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Carbon management index based on physical fractionation of soil organic matter in an Acrisol under long-term no-till cropping systems

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Abstract

The carbon management index (CMI) is derived from the total soil organic C pool and C lability and is useful to evaluate the capacity of management systems to promote soil quality. However, the CMI has not been commonly used for this purpose, possible due to some limitations of the 333 mM $KMnO_4$-chemical oxidation method conventionally employed to determine the labile C fraction. We hypothesized, however, that physical fractionation of organic matter is an alternative approach to determine the labile C. The objectives of this study were (i) to assess the physical fractionation with density (NaI 1.8 Mg m^{-3}) and particle-size separation (53 μm mesh) as alternative methods to the $KMnO_4$-chemical oxidation (60 and 333 mM) in determining the labile C and thus the CMI, and (ii) to evaluate the capacity of long-term (19 years) no-till cropping systems (oat/maize: O/M, oat + vetch/maize: O + V/M, oat + vetch/maize + cowpea: O + V/M + C, and pigeon pea + maize: P + M) and N fertilization (0 and 180 kg N ha^{-1}) to promote the soil quality of a Southern Brazilian Acrisol, using the CMI as the main assessment parameter. Soil samples were collected from 0 to 12.5 cm layer, and the soil of an adjacent native grassland was taken as reference. The mean annual C input of the cropping systems varied from 3.4 to 6.0 Mg ha^{-1} and the highest amounts occurred in legume-based cropping systems and N fertilized treatments. The C pool index was positively related to the annual C input ($r^2 = 0.93$, $P < 0.002$). The labile C determined by density (4.4–10.4% of C pool) and particle-size separation (9.5–17.7% of C pool) had a close relationship ($r = 0.60$ and 0.85, respectively) with the labile C determined using 60 mM $KMnO_4$ (7.3–10.5% of C pool). The labile C resulting from the three methods was related to the annual C input imparted by the cropping systems ($r^2 = 0.67$–0.88), reinforcing the possibility of using physical fractionation as an alternative approach to determine labile C. In contrast, the chemical method using 333 mM $KMnO_4$ was not sensitive to different cropping systems and resulted in too high percentage of labile C, varying from 16.8 to 35.2% of the C pool. The CMI based on physical fractionation was a sensitive tool for assessing the capacity of management systems to promote soil quality, as evidenced by its close correlation ($r = 0.88$, at average) with soil physical, chemical, and biological attributes. The introduction of winter (vetch) and, especially, summer legume cover crops (cowpea and pigeon pea), or application of fertilizer-N, improved the capacity of the management system into promote soil quality in this subtropical Acrisol.

Keywords: Soil C pool; Lability; C management index; No-tillage; Cropping systems

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1. Introduction

The soil organic C pool and the C lability directly influence soil physical, chemical and biological attributes as well as the self-organization capacity of soils (Addiscott, 1995; Blair and Crocker, 2000; Vezzani, 2001). Therefore, the integration of both soil organic C pool and C lability into the C management index (CMI), originally proposed by Blair et al. (1995), can provide a useful parameter to assess the capacity of management systems into promote soil quality (Blair et al., 1995, 2006a,b; Diekow et al., 2005a). In spite of the existence of a large number of long-term experiments that can provide a lot of relevant data pertaining to soil management, however, few are the studies that integrate the total soil organic C pool and the C lability into the CMI as a way to assess the capacity of management systems into promote soil quality.

The C lability is the ratio of labile C to non-labile C. Blair et al. (1995) proposed labile C as oxidizable in 333 mM $KMnO_4$ solution. This concentration, however, is often referred as too strong and not sensitive to detect changes in C lability among some tropical soils, and thus lower concentrations have been proposed (Shang and Tiessen, 1997; Weil et al., 2003). Besides the concentration, other methodological aspects, like reaction time, soil sample moisture (Shang and Tiessen, 1997; Weil et al., 2003) and potential of $KMnO_4$ decomposition due to its exposure to light or reaction with MnO_2 (Blair et al., 1995), are still to be better clarified when using $KMnO_4$ to determine the labile C. These may be the main reasons why the CMI, which depends on C lability, has not been commonly adopted in soil quality assessments.

Taking these constraints of the chemical oxidation method with $KMnO_4$ into account, we hypothesized that physical fractionation of soil organic matter can be an alternative method for determining the content of labile C and thus C lability and CMI. Although the principles of chemical oxidation and physical fractionation are completely different and the labile C determined through these two methods does not match exactly, the main idea is that both methods supply a relative index of soil C lability that allows the assessment of management systems comparatively.

Physical fractionation is based either on density or particle-size of organic matter, or both characteristics (Christensen, 1992). The light fraction obtained through density fractionation is composed mainly of plant residues, roots, and fungal hyphae at different decomposition stages (Gregorich and Janzen, 1996; Baldock and Skjemstad, 2000; Diekow et al., 2005a). Because of its higher turnover rate than the corresponding heavy fraction (Balesdent, 1996), the light fraction is considered to contain labile C. The coarse fraction obtained through particle-size fractionation has similar characteristics and is also considered to contain labile C (Cambardella and Elliott, 1992; Christensen, 1996; Feller and Beare, 1997).

An important argument supporting the physical fractionation is its ability to isolate the particulate organic matter (the fraction that still shows some structural characteristics of its precursor), which is partially decomposed (Baldock and Nelson, 2000) and is not mineral associated. On the other hand, the chemical oxidation may supposedly attack even some mineral-associated organic material that cannot be considered as available to biological activities. Besides, because the chemical oxidation is a surface attack, it is also possible that some labile compounds inside large fragments of particulate organic matter may not be oxidized.

The objectives of this study were (i) to assess the physical fractionation with density and particle-size separation as alternative methods to the $KMnO_4$-chemical oxidation in determining the labile C and thus the CMI, and (ii) to evaluate the capacity of long-term no-till cropping system and N fertilization to promote the soil quality of a Southern Brazilian Acrisol, using the CMI as the main assessment parameter.

2. Materials and methods

2.1. Field experiment, soil sampling and C analysis

This study was based on a long-term experiment (19 years) established at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul, in Eldorado do Sul (RS), Southern Brazil (30°06′35″S and 51°40′37″W). The soil is classified as sandy clay loam Acrisol (FAO, 2002) or as Typic Paleudult (Soil Survey Staff, 2003) and, at the establishment of the experiment in 1983, showed visible signs of physical degradation caused by the conventional tillage management adopted in the previous 13 years of agricultural activities. The particle-size distribution is 540 g sand kg^{-1}, 240 g silt kg^{-1} and 220 g clay kg^{-1}. The clay fraction is composed mainly of kaolinite (720 g kg^{-1}) and iron oxides (109 g Fe_2O_3 kg^{-1}) (Bayer, 1996). The local climate is subtropical humid, Cfa, according to Köppen classification, with mean annual temperature of 19.4 °C and rainfall of 1440 mm.

The experiment comprises 10 no-till cropping systems, set in the main plots (8 m × 5 m), and two

N-fertilization levels, 0 kg N ha^{-1} $year^{-1}$ (0 N) and 180 kg N ha^{-1} $year^{-1}$ (180 N) applied to the maize crop, set in the sub-plots (4 m × 5 m). The experimental arrangement follows a split-plot randomized block design with three replications. Four cropping systems were selected for this study: black oat (*Avena strigosa* Schreb.)/maize (*Zea mays* L.) (O/M), black oat + vetch (*Vicia sativa* L.)/maize (O + V/M), black oat + vetch/ maize + cowpea (*Vigna unguiculata* [L.] Walp.) (O + V/M + C) and pigeon pea (*Cajanus cajan* L. Millsp.) + maize (P + M). We selected these treatments aiming to obtain a wide range of annual C addition. The O/M and O + V/M systems were evaluated in both two N rates, while O + V/M + C and P + M systems were evaluated only without N. Each cropping system has been cultivated for 19 years in the same plot.

Soil samples from 0 to 12.5 cm layer were collected in October 2002 (spring), before the desiccation of winter cover crops and maize sowing. Samples were air dried, ground, and sieved (<2 mm). The amount of surface residue at soil sampling was equivalent to 1.98 Mg C ha^{-1} of black oat in O/M system, 1.12 Mg C ha^{-1} of black oat plus vetch in O + V/M and O + V/M + C, and 7.14 Mg C ha^{-1} of pigeon pea in P + M, according to an assessment performed at two squares of 1.00 m × 0.50 m per plot. Black oat and vetch were at the stages of milky grain and flowering, respectively, while pigeon pea was ending its winter hibernation. The soil of an adjacent area under native grassland with predominance of *Paspalum* sp. and *Andropogon* sp. was also sampled and used as reference.

The total soil organic C concentration was determined by dry combustion, using a TOC analyzer (Shimadzu VCSH). Here samples were ground to pass a 0.25 mm mesh.

2.2. Chemical oxidation with $KMnO_4$

Two concentrations of $KMnO_4$ were used: the original concentration of 333 mM proposed by Blair et al. (1995) and a lower concentration of 60 mM, proposed in this study as being more sensitive to assess the labile C, according to suggestions of Shang and Tiessen (1997) and Weil et al. (2003).

Soil samples containing 15 mg of organic C were placed in 100 mL snap-caps and 25 mL of 333 or 60 mM $KMnO_4$ were added. The suspensions were horizontally shaken for 1 h (60 cycles min^{-1}) and centrifuged at 715 × *g* for 5 min. The supernatant solution was separated, diluted with distilled water at the proportions of 1:1000 and 1:250 for 333 and 60 mM $KMnO_4$, respectively, and then its absorbance at 565 nm was measured with a colorimeter (Spectronic 20 Genesys). The depletion of $KMnO_4$ concentration was directly related to the concentration of oxidizable C, namely of labile C, assuming that 1 mM MnO_4^- is consumed to oxidize 9 mg of C. In order to prevent $KMnO_4$ photooxidation, care was taken to avoid the incidence of light on the solution.

2.3. Physical fractionation

For the density fractionation, based on Six et al. (1998), a suspension of 20 g of soil sample and 70 mL NaI solution (density of 1.8 Mg m^{-3}) was sonicated in a 100 mL centrifuge tube to complete soil dispersion at an energy level of 250 J mL^{-1}. After the suspension was centrifuged at 2000 × *g* for 30 min, the supernatant containing the light fraction was vacuum filtered through a 0.45 μm fiberglass filter (Whatman 1822, previously dried at 50 °C and weighed). The filter and the retained light fraction were rinsed with distilled water to remove NaI salt, dried at 50 °C, grounded in an agate mortar and analyzed for organic C using the TOC analyzer (Shimadzu VCSH).

For particle-size fractionation, 20 g of soil sample and 70 mL of Na hexametaphosphate solution (5 g L^{-1}) were added to a 100 mL snap-cap and horizontally shaken for 15 h (60 cycles min^{-1}). The soil suspension was passed through a 53 μm mesh and the retained coarse fraction was rinsed with a weak stream of distilled water, dried at 50 °C, ground and analyzed for organic C (Cambardella and Elliott, 1992).

2.4. Carbon management index (CMI)

The CMI was obtained according to the mathematical procedures used by Blair et al. (1995), which are described below:

$$CMI = CPI \times LI \times 100 \quad (1)$$

where CPI is the carbon pool index and LI is the lability index.

The CPI and the LI are calculated as follows:

$$CPI = \frac{\text{C pool in treatment}}{\text{C pool in reference}} \quad (2)$$

$$LI = \frac{L\text{ in treatment}}{L\text{ in reference}} \quad (3)$$

where *L* refers to the C lability, calculated as

$$L = \frac{\text{content of labile C}}{\text{content of non-labile C}} \quad (4)$$

The native grassland soil was used as the reference, with a CMI defined as 100. The labile C was considered as the portion of soil organic C that was oxidized by 60 or 333 mM $KMnO_4$, in the chemical oxidation method, and the light and coarse fractions, in the physical fractionation methods. The content of non-labile C was estimated from the difference between total organic C pool and the labile C.

2.5. Correlations and statistical analysis

Data about the annual C addition were compiled from a historical data set of the experiment and used to establish correlations with C pool index and labile C contents as determined through each tested method. Some data of physical, chemical and biological soil attributes considered as soil quality indicators were collected from previous studies conducted in the experiment (Table 1) and were used to establish correlations with CMI.

Analysis of variance for total C pool and labile C fraction were performed using SAS (2005). The Duncan's test ($P < 0.05$) was used for means comparison. Linear regression analyses were used to assess the relationship between annual C addition and total soil organic C pool or labile C pools, and between CMI values and soil chemical, biological, and physical attributes.

3. Results and discussion

3.1. Carbon addition and CPI

The selected cropping systems produced a wide range of annual C addition, which varied from 3.4 to 6.0 Mg ha^{-1}, in average during the 19 years (Table 1).

Table 1
Annual C addition, grain yield of maize and physical, chemical, and biological soil attributes in a subtropical Acrisol subjected to no-till cropping system

Parameter	N rate (kg ha^{-1})	Time[a] (years)	Depth (cm)	Cropping system[b]			
				O/M	O + V/M	O + V/M + C	P + M
Mean annual C addition (Mg ha^{-1} $year^{-1}$)[c]	0	19	–	3.4	4.3	5.1	6.0
	180	19	–	4.3	4.9	–	–
Mean grain yield of maize (Mg ha^{-1})[c]	0	19	–	2.4	3.8	4.4	4.7
	180	19	–	7.1	6.9	–	–
Soil attributes							
Biological[d]							
Microbial biomass (mg C-CO_2 kg^{-1} soil)	0	17	0–10	410	–	469	428
Microbial respiration (mg C-CO_2 kg^{-1} soil)	0	17	0–10	100	–	135	154
β-Glucosidase (μg ρ-nitrofenol g^{-1} soil)	0	17	0–10	97	–	135	146
Urease (μg N-NH_4 g^{-1} soil)	0	17	0–10	40	–	51	53
Acid phosphatase (μg ρ-nitrofenol g^{-1} h^{-1})	0	17	0–10	404	–	518	617
Amidase (μg N-NH_4 g^{-1} soil)	0	17	0–10	199	–	228	267
Arylsulphatase (μg ρ-nitrofenol g^{-1} soil h^{-1})	0	17	0–10	134	–	169	209
Chemical							
Organic N (Mg ha^{-1})[e]	0	19	0–7.5	1.4	1.7	1.8	2.0
CEC effective ($cmol_c$ kg^{-1} soil)[f]	0	10	0–2.5	4.2	4.3	5.0	7.5
CEC at pH 7.0 ($cmol_c$ kg^{-1} soil)[f]	0	10	0–7.5	7.2	7.7	7.8	10.0
Physical (aggregates)[g]							
MDW dry (mm)[h]	0	10	0–7.5	3.4		4.4	4.6
MDW wet (mm)[h]	0	10	0–7.5	1.5		1.7	2.6
Macroaggregates > 0.025 mm, %	0	10	0–7.5	70.3		73.7	74.4

[a] Refers to the age of the experiment when information was obtained.
[b] M: maize; O: oat; V: vetch; C: cowpea; P: pigeon pea.
[c] Compilation from annual historical data (not published). Average values from the 19 years of the experiment.
[d] Schmitz (2003).
[e] Zanatta et al. (2003).
[f] Burle et al. (1997).
[g] Méndez (1996).
[h] MDW: mean diameter weight.

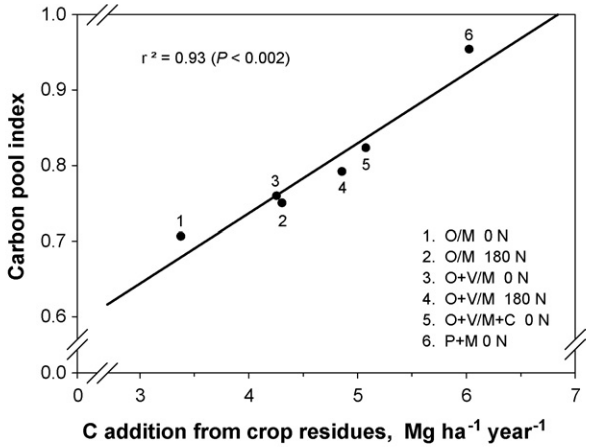

Fig. 1. Relationship between the annual C addition and the C pool index (CPI) in a subtropical Acrisol subjected to no-till cropping systems for 19 years. O/M: oat/maize; O + V/M: oat + vetch/maize; O + V/M + C: oat + vetch/maize + cowpea; P + M: pigeon pea + maize; 0 N: 0 kg N ha^{-1} $year^{-1}$; 180 N: 180 kg N ha^{-1} $year^{-1}$.

Higher additions occurred in the legume-based (O + V/M, O + V/M + C and P + M) than in the gramineous-based cropping system (O/M). This is because legumes, in addition to their own phytomass-C addition, also contribute, due to increments in soil N availability, to higher phytomass production of intercropped non-legume species. Similarly, the N fertilization significantly increased C input, especially in O/M system where the input was almost 1 Mg C ha^{-1} higher in N fertilized than in non-fertilized plots.

The CPI closely correlated with the annual C addition ($r^2 = 0.93, P < 0.002$) (Fig. 1). The CPI for P + M system (0.95) was the most similar to that of the native grassland (arbitrarily defined as 1.00), highlighting the high potential of this grass–legume intercrop in restoring the original soil organic C stocks. The other legume systems O + V/M and O + V/M + C also showed considerable increments in CPI compared to O/M.

Nitrogen application was also important to increase the CPI and to recover the soil C content, as observed in O/M and O + V/M (Fig. 1). These results regarding to the influence of legumes and N application agree with findings of Larson et al. (1972), Paustian et al. (1992), Burle et al. (1997), and Bayer et al. (2000). In addition, they showed that the recovery of the soil organic matter stock in a degraded soil is a viable process after adoption of no-till and cropping systems with high phytomass input, even in warm and humid climatic conditions of subtropics and tropics (Bayer et al., 2000, 2002b; Lal, 2002; West and Post, 2002).

3.2. Soil labile C determined through chemical oxidation and physical fractionation

The recovery of labile C through chemical oxidation varied according to the $KMnO_4$ concentration. With 333 mM $KMnO_4$, the percentage of the total C pool

Table 2
Total C pool (TCP) and labile C as determined through chemical oxidation with $KMnO_4$ (333 and 60 mM) and through physical fractionation (density and particle-size fractionation)

Cropping system[a]	N level (kg ha^{-1})	Total C pool (TCP) (g kg^{-1})	Labile C							
			Chemical oxidation with $KMnO_4$				Density fractionation		Particle-size fractionation	
			333 mM		60 mM		(g C kg^{-1})	(%TCP)	(g C kg^{-1})	(%TCP)
			(g C kg^{-1})	(%TCP)	(g C kg^{-1})	(%TCP)				
O/M	0	10.88 c	3.82 a	35.2	0.90 b	8.3	0.48 b	4.4	1.05 b	9.7
	180	11.55	3.49	30.2	1.21	10.5	0.55	4.8	1.26	10.9
O + V/M	0	11.70 bc	3.58 a	30.6	0.85 b	7.3	0.73 b	6.2	1.11 b	9.5
	180	12.19	3.41	28.0	1.28	10.5	0.79	6.5	1.79	14.7
O + V/M + C	0	12.68 b	4.81 a	38.0	1.33 a	10.5	0.82 b	6.5	1.60 ab	12.6
P + M	0	14.69 a	3.33 a	22.7	1.37 a	9.3	1.45 a	9.8	2.20 a	14.9
NG[b]	0	15.40	2.59	16.8	1.38	9.0	1.60	10.4	2.72	17.7
Mean	0	11.29 A	3.70 A	28.8	0.88 B	9.3	0.61 A	6.9	1.08 B	12.9
	180	11.87 A	3.45 A		1.25 A		0.67 A		1.53 A	

Cropping systems and N fertilization levels followed by the same letters in the column (small and capital letters, respectively) do not differ in the Duncan test at 5% significance level.
[a] M: maize; O: oat; V: vetch; C: cowpea; P: pigeon pea.
[b] Soil under native grassland sampled in adjacent area to the experiment and taken as reference to the estimation of CMI.

estimated as labile ranged from 16.8 to 38.0%, with a mean value of 28.8% (Table 2). On the other hand, an average of only 9.3% of the total C pool was considered as labile when 60 mM $KMnO_4$ was employed, and this percentage was not so different from the average 6.9 and 12.9% obtained through density and particle-size fractionation, respectively (Table 2). This result is a clear indication of the stronger oxidizing capacity of the 333 mM concentration and its corresponding overestimation of the labile C fraction (Shang and Tiessen, 1997; Weil et al., 2003). For chemical oxidation, therefore, the lower concentration of 60 mM $KMnO_4$ seems to provide a better estimation of labile soil C.

Among the physical methods, the lower recovery of labile C in density compared to particle-size fractionation may supposedly be attributed to the fact that NaI solution employed in density separation was not so efficient to recover the light particulate organic matter, as already evidenced in a study of Shang and Tiessen (2001). Recent results of our research team have indicated better efficiency of using Na-polytungstate instead of NaI in promoting the recovery of the light fraction of the organic matter (Conceição, 2006). Another explanation would be the less soil dispersion and the maintenance of microaggregates >53 μm, whose non-labile C (mineral-associated) would erroneously be computed as labile in the particle-size fractionation. However, this explanation is not supported because there was not evidence of such microaggregates when the coarse fraction was observed in optic microscopic, indicating the dispersion of such aggregates was complete.

Based on studies of Bayer et al. (2000, 2002a,b), we assumed that the content of labile C in different no-till cropping systems has a close and direct relation to the annual C addition. These authors verified that cropping systems with high annual C addition showed more labile organic matter, as detected through spectroscopic techniques (nuclear magnetic resonance and electron spin resonance), in comparison to the cropping systems under lower C input. Taking this assumption into account, we used the correlation between the annual C addition and the content of labile C as a way to assess the suitability of the corresponding method of labile C determination. Accordingly, the chemical oxidation with 333 mM $KMnO_4$ solution was not reliable for determining labile C, as pointed by the absence of correlation between C addition and the corresponding labile C determined at the concentration of 333 mM (Fig. 2A). On the other hand, the positive and significant correlations of C addition with labile C determined either through chemical oxidation at 60 mM $KMnO_4$ ($r^2 = 0.67$, $P < 0.047$) (Fig. 2B) or through density ($r^2 = 0.85$, $P < 0.008$) or particle-size fractionation ($r^2 = 0.88$, $P < 0.006$) (Fig. 2C) is a clear indication of

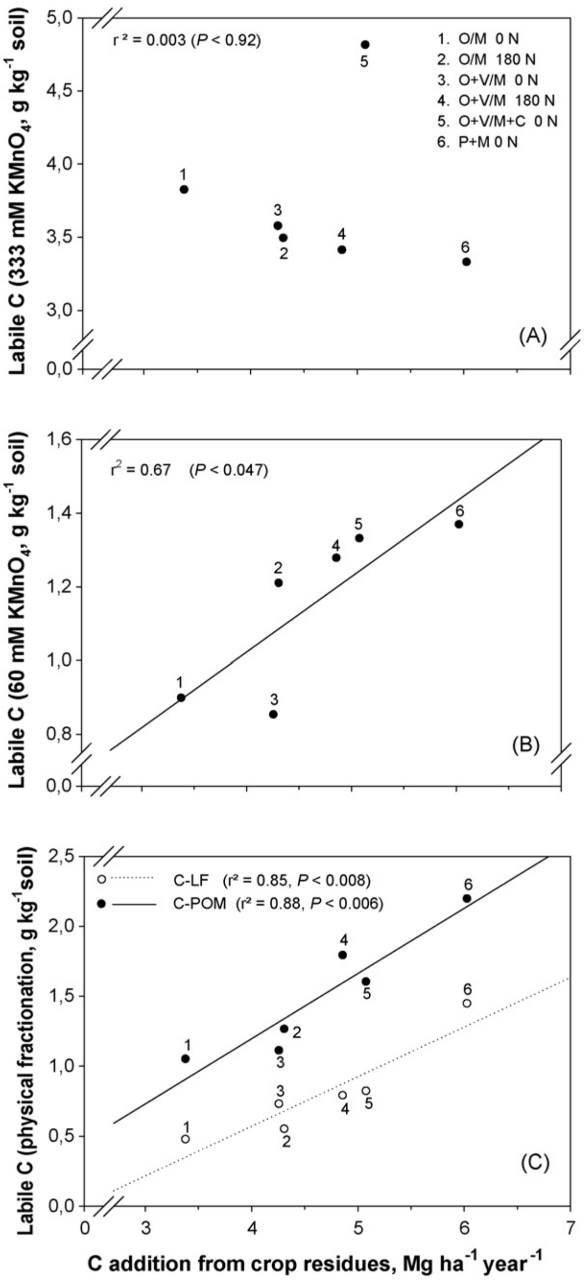

Fig. 2. Relationship between the annual C addition and the labile C determined through chemical oxidation with 333 mM $KMnO_4$ (A) and 60 mM $KMnO_4$ (B) and through physical fractionation with density and particle-size separation (C) in a subtropical Acrisol subjected to no-till cropping systems for 19 years. O/M: oat/maize; O + V/M: oat + vetch/maize; O + V/M + C: oat + vetch/maize + cowpea; P + M: pigeon pea + maize; 0 N: 0 kg N ha^{-1} $year^{-1}$; 180 N: 180 kg N ha^{-1} $year^{-1}$.

the reliability of these methods in determining the content of labile C in soils.

The correlation of C addition and labile C was lower, however, for 60 mM $KMnO_4$ (Fig. 2B) than for physical fractionation (Fig. 2C). This might be related to the characteristic of each method. While physical fractionation recovers the particulate organic matter, which is also directly related to the annual addition of phytomass, is possible that $KMnO_4$ oxidation has not thoroughly attacked some internal or more recalcitrant constituents of this fraction. Additionally, the chemical oxidation may attack part of the mineral-associated organic matter, which is not recovered through physical fractionation.

The values of Lability Index (LI) obtained from labile C estimated by particle-size (varying from 0.44 to 0.75) or density (varying from 0.41 to 0.94) fractionation methods showed a close correlation with the annual C addition ($r^2 = 0.76$, $P < 0.02$; and $r^2 = 0.84$, $P < 0.01$, respectively). On the other hand, the LI obtained from labile C determined by the 60 mM $KMnO_4$ oxidation (varying from 0.79 to 1.21) showed a poor correlation ($r^2 = 0.15$, $P < 0.46$) (data not shown).

In agreement with the labile C and C lability data, the correlations between CMI and annual C additions were also better when labile C was determined through physical fractionation than through chemical oxidation with 60 mM $KMnO_4$ (Fig. 3). For physical fractionation, the correlation of C addition and labile C tended to be better with particle-size than with density separation (Fig. 3B).

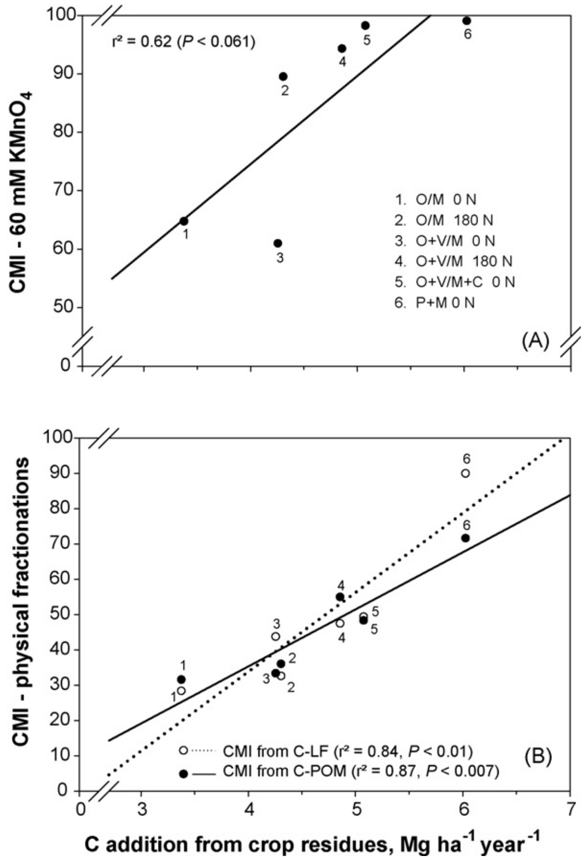

Fig. 3. Relationship between the annual C addition and the carbon management index (CMI) calculated from values of labile C determined through chemical oxidation with 60 mM $KMnO_4$ (A) and through physical fractionation with density and particle-size separation (B) in a subtropical Acrisol subjected to no-till cropping systems for 19 years. O/M: oat/maize; O + V/M: oat + vetch/maize; O + V/M + C: oat + vetch/maize + cowpea; P + M: pigeon pea + maize; 0 N: 0 kg N ha^{-1} $year^{-1}$; 180 N: 180 kg N ha^{-1} $year^{-1}$.

3.3. Effect of cropping systems and N fertilization on CMI

According to results of CPI and labile C, the legume-based cropping systems showed higher CMI than O/M system, which is comprised essentially of gramineous species (Fig. 3). Blair and Crocker (2000), Diekow et al. (2005a) and Blair et al. (2006b) also reported increases in the CMI values when legumes were introduced in crop rotations, reinforcing the role of legumes on the addition of photosynthesized C to the soil. In the present study, the effect of summer legumes as cowpea and pigeon pea can be observed by the highest values of CMI.

Similarly to the legumes effect, the mineral N application increased the CMI by 12–46%, depending on the method of labile C measurement. Mineral fertilization promoted higher CMI values, possibly not only due to the enhancement in the formation of organic matter, as a consequence of the increase in annual C addition, but also due to changes in organic matter quality, such as C/N ratio, contents of lignin, cellulose, hemicellulose, proteins, and carbohydrates, thus modifying the lability of C to $KMnO_4$ oxidation (Tirol-Padre and Ladha, 2004). For this reason, addition of 180 kg N ha^{-1} in the treatments O/M and O + V/M increased relatively more the labile C assessed by chemical oxidation than by physical methods, which did not discriminate the possible qualitative differences.

3.4. The CMI and its relation to biological, chemical and physical attributes

In general, the CMI based on chemical oxidation at 60 mM $KMnO_4$ and physical fractionation showed high correlation with biological, chemical, and physical attributes of soil (Table 3). For approximately 50% of

Table 3
Correlation coefficients between carbon management index (CMI), as determined through oxidation with 60 mM $KMnO_4$ and physical fractionation (density and particle-size separation), and biological, chemical and physical attributes of a subtropical Acrisol subjected to no-till cropping system

Attribute	n	60 mM $KMnO_4$		Density		Particle-size	
		r	P	r	P	r	P
Mean corn yield (Mg ha^{-1})[a] 0 N	4	0.86	<0.14	0.94	<0.06	0.94	<0.06
Soil attributes							
Biological[b]							
Microbial biomass (mg $C\text{-}CO_2$ kg^{-1} soil)	3	0.72	<0.49	0.12	<0.92	0.21	<0.87
Microbial respiration (mg $C\text{-}CO_2$ kg^{-1} soil)	3	0.95	<0.21	0.94	<0.22	0.97	<0.17
β-Glucosidase (μg ρ-nitrofenol g^{-1} soil)	3	0.98	<0.12	0.88	<0.31	0.92	<0.26
Urease (μg $N\text{-}NH_4$ g^{-1} soil)	3	0.99	<0.08	0.85	<0.36	0.89	<0.30
Acid phosphatase (μg ρ-nitrofenol g^{-1} h^{-1})	3	0.90	<0.29	0.98	<0.14	0.99	<0.09
Amidase (μg $N\text{-}NH_4$ g^{-1} soil)	3	0.83	<0.37	0.99	<0.06	1.00	<0.01
Arilsulphatase (μg ρ-nitrofenol g $soil^{-1}$ h^{-1})	3	0.86	<0.34	0.99	<0.09	0.99	<0.04
Chemical							
Organic N (Mg ha^{-1})[c]	4	0.77	<0.23	0.92	<0.08	0.88	<0.12
CEC effective ($cmol_c$ kg^{-1} soil)[d,e]	4	0.76	<0.24	0.98	<0.02	0.98	<0.02
CEC at pH 7.0 ($cmol_c$ kg^{-1} soil)[d,e]	4	0.67	<0.33	0.99	<0.01	0.95	<0.05
Physical (aggregates)[f]							
MDW dry (mm)[g]	3	0.99	<0.09	0.85	<0.35	0.90	<0.29
MDW wet (mm)[g]	3	0.66	<0.54	0.99	<0.11	0.97	<0.16
Macroaggregates > 0.025 mm (%)	3	0.99	<0.09	0.86	<0.35	0.90	<0.29

[a] Compilation from annual historical data (not published).
[b] Schmitz (2003).
[c] Zanatta et al. (2003).
[d] Burle et al. (1997).
[e] Cation exchange capacity.
[f] Méndez (1996).
[g] MDW: mean diameter weight.

the attributes, these correlations were significant at $P \leq 0.20$, and for about 70% of the attributes these correlations were significant at $P \leq 0.30$.

The correlations between CMI and biological attributes, except for microbial biomass, are coherent because the higher the soil C pool and the C lability, the higher the availability of C and energy to microbial and faunal activity and this is a crucial point to soil quality. According to Dick et al. (1996), soils subjected to management systems aiming at promoting soil quality should have high biological activity, with high enzymes production and high potential for stabilizing and protecting such enzymes through interaction with organic colloids or protection in soil aggregates.

The high correlation between CMI and soil aggregation (mean $r = 0.88$) indicates the beneficial effects of the higher fluxes of energy and C on soil structure and thus on the self-organization of the soil system (Addiscott, 1995; Vezzani, 2001). Soil organic carbon and soil structure interact mutually. At the same time that the humified organic matter stabilizes domains and microaggregates and the particulate organic matter stabilizes macroaggregates (Tisdall and Oades, 1982), these same structural units promote the physical protection of organic matter against biological attacks, allowing its accumulation in soil (Golchin et al., 1997; Bayer et al., 2002b; Diekow et al., 2005b).

In general, it was also found close relation between CMI values and enzymatic activities (mean $r = 0.94$), as well as microbial respiration (mean $r = 0.95$). However, microbial biomass did not show a good relationship with CMI when it was calculated by using labile C from physical fractionation (mean $r = 0.17$), oppositely to the better relation obtained when it was used labile C from 60 mM $KMnO_4$ oxidation ($r = 0.72$). It is possible that the labile C present in the microbial biomass was assessed by oxidation, but it was not detectable (or detected in smaller portion) in the physical fractionation methods herein used. The microbial biomass is the main source of enzymes in the soil, and it is hypothesized that the apparent contradiction in the fact that CMI using physical fractions of labile C had very close relation with enzymatic activities but was not related to microbial biomass may be due to the different metabolic rate of microorganisms in the soil under the different cropping systems. It is important mentioning, however, that the evaluations of labile C in the present study were not carried out at the same period in which the biological, chemical, and physical characteristics were analyzed (Table 1), although all of them were performed using the same long-term experiment. Soil sampling for labile C was done in October, 2002, while sampling and analysis for the depicted biological properties were done in October, 2000.

The results of statistical significance need to be evaluated with caution because of the low number of points in the correlation (n). In spite of that, the high values of r allow to infer that the CMI had a close relation with soil biological, chemical, and physical attributes. These results reinforced the suitability of using labile C measured by one of the three methods (oxidation with 60 mM $KMnO_4$, density, or particle-size) for calculating the CMI and assessing the quality of soil management systems.

Since most of the discussed attributes are referred as soil quality indicators (Doran and Parkin, 1994; Vezzani, 2001; Conceição, 2006), it seems reasonable, therefore, to confirm the CMI as a reliable index to assess the capacity of management systems into promote soil quality (Blair et al., 1995; Diekow et al., 2005a). Therefore, it is possible to conclude that leguminous-based maize systems were the most suitable in promoting soil quality and food production, especially summer cover crops (P + M and O + V/M + C). This is coherent to the highest grain yield, biological activity, aggregate stability and nutrients cycling and retention in these systems (Table 1). On the other hand, the O/M system without N application was the less suitable in promoting soil quality, while the O + V/M (winter leguminous-based system) was ranked at intermediate suitability.

4. Conclusion

In studies aiming at determining the CMI, the labile C fraction can be obtained either through chemical oxidation with 60 mM $KMnO_4$ or through physical fractionation with density or particle-size separation. The conventional 333 mM $KMnO_4$, however, was not sensitive to different cropping systems and tended to overestimate the labile C fraction. The CMI appeared to be a sensitive index for assessing the quality of soil management systems as evidenced by its close correlation with physical, chemical, and biological soil attributes that serve as indicators of soil quality. The introduction of legume cover crops or application of fertilizer-N improved the capacity of the management system into promote soil quality in this subtropical Acrisol.

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