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

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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.

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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.

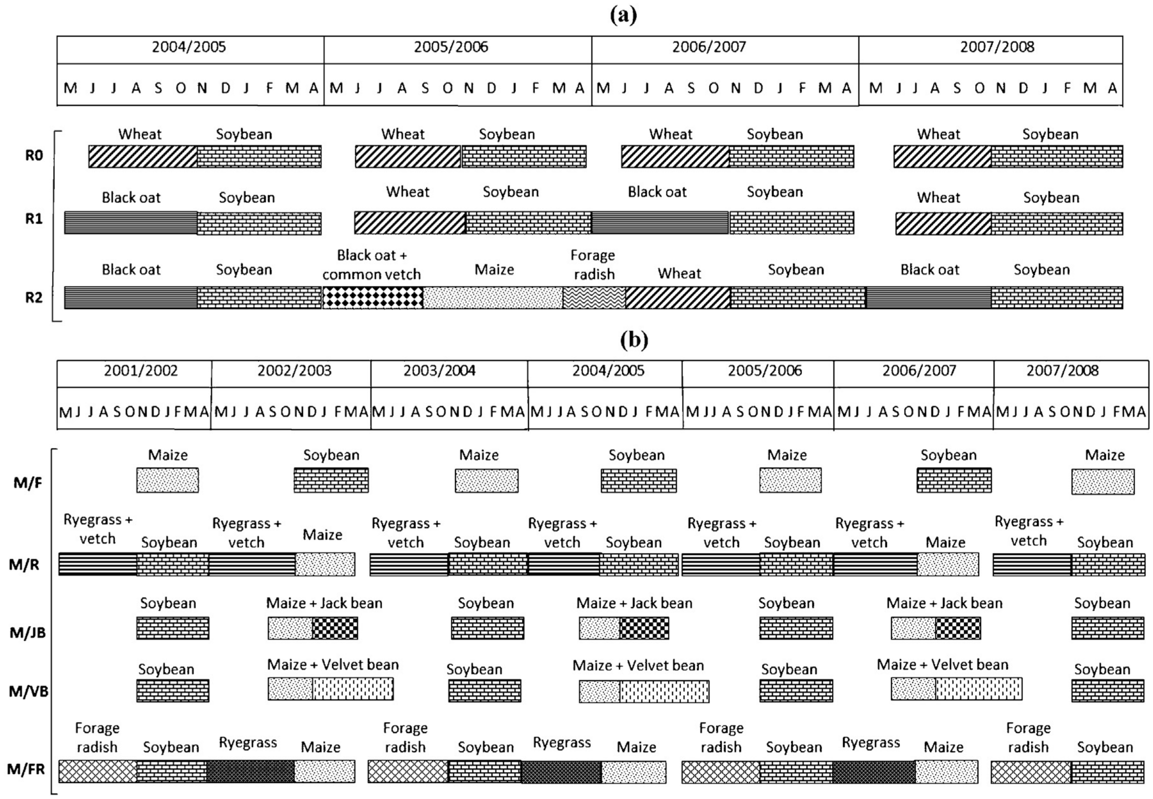

Fig. 1. Description of crop rotation adopted in. (a) Oxisol. (b) Alfisol in Southern Brazil. R0 = continuous crop succession soybean/wheat; R1 = wheat/soybean/oat/soybean; R2 = wheat/soybean/oat/soybean/
oat + vetch/maize/radish. M/JB = maize + jack bean/soybean; M/F = maize/fallow/soybean; M/R = maize/ryegrass + vetch/soybean; M/VB = maize + velvet bean/soybean; M/FR = maize/forage radish/soybean.

NT maintains crop residues on the soil surface and promotes minimum soil disturbance; soil mobilization is restricted to the sowing row. The natural vegetation was pine forest with predominance of *Araucaria angustifolia* (Bertol.) Kuntze and natural pastures consisted of *Paspalum notatum* Fluegge. In the end of 1950s there was a land use change with the conversion of this natural vegetation to agricultural fields with wheat and later soybean.

The cover crop C and N inputs were measured through a square wooden frame of 1 m^2 when plants were at full flowering stage. All of the aboveground biomass was collected and air-dried. For cash crops, the C input was measured over three years (1998–2000) through the previous method. These data were used to generate a correlation between the C input measurement and the C input estimated based on the harvest index (Y (harvest C index) = −0.1372 + 1.074 (C residue input); R^2 = 0.89**). Grain harvest indexes of 0.35 for soybean and 0.40 for wheat and maize were used for the entire experimental period. The N content used to obtain plant N input was determined through micro-Kjeldahl method (Jackson, 1962).

The Oxisol site was amended with 4.3 mg ha^{-1} of dolomitic lime during the establishment of the experiment in 1985. Wheat and maize received 60 and 90 kg N ha^{-1}, respectively. In the first 15 years of the experiment, R1 and R2 crop systems received 52 and 62 kg P_2O_5 ha^{-1} yr^{-1}, respectively, and 75 and 105 kg K_2O ha^{-1} yr^{-1}, respectively. The phosphorus and potassium amendment was later standardized at the rate of 50 kg ha^{-1} yr^{-1}. −1. The N source was urea (45% N), the P source was superphospate triple (41% P), and the K source was potassium chloride (65% K). Further experimental details were as reported by Boddey et al. (2010) and Campos et al. (2011).

The long-term experiment at the Alfisol site had a completely randomized block design with two replications of the following five treatments: (a) maize + jack beans/soybean (M/JB); (b) maize/fallow/soybean (M/F); (c) maize/ryegrass + common vetch/

Table 2
Description of cultivars adopted.

Soil	Culture	2001/2002	2002/2003	2003/2004	2004/2005	2005/2006	2006/2007	2007/2008
Alfisol	Soybean	Cultivar AL72	Cultivar AL72	Cultivar AL72	Cultivar AL72	Cultivar AL72	Cultivar AL72	Cultivar AL72
	Maize	Pioneer 3069	Pioneer 3069	Pioneer 3069	Pioneer 3069	Pioneer 3069	Pioneer 3069	Pioneer 3069
	Jack bean	Common seed[a]	Common seed	Common seed	Common seed	Common seed	Common seed	Common seed
	Velvet bean	Common seed	Common seed	Common seed	Common seed	Common seed	Common seed	Common seed
	Forage radish	Cati AL-1000	Cati AL-1000	Cati AL-1000	Cati AL-1000	Cati AL-1000	Cati AL-1000	Cati AL-1000
Oxisol	Soybean	–	–	–	A 6001 RG	Fundacep 39	Fundacep 54RR	Fundacep 59RR
	Maize	–	–	–	Fundacep 35	Fundacep 35	Fundacep 35	Fundacep 35
	Wheat	–	–	–	Fundacep 40	Fundacep Nova Era	Fundacep 52	Fundacep Raizes
	Black oat	–	–	–	Common seed	Common seed	Common seed	Common seed
	Forage radish	–	–	–	Common seed	Common seed	Common seed	Common seed

[a] Non-pedigreed seed.

Table 3
Analysis of variance (ANOVA) of the two investigated experiments.

Causes of variation	SOC content	CSR
Oxisol		
Tillage systems (M)	**	**
Cropping systems (C)	**	**
Time (T)	**	**
Layer (L)	**	–
CV (%)	11.26	7.52
M × C	**	**
M × T	**	**
C × T	**	**
M × C × T	**	**
M × L	**	–
C × L	**	–
T × L	**	–
T × C × L	**	–
M × T × L	**	–
M × C × L	**	–
M × C × T × L	**	–
CV (%)	5.44	5.93
Alfisol		
Culture systems (C)	**	**
Time (T)	**	**
Layer (L)	**	–
CV (%)	18.08	10.70
C × T	**	**
C × L	**	–
T × L	**	
C × T × L	**	–
CV (%)	13.01	7.59

SOC = soil organic carbon; CSR = carbon strafication ratio.
** $p < 0.01$.

soybean (M/R); (d) maize + velvet beans/soybean (M/VB); and (e) maize/radish oil/soybean (M/FR). Detailed information regarding the cropping systems is shown in Table 2. Information regarding the cultivars used is shown in Table 3. Aboveground C and N inputs in these cropping systems were determined when crops were in full flowering through a square wooden frame of 1 m^2. Details regarding the experimental procedures were as described by Debarba and Amado (1997) and Lanzanova et al. (2010). The soil was amended with 3.5 mg ha^{-1} of dolomitic lime in 1991 and 2.0 mg ha^{-1} of dolomitic lime in 1996. The nitrogen (N) fertilization rate for maize was set at 130 kg N ha^{-1} in the M/F, M/FR and M/R treatments and 65 kg N ha^{-1} in the M/JB and V/B treatments. The phosphorus and potassium amendment was standardized at 60 kg P_2O_5 ha^{-1} yr^{-1} and 50 kg K_2O ha^{-1} yr^{-1}, respectively. The fertilizer sources used were the same as those used at the Oxisol site.

2.2. Soil sampling for SOC concentration

The Alfisol site was sampled in 2001 (T1) and 2007 (T2), corresponding to the 10th and 17th years of the experiment, respectively. The Oxisol site was sampled in 2004 (T1) and 2007 (T2), corresponding to the 19th and 22nd years of the experiment, respectively. In both soils, two small trenches (0.3 m × 0.3 m × 0.15 m) per treatment were used as subsamples. These trenches were manually opened, and soil samples from the 0–0.05 m and 0.05–0.15 m soil layers were collected with a spatula. The samples were air-dried and passed through a 2 mm sieve, the roots and plant residues were removed, and the samples were stored until measurements were performed in the laboratory.

Soil bulk density was determined at the same soil sampling depths in undisturbed soil through sampling with steel rings measuring 0.05 m × 0.04 m (Embrapa, 1997). Soil samples were air-dried, the root and plant residues were manually removed, and the samples were finely ground with a mortar and pestle. The SOC was determined through dry combustion through a C/N analyzer (Flash EA 1112 Series ThermoFinnigan). The SOC stock in the soil layers of 0–0.05; 0.05–0.15 and 0–0.15 m were calculated based on equivalent soil masses (Ellert and Bettany, 1995), taking the treatments M/F (T1) and CT R0 (T1) as references for the Alfisol and the Oxisol sites, respectively.

2.3. Carbon stratification ratio

The CSR was calculated as proposed by Franzluebbers (2002) and is presented in Eq. (1):

$$\mathrm{CSR} = \frac{\text{SOC in the shallow topsoil}\,(0-0.05\,\mathrm{m})}{\text{SOC in adjacent soil layer}\,(0.05-0.15\,\mathrm{m})} \quad (1)$$

where CSR = carbon stratification ratio; SOC = soil organic carbon.

These soil layers were chosen based on the studies by Causarano et al. (2008) and Franzluebbers (2010), which reported strong relationships between the CSR and SOC stock in conservation tillage and a strong relationship between the CSR and soil quality.

The CSR critical value was assessed based on CPI index affected by long-term soil tillage and cropping systems.

2.4. Carbon pool index

The carbon pool index (CPI) was calculated according to Blair et al. (1995) and is presented in Eq. (2):

$$\text{carbon pool index (CPI)} = \frac{\mathrm{SOC_{trat}}\ \text{in soil layer}\,(0-0.15\,\mathrm{m})}{\mathrm{SOC_{ref}}\ \text{in soil layer}\,(0-0.15\,\mathrm{m})} \quad (2)$$

where SOC_{trat} = soil organic carbon in given treatment; SOC_{ref} = - soil organic carbon in the reference treatment (native vegetation), which was 39.7 mg C ha^{-1} for the Oxisol and 17.6 mg C ha^{-1} for the Alfisol.

The CPI index, calculated based on last soil sampling time, was used to assess the improvement in quality of soil management.

2.5. Statistical analysis

The results were submitted to analysis of variance (ANOVA) through the software SISVAR 5.0 (Ferreira, 2010). The means were compared with through the Tukey test ($p < 0.05$). The regression analysis was performed through JMP IN version 7.0.1 (Sall et al., 2005).

2.5.1. Relationships of SOC, CSR and CPI

After twenty-two years (Oxisol) and seventeen years (Alfisol) the stock of SOC in 0–0.15 m soil layer under different soil tillage and cropping systems was used as independent variable and CSR and CPI as dependent variable in order to investigated the relationships of CSR and CPI indices.

3. Results and discussion

3.1. ANOVA

The soil tillage, cropping systems and soil sampling time used had a significant effect on the SOC stock and CSR index in the Oxisol. Cover crops also significantly impacted on the SOC stock and CSR in the Alfisol. Both soils showed significant interaction between SOC stock and the soil depth layer (Table 3).

3.2. C and N input by cropping systems

At the Oxisol site, the soil C input ranged from 3.70 to 6.20 mg C ha^{-1} yr^{-1}; at the Alfisol site, this input ranged from 1.88 to 4.51 mg C ha^{-1} yr^{-1} (Table 4). The soil N input ranged from 98 to 233 kg ha^{-1} yr^{-1} and from 71 to 217 kg ha^{-1} yr^{-1} for the Oxisol

Table 4
Mean annual aboveground crop residues C, N inputs.

Soil	Tillage systems	Cropping systems	N input, cover crop(s) kg ha^{-1}	Annual C input mg ha^{-1}
Oxisol	CT	R0[a]	98 c	3.70 c
	CT	R1[b]	159 b	4.43 c
	CT	R2[c]	224 a	5.34 b
	NT	R0	103 c	4.03 c
	NT	R1	172 b	5.12 b
	NT	R2	233 a	6.20 a
Alfisol	NT	M/F[d]	71 d	1.88 c
	NT	M/R[e]	141 c	3.76 b
	NT	M/JB[f]	217 a	4.07 a
	NT	M/VB[g]	206 a	4.51 a
	NT	M/FR[h]	160 b	4.10 a

NT = no-tillage; CT = conventional tillage; N = nitrogen; C = carbon. Averages followed by the same letters, lower case in the columns, do not differ by the Tukey test, to the level 5% of significance. Comparison is between cropping systems (in the same type of soil).
[a] R0 = succession soybean/wheat.
[b] R1 = wheat/soybean/oat/soybean.
[c] R2 = wheat/soybean/oat/soybean/oat + vetch/maize/radish. T_1 = 2004; T_2 = 2007.
[d] M/F = maize/fallow/soybean.
[e] M/R = maize/ryegrass + vetch/soybean.
[f] M/JB = maize + Jack bean/soybean.
[g] M/VB = maize + velvet bean/soybean.
[h] M/FR = maize/forage radish/soybean.

Table 5
SOC concentration and CSR in the Oxisol as affected by soil tillage and cropping systems.

Sampling period	Cropping systems	Tillage systems CT	NT
SOC concentration, g kg^{-1} (0–0.05 m)			
T1	R0[a]	21.3 Ba	26.7 Aa
	R1[b]	22.5 Ba	27.9 Aa
	R2[c]	23.6 Ba	28.4 Aa
T2	R0	20.4 Ba	24.8 Ab
	R1	20.5 Ba	27.8 Aab
	R2	21.1 Ba	30.9 Aa
SOC concentration, g kg^{-1} (0.05–0.15 m)			
T1	R0	19.6 Aa	17.8 Aa
	R1	19.9 Aa	18.0 Aa
	R2	21.0 Aa	18.6 Aa
T2	R0	18.8 Aa	17.9 Aa
	R1	19.4 Aa	17.8 Aa
	R2	19.2 Aa	18.0 Aa
CSR (0–0.05: 0.05–0.15 m)			
T1	R0	1.04 Ba	1.50 Aa
	R1	1.13 Ba	1.55 Aa
	R2	1.12 Ba	1.53 Aa
T2	R0	1.08 Ba	1.39 Ac
	R1	1.06 Ba	1.56 Ab
	R2	1.10 Ba	1.72 Aa

T1 = 2004; T2 = 2007. SOC = soil organic carbon; CSR = carbon strafication ratio. NT = no-tillage; CT = conventional tillage. CSR = SOC in the shallow topsoil (0–0.05 m)/SOC in adjacent soil layer (0.05–0.15 m). Averages followed by the same letters, small (columns) and capital (lines) do not differ by the Tukey test ($p < 0.05$), between the cropping systems (columns) and tillage systems (lines).
[a] R0 = succession soybean/wheat.
[b] R1 = wheat/soybean/oat/soybean.
[c] R2 = wheat/soybean/oat/soybean/oat + vetch/maize/radish.

and the Alfisol, respectively. The inputs of C and N aboveground were close to those previously reported for cropping systems in other long-term experiments carried out in South Brazil (Conceição et al., 2005; Amado et al., 2006; Bayer et al., 2009; Vieira et al., 2007).

At the Oxisol site, the use of black oats in rotation with wheat on a yearly basis (R1 cropping system) increased the C input by 1.09 mg C ha^{-1} yr^{-1} in NT, compared with the wheat/soybean rotation (R0). While under CT the comparison of these treatments was not significant (Table 4). The intensive cropping system (R2) consisted of a winter rotation of a consortium of cover crops (black oat + common vetch), wheat over three years, forage radish in autumn, and a summer rotation of soybean for two years, followed by a year of maize (Fig. 1a). This system had an increase in C input of 1.64 and 2.17 mg C ha^{-1} yr^{-1} in CT and NT, respectively, compared with that of R0 (Table 4). The N input in R1 increased by 61 and 69 kg ha^{-1} yr^{-1} in CT and NT, respectively, compared with that of R0. The N input in R2 increased by 126 and 130 kg ha^{-1} yr^{-1} in CT and NT, respectively, compared with the reference treatment (R0). In summation, for the same cropping system, input of C was higher in NT, except for C input in R0 that was similar between tillage systems. This result is most likely due to long-term improvements in soil fertility under conservation tillage. Over the 22-year experimental period, NT had a higher C input of 7.9 and 11.7 mg ha^{-1} in R1 and R2, respectively, compared with CT. In the intensive cropping system (R2), the higher C input in NT in relation to CT was equivalent to an extra year of C input every ten years. Comparing the two treatments over the whole experimental period, C and N inputs were 55.0 mg ha^{-1} and 3.0 mg ha^{-1} higher, respectively, in NTR2 compared with that of CTR0.

At the Alfisol site, the use of forage radish (M/FR) to replace winter fallow (M/F) increased C input by 1.88 mg C ha^{-1} yr^{-1} (Table 4). Yet, the N input increased by 70 kg ha^{-1} yr^{-1}. The use of tropical legumes (jack bean and velvet bean) increases the C input by 2.19 and 2.63 mg C ha^{-1} yr^{-1} in M/JB and M/VB, respectively, compared with the reference treatment (M/F). The annual soil N input compared with M/F was 135 N ha^{-1} yr^{-1} greater in M/JB and 146 kg N ha^{-1} yr^{-1} greater in M/VB. During the 17-year experimental period, the M/VB and M/JB had higher accumulated C inputs of 37.2 mg C ha^{-1} and 44.7 mg C ha^{-1}, respectively, compared with M/F. The accumulated N compared with M/F was 2.3 mg ha^{-1} greater in M/VB and 2.5 mg ha^{-1} greater in M/JB.

3.3. *Concentration of SOC in different soil layers*

The CSR index is a comparison of two soil layers usually a shallow topsoil and an adjacent layer. In our study the CSR evaluates the impact of soil tillage and cropping system on these soil layers. The concentration of SOC in 0–0.05 and 0.05–0.15 m soil layers under different tillage and cropping systems are shown in Table 5. Based on last soil sampling time, under CT a homogeneous concentration of SOC was observed with no difference between 0–0.05 and 0.05–0.15 m, regardless of cropping system (Table 5). On the other hand, under NT there was difference in concentration of SOC among cropping systems in 0–0.05 m soil layer. Yet, the concentration of SOC in the shallow topsoil was higher in NT compared with CT (Table 5).

In cropping systems used in the Oxisol, in the last soil sampling time the concentration of SOC (in the 0–0.05 m soil layer) was 27.8 ± 0.72 g kg^{-1} under NT and 20.5 ± 0.68 g kg^{-1} under CT (Table 5). The concentration of SOC in NT was 35.6% greater than in CT. Among contrasting C and N inputs treatments, the concentration of SOC was highest under NT R2 (30.9 ± 0.61 g kg^{-1}) and lowest under CTR0 (21.1 ± 0.30 g kg^{-1}). Therefore, the concentration of SOC in the shallow topsoil was associated with minimum soil disturbance and intensive crop rotation. The R2 cropping system had the highest C input (Table 4), confirming that NT is a C-conservative system.

In the adjacent soil layer (0.05–0.15 m), based on the last soil sampling time the mean concentration of SOC across cropping systems was similar under NT and CT, respectively (Table 5).

Table 6
SOC concentration and CSR in the Alfisol as affected by cropping systems under no-till.

Sampling period	Cropping systems				
	M/F[a]	M/R[b]	M/JB[c]	M/VB[d]	M/FR[e]
SOC concentration, g kg^{-1} (0–0.05 m)					
T1	6.9 Bb	9.2 ABa	8.9 ABb	11.6 Aa	11.9 Aa
T2	10.3 Ba	11.6 ABa	13.6 Aa	12.7 Aa	12.6 Aa
SOC concentration, g kg^{-1} (0.05–0.15 m)					
T1	5.2 Aa	5.3 Aa	4.9 Aa	5.6 Aa	5.9 Aa
T2	6.8 Aa	7.1 Aa	7.4 Aa	7.2 Aa	6.9 Aa
CSR (0–0.05: 0.05–0.15 m)					
T1	1.32 Ca	1.74 Ba	1.81 ABa	2.08 Aa	1.97 ABa
T2	1.51 Ba	1.62 ABa	1.82 Aa	1.76 Ab	1.80 Aa

T1 = 2001; T2 = 2007. SOC = soil organic carbon; CSR = carbon strafication ratio. CSR = SOC in the shallow topsoil (0–0.05 m)/SOC in adjacent soil layer (0.05–0.15 m). Averages followed by the same letters, small (columns) and capital (lines) do not differ by the Tukey test ($p < 0.05$), between the sampling period (columns) and cropping systems (lines).
[a] M/F = maize/fallow/soybean.
[b] M/R = maize/ryegrass + vetch/soybean.
[c] M/JB = maize + Jack bean/soybean.
[d] M/VB = maize + Velvet bean/soybean.
[e] M/FR = maize/forage radish/soybean.

At the Alfisol site, based on the last soil sampling time the mean concentration of SOC across cropping systems in the 0–0.05 m soil layer was 12.1 ± 1.26 g kg^{-1}; individual measurements ranged from 10.3 to 13.6 g kg^{-1} for M/F and M/JB treatments, respectively, these treatments were statically different (Table 6). The surface crop residue input under NT promoted a higher accumulation of SOC in the shallow topsoil (0–0.05 m) in tropical soils (Bayer et al., 2000; Tivet et al., 2013).

For the adjacent soil layer (0.05–0.15 m), the mean concentration of SOC was 7.1 ± 0.24 g kg^{-1}; individual measurements ranged from 6.8 to 7.4 g kg^{-1} for M/F and M/JB treatments, respectively, without statistical significance (Table 6). Therefore, the presence of cover crops increased the concentration of SOC, mainly in the 0–0.05 m soil layer (Balesdent et al., 2000). The concentration of SOC in the shallow topsoil in the last soil sampling time for the treatments M/FR, M/VB and M/JB were 22.3%, 23.3% and 32.0% higher, respectively, than in the M/F treatment.

3.4. Improvement in the quality of soil management

To assess the impact of soil management practices on soil quality, the CPI index was used (Fig. 2). In the Oxisol, the main strategies for improving quality of soil management were reducing soil disturbance by replacing CT for NT and adopting an intensified cropping system (Fig. 1a). Conceição et al. (2005) investigated soil tillage and cropping systems in the Alfisol and reported that the use of NT and crop rotation for 15 years results in the highest soil quality in relation to other treatments. In our study, treatments with frequent tillage operations and a lack of crop rotation (CT R0) had the lowest CPI (Fig. 2).

The tillage impact on soil quality could be assessed by the CPI index. Under CT, the CPI was similar in R0 and R2 treatments. Under NT, the CPI values were 0.91 to 0.98 in R0 and R2, respectively, representing an increase of 7.1% which was statistically different (Fig. 2a). Therefore, CT neglected the impact of crop rotation on the CPI index, while under NT the intensified cropping system (R2) resulting in the highest CPI. Previously, Amado et al. (2006) studied C-sequestration rates under tillage and crop systems and reported that CT negates the crop rotation effect.

In Alfisol, the main improvement in the CPI occurred with the use of cover crops that increased soil C input and tropical legumes that increased N input through biological fixation (Fig. 1b). The treatment M/F, which has winter fallow, had the lowest CPI value. Vieira et al. (2009) reported previously that the SOC stock at a 0–0.175 m depth in NT maize systems in Alfisol with pigeon pea (*Cajanus cajan* L.) or lablab (*Lablab purpureus* L.) had increases of 32% and 53%, respectively, in relation to winter fallow/maize over 19 years. Boddey et al. (2010) reported that cropping systems with legume cover crops showed the highest SOC stocks, highlighting the importance of biological N fixation on increased soil C sequestration under NT. In our study, the CPI index increased by 27.5% and 36.2% in M/VB and M/FR cropping systems, respectively,

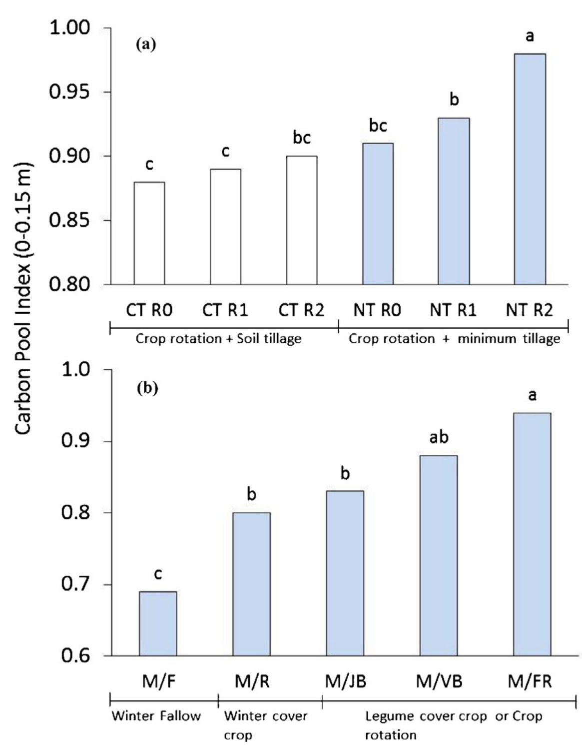

Fig. 2. Soil quality in response to improvements on soil management and crop rotation systems. (a) Oxisol; (b) Alfisol. CT = conventional tillage; NT = no-tillage. R0 = continuous crop succession soybean/wheat; R1 = wheat/soybean/oat/soybean; R2 = wheat/soybean/oat/soybean/oat + vetch/maize/radish. M/JB = maize + jack bean/soybean; M/F = maize/fallow/soybean; M/R = maize/ryegrass + vetch/soybean; M/VB = maize + velvet bean/soybean; M/FR = maize/forage radish/soybean. Carbon Pool Index = SOC in the treatment/SOC in the control (native vegetation). SOC = soil organic carbon. Tukey test, to the level 5% of sigificance.

compared with M/F. Therefore, the low soil quality observed in M/F indicates that minimal soil disturbance was not enough to obtain high soil quality, in agreement with Vieira et al. (2009). Regardless of the soil order, the CPI index was a sensitive indicator quality of soil management.

3.5. Relations of SOC, CSR and CPI indices

The SOC stocks (0–0.15 m) in the topsoil had a positive linear relationship with the CSR in both the Oxisol ($p < 0.002$) and the Alfisol ($p < 0.01$) (Fig. 3a and b). Ferreira et al. (2012) previously reported a relationship between SOC and the CSR ($p < 0.0001$) in the Oxisol in Paraná State (Brazil). The slope of the adjusted equations was similar between the Oxisol and the Alfisol. In the Oxisol, in last soil sampling time an increase of SOC of 3.82 mg ha^{-1} was observed for NT R2 compared with that of CT R0 (Fig. 3a). In the Alfisol, in last soil sampling time, an increase of SOC of 2.25 mg ha^{-1} was observed for M/FR compared with M/F (Fig. 3b). These interactions resulted in an increase in the CSR of 0.64 for the Oxisol NT R2 compared with that of CT R0 and 0.29 for the Alfisol M/FR compared with M/F (Fig. 3a and b).

The Oxisol had C inputs between 3.70 and 6.20 mg ha^{-1}. This was generally greater than the C inputs found in the Alfisol, which ranged between 1.88 and 4.51 mg ha^{-1} (Table 4). The CSR values were lower in the Oxisol compared with the Alfisol (Fig. 3b). In last soil sampling time, the higher SOC stocks in the adjacent soil layer (0.05–0.15 m) of the Oxisol (which ranged from 17.8 to 19.4 mg ha^{-1}) in relation to the Alfisol (which ranged from 6.8 to 7.4 mg ha^{-1}) may explain the lower CSR values in Oxisol (Table 6). The SOC-depleted subsoil in Alfisol explains why the same amount of surface crop C input results in a higher CSR than in the Oxisol, which has a higher concentration of SOC in the subsoil. These results reinforce the fact that the soil type should be considered when evaluating the CSR.

SOC stocks (0–0.15 m) in different soil management practices had positive linear relationships with the CPI in both the Oxisol ($p < 0.0002$) and the Alfisol ($p < 0.001$) (Fig. 3c and d). This result was expected because the CPI index has been reported to be an efficient indicator of soil quality (Blair et al., 1995; Shang and Tiessen, 1997; Dieckow et al., 2005; Vieira et al., 2007). The CPI ranged between maximum and minimum values was 0.10 in the Oxisol (Fig. 3c) and 0.25 in the Alfisol (Fig. 3d). Lower CPI values were observed in the M/F treatment in the Alfisol and the CTR0 treatment in the Oxisol. This result is consistent with the SOC loss in these treatments relative to native vegetation; in last soil sampling time the SOC loss was 13.3% and 11.8% in M/F and CT R0, respectively, compared with native vegetation. Under improved soil management practices (NT R2 and M/FR), both soils achieved higher CPI values (0.98 and 0.94 in the Oxisol and the Alfisol, respectively) (Fig. 3c and d).

Franzluebbers (2002, 2010) suggested that the measurement of the CSR can be as an indicator of quality soil management, with the characteristics of low cost, efficiency, and sensitivity to soil management practices. In our study, as expected, the CSR had a positive linear relationship with the CPI in both the Alfisol ($p < 0.01$) and the Oxisol ($p < 0.02$) (Fig. 4). In the Alfisol, the CSR in last soil sampling time ranged from 1.51 to 1.82, and the CPI ranged from 0.69 to 0.94. In the Oxisol, the CSR ranged from 1.06 to 1.72, and the CPI ranged from 0.88 to 0.98 (Fig. 4a). If the CPI is 0.90 in both soils, the CSR in the Alfisol will be 1.68 and the CSR in the Oxisol will be 1.10, by their respective adjusted equations (Fig. 4b). This result illustrates that soil type has a strong effect on the CSR.

In the Oxisol under CT, the CSR in last soil sampling time ranged from 1.06 (R0) to 1.10 (R2) (Table 5). In the Oxisol under NT, the CSR ranged from 1.39 (R0) to 1.72 (R2). The CPI under CT ranged from 0.88 (R0) to 0.90 (R2). The CPI under NT ranged from 0.91 (R0) to 0.98 (R2) (Fig. 4a). The NT R1 and NT R2 treatments were considered to have a high soil quality; these treatments had CSR values of 1.56 (NT R1) and 1.72 (NT R2) and CPI values of 0.93 (NT R1) and 0.98 (NT R2) (Fig. 4a).

The CSR increases under NT were associated with an accumulation of SOC in the shallow topsoil layer because the

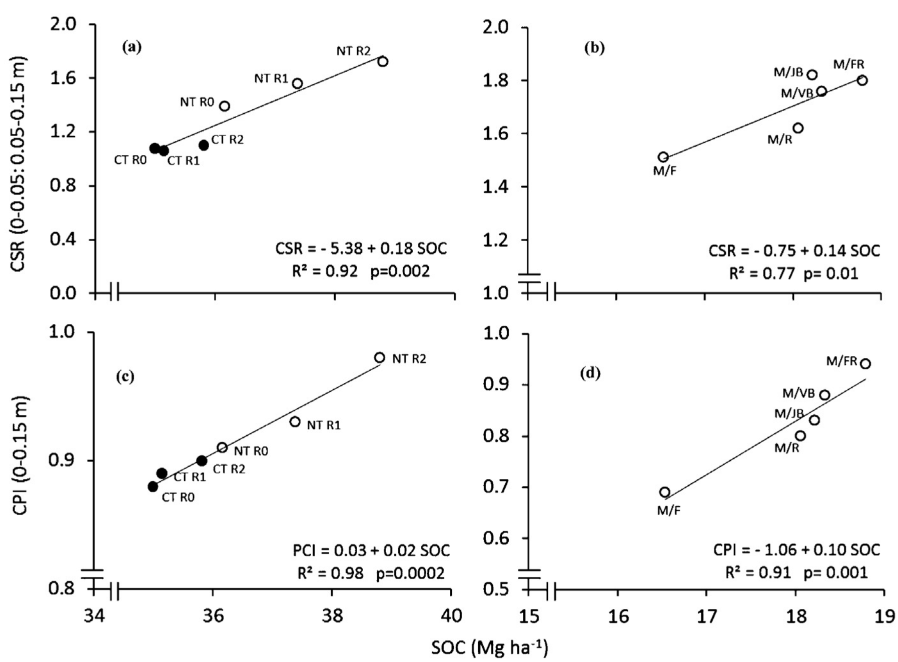

Fig. 3. Relations of SOC (0–0.15 m), CSR (0–0.05: 0.05–0.15 m), and CPI indices (0–0.15 m). (a and c) Oxisol. (b and d) Alfisol. CSR = carbon stratification ratio; CPI = carbon pool index; SOC = soil organic carbon; CT = conventional tillage; NT = no-tillage. R0 = continuous crop succession soybean/wheat; R1 = wheat/soybean/oat/soybean; R2 = wheat/soybean/oat/soybean/oat + vetch/maize/radish. M/JB = maize + jack bean/soybean; M/F = maize/fallow/soybean; M/R = maize/ryegrass + vetch/soybean; M/VB = maize + velvet bean/soybean; M/FR = maize/forage radish/soybean. CPI = SOC in the treatment/SOC in the control (native vegetation). CSR = SOC in the shallow topsoil (0–0.05 m)/SOC in adjacent soil layer (0.05–0.15 m).

Table 7
Carbon stratification ratio (CSR) as affected by long-term tillage and cropping systems in temperate and subtropical agroecosystems.

Climate	Soil	Location	Soil layer (m)	Soil tillage system	NT adoption time	Cropping system	CSR	Source
Temperate	Typic Eutrocryept	Alberta/British, Canadá	0–0.05: 0.125–0.20	NT	7	Small-grain cropping systems	2.1	Franzluebbers (2002)
				CT			1.9	Franzluebbers (2002)
	Typic Hapludults	Virginia coastal plain, EUA	0–0.025: 0.075–0.15	NT	13	Maize/double-crop soybean	2.3	Spargo et al. (2008)
				NT	14	Maize/double-crop soybean	3.2	Spargo et al. (2008)
				NT	14	Maize/double-crop soybean	2.4	Spargo et al. (2008)
	Hapli-Ustic Cambosols	Northeast of China	0–0.05: 0.20–0.40	NT	12	Maize	1.5 a 1.8	Lou et al. (2012)
				CT			1.2 a 1.3	Lou et al. (2012)
	Vertisol (Typic Haploxererts)	Córdoba, Spain	0–0.05: 0.15–0.30	NT	22	Wheat/fallow/wheat-chickpea/ wheat–faba bean/wheat sunflower	3.7	Melero et al. (2012)
				CT			1.5	Melero et al. (2012)
	Typic Paleudalfs	kentucky EUA	0–0.05: 0.15–0.30	NT	30	Maize/Soybean/Wheat/ double-crop soybean.	3.4	Díaz-Zorita and Grove (2002)
Subtropical	Udifluventic Ustochrept	South-Central Texas, EUA	0–0.05: 0.125–0.20	NT	10	Wheat/soybean/sorghum	2.0	Franzluebbers (2002)
				CT			1.2	Franzluebbers (2002)
	Xerofluvent	Seville, Spain	0–0.05: 0.10–0.25	NT	10	Wheat–sunflower	1.6	Moreno et al. (2006)
				CT			1.2	Moreno et al. (2006)
	Xerofluvent	Seville, Spain	0–0.05: 0.25–0.40	NT	10	Wheat–sunflower	2.1	Moreno et al. (2006)
				CT			1.3	Moreno et al. (2006)
	Typic Hapludox	Tibagi, PR, Brasil	0–0.05: 0.05–0.10	NT	20	Soybean/maize/wheat/black oats	1.6	Sá and Lal (2009)
	Typic Hapludox	Ponta Grossa, PR, Brasil	0–0.05: 0.05–0.10	NT	22	Soybean/maize/wheat/black oats	1.7	Sá and Lal (2009)
				CT			1.1	Sá and Lal (2009)
	Rhodic Eutrudox	Palotina, PR, Brasil	0–0.05: 0.10–0.20	NT	9	Maize/wheat/soybean/black oat-forage radish	1.7	Tormena et al. (2004)
				CT		Soybean/maize sucession	1.2	Tormena et al. (2004)
	Typic Hapludox	Ponta Grossa, PR, Brasil	0–0.05: 0.05–0.20	NT	20	Wheat/soybean/black oat + vetch/maize	1.3 a 1.6	Ferreira (2009)

NT = no-tillage; CT = conventional tillage.

concentration of SOC in the adjacent soil layer was similar between cropping systems (Table 5). In last soil sampling time the concentration of SOC in the shallow topsoil layer under NT was 24.8 g kg^{-1} and 30.9 g kg^{-1} for R0 and R2, respectively, representing an increase of 24.6% (Table 5). However, there was no increase in SOC in the adjacent soil layer in the comparison of NT and CT. Increasing concentration of SOC in the shallow topsoil has been reported as critical for soil quality, especially by increasing CEC, nutrient availability, and biological activity and by improving soil structure in addition to positive effects on gas exchange, water infiltration, soil porosity and aggregate stability (Franzluebbers, 2002; Moreno et al., 2006; Causarano et al., 2008; Sá and Lal, 2009; Tivet et al., 2013).

In the Alfisol, the highest soil quality was observed in the M/JB, M/VB and M/FR treatments, which had CSR values of 1.82, 1.76 and 1.80, respectively. The CPI values for M/JB, M/VB and M/FR were 0.83, 0.88 and 0.94, respectively (Fig. 4b). Based on last soil sampling time, the use of legumes and grasses under M/JB promoted a long-term increase in the CSR by 20.5% compared with the M/F treatment. The treatment with the highest soil quality was M/FR (Fig. 4b), most likely due to a higher frequency of maize over soybean and the presence of radish oil (Fig. 1b), which improves the condition of soil physics (Nicoloso et al., 2008; Lanzanova et al., 2010).

3.6. CSR in different agroecosystems

When the data were averaged over sampling times, the CSR values under NT were 1.54 and 1.74 in the Oxisol (Table 5) and the Alfisol (Table 6), respectively. The mean CSR values under CT were 1.09 in the Oxisol (Table 5). Here, we provide a broad review regarding the CSR in long-term soil management from different agroecosystems (Table 7). In temperate soils, CSR values under NT had a mean of 2.7 (ranging between 1.5 and 3.7). Under CT, the CSR had a mean of 1.5 (ranging between 1.2 and 1.9). These mean CSR values are 80% and 38% higher than what we found in the Oxisol for NT and CT, respectively. In the Alfisol, the CSR in temperate climate was 59% higher than what was found in our study. In subtropical soils, the literature reports that the mean CSR under NT was 1.7 (ranging between 1.3 and 2.1). Under CT, the mean CSR was 1.2 (ranging between 1.1 and 1.3) in subtropical soils (Table 7). These values are close to what was found in our study. For similar soil management practices, the CSR was lower in subtropical soils than what was previously reported for temperate soils (Table 6). The lower CSR values in subtropical soils compared with temperate soils could be related to a more oxidative C environment and less stabile chemical C in topsoil (Bayer et al., 2000).

A CSR value of 2.0 was suggested as a critical limit for maintaining soil quality in temperate climates (Franzluebbers, 2002). The critical CSR value for tropical and subtropical soils is still unknown, but based on our study the CSR values of 1.5 and 1.7 for the Oxisol and the Alfisol, respectively discriminate the improvement in the quality of soil management (Fig. 4). Based on this, the NT R1 and NT R2 treatments in the Oxisol could be considered to be high quality. In the Alfisol, the M/JB, M/VB and M/FR treatments also could be classified as high quality.

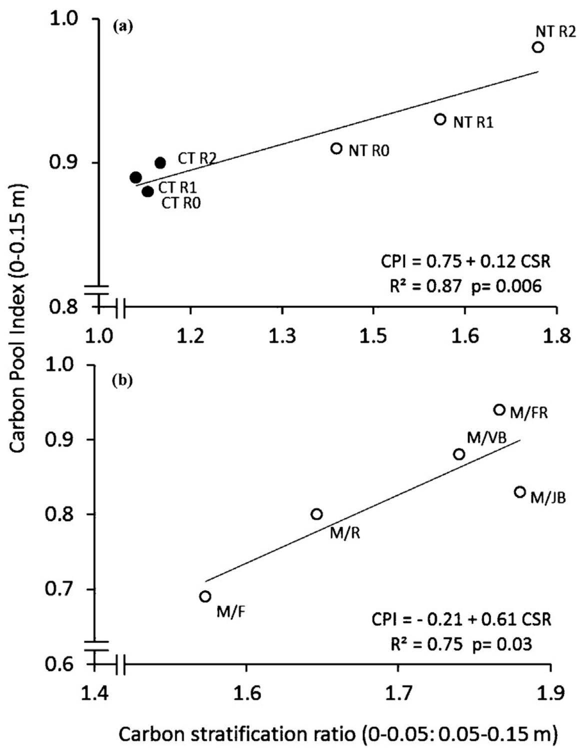

Fig. 4. CSR-based quantitative system proposed for classification of soil quality levels. (a) Oxisol; (b) Alfisol. CPI = carbon pool index; CSR = carbon stratification ratio; CT = conventional tillage; NT = no-tillage. R0 = continuous crop succession soybean/wheat; R1 = wheat/soybean/oat/soybean; R2 = wheat/soybean/oat/soybean/oat + vetch/maize/radish. M/JB = maize + jack bean/soybean; M/F = maize/fallow/soybean; M/R = maize/ryegrass + vetch/soybean; M/VB = maize + velvet bean/soybean; M/FR = maize/forage radish/soybean. CPI = SOC in the treatment/SOC in the control (native vegetation). CSR = SOC in the shallow topsoil (0–0.05 m)/SOC in adjacent soil layer (0.05–0.15 m). SOC = soil organic carbon.

4. Conclusions

The soil order should be considered when defining the critical CSR value to sustain soil quality. In more oxidative environments, such as tropical and subtropical climates, the critical CSR value is lower than previously proposed for temperate soils. In Brazilian agriculture because of the highly oxidative SOC environment, the improvement in quality of soil management is captured by CSR index.

Higher SOC, CSR and CPI values were found when soil was minimally disturbed and crop rotation was intensified. Low indices were found under tilled soils that were associated with short fallow periods and lower crop diversity.

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