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CARBON SEQUESTRATION RATES IN NO-TILLAGE SOILS UNDER INTENSIVE CROPPING SYSTEMS IN TROPICAL AGROECOZONES

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Abstract. The amount and quality of crop residues added through cropping systems with no-tillage (NT) soils is the key component to increase carbon (C) sequestration in agricultural land and mitigate carbon dioxide (CO_2) to the atmosphere. To compare conventional (CT) and NT systems associated with cropping systems, the soil organic carbon (SOC) stock and balance were assessed in four tropical sites - three in Cerrado region in Brazil, and one in the highlands of central Madagascar. The NT cropping systems in the sites were organized in randomized plots with three replicates and compared with CT under a monoculture. The mean C sequestration rate for NT was 1.66 Mg ha^{-1} yr^{-1} (from 0.59 to 2.60 Mg ha^{-1} yr^{-1}). The regression fitted between C cumulative input and SOC sequestered showed a close relationship, and 14.7 percent of each additional Mg C input per hectare was sequestered as SOC. The C sequestration potential with adoption of intensive cropping system under NT can increase estimated decay rate by the first order differential equation increased with the mean annual temperature and decreased when the C cumulative input increased.

Key words: No-tillage, cropping system, SOC balance, SOC sequestration rates

Abbreviations: CT, conventional tillage; NT, no-tillage; SOC, soil organic carbon; SOM, soil organic matter

Resumen. La cantidad y calidad de los residuos de cosecha añadidos a los suelos en los sistemas de cultivo de "no laboreo" (NT) es el componente clave del incremento del secuestro de C en los suelos de cultivo y de la reducción del CO_2 atmosférico. Para comparar sistemas agrícolas convencionales (CT) y de "no laboreo" se evaluaron los contenidos de C del suelo (SOC) y el balance de C orgánico en 4 zonas tropicales. 3 en la región del cerrado brasileño (Mato Grosso) y 1 en las zonas montañosas del centro de Madagascar. Los sistemas NT fueron organizados en parcelas al azar con 3 repeticiones comparándolos con sistemas CT en las mismas condiciones climáticas y de monocultivo. La tasa media de secuestro de C para NT fue de 1,66Mg ha^{-1} a^{-1} (de 0,59 a 2,60 Mg ha^{-1} a^{-1}). El C acumulado en los residuos y el C orgánico secuestrado en el suelo presentan una clara relación y el 14,7% del aporte de C en los residuos fue secuestrado como C orgánico del suelo.

INTRODUCTION.

The recent attention to global warming have motivated the scientific community to search for efficient soil management and cropping systems to convert CO_2 from the air into SOC (Lal, 2007). Agricultural practices can render a soil either a sink or a source of atmospheric carbon dioxide (CO_2), with direct influence on the greenhouse effect (Lugo and Brown, 1993; Lal *et al*., 1995). Several papers have demonstrated C sequestration in NT soils is associated with crop rotation in tropical ecoregions (Bayer *et al*., 2000 b; Sá *et al*., 2001; Six *et al*., 2002 a; Sisti *et al*., 2004; Diekow *et al*., 2005; Bernoux *et al*., 2006; Bayer *et al*., 2006; Cerri *et al*., 2007). Some authors have suggested that the most important factors to increase CO_2 mitigation and the SOC stock are the amount and quality of the crop residues added, whatever the climate effect on the decomposition rates and whatever the characteristics of soil mineralogy and soil type (Paustian *et al*., 1997; Sá *et al*., 2001; Six *et al*. 2002 b; Kong, *et al*., 2005; Bayer *et al*., 2006; Tristram & Six, 2007). Studies have shown C storage is directly linked with C from crop residue input (Paustian *et al*., 1997; Sá *et al*., 2001; Kong, *et al*., 2005; Séguy *et al*., 2006; Bernoux *et al*., 2006; Bayer *et al*., 2006; Cerri *et al*., 2007). The C sequestration rates vary widely for tropical zones (- 0.03 to 1.7 Mg ha^{-1} yr^{-1}) and could be increased knowing the potential of biomass production of those agroecozones (Corbeels *et al*. 2006; Bayer *et al*., 2006; Bernoux *et al*., 2006; Cerri *et al*., 2007). Cropping systems with high biomass input to maintain the soil permanently covered imitate the conditions found with natural vegetation and develop the stratification of the SOC pools similar to the natural vegetation (Sá and Lal, 2008). They provide a continuous mass and an energy flow that release organic compounds to stimulate the soil biota biodiversity and the soil organic matter (SOM) changes (Uphoff *et al*., 2006; Six *et al*., 2006; Séguy *et al*., 2006). This concept is based on the multifunctional action of each species in the cropping system interacting with the soil attributes and stimulating the biological activity in a systemic interdependence of the soil structure and the soil organic matter pools (Uphoff *et al*., 2006; Séguy *et al*., 2006).

The objectives of this study were (i) to determine C storage and sequestration rates affected by tillage management associated with intensive cropping systems in tropical agroecozones and (ii) to estimate the SOC decay rate for each site by a model based on a first-order differential equation, and (iii) the C sequestration potential with adoption of the intensive cropping system for those agroecozones.

MATERIAL AND METHODS

Site Description

Field experiments were conducted at four sites in tropical climate zones. These places were chosen to combine the databases of experiments on long-term tillage systems in tropical areas that were developed by the research program in cropping systems by the Centre de Coopération Internationale en Recherche Agronomique pour le Développement-CIRAD. In addition, these sites provided an opportunity to assess the impact of high biomass input on SOC dynamics under no-tillage.

The sites involved three locations in Mato Grosso State (Brazil) and one site in the highlands of central Madagascar. The natural vegetation before conversion to agriculture in Mato Grosso was extensive woodland-savanna with a pronounced dry season. The Cerrado region spreads across 2,031,990 km^2 of the central Brazilian Plateau and is the second largest of Brazil's major biomes, after Amazonia. In Madagascar, before conversion to agriculture the natural vegetation was tropical forest and the site is located in the transition from subtropical and tropical climate. The details about each site (location, climate, soil type, and chemical analyses and particle size class) are presented in table 1.

Experimental Design, Tillage, and Cropping Systems

In Mato Grosso, the sites are in three tropical regions: Sinop (Snp), Lucas do Rio Verde (LRV), and Campo Verde (CV). The experiments were set up to compare the standard tillage management for each region (e.g., monoculture of soybean, cotton, or maize under conventional tillage) with systems under no-tillage and crop rotation with high addition of carbon. The experimental design in all sites was arranged in a field scale plot comprising a randomized plot with the local standard management, no-tillage, and cropping systems in 100- to 100-m dimensions for each plot with three replicates. In Sinop (Snp) the experiment started in 1999 with three tillage systems involving a soybean monoculture under conventional tillage and two no-tillage treatments associated with an intensive cropping system. The soil samples were taken in 1999 and 2001. In Lucas do Rio Verde (LRV) the experiment started in 1996 with four tillage systems involving a soybean monoculture under conventional tillage and three no-tillage treatments associated with intensive cropping system. The soil samples were taken in 1996 and 2001. In Campo Verde (CV) the experiment started in 2001 with four tillage systems involving a cotton monoculture under conventional tillage and three no-tillage treatments associated with intensive cropping systems. The soil samples were taken in 2001 and 2005.

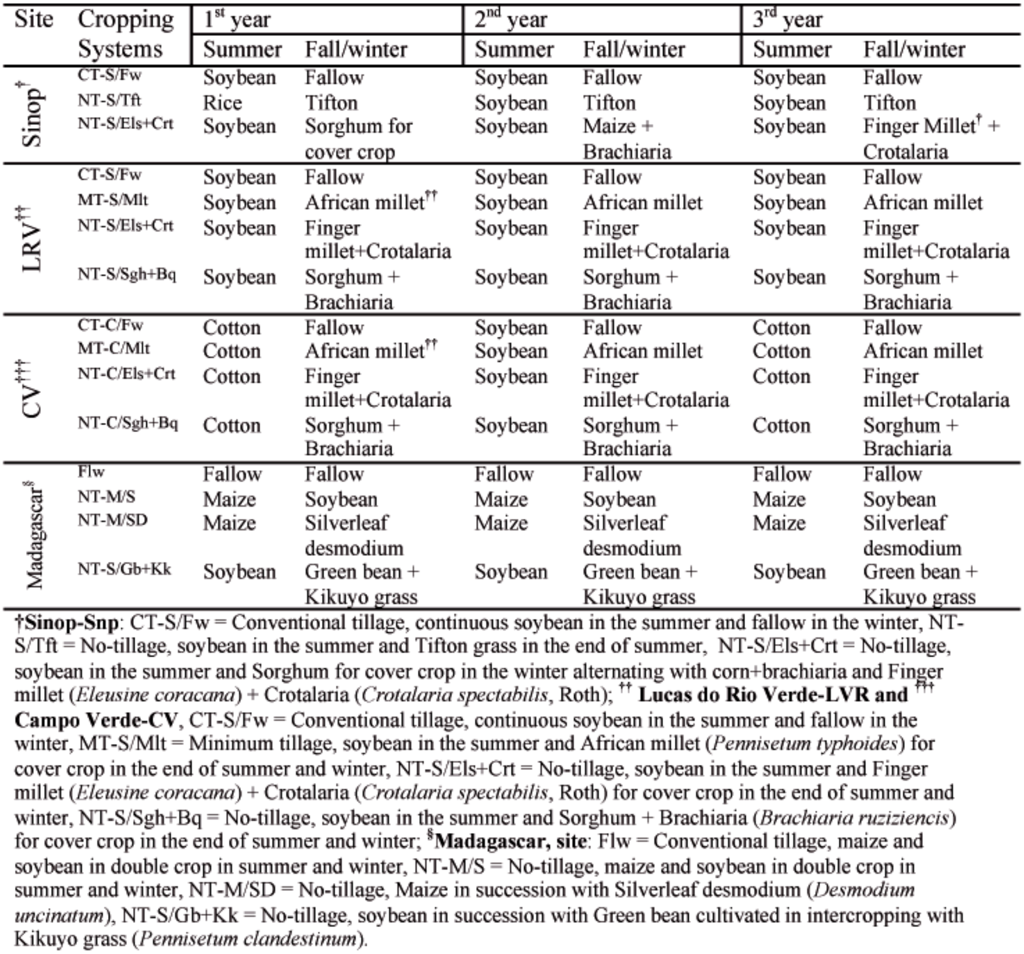
TABLE 1. Descriptions of the study sites: location, climate, soil type, soil texture, soil parent material and chemical analyses.

Country		Brazil			Madagascar
State		Mato Grosso-MT	Mato Grosso-MT	Mato Grosso-MT	Antananarivo
City		Campo Verde	Lucas do Rio Verde	Sinop	Antisrabe
Site		Mourão Farm	Progresso Farm	Agronorte Farm	Andranomanelatra Farm
Location	Latitude	15° 29’ S	12° 59’ S	11° 42’ S	19° 46’ S
	Longitude	54° 54’ W	55° 57’ W	55° 27’ W	47° 07’ E
	Altitude	697 m	433 m	401 m	1600 m
Climate	Caracteristics	Megathermic Summer wet, Winter dry, hot	Megathermic Summer wet, Winter dry, hot	Megathermic Summer Wet, Winter short dry	Mesothermic Summer wet, Winter dry, cold
	Type[††]	Aw	Aw	Am	Cfa
	MATmax[‡]	28.9°C	31.8°C	32.40°C	23.2°C
	MATmin[‡‡]	15.2°C	18.3°C	19.3°C	10.4°C
	MAT[‡‡‡]	22.0°C	23,9°C	24.1°C	16.5°C
	MAR[‡‡‡‡]	1480 mm	1881 mm	2171 mm	1350 mm
Soil	Type	Dark Red Latosol, Oxisol, Typic Haplustox	Red Yellow Latosol, Oxisol, Typic Haplustox	Red Yellow Latosol, Oxisol, Typic Haplustox	Dark Red Inceptisol, Andic Dystrustept
	Texture	Sandy Clay (Clay, 340 g kg^{-1})	Clayey (Clay, 420 g kg^{-1})	Clayey (Clay, 650 g kg^{-1})	Clayey (Clay, 730 g kg^{-1})
	Parent Material	Sedimentary, Sandstone Lateritic	Sedimentary, Sandstone lateritic	Sedimentary, lateritic	Quaternary, Volcano-lacustre deposit
Chemical analyses [§]					
pH (H$_2$O, 1:1)		5.3	5.1	5.1	4.3
P (Mehlich 1, mg kg^{-1})		8.2	9.1	5.8	38[a]
K (Mehlich 1, mg kg^{-1})		43	59	32	39
Ca (KCl 1M, cmol$_c$ L^{-1})		3.1	3.0	3.97	0.13
Mg (KCl 1M, cmol$_c$ L^{-1})		1.1	1.6	1.45	0.15
Al (KCl 1M, cmol$_c$ L^{-1})		0.12	0.18	0.15	nd

[††] Climate classification according Koeppen; [‡] MATmax = Mean Annual Temperature maximum; [‡‡] MATmin = Mean Annual Temperature minimum; [‡‡‡] MAT = Mean Annual Temperature; [‡‡‡‡] MAR = Mean Annual Rainfall; [§] Average of all replicates; [a] Olsen method

In Madagascar (Mdg) the experiment started in 1998 with four tillage systems involving a maize monoculture under conventional tillage and no-tillage treatments with cropping system. The soil samples were taken in 1998 and 2005. The detailed description of the treatments (tillage and cropping systems) for each site is presented in table 2.

TABLE 2. Tillage and cropping system description for each site, and for three year period



Site	Cropping Systems	1st year		2nd year		3rd year	
		Summer	Fall/winter	Summer	Fall/winter	Summer	Fall/winter
Sinop†	CT-S/Fw	Soybean	Fallow	Soybean	Fallow	Soybean	Fallow
	NT-S/Tft	Rice	Tifton	Soybean	Tifton	Soybean	Tifton
	NT-S/Els+Crt	Soybean	Sorghum for cover crop	Soybean	Maize + Brachiaria	Soybean	Finger Millet† + Crotalaria
LRV††	CT-S/Fw	Soybean	Fallow	Soybean	Fallow	Soybean	Fallow
	MT-S/Mlt	Soybean	African millet††	Soybean	African millet	Soybean	African millet
	NT-S/Els+Crt	Soybean	Finger millet+Crotalaria	Soybean	Finger millet+Crotalaria	Soybean	Finger millet+Crotalaria
	NT-S/Sgh+Bq	Soybean	Sorghum + Brachiaria	Soybean	Sorghum + Brachiaria	Soybean	Sorghum + Brachiaria
CV†††	CT-C/Fw	Cotton	Fallow	Soybean	Fallow	Cotton	Fallow
	MT-C/Mlt	Cotton	African millet††	Soybean	African millet	Cotton	African millet
	NT-C/Els+Crt	Cotton	Finger millet+Crotalaria	Soybean	Finger millet+Crotalaria	Cotton	Finger millet+Crotalaria
	NT-C/Sgh+Bq	Cotton	Sorghum + Brachiaria	Soybean	Sorghum + Brachiaria	Cotton	Sorghum + Brachiaria
Madagascar§	Flw	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow
	NT-M/S	Maize	Soybean	Maize	Soybean	Maize	Soybean
	NT-M/SD	Maize	Silverleaf desmodium	Maize	Silverleaf desmodium	Maize	Silverleaf desmodium
	NT-S/Gb+Kk	Soybean	Green bean + Kikuyo grass	Soybean	Green bean + Kikuyo grass	Soybean	Green bean + Kikuyo grass

†**Sinop-Snp**: CT-S/Fw = Conventional tillage, continuous soybean in the summer and fallow in the winter, NT-S/Tft = No-tillage, soybean in the summer and Tifton grass in the end of summer, NT-S/Els+Crt = No-tillage, soybean in the summer and Sorghum for cover crop in the winter alternating with corn+brachiaria and Finger millet (*Eleusine coracana*) + Crotalaria (*Crotalaria spectabilis*, Roth); †† **Lucas do Rio Verde-LVR and** ††† **Campo Verde-CV**, CT-S/Fw = Conventional tillage, continuous soybean in the summer and fallow in the winter, MT-S/Mlt = Minimum tillage, soybean in the summer and African millet (*Pennisetum typhoides*) for cover crop in the end of summer and winter, NT-S/Els+Crt = No-tillage, soybean in the summer and Finger millet (*Eleusine coracana*) + Crotalaria (*Crotalaria spectabilis*, Roth) for cover crop in the end of summer and winter, NT-S/Sgh+Bq = No-tillage, soybean in the summer and Sorghum + Brachiaria (*Brachiaria ruziziencis*) for cover crop in the end of summer and winter; §**Madagascar, site**: Flw = Conventional tillage, maize and soybean in double crop in summer and winter, NT-M/S = No-tillage, maize and soybean in double crop in summer and winter, NT-M/SD = No-tillage, Maize in succession with Silverleaf desmodium (*Desmodium uncinatum*), NT-S/Gb+Kk = No-tillage, soybean in succession with Green bean cultivated in intercropping with Kikuyo grass (*Pennisetum clandestinum*).

Biomass Input – Aboveground and Belowground

The aboveground and belowground dry biomass was obtained using the grain yield/shoot ratio and root/shoot ratio for crops and was 0.83 and 0.16 for cotton, 1.65 and 0.26 for sorghum, 1.0 and 0.38 for brachiaria, 1.0 and 0.36 for finger millet (Eleusine coracana), 1.0 and 0.27 for African millet (Pennisetum typhoides), 1.0 and 0.34 for Tifton, and 1.21and 0.22 for rice. Total biomass was calculated as the sum of shoot and root biomass.

Carbon Analyses in a Whole Soil Layer

Soil samples from each depth were air-dried and ground to pass through a 2-mm sieve. A portion of each sample was ground to pass through a 150-μm opening size sieve to determine the SOC contents using a Carbon analyzer - LECO, model CR-412 .

Soil Sampling, SOC Stock Calculations, and Correction for Soil Compaction

Undisturbed samples to measure the soil bulk density (ρb) for each layer were obtained by the core method (Blake and Hartge, 1986), using a core sampler with a 5.0-cm diameter and 5.0-cm deep for the 5- to 10-cm, 10- to 20-cm, and 20- to 40-cm depths. The core was taken in the middle of the layer for the 10- to 20-cm and 20- to 40-cm depth. Cores of 5.0-cm diameter by 2.5-cm deep were used for 0- to 2.5-cm and 2.5- to 5-cm depths. Disturbed samples in the surface layers (e.g., 0- to 2.5-cm and 2.5- to 5-cm) were obtained by digging small pits with dimensions of 20- x 20- x 2.5-cm and 20- x 20- x 5-cm. In these samples were opened three pits for each replicate for a composed sample and the soil were taken after a carefully cleaning of the surface litter. The SOC pool, expressed as Mg ha-1 for each layer, were converted to a volumetric scale by multiplying C concentrations by the thickness of the layer and the soil's bulk density. Differences in soil bulk density among various tillage treatments were factored into the assessment of C storage as recommended by Ellert and Bettany (1995).

Particle Size Fractionation in the Soil Samples

In the Sinop sites the particle size fractionation was done according to Sá *et al.* (2001). A 40-g oven-dried subsample sieved through a 2-mm sieve, from each treatment and each depth, was wetted overnight at 14oC in 200 mL of deionized H_2O. Aggregate disruption was accomplished by a rotary shaking at a frequency of 50 rpm with three agate balls (10-mm diameter) for 4 hours. The soil suspension was wet sieved through a 210-μm opening size sieve to obtain the 210- to 2000-μm fraction. The fractions remaining on the sieve were washed with deionized water, and the washing was added to the suspension passed through a 210-μm sieve. The disrupted soil suspension using a probe-type ultrasonic was passed through 53-μm sieves to obtain the < 53-μm fraction.

Statistical Analyses

The data were statistically analyzed with an analysis of variance (ANOVA), and means were compared using the least significant difference test (LSD, P = 0.05). Regressions were used to evaluate associations between the SOC sequestered and the cumulative C input by cropping systems. To incorporate the results of the other experiments, we used a simple model adapted of Izaurralde (2001) to estimate the decay rate. This model is based on two assumptions: (i) a portion k1 (e.g., isohumic coefficient) of the carbon added through the crop residues (dry matter of the crop residues in Mg ha-1) after the harvest is transformed into soil organic carbon (Mg ha-1); and (ii) a first order differential equation is supposed to govern the decomposition of this SOC, considered as a single compartment. This SOC then depletes exponentially at the annual rate k2 (yr-1). As harvests occur about every 6 months, the model proposed is as follows:

SOC(t+0.5) = SOC(t) exp(-0.5k2t) + k1 DM(t)

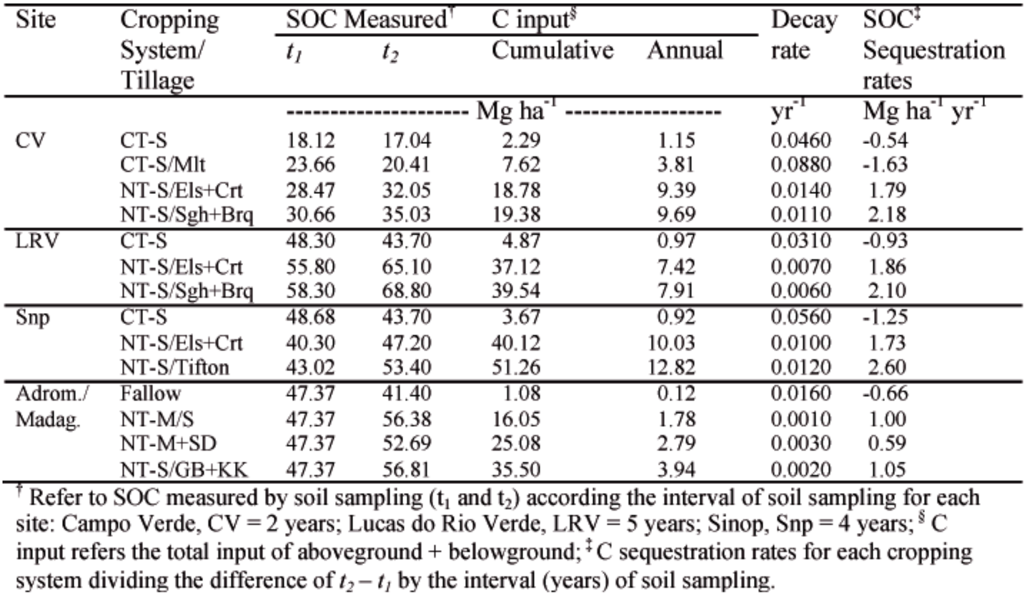
where t is the time from an arbitrary origin (yr).

The portion k1 of crop residues converted into soil organic carbon was taken from previous studies (Sá *et al*., 2001) in similar areas. The annual decay rate k2 was estimated from available data using proc NLIN of SAS/Stat (SAS Institute, 2004). A 95% confidence interval for k2 was calculated for the experiments. The asterisks * were used in the graphics to represent statistical differences among the means at (LSD, P = 0.05). The vertical bars in the graphics represent the standard deviation.

RESULTS AND DISCUSSION

Soil Organic Carbon Stock Affected by Carbon Input

TABLE 3. Components of C Model to calculate the SOC balance for 0- to 20-cm depth for experimental sites



Site	Cropping System/ Tillage	SOC Measured†		C input§		Decay rate	SOC‡ Sequestration rates
		t_1	t_2	Cumulative	Annual		
		Mg ha^{-1}				yr^{-1}	Mg ha^{-1} yr^{-1}
CV	CT-S	18.12	17.04	2.29	1.15	0.0460	-0.54
	CT-S/Mlt	23.66	20.41	7.62	3.81	0.0880	-1.63
	NT-S/Els+Crt	28.47	32.05	18.78	9.39	0.0140	1.79
	NT-S/Sgh+Brq	30.66	35.03	19.38	9.69	0.0110	2.18
LRV	CT-S	48.30	43.70	4.87	0.97	0.0310	-0.93
	NT-S/Els+Crt	55.80	65.10	37.12	7.42	0.0070	1.86
	NT-S/Sgh+Brq	58.30	68.80	39.54	7.91	0.0060	2.10
Snp	CT-S	48.68	43.70	3.67	0.92	0.0560	-1.25
	NT-S/Els+Crt	40.30	47.20	40.12	10.03	0.0100	1.73
	NT-S/Tifton	43.02	53.40	51.26	12.82	0.0120	2.60
Adrom./ Madag.	Fallow	47.37	41.40	1.08	0.12	0.0160	-0.66
	NT-M/S	47.37	56.38	16.05	1.78	0.0010	1.00
	NT-M+SD	47.37	52.69	25.08	2.79	0.0030	0.59
	NT-S/GB+KK	47.37	56.81	35.50	3.94	0.0020	1.05

† Refer to SOC measured by soil sampling (t_1 and t_2) according the interval of soil sampling for each site: Campo Verde, CV = 2 years; Lucas do Rio Verde, LRV = 5 years; Sinop, Snp = 4 years; § C input refers the total input of aboveground + belowground; ‡ C sequestration rates for each cropping system dividing the difference of $t_2 - t_1$ by the interval (years) of soil sampling.

In contrast, in the CT and MT treatments under continuous soybean the SOC losses ranged from 0.54 to 1.63 Mg ha^{-1} yr^{-1}, respectively. The regression between cumulative C input (x, axis) for no-tillage treatments and cumulative SOC sequestered (y, axis) showed a close linear relationship (ySOC sequestered = 0.147 C input + 2.97, R2 = 0.45, $P < 0.05$) and for each extra Mg of C, 14.7 % was transformed for SOC. Our data are corroborated by the equation (ySOC sequestered = 0.0754 C input + 2.3851, R2 = 0.70, P = 0.003) fitted by Kong *et al*. (2005) and support the arguments that C accumulation is a linear function by C input until the C-saturation point is reached (Six *et al*., 2002 b; Tristram and Six, 2007). Meanwhile, our slope was 1.95 times greater than that of Kong *et al*. (2005). In our data (Table 3), only the CT treatments had negative C-sequestration rates and, in contrast, the C-sequestration rate in no-tillage treatments was greater than the highest value (+ 0.56 Mg ha-1) in the data of Kong *et al*. (2005). Furthermore, the soil texture in our experimental sites (Table 1) is mostly clayey and can sequester more C (Feller *et al*., 1999; Six *et al*., 2000; Six et al., 2002 b). In tropical areas under high precipitation in the summer and dry periods in the winter, the challenge is to develop cropping systems to produce high amounts of biomass rapidly (Séguy et al., 2006). In addition, the quality of crop residues added is based mainly on intercrops combining grass and legume (e.g., Crotalaria) or grass alternating with legume (e.g., Soybean). On the other hand, the cropping system with high biomass input provides residual mulch maintaining the soil permanently covered all year and resulting in greater protection of the macroaggregates through optimum long-term soil moisture, and stimulating a rapid C-turnover by microbial biomass. In addition, continuously covered soil provides a micro environment due the remaining residues, which drives formation of new macroaggregates as a layer and protects the young SOC. The annual C-sequestration rates for the CV site ranged from – 1.63 to + 2.18 Mg ha^{-1} and showed contrasted values. Although its C input was greater than 5 Mg ha^{-1} yr^{-1} for MT-S/Mlt (e.g., double cropping alternating soybean and

"African millet" - Pennisetum typhoideum), SOC losses were observed. The C loss may have occurred by tilling twice with 60-cm narrow disk to break the clods and spread the seeds, followed by chisel plow. The mixture of legume and grass residues enriched the soil surface and stimulated the microbial biomass to enhance the C turnover, with direct release as CO_2 to the atmosphere. In contrast, the more C-crop residues added the more SOC increased in the NT-S/Sgh+Brq. Although the total C-sequestered and the annual rate for the NT-S/Els+Crt treatment was 18% smaller than NT-S/Sgh+Brq at the CV site, no such difference was observed at the LRV and Snp sites. At the LRV and Snp sites under Els+Crt cover crop, C-sequestered tended to be enhanced, although the C input was similar. In warmer climate with extended rainy season the legume dry biomass production was higher than at the CV site, and the N contribution in mixed grass residues can increase the efficiency of C-accumulation, which corroborates findings by Kong *et al.* (2005). The SOC increase by legumes in the LRV and Snp rainy areas was 0.57 and 0.8 Mg ha^{-1}, respectively. The legume association with C4 species in tropical and rainy summer areas can improve the crop residue quality and increase the C sequestration (Boddey *et al.*, 2006 a, and 2006 b). At the CV, LRV, and Snp sites in the case of no-tillage associated with cropping systems having C input greater than 6.2 Mg ha^{-1} yr^{-1} (e.g., 13.93 Mg ha^{-1} yr^{-1} of crop residues, 43.8 % of C content), 19 to 28 % of crop residues remained on the soil.

The SOC stock in the particle size fractions at the CV site can explain why the high biomass input changes the C pools rapidly. In the 0- to 10-cm depth the SOC stock for NT-C/Sgh+Bq was significantly greater in the coarse 210- to 2000-µm fraction, in the 53- to 210-µm fraction and < 53-µm fractions than MT-C/Mlt and CT-C/FW (Fig. 1).

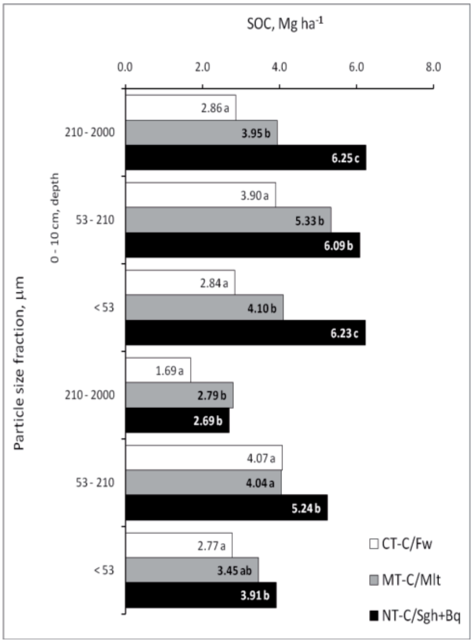


FIGURE 1. SOC stock in the particle size fractions for 0- to 10-cm and 10- to 20-cm depth affected by tillage and cropping systems in Mato Grosso, Campo Verde (CV) site. Within a bar for each particle size fraction the numbers followed with the same letter are not significantly different to the LSD0.05

From our point of view, the high aboveground input had a greater impact than belowground in this layer because of high protection of the aboveground in the soil surface. However, in the 10- to 20- cm depth was substantial and significant difference for the 53- to 210-μm compared with other fractions, indicating that the main effect can be caused by the root system (Wander et al., 2000). Introducing grass species with legume may be the best way to improve C sequestration on deep layers and to provide a C flux as a biological pump to support the labile and the stable C fractions. In addition, the N source from the legume can be the key point to control the C sequestration in cropping systems with crop residues with high C:N ratio. Our visual assessment on soil profile (e.g., digging profiles of 100-cm x 100-cm {surface area} x 100-cm deep) verified the presence of roots below 100-cm at the end of the dry season. This is evidence that intercrops (grass and legume mixed or intercrop) are more efficient to develop deep roots and to use the water storage in deeper layers mainly in the dry season.(Fig. 2).

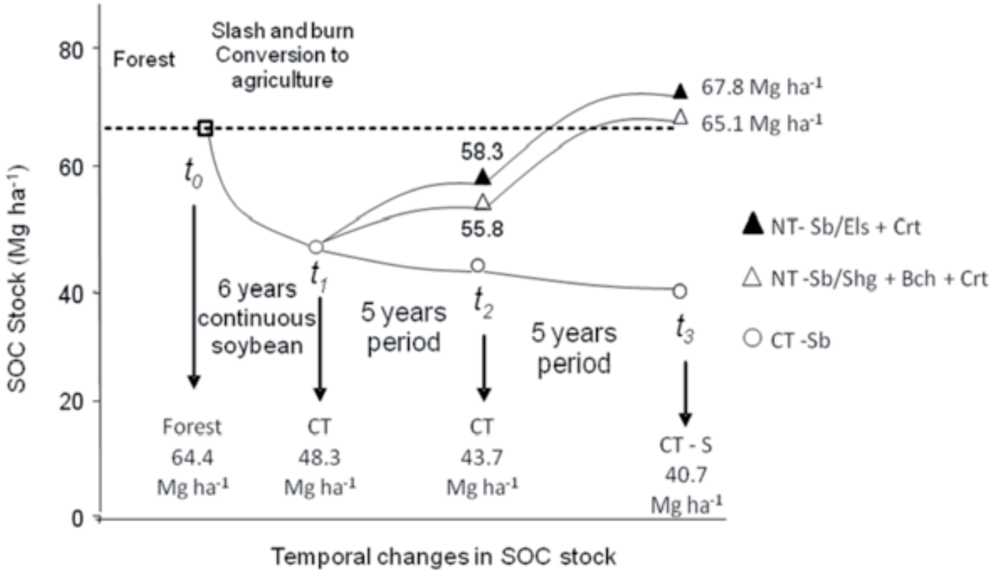


FIGURE 2. Temporal changes in SOC stock after 16 years period of slash and burn with three management systems in a tropical area (Lucas do Rio Verde, MT).

In highland plots of Madagascar the C-sequestered and the rate were lower than in the other tropical sites, with a cumulative C input lesser than at the other sites. In addition a high ratio was observed between annual input and annual C sequestered in the NT-S/GB+kk treatment. In this case two legumes (soybean and green bean) that are associated with Kikuyu grass (e.g., Pennisetum clandestinum) can have the same root development as at Brazilian sites. These results suggest that for tropical areas it is crucial to drive cropping systems with the objective of maintaining the soil covered all year to sequester C.

C-Sequestration Rates in the Cropping Systems

The model used by Izaurralde et al. (2001) to estimate the decay rate and the C balance in long-term experiments was adapted for a different interval between t1 and t2 at the cropping system sites.

The aggregation process is implemented under simultaneous actions and changes of each pool are thus related with the biological pump activity, which means a linkage between C input, microbial activity, and C turnover (Rodney *et al*., 2004; Six et al., 2006). Our results showed considerable enhancement of C in the coarse fraction of the surface layer (e.g., 0- to 5-cm or 0- to 10-cm depth). However, the highest C content and C stock were observed in the 53- to 210-µm microaggregates. The challenge for the farmers in tropical areas is to find a profitable cropping system that can "close the window" of the dry season with the soil covered to maintain aggregate stability in favor of plant growth and C-sequestration. Such a cropping system may combine a cash crop during the summer period associated with single crops or intercrops to take advantage of the water use (Hobbs, 2007). The decay rate average calculated by the model for all treatments was 0.0216 (Table 3), which is 10.3 times greater than that of Izaurralde et al. (2001) for temperate zones (average of C2 and C3 = 0.0021). According to Lal and Logan (1995) the decay rate in tropical and subtropical zones is 5 to 10 times greater than in temperate zones.

The average annual SOC sequestered rate for no-tillage soils in the tropical sites it ranged from 0.59 to 2.60 Mg C ha^{-1} yr^{1} in this study, and it is superior with the recent data for tropical areas reported by Bernoux et al. (2006), Bayer et al. (2006), and Cerri et al. (2007). The highest rates cited by those authors were reached in no-tillage soils under intensive cropping system with high biomass input and supporting our data

Potential of CO_2 mitigation with intensive cropping system under no-tillage

The area estimated with annual crops in the Brazilian Cerrado region is close to 22.71 Mha (Resck *et al.* 2008), and today, only 5 to 10% of the farmers adopted intensive cropping systems in no-tillage soils. If we consider the rates for C sequestration reported by Bayer *et al* (2006) and Cerri *et al.* (2007) ranging from 0.34 to 0.81 Mg C ha-1 yr-1 for this region, and the potential of C-sequestration can be around 7.72 to 18.39 Tg yr^{-1}, if a 100% of the cerrado crop area is under NT. However, if we consider an increase of 20 to 40% with intensive cropping system at the C-sequestration rate of 2.17 Mg ha^{-1} yr^{1} (average of the best treatments of this study) the SOC sequestration potential can arise to 18.48 Tg yr^{-1} to 30.74 Tg yr^{-1}.

SUMMARY AND CONCLUSIONS

The C pools and SOC stock changes were strongly associated with C input rate in no-tillage soils and the C losses associated with conventional treatments agree with previous findings. In the tropical sites C increased in the upper and deeper layers, indicating the importance of the root system of the grass plants when developed in deeper layers during the dry season. These findings demonstrate the importance of introducing species of plants with high biomass input and with high adaptation capacity in adverse environments. Thus it is crucial in tropical areas to develop cropping systems with high biomass input able to reach environmental and economic sustainability.

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