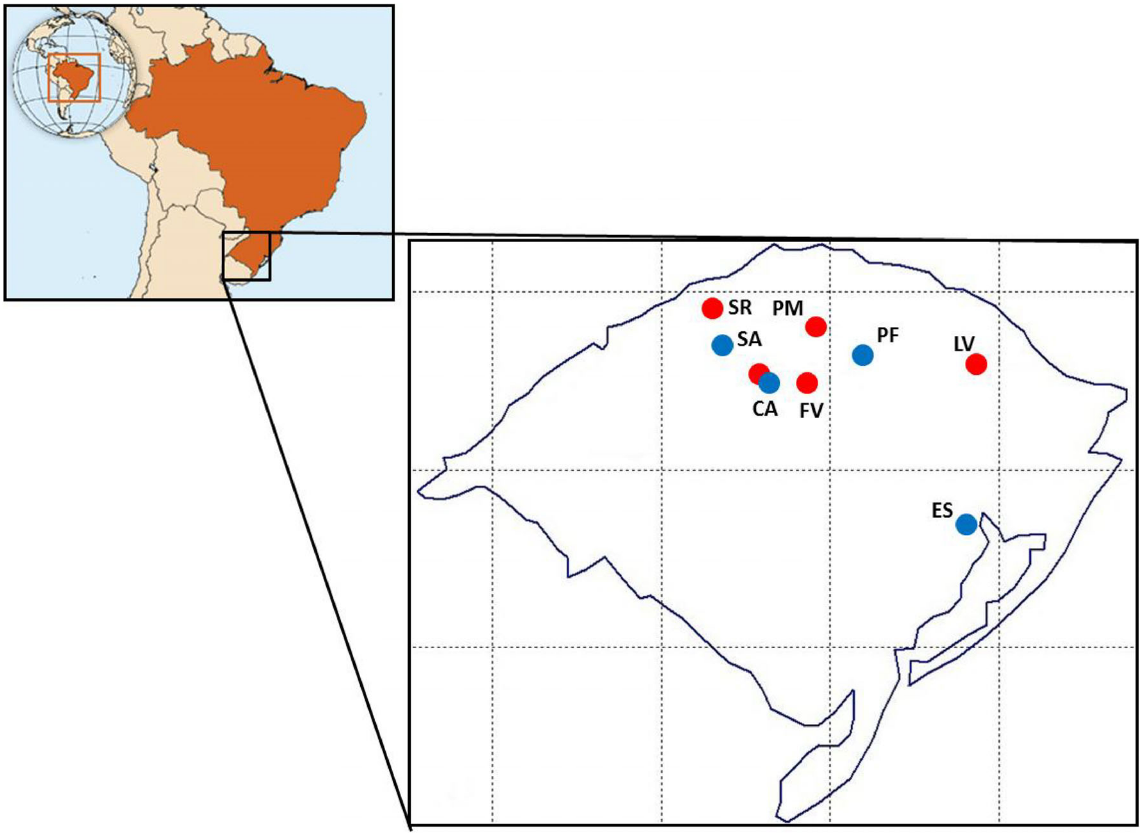


FIGURE 1 Location map of *farming systems* and *long-term experiments* ● *Farming systems*: *SR- Santa Rosa- Site 1; PM- Palmeira das Missões- Site 2*; *LV- Lagoa Vermelha- Site 3*; *CA- Cruz Alta- Site 4 and FV- Fortaleza dos Valos- Site 5*. ● *Long-term experiments*: SA- *Santo Ângelo- Site 1; CA- Cruz Alta/ FUNDACEP - Site 2; Passo Fundo- EMBRAPA Wheat Research Centre- Site 3; ES- Eldorado do Sul/ UFRGS - Site 5* [Colour figure can be viewed at wileyonlinelibrary.com]

subtropical prairies. The dry plant biomass yielded 2.0 to 3.4 Mg ha^{-1} of dry mass (Pillar et al., 2009).

2.3 | Historical land use and management—long-term experiments

This study included the long-term experiments in Rio Grande do Sul as a reference to the nearest cropland. Most experiments were established between 1979 and 1991, during the period of early NT adoption (Table 2). Before establishing these field experiments, the experimental areas had been under continuous wheat (winter)/soybean (summer) under CT (business as usual) for at least 15–20 years. The chronology of the areas and the cultivation systems for each experiment are shown in Table 2 and Figure 2. Plant biomass inputs (Mg ha^{-1}) for each experiment are shown in Figure 2 and Supplementary Table.

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

Soil samples were collected in paired areas of native vegetation and farm level CA system by opening 10 pits with dimensions of 0.3 × 0.3 × 1 m at each one of five sites ((i.e., five in NT and five in native vegetation (NV) totaling 10 samples per site)) taking into account similar slope position. Samples were collected with a spatula on the pit face for the following depths: 0–0.15, 0–0.30, and 0–1.0 m. Briefly, the samples were dried in an oven at 40°C until constant weight, ground with a wood roll, and passed through a 2 mm sieve. Total organic C (TOC) was determined by wet combustion by the method of Mebius modified in the digestion block (Nelson & Sommers, 1996; Rheinheimer et al., 2008).

Undisturbed samples in each site were collected from the pits at depths of 0–0.15, 0–0.30, and 0–1.0 m using steel rings with dimensions of 0.05 m of diameter by 0.04 m height to determine soil bulk density (BD) by the core method (Blake & Hartge, 1986).

2.5 | Carbon stock recovery

The SOC recovery was assessed on the basis of the percentage of stock recovered by CA (farming systems or long-term experiments) in comparison with that under native vegetation (NV:undisturbed field). The C recovery (%) among NT and NV was estimated using Equation 1:

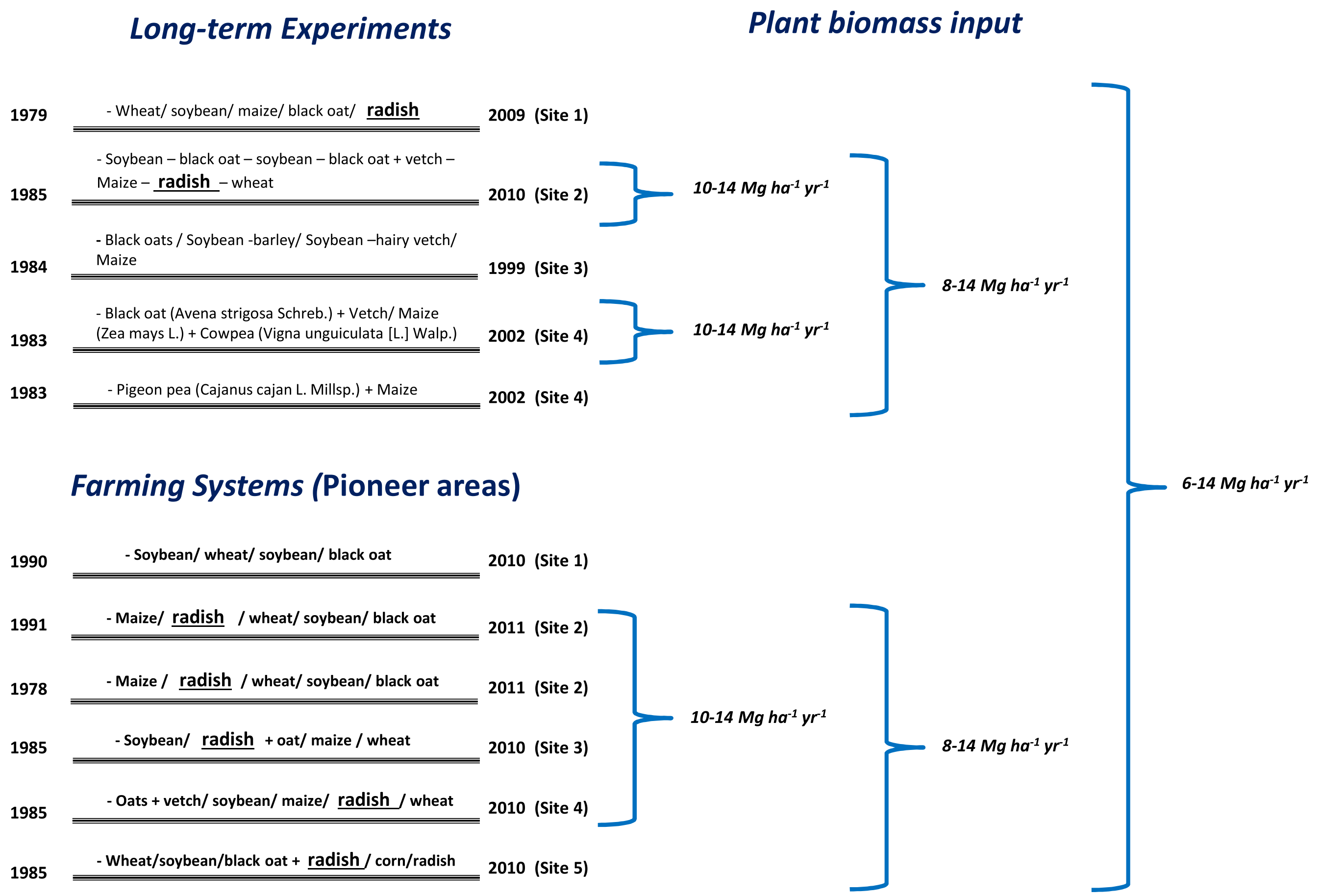


FIGURE 2 Chronology of land use and plant biomass input (mg ha-1) in the farming systems and long-term experiments in Rio Grande do Sul State (Southern Brazil) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Chronology of land use in the *Farming systems* in Rio Grande do Sul (Southern Brazil)

Sites	Conversion to agriculture	Conventional tillage	Reduced tillage	Long-term no-till
Site 1 - Santa Rosa	1965	1985–1987[a]	1987–1990	1990-2010 [I]
Site 2 - Palmeira das Missões	1960	1960–1991[a]	–	1991-2011 [II]
Site 2 - Palmeira das Missões	1960	1960–1978[a]	–	1978-2011 [III]
Site 3 - Lagoa Vermelha	1965	1965–1983[a]	1983–1985	1985-2010 [IV]
Site 4 - Cruz Alta	1965	1965–1981[a]	1981–1985	1985-2010 [V]
Site 5 - Fortaleza dos Valos	1965	1965–1982[a]	1982–1985	1985-2010 [VI]

[a]= wheat/soybean; [I] = soybean/wheat/ soybean/black oat; [II] = 1991/1994/1997/2000/2003/2006//2009 (maize/radish/wheat/soybean); 1992/1998/2004/2010 (soybean /fallow/wheat/soybean); 1993/1996/1999/2002/2005/2008/2011 (soybean/black oat/maize); 1995/2001/2007 (soybean/ fallow/white oat/soybean); [III] = 1978/1981/1984/1987/1990/1993/1996/1999/2002/2005/2008/2011 (soybean/ black oat/ maize); 1980/1986/1992/1998/2004/2010 (soybean/fallow/white oat/soybean); 1979/1982/1985/1988/1991/1994/1997/2000/2003/2006/2009 (maize/ radish/wheat/soybean); 1983/1989/1995/2001/2007 (soybean /fallow/wheat /soybean); [IV] = soybean/radish + oat / maize/wheat; [V] = oats + vetch/ soybean/maize/radish/ wheat; [VI] = wheat/soybean/black oat + radish/maize/ radish

$$\mathrm{SOCrecovery}(\%) = \frac{\mathrm{SOC}_{CA}\left(\mathrm{Mgha}^{-1}\right) \times 100}{\mathrm{SOC}_{NV}\left(\mathrm{Mgha}^{-1}\right)} \qquad (1)$$

Where: $\mathrm{SOC}_{\mathrm{CA}}$ and $\mathrm{SOC}_{\mathrm{NV}}$ refer to SOC stock under CA (farming systems or long-term experiments) and NV , respectively.

2.6 | Statistical analysis

A pairwise *t*-test ($p < 0.05$) compared native vegetation (undisturbed field) versus CA (farming systems or long-term experiments) at the different sampling depths (0–0.15, 0–0.30, and 0–1.0 m). Spearman correlation analysis explored the relationship between the variables. The

TABLE 2 Chronology of land use in the *Long-term experiments* in Rio Grande do Sul (Southern Brazil)

Long-term experiments		Previous to experiment installation	Experiment installation	Long-term no-till		References
Site 1 - Santo Ângelo	Year	1964–1979	1979	1986–1999	1999–2009	Reis et al. (2014)
	Crop rotation	Wheat (*Triticum aestivum* L.)/ soybean [*Glycine max* (L) Merr.] under CT	Succession of crops with and without subsoiling	Oilseed rape (*Brassica napus* L.)/soybean/ wheat/black oat/maize Vetch/sincho (*Lathyrus sativus*)/clover (*Trifolium repens* L.)/maize	wheat/ soybean/maize/black oat/forage radish	
Site 2 - Cruz Alta/ FUNDACEP	Year	1955	1985	1985–2010		Campos et al. (2011); De Oliveira Ferreira et al. (2013) and Ruedell et al. (2019)
	Crop rotation	Wheat with burn residues 1955–1970 fallow Wheat/soybean (1970–1985) under CT		R2 - soybean/ black oat / soybean/ black oat + vetch [*Vicia sativa* (L.) Walp.]/ maize / forage radish (*Raphanus sativus* L.)/ wheat		
Site 3 - Passo Fundo/ EMBRAPA Trigo	Year	1964–1984	1984	1984–1999		Boddey et al. (2010)
	Crop rotation	Wheat/soybean Under CT		Black oats (*Avena strigosa*)/soybean/barley (*Hordeum vulgare*)/ soybean/hairy vetch/maize		
Site 4 - Eldorado do Sul/UFRGS	Year	1970–1983	1983	1983–2002		Bayer et al. (2000); Vieira et al. (2007) and Veloso et al. (2019)
	Crop rotation	Conventional		Black oat (*Avena strigosa* Schreb.) + vetch/ maize (*Zea mays* L.) + cowpea [*Vigna unguiculata (L.) Walp.*]		
	Year	1970–1983	1983	1983–2002		
	Crop rotation	Conventional		Pigeon pea (*Cajanus cajan* L. Millsp.) + maize		

Spearman coefficient was chosen for its flexibility in dealing with non-normal or linear data. Additionally, the dataset variance was analyzed by principal component analyses, one for each depth (0–15, 0–30, and 0–100 cm), to explore the driving factors of SOC. This analysis validated the SOC accumulation and recovery of farm level and plot-level CA. All statistical analyses were made using R version 3.4.1 (RC Team, 2014).

3 | RESULTS

3.1 | SOC stocks and recovery

For SOC stocks, considering plant biomass input rates (6–14, 8–14, and 10–14 Mg ha^{-1} yr^{-1}) and the sampled soil layers (0–0.15, 0–0.30, and 0–1.0 m), no statistical differences ($p < 0.05$) were observed between the long-term experiments and farming systems (Figure 3).

Considering the long-term experiments with plant biomass inputs of 6–14 Mg ha^{-1} yr^{-1} [Figure 4(a)], SOC recovery averaged 81.2, 85.5, and 88.3% for the soil layers of 0–0.15, 0–0.30, and 0–1.0 m, respectively. For the farming systems with similar plant biomass inputs, SOC recovery was 88.6, 85.2, and 87.9% for the soil layers of 0–0.15, 0–0.30, and 0–1.0 m, respectively.

The SOC recovery of the long-term experiments with plant biomass inputs of 8–14 Mg ha^{-1} yr^{-1} [Figure 4(b)] was 89.6, 90.9, and 91.8% for the soil layers of 0–0.15, 0–0.30, and 0–1.0 m, respectively. For the farming systems with similar plant biomass inputs, soil C recovery was 93.2, 88.7, and 93.4% for the same previous soil layers. Finally, cropping systems with plant biomass inputs of 10–14 Mg ha^{-1} yr^{-1} [Figure 4(c)] SOC recovery of the long-term experiments was 86.9, 90.9, and 85.8% for the soil layers of 0–0.15, 0–0.30, and 0–1.0 m, respectively. SOC recovery was 97.0, 92.5, and 96.8% for the farming systems for the same previous soil layers.

3.2 | Spearman correlation

The Spearman correlation analysis for the 0–0.15 m layer [Figure 5(a)] highlighted the quantity of plant biomass input as drivers for soil carbon recovery. However, soil C stocks in farm level and plot-level CA systems may take a longer time (>30 years) to reach full recovery. Mean air temperature was negatively correlated with soil carbon stock.

The 0–0.30 and 0–1.0 m layers [Figure 5(b), (c)] had the same behavior as the 0–0.15 m layer. The positive correlation between SOC stocks in the agriculture sites and native vegetation was stronger for the 0–1.0 m depth, indicating the effect of soil management on SOC stock was more pronounced in the 0–0.15 m layer. The relationship between plant biomass input, and carbon recovery was only observed in the 0–0.30 m layer. The effect of mean temperature on soil carbon stocks was lower for the 0–1.0 m layer, and the elevation effect was greater, indicating that soil carbon was mainly affected by terrain characteristics at deeper layers.

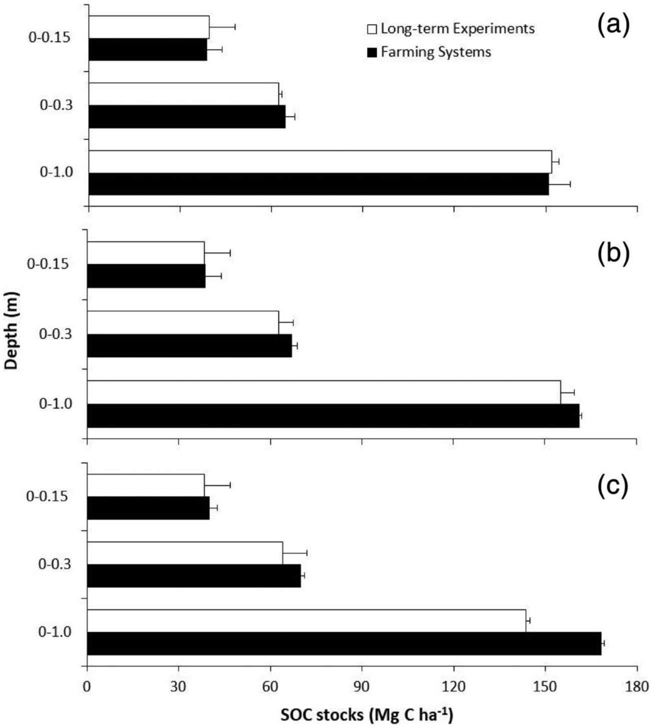


FIGURE 3 Soil organic carbon stocks in long-term experiments and *farming systems* (pioneer areas) under no-till (NT) in Rio Grande do Sul (Southern Brazil). (a) plant biomass input = 6–14 mg ha^{-1} yr^{-1}; (b) plant biomass input = 8–14 mg ha^{-1} yr^{-1}; (c) plant biomass input = 10–14 mg ha^{-1} yr^{-1}

3.3 | Principal component analysis

Principal component analysis for the 0–0.15 m layer [Figure 6(a)] explained 65.7% of the total variance. The first component was composed of clay, precipitation, soil carbon stock, time of CA adoption, frequency of radish oil in the crop rotation and elevation; and the second component included plant biomass inputs and carbon recovery. The correlation of SOC between clay, precipitation, and elevation was associated with soil genesis factors and therefore, were not affected by soil management. Radish frequency in the crop rotation, time of adoption of CA, and plant biomass inputs were important drivers of SOC stock that can be managed by farmers. The lack of correlation between carbon stocks and carbon recovery may be explained by the carbon recovery dependence on the original level of native vegetation carbon stocks.

Principal component analysis for the 0–0.30 m layer [Figure 6(b)] explained 71.9% of the total variance. The first component indicated clay, precipitation, soil carbon stock in native vegetation, time of adoption of CA, frequency of radish oil in the crop rotation, and elevation, while the second component included plant biomass inputs and carbon recovery as observed in the 0–0.15 m analysis. The positive correlation between soil carbon stocks of native vegetation with clay content and precipitation emphasizes the effect of soil and climatic factors for this layer. Moreover, the correlation between plant biomass inputs and carbon recovery indicated that soil management was also a driver of soil carbon stocks for this layer.

Principal component analysis for the 0–1.0 m layer [Figure 6(c)] explained 67.6% of the total variance. The first component included the correlation between soil carbon stock and carbon recovery, while the second component included plant biomass input, frequency of radish oil in crop rotation, and time of adoption of CA. The correlation between soil carbon stocks and carbon recovery indicates that soil management was a driver of soil carbon stocks even when the whole 0–1.0 m soil layer was considered. These results emphasized the importance of radish oil frequency in the crop rotation and time of adoption of CA as strategies to increase carbon in deeper soil layers, which is more difficult to accomplish than for shallow layers.

4 | DISCUSSION

4.1 | SOC stocks under CA

In general, the higher SOC stocks in NV in relation to agricultural systems (Supplementary Table) was explained in part by deeper plant roots of non-domesticated plants (Jobbágy & Jackson, 2000). Fisher et al. (1994) estimated that the introduction of deep-rooted grasses in South America could sequester approximately 100–500 million metric tons of carbon per year. In addition, SOC stocks of NV areas were expected to be at steady state, where the C inputs and losses were at 'dynamic equilibrium' (Sá et al., 2001; Vezzani & Mielniczuk, 2011).

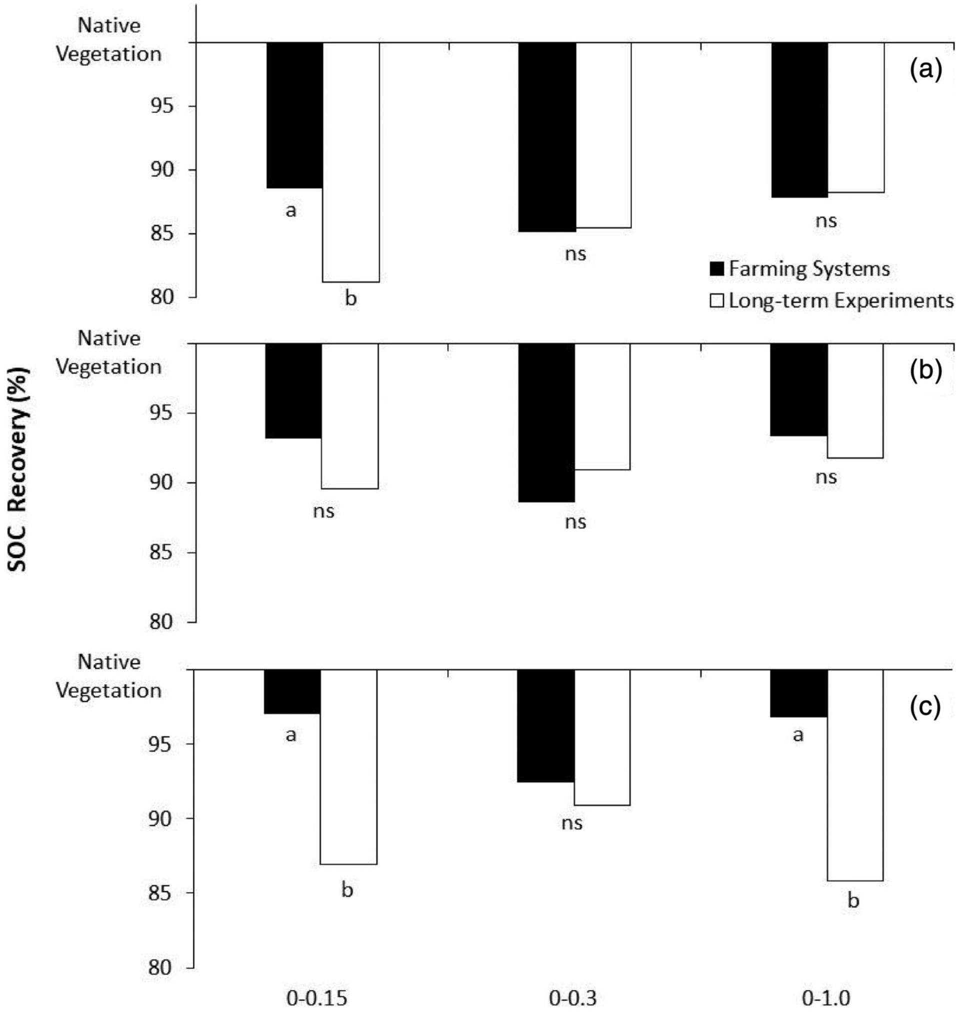
The soil carbon stocks in native vegetation was related to high rainfall, clay content and lower temperatures (Figure 6). Rainfall affects net primary production, including roots. Clays provide sites for protection of carbon from microbial decomposition and enhance stabilization. Soil oxides promote soil carbon sequestration, especially for tropical and subtropical soils (Boddey et al., 2010; Gonçalves et al., 2017; Jagadamma et al., 2014; Sá et al., 2009; Saidy et al., 2012; Zinn et al., 2007). The negative effect of temperature is a consequence of increasing microbial activity and soil carbon oxidation.

Previous studies on farm level CA systems in Southern Brazil show that the increases in pH, nutrient availability, CEC, crop rotation, soil compaction alleviation supported increases in SOC. (De Oliveira Ferreira et al., 2016; De Oliveira Ferreira et al., 2018; De Oliveira Ferreira et al., 2018; Gonçalves et al., 2019; Inagaki et al., 2021; Sá et al., 2018).

4.2 | SOC recovery affected by high C input and oilseed radish frequency

The SOC recovery in the farm level CA systems with high plant biomass inputs (10–14 Mg ha^{-1} yr^{-1}) was higher for the 0–0.15 m and 0–1.0 m soil layer than observed in the plot-level CA systems [Figure 4(c)].

FIGURE 4 Carbon stock recovery as affected by plant biomass input for different soil layers in long-term experiments and farming systems (pioneer areas) under conservation agriculture in Rio Grande do Sul State (Southern Brazil). (a) plant biomass input = 6–14 mg ha^{-1} yr^{-1}; (b) plant biomass input = 8–14 mg ha^{-1} yr^{-1}; (c) plant biomass input = 10–14 mg ha^{-1} yr^{-1}. Lower-case letters within the same depth indicate difference between long-term experiments and farming systems at P ≤ 0.05. Ns = not significant



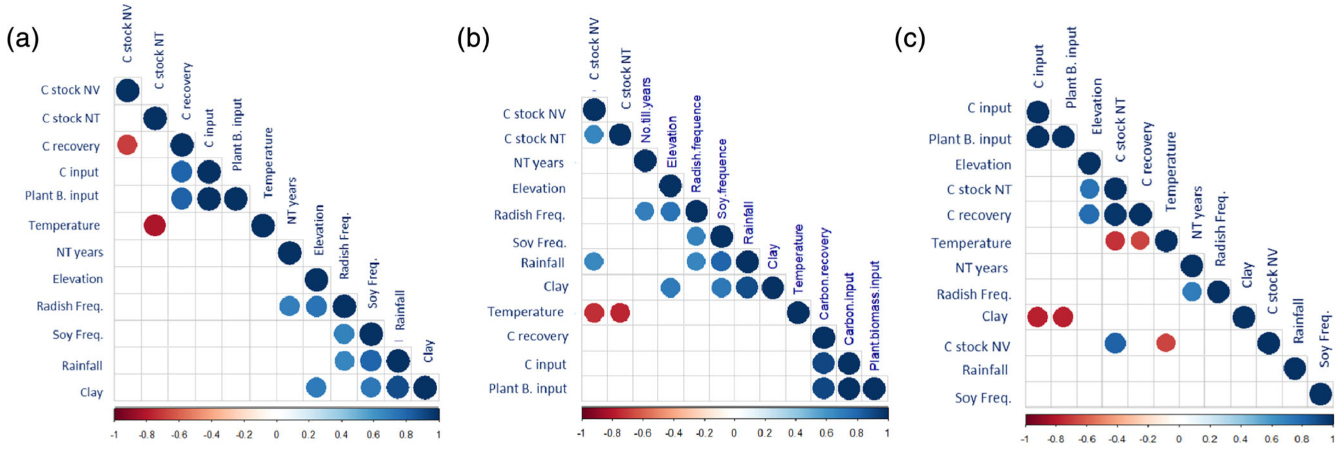


FIGURE 5 *Spearman correlation* in *long-term experiments* and *farming systems* (pioneer areas) under no-till in Rio Grande do Sul (Southern Brazil). (a) 0–0.15 m; (b) 0–0.30 m; (c) 0–1.0 m [Colour figure can be viewed at wileyonlinelibrary.com]

The high SOC recovery in CA was related to the frequency of oilseed radish in the time between maize and wheat in the crop rotation or in a mixture with black oat after soybean (Table 1, Table 2, Figure 6(c), Supplementary Table). The crop sequence in the farm-level CA systems had >80% oilseed radish during the autumn/winter period (Table 1). On the other hand, the plot-level frequency of oilseed radish was only 40% of (Table 2, Figure 2). Villar et al. (2019) reported an average 10% increase of cereal yield due to oilseed radish. Similar results have been reported to Southern Brazil (Inagaki et al., 2021).

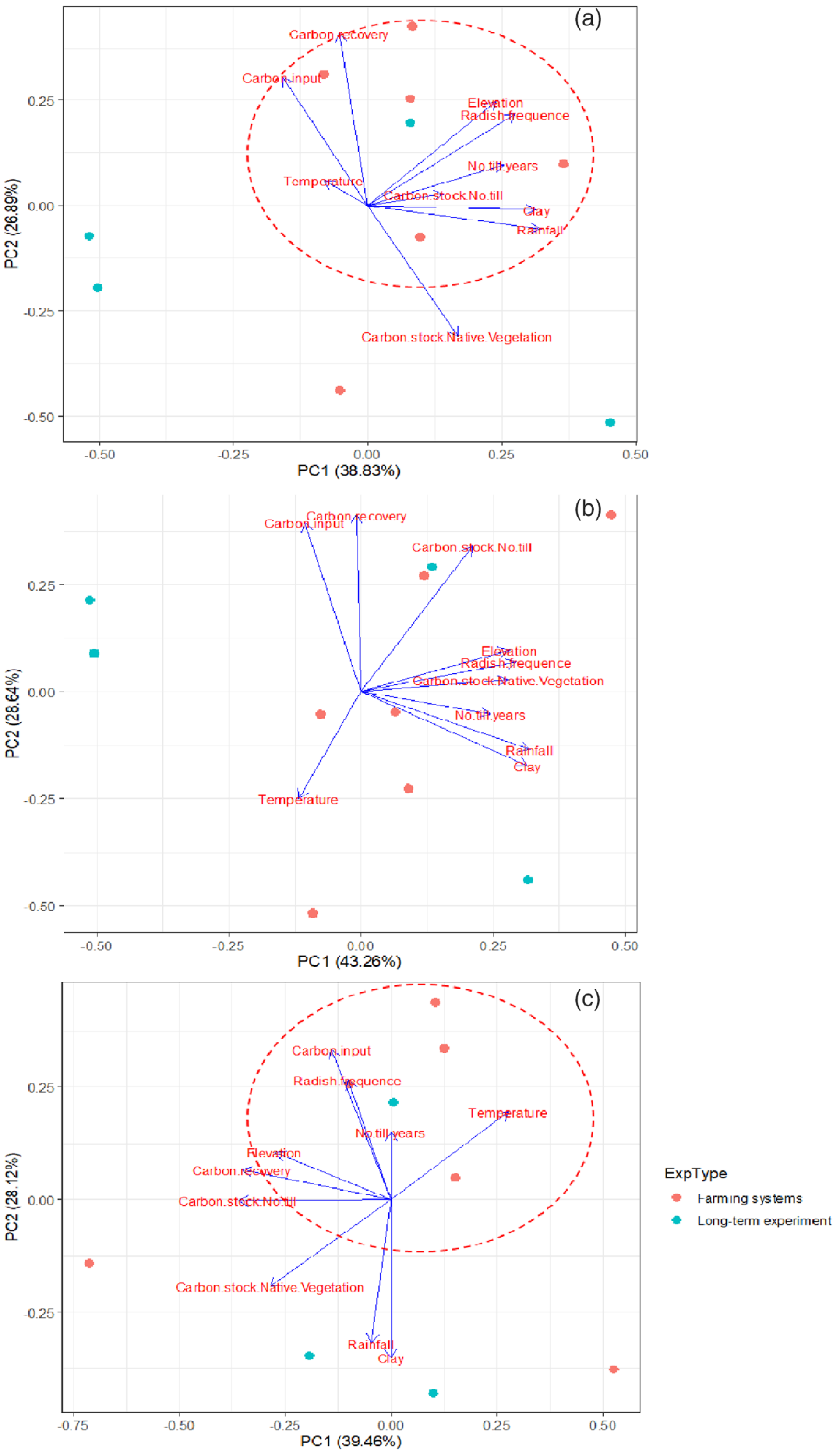


FIGURE 6 Principal component analysis in Long-term experiments and Farming systems (pioneer areas) under no-till in Rio Grande do Sul State (Southern Brazil). a) 0-0.15 m; b) 0-0.30 m; c) 0-1.0 m [Colour figure can be viewed at wileyonlinelibrary.com]

Oilseed radish has multiple functions in crop rotation, creating biopores that alleviate soil compaction and thus creating favorable conditionsfor root growth (Amado et al., 2007; Chen & Weil, 2010). The biological chiseling promoted by oilseed radish is important in CA systems where mechanical tillage is avoided. Lehrsch and Gallian (2010) found radish effects on water-stable aggregate size distribution, bulk density, field-saturated water content, infiltration, and hydraulic conductivity. In addition, these authors report radish decrease nematodes, rhizoctonia, and other soil diseases. Chen and Weil (2010) reported that after oilseed radish, corn root growth was two times that after rye or winter fallow. Chen (2009) reported a linear relationship between cover crop root (including oilseed radish) and maize root. Roots are the most efficient source of C to soil (Fulton-Smith & Cotrufo, 2019). In addition, biopores formed by the oilseed radish roots are stable and act as preferential paths for water and air (Williams & Weil, 2004). In a three-year experiment, Elhakeem et al. (2019) reported that a mixture of oat + vetch + oilseed radish accumulated significantly more shoot biomass and shoot N than the corresponding pure stands. The yield benefit of mixtures was 0.66 t ha^{-1}and 10.7 kg N ha^{-1} compared to an average single species cover crop. These advantages were related to the complementary traits of the species. Species with different root architectures may occupy niches that do not fully overlap. For instance, different rooting patterns in soil may result in partitioning the uptake of water and nutrients in the soil, with competition only occurring in as much as the root systems occupy the same soil volume. Such niche differentiation results in enhanced resource capture and may partially lift competitive restraints on growth, resulting in higher soil C and N. Another advantage is that radish oil in mixtures is mitigating risks of biomass input fail. If one species fails to accumulate biomass due to unfavorable weather for growth, the companion species can take over. In this particular, radish oilseed has a strong dominance factor (selection effect) compared to vetch and oat (Elhakeem et al., 2019).

These results emphasize the importance of using cover crop species with deep root systems to increase the C recovery in both the topsoil layer (0–0.15 m) and the soil profile (0–1.0 m). The deep and continuous biopores could connect the shallow layer and deep layer, supporting C translocation through the soil profile (Chabbi et al., 2009; Leal et al., 2020; Nicoloso et al., 2018; Rumpel & Kogel-Knabner, 2011). The increase of C storage at depth is related to the high precipitation, soil structure, and well-drained Oxisol characteristics that allow deep root growth and continuous dissolved C movement into the soil profile (Nicoloso et al., 2018; Rumpel & Kogel-Knabner, 2011). In addition, the use of long-term NT with minimum soil disturbance maintains root and macrofauna channels, facilitating root development that will be a C source to deeper layers (Boddey et al., 2010). Soil macrofauna, directly and indirectly, affects litter decomposition and nutrient cycling in processing 20–40% of the annual litter input (Winsome, 2005). Macrofauna are responsible for fragmentation and transport of organic residues, solubilization of C, N, and mineral nutrients, and increasing oxygen availability (Winsome, 2005).

Sokolova et al. (2019) reported that high biomass production of oilseed radish (3–5 tons of dry matter per ha) offsets C losses. According to the same authors, oilseed radish was an effective cover crop, since it reduces and/or completely offsets the carbon balance deficit in comparison with fallow. In this study, the farming systems that adopted oilseed radish (100% of sampled areas) had higher soil C recovery [Figure 4(c)].

Oilseed radish is efficient in the cycling of nitrogen, phosphorus, sulfur, and potassium. Cotrufo et al. (2015) and Lavallee et al. (2020) suggest that crop residue of high quality are used by the microbes with high efficiency, and the C is stabilized with the mineral fraction supporting the increase in SOC (Mutegi et al., 2013). Furthermore, oilseed radish with high root biomass also supports soil carbon sequestration because root-derived carbon has a lower turnover rate than aboveground biomass (Rasse et al., 2005). Mutegi et al. (2013) suggested that 8–10% of oilseed radish C input can be stored in the soil resulting in a soil C input of 4.9 t C ha^{-1} with a residence time of around 20 years.

The frequency of maize in the summer crop rotation with soybean is another strategy to increase SOC (Amado et al., 2006; Campos et al., 2011; Sisti et al., 2004); De Oliveira Ferreira et al., 2012; Leal et al., 2020). These authors observed that maize, following a leguminous cover crop, increases the biomass input resulting in the increase of SOC.

In our study, SOC recovery was 96.8% in the 0–1.0 m layer in farm-level CA systems and 85.8% in plot-level CA systems [Figure 4(c)]. The SOC recovery of farm-level CA systems was due to the higher rate and diversity of plant biomass inputs with oilseed radish as a cover crop proceeding of maize or wheat (i.e., *maize/radish/wheat/soybean/black oat* or *soybean/radish + oat/maize/wheat*) (Table 1, Table 2, Supplementary Table). In general, in our study CA-based farming systems can restore SOC to the same or higher level than plot level experiments. Inagaki et al. (2021) demonstrated that the use of radish as an intercrop for alleviating soil compaction was an efficient alternative due to its superior performance in increasing SOC stocks, promoting higher root development and crop yield. The same authors observed that the higher root development of wheat and soybean after oilseed radish contributed significantly to the increase in SOC stocks.

5 | CONCLUSIONS

Farm level CA systems restored SOC at the same or higher level as Long-term plot-level experiments. For Farm-level systems, SOC recovery was 92.5% (0–0.30 m) and 96.8% iel the soil profile (0–1.0 m) of native vegetation. For the long-term plot-level experiments, SOC recovery averaged 90.9 and 85.8%, for the same soil layers. These results support CA projects in Brazil because it provides evidence that large-scale grain producers (in Rio Grande do Sul (Southern Brazil) were able to accumulate and recover carbon depleted soil.

The drivers for SOC recovery (0–1.0 m) were soil management based on high plant input (maize) combined with crop diversification by oilseed radish in the crop rotation.

DATA AVAILABILITY STATEMENT

The authors declare that the data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENC

Amado, T. J. C., Bayer, C., Conceição, P. C., Spagnollo, E., De Campos, B.-H. C., & Veiga, M. (2006). Potential of carbon accumulation in no-till soils with intensive use and cover crops in Southern Brazil. *Journal of Environmental Quality*, *35*, 1599–1607. https://doi.org/10.2134/jeq2005.0233

Amado, T. J. C., Peres, R. B., Costa, J. A., Nicoloso, R. S., & Teixeira, T. (2007). A safra recorde analisada pelos mapas de rendimento no RS. *Revista Plantio Direto*, *101*, 18–123.

Bayer, C., Dieckow, J., Amado, T. J. C., Eltz, F. L. F., & Vieira, F. C. B. (2009). Cover crop effects increasing carbon storage in a subtropical no-till sandy Acrisol. *Communications in Soil Science and Plant Analysis*, *40*, 1499–1511. https://doi.org/10.1080/00103620902820365

Bayer, C., Mielniczuk, J., Amado, T. J. C., Martin-Neto, L., & Fernandes, S. V. (2000). Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in Southern Brazil. *Soil and Tillage Research*, *54*, 101–109. https://doi.org/10.1016/S0167-1987(00)00090-8

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis part I. Physical and mineralogical methods* (pp. 363–376). Ankeny, Iowa: Soil Science Society of America, Inc.. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Boddey, R. M., Jantalia, C. P., Conceicao, P. C., Zanatta, J. A., Bayer, C., Mielniczuk, J., Dieckow, J., Dos Santos, H. P., Denardin, J. E., & Aita, C. (2010). Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. *Global Change Biology*, *16*, 784–795. https://doi.org/10.1111/j.1365-2486.2009.02020.x

Bolliger, A., Magid, J., Amado, T. J. C., Neto, F. S., Ribeiro, M. F. S., Calegari, A., Ralisch, R., & De Neergaard, A. (2006). Taking stock of the Brazilian "zero-till revolution": A review of landmark research and farmers' practice. *Advances in Agronomy*, *91*, 47–110. https://doi.org/10.1016/S0065-2113(06)91002-5

Campos, B.-H. C. D., Amado, T. J. C., Bayer, C., Nicoloso, R. D. S., & Fiorin, J. E. (2011). Carbon stock and its compartments in a subtropical oxisol under long-term tillage and crop rotation systems. *Revista Brasileira de Ciência do Solo*, *35*, 805–817. https://doi.org/10.1590/S0100-06832011000300016

Chabbi, A., Kögel-Knabner, I., & Rumpel, C. (2009). Stabilised carbon in subsoil horizons is located in spatially distinct parts of the soil profile. *Soil Biology and Biochemistry*, *41*, 256–261. https://doi.org/10.1016/j.soilbio.2008.10.033

Chen, G. (2009). Alleviation of soil compaction by brassica cover crops (doctoral diss.), University of Maryland (College Park, Md.). http://www.lib.umd.edu/drum/bitstream/1903/9517/1/Chen_umd_0117E_10536

Chen, G., & Weil, R. R. (2010). Penetration of cover crop roots through compacted soils. *Plant and Soil*, *331*, 31–43. https://doi.org/10.1007/s11104-009-0223-7

Cotrufo, M. F., Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H. H., & Parton, W. J. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geoscience*, *8*, 776–779. https://doi.org/10.1038/NGEO2520

De Oliveira Ferreira, A., Amado, T., Rice, C. W., Diaz, D. A. R., Keller, C., & Inagaki, T. M. (2016). Can no-till grain production restore soil organic carbon to levels natural grass in a subtropical Oxisol? *Agriculture, Ecosystems & Environment*, *229*, 13–20. https://doi.org/10.1016/j.agee.2016.05.016

De Oliveira Ferreira, A., Amado, T. J. C., Nicoloso, R. S., Sá, J. C. M., Fiorin, J. E., Hansel, D. S. S., & Menefee, D. (2013). Soil carbon stratification affected by long-term tillage and cropping systems in Southern Brazil. *Soil & Tillage Research*, *133*, 65–74. https://doi.org/10.1016/j.still.2013.05.011

De Oliveira Ferreira, A., Amado, T. J. C., Rice, C. W., Diaz, D. A. R., Briedis, C., Inagaki, T. M., & Goncalves, D. R. P. (2018). Driving factors of soil carbon accumulation in Oxisols in long-term no-till systems of South Brazil. *Science of the Total Environment*, *622-623*, 735–742. https://doi.org/10.1016/j.scitotenv.2017.12.019

De Oliveira Ferreira, A., Sá, J. C. M., Harms, M. G., Miara, S., Briedis, C., Quadros Netto, C., Santos, J. B., & Canalli, L. B. (2012). Carbon balance and crop residue management in dynamic equilibrium under a no-till system in Campos Gerais. *Revista Brasileira de Ciência do Solo*, *36*, 1583–1590. https://doi.org/10.1590/S0100-06832012000500022

De Oliveira Ferreira, A., Sá, J. C. M., Lal, R., Amado, T. J. C., Inagaki, T. M., Briedis, C., & Tivet, F. (2021). Can no-till restore soil organic carbon to levels under natural vegetation in a subtropical and tropical Typic Quartzipisamment? *Land Degradation & Development*, *32*, 1742–1750. https://doi.org/10.1002/ldr.3822

De Oliveira Ferreira, A., Sá, J. C. M., Lal, R., Tivet, F., Briedis, C., Inagaki, T. M., Gonçalves, D. R. P., & Romaniw, J. (2018). Macroaggregation and soil organic carbon restoration in a highly weathered Brazilian Oxisol after two decades under no-till. *Science of the Total Environment*, *621*, 1559–1567. https://doi.org/10.1016/j.scitotenv.2017.10.072

Dick, D. P., Reis, C. E. S., Bayer, C., & Caldas, J. S. (2013). Carbon sequestration in subtropical oxisol profiles: Retention capacity and effect of soil management. In J. Xu, J. Wu, & Y. He (Eds.), *Functions of natural organic matter in changing environment* (Vol. 1, 1st ed., pp. 353–358). Dordrecht: Springer. https://doi.org/10.1007/978-94-007-5634-2_64

Dieckow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D. P., & Kogel-Knabner, I. (2005). Composition of organic matter in a subtropical Acrisol as influenced by land use, cropping and N fertilization, assessed by CPMAS C-13 NMR spectroscopy. *European Journal of Soil Science*, *56*, 705–715. https://doi.org/10.1111/j.1365-2389.2005.00705.x

Elhakeem, A., van der Werf, W., Ajal, J., Lucà, D., Claus, S., Vico, R. A., & Bastiaans, L. (2019). Cover crop mixtures result in a positive net biodiversity effect irrespective of seeding configuration. *Agriculture, Ecosystems & Environment*, *285*, 106627. https://doi.org/10.1016/j.agee.2019.106627

EMATER, (2014). Levantamento de área semeada com soja no Rio Grande do Sul. Porto Alegre: EMATER. *Informações Agropecuárias (Séries Históricas)*, http://www.emater.tche.br/site/info-agro/serie_historica.php.

Fisher, M. J., Rao, I. M., Ayarza, M. A., Lascano, C. E., Sanz, J. I., Thomas, R. J., & Vera, R. R. (1994). Carbon storage by introduced deep-rooted grasses in the South American savannas. *Nature*, *371*, 236–238. https://doi.org/10.1038/371236a0

Fulton-Smith, S., & Cotrufo, M. F. (2019). Pathways of soil organic matter formation from above and belowground inputs in a *Sorghum bicolor* bioenergy crop. *Global Change Biology Bioenergy*, *11*, 971–987. https://doi.org/10.1111/gcbb.12598

Gonçalves, D. R. P., Sá, J. C. M., Mirsha, U., Cerri, C. E. P., Ferreira, L. A., & Furlan, F. J. F. (2017). Soil type and texture impacts on soil organic carbon storage in a sub-tropical agroecosystem. *Geoderma*, *286*, 88–97. https://doi.org/10.1016/j.geoderma.2016.10.021

Gonçalves, D. R. P., Sá, J. C. M., Mishra, U., Fornari, A. J., Furlan, F. J. F., Ferreira, L. A., Inagaki, T. M., Romaniw, J., De Oliveira Ferreira, A., & Briedis, C. (2019). Conservation agriculture based on diversified and high-performance production system leads to soil carbon sequestration in subtropical environments. *Journal of Cleaner Production*, *219*, 136–147. https://doi.org/10.1016/j.jclepro.2019.01.263

Hok, L., Sá, J. C. M., Boulakia, S., Reyes, M. R., De Oliveira Ferreira, A., Tivet, F., Saab, S. C., Auccaise, R., Inagaki, T. M., Schimiguel, R., Ferreira, L. A., Briedis, C., Canalli, L. B. S., Kong, R., & Leng, V. (2021). Dynamics of soil aggregate-associated organic carbon based on diversity and high biomass-C input under conservation agriculture in a savanna ecosystem in Cambodia. *Catena*, *198*, 105065. https://doi.org/10.1016/j.catena.2020.105065

Inagaki, T. M., Sá, J. C. M., Tormena, C. A., Dranski, A., Muchalak, A., Briedis, C., De Oliveira Ferreira, A., Giarola, N. F., & Silva, A. P. (2021). Mechanical and biological chiseling impacts on soil organic C stocks, root growth, and crop yield in a long-term no-till system. *Soil & Tillage Research*, *211*, 104993. https://doi.org/10.1016/j.still.2021.104993

Jagadamma, S., Mayes, M. A., Zinn, Y. L., Gísladottir, G., & Russell, A. E. (2014). Sorption of organic carbon compounds to the fine fraction of surface and subsurface soils. *Geoderma*, *213*, 79–86. https://doi.org/10.1016/j.geoderma.2013.07.030

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*, 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Kassam, A. (Ed.). (2020). *Advances in conservation agriculture: Practice and benefits*. (2nd, 498p.). Cambridge, UK: Burleigh Dodds Science Publishing.

Kassam, A., Friedrich, T., & Derpsch, R. (2019). Global spread of conservation agriculture. *International Journal of Environmental Studies*, *76*, 29–51. https://doi.org/10.1080/00207233.2018.1494927

Lavallee, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, *26*, 261–273. https://doi.org/10.1111/gcb.14859

Leal, O. A., Amado, T. J. C., Fiorin, J. E., Keller, C., Reimche, G. B., Rice, C. W., Nicoloso, R. S., Bortolotto, R. P., & Schwalbert, R. (2020). Linking cover crop residue quality and tillage system to CO_2-C emission, soil C and N stocks and crop yield based on a long-term experiment. *Agronomy*, *10*, 1848. https://doi.org/10.3390/agronomy10121848

Lehrsch, G. A., & Gallian, J. J. (2010). Oilseed radish (*Raphanus sativus*), effects on soil structure and soil water relations. *Journal of Sugarbeet Research*, *47*, 1–21. https://doi.org/10.5274/JSBR.47.1.1

Martins, S. C., Assad, E. D., Pavão, E., & Lopes-Assad, M. L. R. C. (2018). Inverting the carbon footprint in Brazilian agriculture: An estimate of the effects of the ABC Plan. *Revista Ciência, Tecnologia e Ambiente*, *7*, 43–52. https://doi.org/10.4322/2359-6643.07106

Mishra, U., Lal, R., Liu, D., & Van Meirvenne, M. (2010). Predicting the spatial variation of the soil organic carbon pool at a regional scale. *Soil Science Society of America Journal*, *74*, 906–914. https://doi.org/10.2136/sssaj2009.0158

Mutegi, J., Petersen, B. M., & Munkholm, L. J. (2013). Carbon turnover and sequestration potential of fodder radish cover crop. *Soil Use and Management*, *29*, 191–198. https://doi.org/10.1111/sum.12038

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon and organic matter. Method of soil analysis: Chemical methods. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston & M. E. Sumner, (Eds.), *Methods of Soil Analysis: Part 3 Chemical Methods*, *5.3*, (Vol. 5, pp. 961–1010). Madison, USA: SSSA Book Series. https://doi.org/10.2136/sssabookser5.3.c34

Nicoloso R. S., & Rice, C. W. (2021). Intensification of no-till agricultural systems: An opportunity for carbon sequestration. *Soil Science Society of America Journal*. http://dx.doi.org/10.1002/saj2.20260.

Nicoloso, R. S., Rice, C. W., Amado, T. J. C., Costa, C. N., & Akley, E. K. (2018). Carbon saturation and translocation in a no-till soil under organic amendment. *Agriculture, Ecosystems & Environment*, *264*, 73–84. https://doi.org/10.1016/j.agee.2018.05.016

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions*, *4*, 439–473. https://doi.org/10.5194/hess-11-1633-2007

Pillar, V. D. P., Müller, S. C., Castilhos, Z. M. D. S., & Jacques, A. V. Á. (2009). *Campos sulinos-conservação e uso sustentável da biodiversidade*. Brasília/DF: Ministério do Meio Ambiente-MMA.

Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T., & van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*, 365–368. https://doi.org/10.1038/nature13809

Rasse, D. P., Rumpel, C., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilization. *Plant and Soil*, *269*, 341–356. https://doi.org/10.1007/s11104-004-0907-y

RC Team. (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing; 2012, Vienna, Austria. http://cran.r- project.org.

Reis, C. E. S., Dick, D. P., Caldas, J. S., & Bayer, C. (2014). Carbon sequestration in clay and silt fractions of Brazilian soils under conventional and no-tillage systems. *Scientia Agricola*, *71*, 292–301. https://doi.org/10.1590/0103-9016-2013-0234

Rheinheimer, D. S., de Campos, B.-H. C., Giacomini, S. J., Conceição, P. C., & Bortoluzzi, E. C. (2008). Comparação de métodos de determinação de carbono orgânico total no solo. *Revista Brasileira de Ciência do Solo*, *32*, 435–440. https://doi.org/10.1590/S0100-06832008000100041

Ruedell, J., Fiorin, J. E., Fernandes, A. M. F. (2019). Resultados comparativos de 32 anos dos sistemas plantio direto e convencional. 1. ed. Porto Alegre - RS: Sescoop/RS, v. 1. 208 p.

Rumpel, C., & Kogel-Knabner, I. (2011). Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant and Soil*, *338*, 143–158. https://doi.org/10.1007/s11104-010-0391-5

Sá, J. C. M., Cerri, C. C., Dick, W. A., Lal, R., Solismar Filho, P. V., Piccolo, M. C., & Feigl, B. E. (2001). Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. *Soil Science Society of America Journal*, *65*, 1486–1499. https://doi.org/10.2136/sssaj2001.6551486x

Sá, J. C. M., & De Oliveira Ferreira, A. (2018). The soil science in the evolution of no-till system in Brazil. *SBCS Bulletim (Brazilian Society of Soil Science)*, *44*, 54–57.

Sá, J. C. M., Gabardo, G., Junior, A. C. S., & Sá, M. F. M. (2009). Estoque de carbono em uma pedosseqüência manejada no sistema plantio direto na região dos campos gerais. *Synergismus Scyentifica UTFPR*, *4*, 1–3.

Sá, J. C. M., Potma Gonçalves, D. R., Ferreira, L. A., Mishra, U., Inagaki, T. M., Ferreira Furlan, F. J., Moro, R. S., Floriani, N., Briedis, C., & de Oliveira Ferreira, A. (2018). Soil carbon fractions and biological activity based indices can be used to study the impact of land management and ecological successions. *Ecological Indicators*, *84*, 96–105. https://doi.org/10.1016/j.ecolind.2017.08.029

Sá, J. C. M., Santos, J. B., Lal, R., Moraes, A., Tivet, F., Sá, M. F. M., Briedis, C., De Oliveira Ferreira, A., Eurich, G., Farias, A., & Friedrich, T. (2013). Soil-specific inventories of landscape carbon and nitrogen stocks under no-till and native vegetation to estimate carbon offset in a subtropical ecosystem. *Soil Science Society of America Journal*, *77*, 2094–2110. https://doi.org/10.2136/sssaj2013.01.0007

Sá, J. C. M., Séguy, L., Tivet, F., Lal, R., Bouzinac, S., Borszowskei, P. R., Briedis, C., Dos Santos, J. B., Da Cruz Hartman, D., Bertoloni, C. G., Rosa, J., & Friedrich, T. (2015). Carbon depletion by plowing and its restoration by no-till cropping systems in Oxisols of subtropical and tropical agro-ecoregions in Brazil. *Land Degradation & Development*, *26*, 531–543. https://doi.org/10.1002/ldr.2218

Sá, J. C. M., Tivet, F., Lal, R., Briedis, C., Hartman, D. C., Santos, J. Z., & Santos, J. B. (2014). Long-term tillage systems impacts on soil C dynamics, soil resilience and agronomic productivity of a Brazilian Oxisol. *Soil & Tillage Research*, *136*, 38–50. https://doi.org/10.1016/j.still.2013.09.010

Sá, J. C. M., Tivet, F., Lal, R., De Oliveira Ferreira, A., Briedis, C., Inagaki, T. M., Gonçalves, D. P., & Romaniw, J. (2020). Carbon management practices and benefits in conservation agriculture systems: carbon sequestration rates. In A. Kassam (Ed.), *Burleigh Dodds Series in*

Agricultural Science (Vol. 2, 2nd ed., pp. 199–228). Cambridge, UK: Burleigh Dodds Science Publishing. https://doi.org/10.19103/AS.2019.0049.08.

Saidy, A. R., Smernik, R. J., Baldock, J. A., Kaiser, K., Sanderman, J., & Macdonald, L. M. (2012). Effects of clay mineralogy and hydrous iron oxides on labile organic carbon stabilisation. *Geoderma*, *173-174*, 104–110. https://doi.org/10.1016/j.geoderma.2011.12.030

Sisti, C. P. J., Santos, H. P., Kohhann, R., Alves, B. J. R., Urquiaga, S., & Boddey, R. M. (2004). Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in Southern Brazil. *Soil and Tillage Research*, *76*, 39–58. https://doi.org/10.1016/j.still.2003.08.007

Sokolova, L. G., Yu Zorina, S., Pomortsev, A. V., & Dorofeev, N. V. (2019). Carbon balance in case of short-term green manure of a fallow in the conditions of the Baikal forest-steppe. IOP Conference Series: Earth and Environmental Science, vol. *315*, 5. https://doi.org/10.1088/1755-1315/315/5/052050

Tivet, F., Sá, J. C. M., Lal, R., Briedis, C., Borszowskei, P. R., Burkner, J. D. S., Farias, A., Eurich, G., Hartman, D. D. C., Nadolny, M. J., & Bouzinac, S. L. S. (2013). Aggregate C depletion by plowing and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. *Soil & Tillage Research*, *126*, 203–218. https://doi.org/10.1016/j.still.2012.09.004

Veloso, M. G., Angers, D. A., Tiecher, T., Giacomini, S., Dieckow, J., & Bayer, C. (2018). High carbon storage in a previously degraded subtropical soil under no-tillage with legume cover crops. *Agriculture Ecosystems & Environment*, *268*, 15–23. https://doi.org/10.1016/j.agee.2018.08.024

Veloso, M. G., Dick, D. P., Costa, J. B., & Bayer, C. (2019). Cropping systems including legume cover crops favour mineral-organic associations enriched with microbial metabolites in no-till soil. *Soil Research*, *57*, 851–858. https://doi.org/10.1071/SR19144

Vezzani, F. M., & Mielniczuk, J. (2011). Agregação e estoque de carbono em Argissolo submetido a diferentes práticas de manejo agrícola. *Revista Brasileira de Ciência do Solo*, *35*, 213–223. https://doi.org/10.1590/S0100-06832011000100020

Vieira, F. C. B., Bayer, C., Zanatta, J. A., Dieckow, J., Mielniczuk, J., & He, Z. L. (2007). Carbon management index based on physical fractionation of soil organic matter in an Acrisol under long-term no–till cropping systems. *Soil and Tillage Research*, *96*, 195–204. https://doi.org/10.1016/j.still.2007.06.007

Villar, N., Aranguren, M., Castellon, A., Besga, G., & Aizpurua, A. (2019). Soil nitrogen dynamics during an oilseed rape (*Brassica napus* L.) growing cycle in a humid Mediterranean climate. *Scientific Reports*, *9*, 13864. https://doi.org/10.1038/s41598-019-50347-1

Williams, S. M., & Weil, R. R. (2004). Crop cover root channels may alleviate soil compaction effects on soybean crop. *Soil Science Society of America Journal*, *68*, 1403–1409. https://doi.org/10.2136/sssaj2004.1403

Winsome, T. (2005). Fauna. In D. Hillel (Ed.), *Encyclopedia of soils in the environment* (pp. 539–548). Amsterdam: Elsevier. https://doi.org/10.1016/B0-12-348530-4/00132-6

Zinn, Y. L., Lal, R., Bigham, J. M., & Resck, D. V. S. (2007). Edaphic controls on soil organic retention in the Brazilian cerrado: Texture and mineralogy. *Soil Science Society of America Journal*, *71*, 1204–1214. https://doi.org/10.2136/sssaj2006.0014

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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