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Cover Crop Effects Increasing Carbon Storage in a Subtropical No-Till Sandy Acrisol

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Abstract: The long-term (8-year) effects of summer (*Mucuna* spp.) and winter cover crops (*Avena strigosa* + *Vicia sativa* and *Lolium multiflorum* + *Vicia sativa*) in maize-based cropping systems on the total, particulate, and mineral-associated soil carbon (C) stocks in the 0- to 0.2-m layer of a no-till South Brazilian Acrisol ($87\,\mathrm{g\,kg^{-1}}$ clay) were evaluated. Annual C sequestration rates and the carbon management index (CMI) were calculated taking a fallow/maize (F/M) system as reference. A greater average C sequestration rate ($0.68\ \mathrm{Mg\ ha^{-1}\,yr^{-1}}$) and greater C lability (particulate C/mineral-associated C) were observed in the soil under the *Mucuna* system, and this was related to the higher biomass input in comparison to the winter cover crop systems. These cropping system effects on amount and lability of soil C were summarized through the CMI. The results highlight the potential of C retention in soils under warm and humid subtropical climate through the adoption of high C input summer cover crops in no-till production systems aimed at further improvement in soil and environmental quality.

Keywords: Carbon management index, C stocks, legumes, no-till, particulate C

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INTRODUCTION

No-till can succeed as a soil management practice to improve soil organic carbon (C) contents if high-input cropping systems are simultaneously adopted. Legume species of high phytomass production are suitable options to achieve this target, especially when associated with grass species that uses the biologically fixed nitrogen (N_2) (Amado et al. 2006; Bayer et al. 2000a, 2000b; Boddey et al. 1997; Diekow et al. 2005a). Because of their characteristics acquired during the long evolutionary process in the sunny, warm, and moist conditions of tropics, most of the summer legumes have the capacity to produce high amounts of phytomass (Burle, Mielniczuk, and Focchi 1997).

No-till management is being widely adopted by Brazilian farmers in a cropland area of approximately 25 million hectares (FEBRAPDP 2007). The cultivation of summer legume cover crops would be a promising strategy to enhance soil organic C stocks (Barthes et al. 2004; Bayer et al. 2003, 2004; Whitbread, Jiri, and Maasdorp 2004), particularly in the no-till maize production systems. However, this is rarely done by maize producers, except by some smallholder farmers, because these legumes intercropped with maize can cause operational problems, particularly in fields with mechanized harvests. In spite of this problem, the potential of such legume species to increase C stock in no-till soils needs to be further investigated. In croplands where legume–maize intercropping is adopted, *Mucuna* (*Stizolobium* spp. or *Mucuna* spp.) is largely employed (Spagnollo et al. 2002). *Mucuna* has a prostrate habit of growth, a vigorous biomass accumulation, and a high efficiency of symbiotically N fixation, thus making it an excellent species for soil covering (Sodré-Filho et al. 2004).

Details about the influence of no-till cropping systems on the soil organic C dynamics can be obtained through the physical fractionation of soil samples (Amado et al. 2006; Bayer et al. 2001; Christensen 1992; Diekow et al. 2005b). One approach is to separate the total C pool in two dynamically distinct fractions: the particulate organic C fraction, constituted by plant or animal fragments that still exhibits remains of the cellular structure, and the mineral-associated C fraction, constituting a more humified organic matter that interacts with mineral surfaces, forming organomineral complexes. The particulate C is considered the labile fraction, and although it generally represents a small proportion of the total C stock, it is more sensitive to the effects of soil management changes than the mineral-associated C or the total organic C pools (Freixo et al. 2002; Janzen et al. 1992).

The effect of soil management systems on organic-matter dynamics can be evaluated by a single C management index (CMI), an index that assembles the effect of agricultural practices on stocks and lability of soil C. The CMI was originally proposed by Blair, Lefroy, and Lisle (1995), who considered the labile fraction as the one oxidized by potassium permanganate ($KMnO_4$). However, the CMI can also be calculated by considering the particulate C obtained through physical fractionation as the labile fraction (Diekow et al. 2005b; Vieira et al. 2007), because the particulate C fraction is related to the labile fraction of C oxidized by $KMnO_4$ (Skjemstad, Swift, and McGowan 2006; Vieira et al. 2007) and has a close relationship with soil chemical, physical, and biological attributes (Vieira et al. 2007).

This study is aimed at assessing the influence of summer and winter legume cover crops in maize-based cropping systems on the total, particulate, and mineral-associated soil C stocks in a sandy no-till Acrisol from the south of Brazil. The C sequestration rates and the CMI were evaluated for potential benefits of conservation tillage systems on environmental and soil quality.

MATERIALS AND METHODS

Field Experiment

The study was based on a long-term (8-year) experiment carried out in Santa Maria, Rio Grande do Sul, Brazil (29° 45′ S and 53° 42′ W). The soil is classified as a sandy loam Acrisol in the Food and Agriculture Organization of the United Nations scheme of classification, and the climate is humid subtropical (Cfa, Köppen) with year-round precipitation (1769 mm) and mean monthly temperatures ranging from 9.3 °C in June to 31.5 °C in January.

The experiment was established in 1991 in a randomized-block design with two replications. For this study, we used four cover crop treatments with no-till maize cultivation: (1) single maize cultivation (fallow/maize system—F/M), (2) oat (*Avena strigosa* Schreb.) + vetch (*Vicia sativa* L.), (3) ryegrass (*Lolium multiflorum* Lam.) + vetch preceding maize (O+V/M and R+V/M, respectively), and (4) *Mucuna* (*Stizolobium cinereum* Piper & Tracy) intercropped with maize (F/Mu+M). Data of annual C and N addition by the crops were taken from Amado et al. (2001).

Information about particle-size distribution and bulk density of the soil of the experimental area were assessed by the pipette method (Gee and Bauder 1986) and the soil core method (Blake and Hartge 1986), respectively, and results are provided in Table 1. Particle-size distribution analysis was performed in soil sampled randomly from the experimental field.

Soil Sampling and Physical Fractionation of Organic Matter

In October 1999, soil depths of 0–0.025, 0.025–0.05, 0.05–0.075, 0.075–0.10, 0.10–0.15, and 0.15–0.2 m were manually sampled with a spatula in a 10-cm × 50-cm area. Soil samples were air dried, crushed with a wood roll (<2 mm sieve), and stored in plastic pots. A 20-g subsample was submitted for physical fractionation. Soil was dispersed by horizontally shaking (60 cycles $\min^{-1}$) for 12 h in 70 mL sodium hexametaphosphate [$(NaPO_3)_6$] solution at 8.17 mM ($5\,g\,L^{-1}$). Afterward, the suspension was passed through a 50-µm mesh to separate the particulate C fraction (>50 µm) and oven dried (40 °C) according to adaptations of the procedure used by Cambardella and Elliot (1992).

The C content of the whole soil samples and particulate fractions were determined through the Walkley–Black rapid dichromate ($K_2Cr_2O_7$) oxidation method (Nelson and Sommers 1996), and the C stocks were calculated taking account the soil bulk density for the sampled soil layers (Table 1). The C content in the mineral-associated fraction was calculated by the difference between the C content in the whole soil and that in the particulate fraction.

Carbon Management Index

The CMI based on results from the physical fractionation is an adaptation of the original method proposed by Blair, Lefroy, and Lisle (1995). The CMI is constituted by the C pool index (CPI) and the lability index (LI):

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100$$

Table 1. Particle-size distribution (0–20 cm) and soil bulk density (0–5, 5–10, and 10–20 cm) of the soil layers as affected by cropping systems

System[a]	Particle-size distribution[b] ($g\,kg^{-1}$)			Soil bulk density ($Mg\,m^{-3}$)		
	Sand	Silt	Clay	0–5	5–10	10–20
F/M	660	253	87	1.44	1.49	1.45
O+V/M				1.52	1.72	1.58
R+V/M				1.56	1.59	1.64
F/Mu+M				1.46	1.68	1.61

[a] F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna.*
[b] Mean particle-size distribution in the soil of experimental area.

The CPI represents the change in the total C stock, whereas the LI represents the change in the C lability, both compared to a reference system:

$$\mathrm{CPI} = \frac{\text{total soil C stock in the treatment}}{\text{total soil C stock in reference}}$$

$$\mathrm{LI} = \frac{\text{lability in treatment}}{\text{lability in reference}}$$

The C lability (L) is given by

$$\mathrm{L} = \frac{\text{labile C}}{\text{nonlabile C}}$$

In this study, the particulate C was taken as the labile and the mineral-associated C as the nonlabile pool. The fallow/maize system was considered as the reference (CMI = 100).

Statistical Analysis

The significance ($P \leqslant 0.05$) of the effects of cover crops on the investigated variables was tested using the analysis of variance (ANOVA). The difference between means was evaluated by Tukey's test ($P \leqslant 0.05$).

RESULTS AND DISCUSSION

Carbon and Nitrogen Addition

The annual C addition by the aboveground part was 4.51 Mg ha^{-1} in the F/Mu+M system and lower additions were observed in the O+V/M (4.24 Mg ha^{-1}), R+V/M (3.76 Mg ha^{-1}), and F/M systems (2.78 Mg ha^{-1}) (Table 2). The annual N addition by cover crops varied from 20 to

Table 2. Mean annual additions of C and N by the aboveground of cover crops and or maize plants

System[a]	N addition,[b] cover crop(s) (kg ha^{-1})	Annual C addition[b] (Mg ha^{-1})		
		Cover crop(s)	Maize	Total
F/M	20	0.72	2.06	2.78
O+V/M	80	1.69	2.55	4.24
R+V/M	60	1.35	2.41	3.76
F/Mu+M	140	2.00	2.51	4.51

[a] F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna*
[b] Data from Amado et al. (2001).

$140\,\text{kg}\,\text{ha}^{-1}$, with the highest value being observed in the F/Mu+M system and the lowest in the F/M. In comparing vetch-based systems to *Mucuna*-based system, it becomes clear that this last summer legume cover crop has a greater capacity to promote C and N addition than does the winter legume cover crop, corroborating some results already observed in tropical and subtropical soils (Amado et al. 2001; Burle, Mielniczuk, and Focchi 1997; Sodré-Filho et al. 2004).

The differences in total C additions among the treatments are primarily attributed to variations in the cover crop C addition (0.72 Mg C ha^{-1} to 2.00 Mg C ha^{-1}), because the variations in maize C addition were relatively less substantial (2.06 Mg C ha^{-1} to 2.55 Mg C ha^{-1}) (Table 2). The F/M system had the least annual C addition (cover crop + maize), and this result is ascribed to the small biomass production of spontaneous winter plants, which grow during fallow period, and to possibly less N availability due to the lack of legume cover crop cultivation (Table 2).

The C addition by *Mucuna* cover crop observed in this study was slightly less than those noticed in other studies (Alvarenga et al. 1995; Sodré-Filho et al. 2004), and this is likely related to the low fertility of the sandy Acrisol on which the experiment was established. In spite of that, the higher C addition by *Mucuna* compared to the other cover crops evidences the great potential for biomass production of this summer legume species compared to the winter legume (vetch) and grasses species (oat and ryegrass) even at low fertility conditions as the soil herein evaluated. Moreover, the high biomass production of *Mucuna* associated with its prostrate habit of growth make this cover crop species an excellent alternative to soil cover and protection against the erosive effects of intensive rains that frequently occur in the south of Brazil.

The role of legume cover crops in contributing to soil C accumulation is probably not restricted only to supply N for higher biomass production of nonlegume crops. A further beneficial long-term effect of the N derived from legumes has been observed in comparison to the mineral N fertilizer–based maize cropping systems (Lovato et al. 2004; Zanatta 2007). The hypothesis is that while legume N is released at a relatively slow pace, synchronized to the maize N uptake process, the application of soluble fertilizer N may increase the inorganic N content in soil and trigger, at least in the short term before absorption by roots, a kind of priming effect that reduces the potential of C accumulation per unit of added N (Kuzyakov, Friedel, and Stahr 2000). Another explanation is that legumes per se accumulate C. This means that the legume N, even before contributing to C assimilation in maize plants, has already played a role in a C assimilation process (i.e., that of the legume). Carbon and N dynamics in soil are closely linked, and this highlights the importance of using legume cover crops when soil organic C accumulation is a goal.

Soil Organic Carbon Stocks

The soil subjected to F/Mu+M system for 8 years contained higher concentrations of total C, particulate C, and mineral associated C in the first two layers (0–0.025 and 0.025–0.05 m) than the soils subjected to the other systems (Table 3), and this effect was related to the annual C addition by aboveground crop residues (Bayer et al. 2000a; Burle, Mielniczuk, and Focchi 1997). This trend was extended to the concentrations of mineral-associated C and total C up to 15 cm deep (Table 3). The concentration of particulate C did not differ among systems below the 5-cm depth, which is consistent with the fact that in no-till soils most of the crop residues are deposited in these layers (Bayer et al. 2001, 2002).

The total, particulate, and mineral-associated C stocks in the 0- to 20-cm layer reflected the respective C concentrations in the two top layers (Table 3). The total C stock in the soil under F/Mu+M system (27.5 Mg C ha^{-1}) was significantly greater than the other cropping systems, which in average contained 22.7 Mg C ha^{-1}. In the particulate fraction, the C content decreased according to a gradient from F/Mu+M system to F/M

Table 3. Concentration and stocks of total, particulate, and mineral associated C as affected by cropping systems

System[a]	Soil layer (cm) ($g\,cm^{-3}$)						Total (0–20 cm), ($Mg\,ha^{-1}$)
	0–2.5	2.5–5.0	5.0–7.5	7.5–10	10–15	15–20	
Total C							
F/M	14.6 b[b]	11.2 b	11.1 ab	11.1 ab	10.1 b	10.0 ab	22.1 b
O+V/M	15.9 b	12.5 b	11.6 ab	12.8 a	10.3 b	9.9 ab	23.3 b
R+V/M	17.4 ab	11.9 b	10.0 b	9.2 b	9.9 b	11.4 a	22.8 b
F/Mu+M	22.0 a	16.1 a	13.2 a	12.4 a	12.1 a	11.0 a	27.5 a
Particulate C							
F/M	2.4 b	0.8 b	0.5 ns	0.4 ns	0.4 ns	0.3 ns	1.4 b
O+V/M	3.2 ab	0.7 b	0.5	0.4	0.4	0.3	1.6 b
R+V/M	3.8 ab	1.0 b	0.7	0.5	0.5	0.2	1.8 ab
F/Mu+M	5.6 a	2.1 a	0.6	0.3	0.2	0.2	2.4 a
Mineral- associated C							
F/M	12.2 b	10.4 b	10.6 ab	10.7 ab	9.7 b	9.7 ab	20.7 b
O+V/M	12.7 b	11.8 b	11.1 ab	12.4 a	9.9 b	9.6 ab	21.7 b
R+V/M	13.6 b	10.9 b	9.3 b	8.7 b	9.4 b	11.2 a	21.0 b
F/Mu+M	16.4 a	14.0 a	12.6 a	12.1 a	11.9 a	10.8 a	25.1 a

[a] F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna*.

[b] Values followed by the same letter in columns do not differ significantly (Tukey's test, $P < 0.05$).

system, in such a way that differences among treatments were not as clear as in total and mineral-associated fractions. However, particulate C stocks in the 0- to 20-cm soil layer of F/M and O+V/M were significantly less than that in F/Mu+M. In the mineral-associated SOM, the F/Mu+M system has a stock of 25.1 Mg C ha^{-1}, corresponding to 91% of the total C stock, whereas the other systems have on average 21.0 Mg C ha^{-1}, nearly 93% of the total stock (Table 3).

Taking the F/M system as the baseline, the annual C sequestration rate in the 0- to 20-cm layer during these 8 years ranged from an average value of 0.11 Mg C $ha^{-1} yr^{-1}$ in O+V/M and R+V/M to 0.68 Mg C $ha^{-1} yr^{-1}$ in the F/Mu+M system (Figure 1). This C sequestration rate for F/Mu+M system is slightly higher than the average C sequestration rate of 0.48 Mg C $ha^{-1} yr^{-1}$ estimated by Bayer et al. (2006) for several no-till cropping systems in the subtropical region of Brazil. This capacity of F/Mu+M system in promoting C sequestration was also observed in a tropical African Ultisol, where C sequestration rate was 1.3 Mg C $ha^{-1} yr^{-1}$ (Barthes et al. 2004). These results unambiguously prove the potential of no-till *Mucuna* maize cropping systems in promoting C sequestration in tropical soils and thus contribute to the mitigation of elevated carbon dioxide levels in the atmosphere. Similar behavior was observed for other summer cover crops, which have a high capacity for

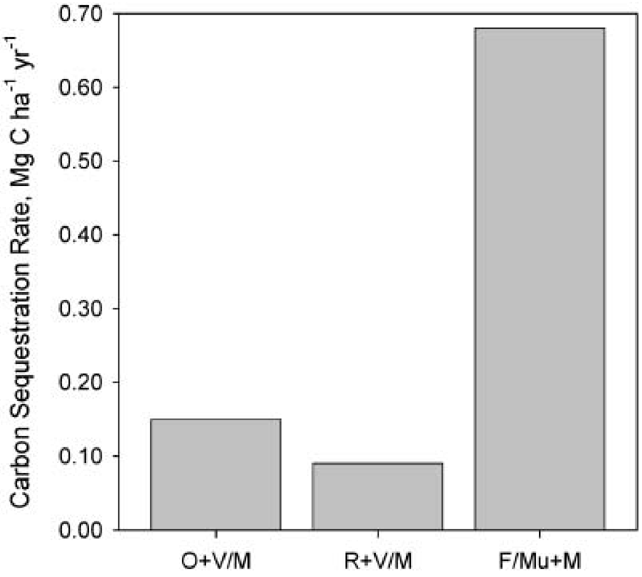

Figure 1. Annual carbon sequestration rates in the 0- to 20-cm layer as affected by cropping systems, taking the fallow/maize system as reference. F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna.*

biomass production in low fertility tropical and subtropical soils (Bayer et al. 2003; Spagnollo et al. 2002).

Cropping systems also increased the lability of organic C as evidenced by the increase of the particulate C / mineral-associated C ratio in soil surface layers (0–0.05 m). This increase on C lability was due to the crop residues deposition on the soils that were incorporated in particulate soil organic matter (SOM) more rapidly than in mineral-associated SOM fraction (Figure 2). Particulate SOM has a faster turnover time in comparison to the mineral-associated SOM fraction and thus is more sensitive to soil management practices than the humic fraction associated with soil minerals. This increase of soil C lability in no-tillage soils compared to conventional tilled soils has been verified frequently (Bayer et al. 2002) and also in no-tillage systems with greater crop residue addition than cropping systems with less crop residues addition (Bayer et al. 2001).

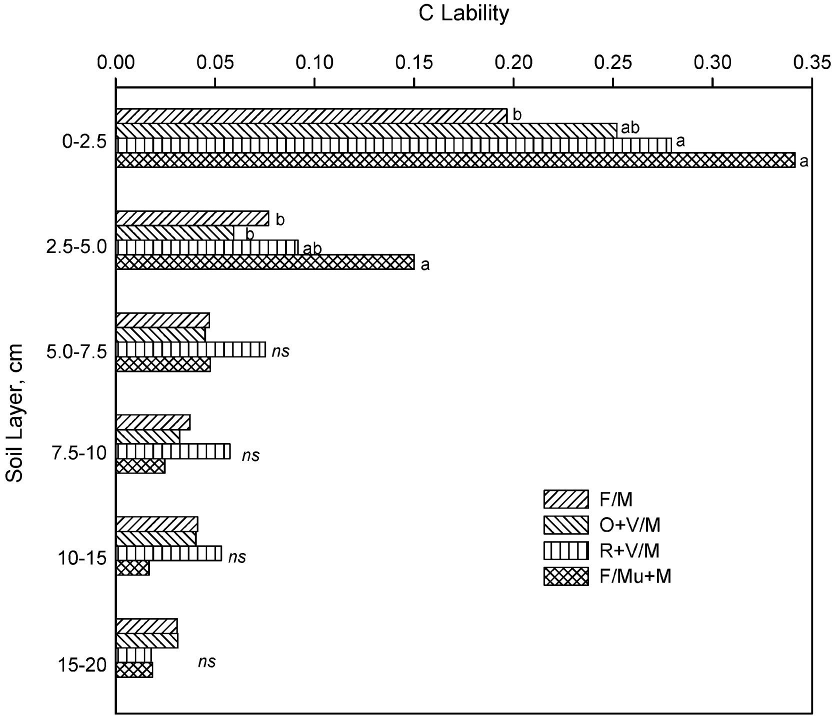

Figure 2. Carbon lability in different soil layers as affected by cropping systems. Letters on bars refer to the significance of the differences within each layer, according to Tukey's test ($P < 0.05$). F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna*.

The effect of management on C lability is linked to its effect on biological, physical, and chemical soil quality (Vezzani 2001). Soil management systems that lead to accumulation of greater quantities of labile C forms contribute to greater energy and C fluxes through the activity of heterotrophic soil microorganisms that improve soil aggregate stabilization, stable macropores, nutrient mineralization, accumulation of physically protected SOM into soil aggregates, increase of cation exchange capacity derived from SOM, and inactivation of toxic Al by formation of complexes with SOM, among others. Therefore, in addition to the quantitative component of SOM, C lability evaluations are crucial in studies related to the effect of soil management on SOM dynamics and soil quality. In this sense, the CMI is a suitable tool as proposed by Blair, Lefroy, and Lisle (1995) using chemical oxidation of SOM and adapted by Diekow et al. (2005b) and Vieira et al. (2007) for using physical fractionation that allows integration of the effect of soil management on stocks and lability of soil organic C into a single index, highlighting their effects (Blair et al. 2006; Dieckow et al. 2005b; Vieira et al. 2007).

Carbon Management Index

The highest CMI in the F/Mu+M system (168) (Table 4) confirmed the capacity of this system in improving SOM status, emphasizing summer legume-based systems as efficient for improving SOM in tropical and subtropical soils in comparison to the reference system (F/M, CMI = 100) or grass plus winter legume–based systems (O+V/M, CMI = 109, and R+V/M, CMI = 128). In other long-term field experiments conducted at the same region, the summer legume-based systems had a

Table 4. Carbon pool index (CPI), lability (L), lability index (LI), and carbon management index (CMI) in the 0- to 20-cm layer as affected by cropping systems

System[a]	CPI[b]		L[c]		LI[d]		CMI[e]	
F/M	1.00	b[f]	0.07	b	1.00	b	100	b
O+V/M	1.06	b	0.07	b	1.03	b	109	b
R+V/M	1.03	b	0.09	a	1.23	ab	127	ab
F/Mu+M	1.25	a	0.09	a	1.35	a	168	a

[a] F = fallow; M = maize; O = oat; V = vetch; R = ryegrass; Mu = *mucuna*.

[b] CPI = total soil C stock in the treatment / total soil C stock in F/M.

[c] L = labile C / nonlabile C = particulate C stock / mineral-associated C stock.

[d] LI = L in the treatment / L in the reference treatment (F/M).

[e] CMI = CPI × LI × 100.

[f] Values followed by the same letter in columns do not differ significantly (Tukey's test, $P < 0.05$).

significantly higher CMI than the grass plus winter legume based–systems, and these results were related to the amount of crop biomass added annually to the soil (Diekow et al. 2005b; Vieira et al. 2007).

CONCLUSIONS

The cropping systems based on summer legume cover crops have a greater potential for C addition than cropping systems based on winter legume plus grasses species. The cultivation of summer legumes in no-till cropping systems improves the SOM status by increasing either the stocks or lability of organic C, and these effects may be adequately summarized by the CMI. *Mucuna* has a remarkable potential to increase soil C stocks and promote C sequestration in subtropical no-till soils; thus it is advisable to include this species in management systems aimed at enhancing soil and environmental quality.

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