Original Research

Management Impacts on Soil Organic Matter of Tropical Soils

Gustavo S.A. Castro, Carlos A.C. Crusciol, Juliano C. Calonego, Ciro A. Rosolem*

Increased soil organic matter (SOM) improves the cation exchange capacity of tropical weathered soils, and liming is required to achieve high yields in these soils. Despite a decrease in SOM in the short term, liming may increase SOM with time by improving cation chemical bonds with soil colloids. Soil C may also be increased in high dry matter input cropping systems. We evaluated C changes in a Typic Rhodudalf as affected by four production systems with increasing residue inputs, with or without limestone or silicate. Soil use intensification by increasing the number of species in rotation as well as acidity remediation resulted in higher plant residue production. Introducing a green manure or a second crop in the system increased plant residue by 89% over fallow, but when a forage crop was used, plant residues more than doubled. Soil acidity amelioration increased plant residue deposition by 21% over the control. The introduction of a forage crop increased labile SOM and C contents in the particulate fraction, and lime or silicate application led to increases in the more stable SOM fraction. High amounts of plant residues (>70 Mg ha^{-1} in 5 yr) are effective in raising soil labile C, but the alleviation of soil acidity results in increased soil stable C irrespective of crop rotations in tropical weathered soils, and in this case plant residue deposition can be lower. Lime and silicate are equally effective in alleviating soil acidity and increasing soil C, probably due to the formation of cation bridges with soil colloids.

Abbreviations: MOC, mineral-associated organic carbon; NT, no-till; OM, organic matter; POC, particulate organic carbon; SOM, soil organic matter; TOC, total organic carbon.

The introduction of a forage into cropping systems under a tropical climate is important to increase soil particulate C, but more stable C is increased only when soil acidity is alleviated.

G.S.A. Castro, Brazilian Agricultural Research Corporation (EMBRAPA), Juscelino Kubitschek Road, km 5, No. 2600 P.O. Box 10, 68903-419, Macapá, State of Amapá, Brazil; C.A.C. Crusciol and C.A. Rosolem, São Paulo State University (UNESP), College of Agricultural Science, Dep. of Crop Science, José Barbosa de Barros Road, 1780, P.O. Box 237, 18603-970, Botucatu, State of São Paulo, Brazil; and J.C. Calonego, Center of Agricultural Sciences (UNOESTE), 19067-175, Rodovia Raposo Tavares, Km 572, 19067-175, Presidente Prudente, State of São Paul, Brazil. *Corresponding author (rosolem@fca.unesp.br).

Vadose Zone J.
doi:10.2136/vzj2014.07.0093
Received 18 July 2014.
Accepted 1 Oct. 2014.

Soil organic matter (SOM) is an indicator of soil quality and affects soil physical, chemical, and biological characteristics. No-till (NT) management can increase SOM, both through constant addition of plant residues on the soil surface and through a decrease in its decomposition rate (de Souza Nunes et al., 2011). Positive results in SOM accumulation under NT systems are related to a decrease in soil C emissions to the atmosphere (Bayer et al., 2009), a decrease in soil C lost via surface runoff (Larsen et al., 2014), and an increase in soil C as a result of crop rotations (Conceição et al., 2013). An important effect to be emphasized is the possibility of recovering lost SOC fractions by adopting high biomass-C inputs (>7 Mg ha^{-1}) in cropping systems under NT management (Tivet et al., 2013), but the impact of NT management on SOC is soil and site specific (Christopher et al., 2009; Mishra et al., 2010). However, most of the research done so far has compared cropping systems at different sites, with weak experimental control, and Ogle et al. (2014) suggested that the agricultural research on this topic should have more experimental control.

Most weathered tropical soils have low organic matter (OM) content. Furthermore, high temperatures and moisture in part of the year result in fast decomposition of plant residues incorporated in the soil or maintained on the surface (Bolliger et al., 2006). In addition, irregular rainfall and a dry winter hinder C additions because the growth of cover crops is impaired and the amount of plant residues produced in the off-season is low. Therefore, the choice of cover crops is paramount for the sustainability of NT systems in tropical regions by adding biomass C and protecting the soil. The system sustainability and productivity may be also increased because a high and diversified input of biomass C can increase the resilience of soil C pools (Tivet et al., 2013).

Most Oxisols have medium to high acidity, which limits plant growth as a result of Al toxicity and Ca and P deficiency. Hence, agricultural use of acidic soils requires acidity alleviation to neutralize toxic elements such as Al and supply Ca and Mg. In Brazil, the material most used for soil acidity alleviation is limestone; however, Ca silicate and Mg silicate were also shown to be suitable substitutes, with the advantage of supplying Si and having a faster reaction in the soil profile. Under NT management, surface application of both lime and silicate is recommended (Castro and Crusciol, 2013). Furthermore, the lime reaction in soil results in free CO_2 being released to the atmosphere. Mineralization of lime carbonates has been suggested as one of the major sources of CO_2 emission from acid soils during agricultural liming (Dumale et al., 2011). Although soil acidity alleviation accelerates SOM decomposition (Yao et al., 2009) by increasing microbial activity, there is evidence that soil C can be increased in the long term due to better edaphic conditions (Briedis et al., 2012) favoring crop development (Grière et al., 2005). In addition, the application of lime or silicate on the surface without soil turnover allows the maintenance of soil aggregates and prevents SOM decomposition (Caires et al., 2006).

Soil amendments such as lime and silicate may also have an indirect effect on soil physical properties because they favor plant growth and increase SOM contents and microbial activity, which assist in soil aggregation (Grière et al., 2005). However, as the analyses of SOM do not always detect soil changes caused by management systems, it is interesting to analyze soil total organic C (TOC) pools, which are more sensitive to soil management and better indicators of this dynamic (Dou et al., 2008). The C contained in the different soil fractions, separated by size, is one of the best indicators of the degree of protection of SOM and its susceptibility to microbial degradation (Balabane and Plante, 2004).

Altering the crop rotation can influence soil C stocks by changing the quantity and quality of organic matter inputs (Govaerts et al., 2009), and a high (>7 Mg ha^{-1}), diversified input of biomass C in intensive NT systems resulted in higher C resilience (Tivet et al., 2013). The addition of lime or silicate to alleviate soil acidity also adds Ca and Mg, cations needed to bind SOM to soil colloids (Muneer and Oades, 1989). The interaction of crop rotations and soil acidity alleviation on SOM are not known. We hypothesized that a crop rotation with high and diversified biomass-C inputs and soil acidity alleviation with lime or silicate would result in increased SOM by modifying the chemical and physical characteristics of the profile. Therefore, the aim of this study was to evaluate the changes in SOM amount and quality in the profile of a Typic Rhodudalf as affected by crop rotations with different dry matter inputs and surface application of lime or silicate for 5 yr.

Methodology

Site Characteristics

The experiment was set up in October 2006 in Botucatu, SP, Brazil, 48°25′ W, 22°48′ S, at an altitude of 770 m. The soil is a clay Typic Rhodudalf (Soil Survey Staff, 2006) with 60 to 79% kaolinite and 13 to 20% gibbsite. The predominant climate is highland tropical, with dry winters and wet, rainy summers. Monthly mean values of rainfall and temperature during the experiment are shown in Fig. 1. The area had been under NT for 4 yr, with a soybean [*Glycine max* (L.) Merr.]–black oat (*Avena strigosa* Schreb.) rotation. In July 2006, before the beginning of the experiment, soil samples were collected and analyzed for selected chemical (van Raij et al., 2001) and physical characteristics (de Camargo et al., 2009) (Table 1).

Experiment Design

Treatments consisted of four production systems, with different species cropped as monocrops each year in the off-seasons of the cash crops from 2007 to 2011 (Table 2) according to environmental conditions in each year. In the first system, called *forage crop*, ruzi grass [*Urochloa ruziziensis* (R. Germ. & C.M. Evrard) Crins] was used in each off-season. In the second system, called *second crop*, common oat (*Avena sativa* L.), common bean (*Phaseolus vulgaris* L.), castor bean (*Ricinus communis* L.), sorghum grain [*Sorghum bicolor* (L.) Moench], and crambe (*Crambe abyssinica* Hochst. ex R.E. Fr.) were grown. In the third system, called *cover crops*, pearl millet (*Pennisetum glaucum* L.), lupin (*Lupinus albus* L.), pigeon pea [*Cajanus cajan* (L.) Huth], and sunn hemp (*Crotalaria juncea* L.) were cropped. Finally, the fourth system was *fallow*, i.e., without cover crops in the off-season. These cropping systems comprised the main plots, and lime, silicate, or a control were the subplots for a total of 12 treatments with eight replications. Plots were 5.4 m wide and 30 m long, while the subplots were 5.4 m wide and 10 m long. One row on each side of the subplots and 1.0 m at both ends were discarded as borders. Details on crops, planting, harvests, and crop management are shown in Table 3.

Lime and silicate rates were calculated to raise the soil base saturation to 70%. In October 2006, before planting the first crop, 3.8 Mg ha^{-1} of limestone (360 g kg^{-1} CaO and 120 g kg^{-1} MgO, effective $CaCO_3$ equivalent [ECC] of 90%), and 4.1 Mg ha^{-1} of Ca-Mg silicate (340 g kg^{-1} CaO and 100 g kg^{-1} MgO, ECC 10%; and 220 g kg^{-1} SiO_2, ECC 80%) were applied to the corresponding plots.

Plant and Soil Sampling and Analyses

Dry matter yields of the second crop, cover crops, and the summer crop were determined at full flowering. Three subsamples were randomly taken from each subplot using a wooden square (0.25 by 0.25 m). In the other treatments (fallow and forage crop), samples were taken before planting the summer crop in the following crop year. The plant material collected was dried to constant weight in a forced-air oven at 65°C. Soil samples were collected after the

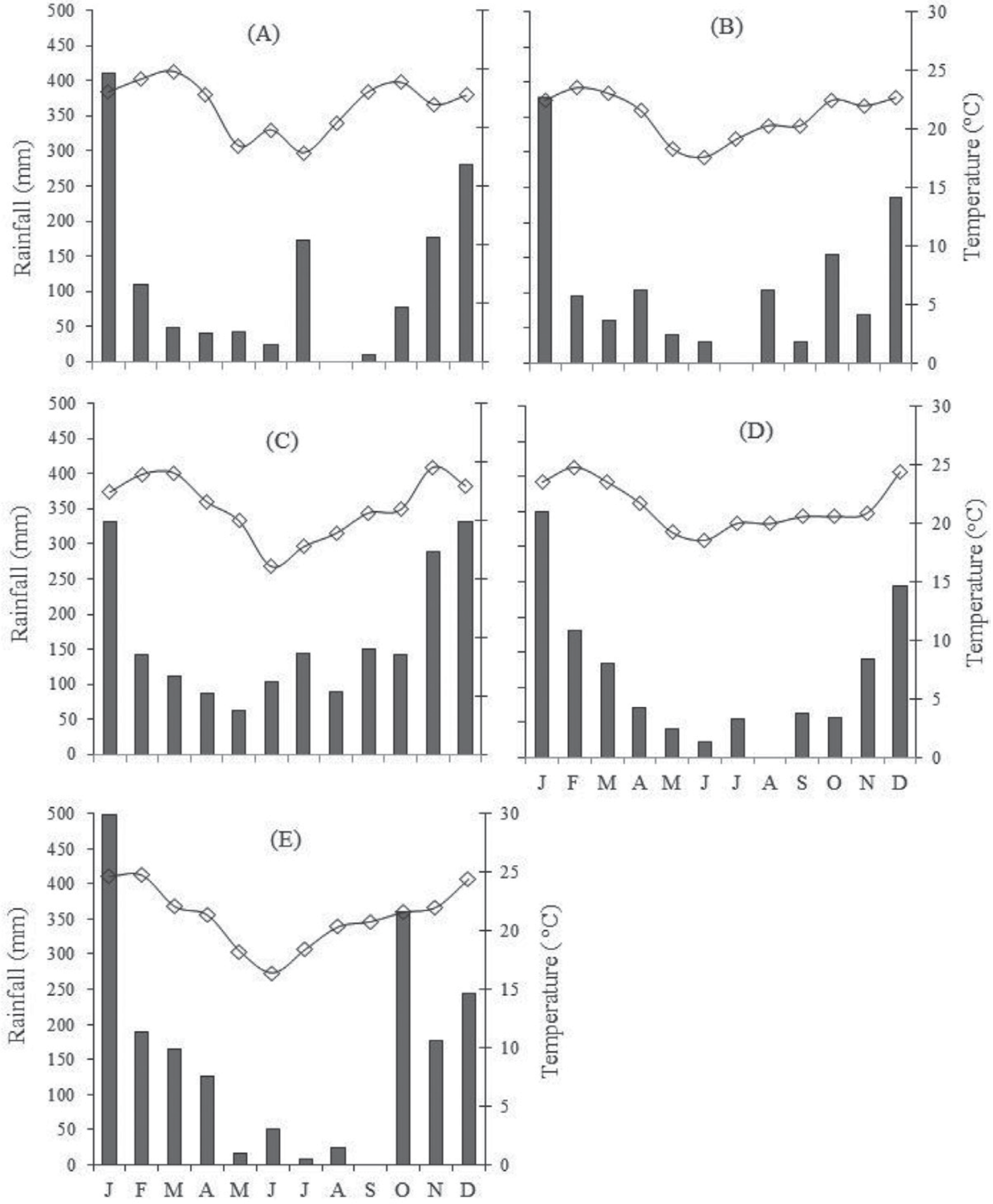

Fig. 1. Rainfall (bars) and average temperatures (lines) recorded during the experiment in (A) 2007, (B) 2008, (C) 2009, (D) 2010, and (E) 2011.

second crop of the third year, i.e., in October 2011 from the 0- to 0.05-, 0.05- to 0.10-, and 0.10- to 0.20-m soil layers using a soil core probe. These soil depths were chosen because differences in soil C were observed only down to 0.20 m after 6 yr (Franzluebbers and Stuedemann, 2013). Four subsamples were taken at random from each subplot and combined into one composite. Soil samples were air dried, ground, passed through a 2-mm sieve, and then analyzed for TOC and total N using dry combustion in a CHN-S elemental analyzer (LECO TruSpec). Soil organic matter was fractionated as proposed by Cambardella and Elliott (1992). In short, 20 g of soil (air-dried fine soil) were placed in 200-mL plastic cups with lids, and 80 mL of sodium hexametaphosphate was added (5 g L^{-1}). The samples were then placed in a horizontal shaker for 15 h. The suspension was passed through a 0.053-mm sieve, and the material retained in the sieve was dried to constant weight at 50°C. Dry matter was determined, the material was ground in a porcelain mortar, and organic C was determined by dry combustion. This was considered the particulate organic C (POC). The

Table 1. Selected chemical and physical properties in the 0–0.20 m soil layer setting up the experiment

Soil attribute	Value
Resin-extractable P, $\mathrm{mg\,L^{-1}}$ †	3.6
Organic matter, $\mathrm{g\,L^{-1}}$†	18
pH ($CaCl_2$) †	4.2
K, $\mathrm{mmol_c\,L^{-1}}$†	0.7
Ca, $\mathrm{mmol_c\,L^{-1}}$†	12
Mg, $\mathrm{mmol_c\,L^{-1}}$†	6
H + Al, $\mathrm{mmol_c\,L^{-1}}$†	54
Al, $\mathrm{mmol_c\,L^{-1}}$†	4
Si, $\mathrm{mg\,L^{-1}}$†	6.2
Base saturation, %	25
Sand, $\mathrm{g\,kg^{-1}}$‡	469
Clay, $\mathrm{g\,kg^{-1}}$‡	440
Silt, $\mathrm{g\,kg^{-1}}$‡	91
Weighted mean diameter, mm‡	2.9
Mean geometric diameter, mm‡	2.8
Aggregate stability index, %‡	99
Soil bulk density, $\mathrm{Mg\,m^{-3}}$‡	1.40
Total porosity, $\mathrm{m^3m^{-3}}$‡	0.39
Microporosity, $\mathrm{m^3m^{-3}}$‡	0.32
Macroporosity, $\mathrm{m^3m^{-3}}$‡	0.07

† Analyzed according to van Raij et al. (2001).
‡ Analyzed according to Camargo et al. (2009).

Table 2. Schema of crop rotations in Systems I, II, III, and IV from 2006 to 2011.

Season	System I (forage crop)	System II (second crop)	System III (cover crops)	System IV (fallow)
	2006			
Off-season	–	–	–	–
Crop season	soybean	soybean	soybean	soybean
	2007			
Off-season	ruzi grass	common oat	pearl millet	fallow
Crop season	maize	maize	maize	maize
	2008			
Off-season	ruzi grass	common bean	pigeon pea	fallow
Crop season	rice	rice	rice	rice
	2009			
Off-season	ruzi grass	castor bean	sunn hemp	fallow
Crop season	soybean	soybean	soybean	soybean
	2010			
Off-season	ruzi grass	grain sorghum	pearl millet	fallow
Crop season	maize	maize	maize	maize
	2011			
Off-season	ruzi grass	crambe	lupine bean	fallow
Crop season	–	–	–	–

mineral-associated organic C (MOC) was calculated by the difference between TOC and POC. Soil C lability was determined as the POC/MOC ratio (Bayer et al., 2009).

Statistical Analysis

The experimental design was a split plot in randomized complete blocks with eight replications. The cropping systems were the main plots, and lime, silicate, and the control were the subplots. Results were analyzed using ANOVA. All statistical analyses were performed using the SAS/STAT software package (SAS Institute, 2000). Means were compared using the least significant difference (LSD, $p < 0.05$).

Results

There was no significant interaction of the production systems with soil acidity alleviation (Table 4). Soil acidity alleviation resulted in increased dry matter production, which was proportional to the soil use intensity and highest in the system where a forage crop was present (Table 5). Lime and silicate application had no effect on total soil N, but fallow in the off-season resulted in higher total N contents in the 0.10- to 0.20-m layer compared with the second crop and cover crops treatments (Table 6). This effect was not observed in the uppermost soil layers. However, both lime and silicate application led to greater TOC contents in the upper 0.10-m soil layer compared with the control, with no effect of the cropping system. The introduction of a forage crop in the system increased POC down to 0.10 m in the soil profile. Soil acidity remediation increased POC in the 0.05- to 0.10-m layer. Mineral-associated C was increased in the 0- to 0.05-m soil layer by soil acidity alleviation (Table 6).

With regard to the soil C/N ratio, there was a difference only in the 0- to 0.05-m layer as a result of soil acidity remediation. The use of limestone or silicate increased the C/N ratio in this layer (Table 7). The POC/MOC ratio was increased with soil use intensity (Table 7).

Discussion

As expected, cropping systems resulted in a wide variation in the amount of straw produced and left on the soil surface (Table 5). Nitrogen inputs were different in each cropping system due to the introduction of legumes such as pigeon pea; however, an expected increase in soil N was not observed (Table 6). An explanation for this result is that under NT, a major part of the N in the system is retained in plant residues, as the rate of N recycling to the soil is slow, depending on the mineralization rate of the straw (Rosolem et al., 2010). Besides, a higher N demand by plants grown in the off-season was probably compensated by the mineralization of the greater amount of residues remaining on the soil surface in each season. An increase in soil N in the layer from 0.10 to 0.20 m under fallow was

Table 3. Cultivar, planting date, row spacing, planting density, and date of harvest or management of the species used in crop rotations from 2006 to 2011.

Crop	Cultivar	Sowing date	Spacing between rows	Sowing density	Date of harvest or management
			m		
Soybean	Embrapa 48	29 Nov. 2006	0.45	22 plants m^{-1}	3 Apr. 2007
	CD 202	30 Nov. 2009		18 plants m^{-1}	29 Mar. 2010
Pearl millet	BRS 1501	10 Apr. 2007	0.45	25 kg ha^{-1}	30 May 2007, 4 July 2007
	ADR 500	30 Mar. 2010		15 kg ha^{-1}	24 May 2010, 3 July 2010
Common oat	IAC 7	10 Apr. 2007	0.45	133 seeds m^{-2}	30 July 2007
Ruzi grass	*Urochloa ruziziensis*	10 Apr. 2007	0.45	2.5 kg ha^{-1}	1 Dec. 2007
		5 Apr. 2008			25 Oct. 2008
		10 Apr. 2009			28 Nov. 2009
		30 Mar. 2010			10 Nov. 2010
		22 Apr. 2011			1 Nov. 2011
Maize	hybrid 2B570	2 Dec. 2007	0.45	3 seeds m^{-1}	1 Apr. 2008
	hybrid 2B433	18 Nov. 2010			21 Mar. 2011
Common bean	Pérola	5 Apr. 2008	0.45	18 seeds m^{-1}	29 June 2008
Pigeon pea	IAPAR 43	5 Apr. 2008	0.45	20 seeds m^{-1}	1 July 2008
Rice	IAC 202	29 Oct. 2008	0.45	200 seeds m^{-2}	3 Apr. 2009
Castor bean	IAC 2028	10 Apr. 2009	0.45	3 seeds m^{-1}	01 Oct. 2009
Sunn hemp	IAC-KR1	10 Apr. 2009	0.45	25 kg ha^{-1}	19 July 2009
Grain sorghum	hybrid AG-1040	30 Mar. 2010	0.45	10 kg ha^{-1}	29 July 2010
Crambe	FMS Brilhate	22 Apr. 2011	0.34	15 kg ha^{-1}	8 Aug. 2011
Lupine bean	Comum	22 Apr. 2011	0.34	50 kg ha^{-1}	8 Aug. 2011

observed, probably as a result of a lower extraction of this nutrient in this layer, corroborating results obtained by Nascente et al. (2013).

The increases in TOC due to soil acidity alleviation were, on average, 17 and 11% in the 0- to 0.05- and 0.05- to 0.10-m layers, respectively, compared with the control (Table 6). Franzluebbers and Stuedemann (2013) analyzed C stocks of the soil profile down to 1.5 m and observed differences between soil management systems only in the soil layer from 0 to 0.20 m. The TOC increase in the uppermost soil layers may be due to the greater input of dry matter through plant residues in treatments with limestone or silicate (Table 5) because the maintenance of residues on the soil surface accumulates more C in stable macroaggregates and increases soil organic C (Tian et al., 2014). Briedis et al. (2012) also observed an increase in TOC contents to the depth of 20 cm after 8 yr of surface application of limestone, and the greatest proportional increase in TOC occurred in the labile fraction of the SOM. According to them, greater accumulation of TOC in the uppermost soil layer is common under NT and is due to the continual contribution of residues without soil turnover.

Although the different production systems did not affect the contents and stocks of TOC in the soil, the forage crop treatment increased POC down to 0.20 m (Table 6). The more labile soil C fractions are the first to be affected by crop rotations in the short term and are more efficiently increased by grasses than by legumes (Garcia et al., 2013), which is consistent with our results. Furthermore, a differential input of plant residues by roots was observed in an integrated crop–livestock system compared with systems without grasses, both on the surface and in the soil profile (Salton et al., 2011). The increase in POC is related to the increase in aggregate stability, which was shown to be possible to achieve by growing cover crops for 50 to 60 d during the spring for three consecutive years (Calonego and Rosolem, 2008; Garcia et al., 2013). Castro et al. (2011) observed that soil aggregation is greater when ruzi grass is used as a cover crop under NT.

In the present experiment, treatments including a forage crop and/or soil acidity amelioration resulted in the highest POC contents, corroborating the results of Garcia et al. (2013), who obtained lower TOC and POC contents up to the 0.10-m depth in areas lying fallow in the spring on a very similar soil. This positive relationship between dry matter input and POC arises because this fraction of SOM represents the coarse and most labile fraction of the OM, being composed of particles derived from plant residues and fungal hyphae (Cambardella and Elliott, 1992; Bayer et al., 2002). Therefore, under NT the increase in C contents in this fraction of the SOM is common, especially in the uppermost soil layers, due to the input and maintenance of plant residues on the soil, as observed by Nascente et al. (2013).

Table 4. Probabilities of the *F* values calculated and coefficients of variation for the total N content (TN), total organic C (TOC), particulate organic C (POC), mineral-associated organic C (MOC), and C/N ratio of the soil and lability of the organic matter (POC/MOC) in the 0- to 0.05-, 0.05- to 0.10-, and 0.10- to 0.20-m layers and for the stock of C and N in the 0- to 0.20-m layer of the soil.

Factor of variation	TN	TOC	POC	MOC	C/N	POC/MOC
	0–0.05 m					
System (S)	0.686	0.265	0.031	0.713	0.716	0.050
Amendment (A)	0.722	0.044	0.117	0.049	0.050	0.962
S ′ A	0.677	0.791	0.167	0.539	0.506	0.437
CV(S), %	27.70	17.84	32.35	24.72	23.53	48.77
CV(A), %	23.14	18.48	22.98	23.34	21.45	57.51
	0.05–0.10 m					
System	0.761	0.559	0.001	0.984	0.971	0.049
Amendment	0.300	0.016	0.049	0.325	0.516	0.414
S ′ A	0.759	0.806	0.190	0.731	0.496	0.242
CV(S), %	27.53	21.99	11.20	33.88	24.28	45.15
CV(A), %	24.41	9.50	19.04	15.50	20.40	29.66
	0.10–0.20 m					
System	0.041	0.675	0.171	0.924	0.504	0.613
Amendment	0.863	0.148	0.157	0.708	0.299	0.413
S ′ A	0.951	0.920	0.955	0.942	0.869	0.905
CV(S), %	15.84	24.04	28.30	37.10	36.71	91.12
CV(A), %	25.52	15.47	40.52	23.01	25.20	88.50

Table 5. Accumulated straw production from 2006 to 2011 as a function of the crop rotation system and the soil acidity amendment.

Factor of variation	Accumulated straw production
	Mg ha^{-1}
System	
Forage crop	70.9 a†
Second crop	57.1 c
Cover crops	64.4 b
Fallow	32.2 d
Soil acidity amelioration	
Control	48.8 B
Silicate	60.5 A
Limestone	59.1 A
ANOVA	
System (S)	<0.001
Soil acidity amelioration (A)	<0.001
S ′ A	0.1262
CV(S), %	4.44
CV(A), %	6.77

† Values followed by the same letter (lowercase for cropping system and uppercase for soil acidity amelioration) are not significantly different (LSD, $p < 0.05$).

As also reported by Nascente et al. (2013), physical fractionation of SOM was important to assess soil quality, especially in detecting effects in the short term, since analysis of only TOC contents may not be enough to detect the effects of management practices. The particulate fraction of SOM is more sensitive to soil management practices because it changes according to variations in the input of plant residues and in the decomposition rates resulting from soil tillage (Bayer et al., 2002).

An effect of crop rotation on MOC, the SOM fraction with the greatest stability, was not observed due to an interaction with the surface of the minerals, as reported previously (Buyanovsky et al., 1994; Dieckow et al., 2009). Soil organic matter can be affected by management systems only in the long term, especially in clayey and very clayey soils (Diekow et al., 2005; de Souza Nunes et al., 2011). However, significant differences in MOC occurred in the 0- to 5-cm layer as a result of the use of lime and silicate, which resulted in 20% more MOC on average than the control treatment. This result may be related to the effect of soil acidity alleviation improving soil fertility and, eventually, increasing dry matter yield and C inputs, as discussed above. In tropical soils with a predominance of kaolinitic clays and Fe and Al oxides in their clay fraction, an increase of C in the silt- and clay-associated fractions with soil acidity remediation may be explained by considering that the increased soil pH generates charges through the dissociation of the H^+ of OH groups from OM, clay minerals, and Fe and Al oxides, increasing the cation exchange capacity (Soares et al., 2005). At the same time, higher Ca^{2+} and Mg^+ availability in the soil solution may facilitate the association between clay and humus, which is supported by the high correlation observed between TOC and the Ca^{2+} contents (Briedis et al., 2012). The formation of cation chemical bonds between silicate clays and organic radicals is a common mechanism of SOM stabilization, and Ca is very important in the establishment of these bonds (Muneer and Oades, 1989). Hence, these metal chemical bonds between the SOM and the minerals of the finest soil fractions constitute a chemical protection of the organic compounds, impeding their decomposition (Paul and Clark, 1989).

Because there was no effect of the crop rotation systems on MOC but rather on POC to the depth of 0.10 m with the forage crop (Table 6), SOM lability was affected (Table 7). In the 0- to 0.10-m layer, the greatest proportion of labile organic matter was obtained with the introduction of a forage crop into the system. Bayer et al. (2009) observed a greater rate of C sequestration and an increase in the labile C ratios (POC/MOC) in systems where velvet bean (*Mucuna* ssp.) was present compared with other winter cover crops. These results may be due to a higher dry matter yield and root growth of velvet bean during the 8 yr of the experiment.

The increase in the C/N ratio in the uppermost soil layer with soil acidity remediation (Table 7) is a result of the increased

Table 6. Total N (TN), total organic C (TOC), particulate organic C (POC) and mineral-associated organic C (MOC) contents in the 0- to 0.05-, 0.05- to 0.10-, and 0.10- to 0.20-m soil layers.

Factor of variation	TN	TOC	POC	MOC
	———————— $g\ kg^{-1}$ ————————			
	0 to 0.05 m			
System				
Forage crop	1.17 a†	17.79 a	8.24 a	9.55 a
Second crop	1.11 a	15.91 a	5.40 b	10.51 a
Cover crops	1.13 a	16.23 a	5.52 b	10.72 a
Fallow	1.00 a	14.74 a	4.66 b	10.08 a
Soil acidity amelioration				
Control	1.15 A	14.22 B	5.27 A	8.96 B
Silicate	1.07 A	17.01 A	6.13 A	10.89 A
Limestone	1.09 A	17.26 A	5.98 A	10.79 A
	0.05 to 0.10 m			
System				
Forage crop	0.90 a	14.56 a	5.37 a	9.69 a
Second crop	0.82 a	12.81 a	3.85 b	8.96 a
Cover crops	0.79 a	12.87 a	3.53 b	9.33 a
Fallow	0.83 a	12.92 a	3.39 b	9.53 a
Soil acidity amelioration				
Control	0.80 A	12.31 B	3.58 B	8.72 A
Silicate	0.90 A	13.73 A	4.21 AB	9.68 A
Limestone	0.81 A	13.82 A	4.32 A	9.74 A
	0 to 0.20 m			
System				
Forage crop	0.72 ab	12.83 a	4.17 a	8.66 a
Second crop	0.67 b	11.52 a	3.19 a	8.33 a
Cover crops	0.67 b	11.36 a	3.63 a	7.73 a
Fallow	0.86 a	11.48 a	3.06 a	8.42 a
Soil acidity amelioration				
Control	0.73 A	10.95 A	2.84 A	8.11 A
Silicate	0.73 A	12.47 A	3.79 A	8.67 A
Limestone	0.74 A	11.98 A	3.91 A	8.08 A

† Values followed by the same letter (lowercase for cropping system and uppercase for soil acidity amelioration) are not significantly different (LSD, $p < 0.05$).

Table 7. Soil C/N ratio and lability of the organic matter determined as the particulate organic C/mineral-associated organic C ratio (POC/MOC) in the 0- to 0.05-, 0.05- to 0.10-, and 0.10- to 0.20-m soil layers.

Factor of variation	C/N	POC/MOC
	0 to 0.05 m	
System		
Forage crop	16.40 a†	0.94 a
Second crop	14.59 a	0.62 ab
Cover crops	14.74 a	0.62 ab
Fallow	15.21 a	0.54 b
Soil acidity amelioration		
Control	13.17 B	0.69 A
Silicate	16.50 A	0.65 A
Limestone	16.04 A	0.69 A
	0.05 to 0.10 m	
System		
Forage crop	16.73 a	0.65 a
Second crop	15.90 a	0.45 ab
Cover crops	16.59 a	0.39 b
Fallow	16.49 a	0.37 b
Soil acidity amelioration		
Control	15.66 A	0.42 A
Silicate	16.37 A	0.47 A
Limestone	17.26 A	0.50 A
	0 to 0.20 m	
System		
Forage crop	19.01 a	0.54 a
Second crop	17.24 a	0.40 a
Cover crops	17.56 a	0.62 a
Fallow	14.35 a	0.38 a
Soil acidity amelioration		
Control	15.41 A	0.36 A
Silicate	17.88 A	0.49 A
Limestone	17.83 A	0.60 A

† Values followed by the same letter in a column for each factor of variation and each depth (lowercase for systems and uppercase for soil acidity amelioration) are not significantly different (LSD, $p < 0.05$).

TOC, with no effect on total N contents (Table 6). In treatments with and without lime or silicate, the C/N ratio in the 0- to 0.05-m layer was around 16 and 13, respectively, indicating that soil acidity alleviation increases unstabilized TOC because in unplowed tropical soils, the C/N ratio stabilizes in the range from 10 to 15 (Stevenson, 1994). Therefore, it is suggested that in treatments with high yields and very high C input to the system, N may have been deficient so as to maintain the balance of the soil C/N ratio, since these management practices did not affect total N (Table 6). According to Boddey et al. (2010), in crop rotation systems in which N is deficient, C is lost mainly as CO_2.

Conclusion

The use of limestone and silicate to alleviate soil acidity resulted in increased SOM quantity and quality, showing that the amount of C lost to the atmosphere with liming may not be significant when the entire system is considered. Management practices that improve crop dry matter yields may be effective in increasing total soil C in the long term, but in the short term, 5 yr in the present study, there was no correlation between the amount of straw on the soil surface and soil C. However, the interaction of crop rotation with soil acidity alleviation increased soil C down to a depth of 10 cm in the soil profile, probably through C stabilization by cation chemical bonds. Although a higher resilience has been observed for some soil C pools with large and diversified inputs of biomass C in intensive NT systems, we demonstrated that the introduction of a forage crop in the off-season is sufficient to increase dry matter to the system and labile SOM, with an increase just in the particulate C fraction. However, it is necessary to apply lime or silicate to increase the mineral-associated SOM fraction, which is a more stable form of SOC.

Acknowledgments

We thank the São Paulo Research Foundation (FAPESP) for financial support (Registry numbers: 2006/01705-4, 2009/10232-0, and 2009/05066-4) and the National Council for Scientific and Technological Development (CNPq) for an award for excellence in research to Carlos A.C. Crusciol and Juliano C. Calonego.

References

Balabane, M., and A.F. Plante. 2004. Aggregation and carbon storage in silty soil using physical fractionation techniques. Eur. J. Soil Sci. 55:415–427. doi:10.1111/j.1351-0754.2004.0608.x

Bayer, C., J. Dieckow, T.J.C. Amado, F.L.F. Eltz, and F.C.B. Vieira. 2009. Cover crop effects increasing carbon storage in a subtropical no-till sandy Acrisol. Commun. Soil Sci. Plant Anal. 40:1499–1511. doi:10.1080/00103620902820365

Bayer, C., J. Mielniczuk, L. Martin-Neto, and P.R. Ernani. 2002. Stocks and humification degree of organic matter fractions as affected by no-tillage on a subtropical soil. Plant Soil 238:133–140. doi:10.1023/A:1014284329618

Boddey, R.M., C.P. Jantalia, P.C. Conceição, J.A. Zanatta, C. Bayer, J. Mielnizuk, et al. 2010. Carbon accumulation at depth in Ferralsols under zero till subtropical agriculture. Global Change Biol. 16:784–795. doi:10.1111/j.1365-2486.2009.02020.x

Bolliger, A., J. Magid, T.J.C. Amado, F. Skóra Neto, M.F.S. Ribeiro, A. Calegari, et al. 2006. Taking stock of the Brazilian “Zero Till Revolution.” Adv. Agron. 91:47–110. doi:10.1016/S0065-2113(06)91002-5

Briedis, C., J.C.M. Sá, E.F. Caires, J.F. Navarro, T.M. Inagaki, A. Boer, et al. 2012. Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma 170:80–88. doi:10.1016/j.geoderma.2011.10.011

Buyanovsky, G.A., M. Aslam, and G.M. Wagner. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58:1167–1173. doi:10.2136/sssaj1994.03615995005800040023x

Caires, E.F., J.C.L. Correa, S. Churka, G. Barth, and F.J. Garbuio. 2006. Surface application of lime ameliorates subsoil acidity and improves root growth and yield of wheat in an acid soil under no-till system. Sci. Agric. 63:502–509.

Calonego, J.C., and C.A. Rosolem. 2008. Soil aggregate stability after management with crop rotation and chiseling. (In Portuguese, with English abstract.) Rev. Bras. Cienc. Solo 32:1399–1407. doi:10.1590/S0100-06832008000400004

Cambardella, C.A., and E.T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777–783. doi:10.2136/sssaj1992.03615995005600030017x

Castro, G.S.A., J.C. Calonego, and C.A.C. Crusciol. 2011. Soil physical properties in crop rotation systems as affected by liming materials. (In Portuguese, with English abstract.) Pesqi. Agropecu. Bras. 46:1690–1698. doi:10.1590/S0100-204X2011001200015

Castro, G.S.A., and C.A.C. Crusciol. 2013. Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. Geoderma 195-196:234–242. doi:10.1016/j.geoderma.2012.12.006

Christopher, S.F., R. Lal, and U. Mishra. 2009. Long-term no-till effects on carbon sequestration in the midwestern United States. Soil Sci. Soc. Am. J. 73:207–216. doi:10.2136/sssaj2007.0336

Conceição, P.C., J. Dieckow, and C. Bayer. 2013. Combined role of no-tillage and cropping systems in soil carbon stocks and stabilization. Soil Tillage Res. 129:40–47. doi:10.1016/j.still.2013.01.006

de Camargo, O.A., A.C. Moniz, J.A Jorge and J.M.A.S Valadares. 2009. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Bol. Téc. 106. Inst. Agron., Campinas, SP, Brazil.

de Souza Nunes, R., A.A.C. Lopes, D.M.G. de Sousa, and I.C. Mendes. 2011. Management systems and the carbon and nitrogen stocks of cerrado Oxisol under soybean–maize succession. (In Portuguese, with English abstract.) Rev. Bras. Cienc. Solo 35:1407–1419. doi:10.1590/S0100-06832011000400035

Dieckow, J., C. Bayer, P.C. Conceição, J.A. Zanatta, L. Martin-Neto, D.B.M. Milori, et al. 2009. Land use, tillage, texture and organic matter stock and composition in tropical and subtropical Brazilian soils. Eur. J. Soil Sci. 60:240–249. doi:10.1111/j.1365-2389.2008.01101.x

Diekow, J., J. Mielniczuk, H. Knicker, C. Bayer, D.P. Dick, and I. Kögel-Knabner. 2005. Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilization. Plant Soil 268:319–328. doi:10.1007/s11104-004-0330-4

Dou, F., A.L. Wright, and F.M. Hons. 2008. Sensitivity of labile soil organic carbon to tillage in wheat-based cropping systems. Eur. J. Soil Sci. 72:1442–1453.

Dumale, W.A., Jr., T. Miyasaki, K. Hirai, and T. Nishimura. 2011. SOC turnover and lime-CO$_2$ evolution during liming of an acid Andisol and Ultisol. Open J. Soil Sci. 1:49–53. doi:10.4236/ojss.2011.12007

Franzluebbers, A.J., and J.A. Stuedemann. 2013. Soil-profile distribution of organic C and N after 6 years of tillage and grazing management. Eur. J. Soil Sci. 64:558–566. doi:10.1111/ejss.12057

Garcia, R.A., Y. Li, and C.A. Rosolem. 2013. Soil organic matter and physical attributes affected by crop rotation under no-till. Soil Sci. Soc. Am. J. 77:1724–1731. doi:10.2136/sssaj2012.0310

Govaerts, B., N. Verhulst, A. Castellanos-Navarrete, K.D. Sayre, J. Dixon, and L. Dendooven. 2009. Conservation agriculture and soil carbon sequestration: Between myth and farmer reality. Crit. Rev. Plant Sci. 28:97–122. doi:10.1080/07352680902776358

Grième, I.C., D.A. Davidson, and P.M.C. Bruneau. 2005. Effects of liming on void space and aggregation in an upland grassland soil. Geoderma 125:39–48. doi:10.1016/j.geoderma.2004.06.004

Larsen, E., J. Grossman, J. Edgell, G. Hoyt, D. Osmond, and S. Hu. 2014. Soil Tillage Res. 139:37–45. doi:10.1016/j.still.2014.02.002

Mishra, U., D. Ussiri, and R. Lal. 2010. Tillage effects on soil carbon storage and dynamics in Corn Belt of Ohio USA. Soil Tillage Res. 107:88–96. doi:10.1016/j.still.2010.02.005

Muneer, M., and J.M. Oades. 1989. The role of Ca–organic interactions in soil aggregate stability: III. Mechanisms and models. Aust. J. Soil Res. 27:411–423. doi:10.1071/SR9890411

Nascente, A.S., Y.C. Li, and C.A.C. Crusciol. 2013. Cover crops and no-till effects on physical fractions of soil organic matter. Soil Tillage Res. 130:52–57. doi:10.1016/j.still.2013.02.008

Ogle, S.M., L. Olander, L. Wollenberg, T. Rosenstock, F. Tubiello, K. Paustian, et al. 2014. Reducing greenhouse gas emissions and adapting agricultural management for climate change in developing countries: Providing the basis for action. Global Change Biol. 20:1–6. doi:10.1111/gcb.12361

Paul, E.A., and F.E. Clark. 1989. Soil microbiology and biochemistry. Academic Press, San Diego.

Rosolem, C.A., R. Werle, and R.A. Garcia. 2010. Nitrogen washing from C$_3$ and C$_4$ cover grasses residues by rain. Rev. Bras. Cienc. Solo 34:1899–1905. doi:10.1590/S0100-06832010000600014

Salton, J.C., J. Mielniczuk, C. Bayer, A.C. Fabrício, M.C.M.E. Macedo, and D.L. Broch. 2011. Contents and dynamics of soil carbon in integrated crop-livestock systems. (In Portuguese, with English abstract.) Pesqi. Agropecu. Bras. 46:1349–1356. doi:10.1590/S0100-204X2011001000031

SAS Institute. 2000. SAS/STAT user’s guide, Version 8. SAS Inst., Cary, NC.

Soares, M.R., L.R.F. Alleoni, P. Vidal-Torrado, and M. Coope. 2005. Mineralogy and ion exchange properties of the particle size fractions of some Brazilian soils in tropical humid areas. Geoderma 125:355–367. doi:10.1016/j.geoderma.2004.09.008

Soil Survey Staff. 2006. Keys to soil taxonomy. 10th ed. NRCS, Washington, DC.

Stevenson, F. 1994. Humus chemistry: Genesis, composition, reactions. John Wiley & Sons, New York.

Tian, S., Y. Wang, T. Ning, N. Li, H. Zhao, B. Wang, et al. 2014. Continued no-till and subsoiling improved soil organic carbon and soil aggregation levels. Agron. J. 106:212–218. doi:10.2134/agronj2013.0288

Tivet, F., J.C.M. Sá, R. Lal, P.R. Borszowskei, C. Briedis, J.B. Santos, et al. 2013. Soil organic carbon fraction losses upon continuous plow-based tillage and its restoration by diverse biomass-C inputs under no-till in subtropical and tropical regions of Brazil. Geoderma 209–210:214–225. doi:10.1016/j.geoderma.2013.06.008

van Raij, B., J.C. Andrade, H. Cantarella, and J.A. Quaggio. 2001. Análise química para avaliação da fertilidade de solos tropicais. Inst. Agron. Campinas, SP, Brazil.

Yao, H.Y., D. Bowman, T. Rufty, and W. Shi. 2009. Interactions between N fertilization, grass clipping addition and pH in turf ecosystems: Implications for soil enzyme activities and organic matter decomposition. Soil Biol. Biochem. 41:1425–1432. doi:10.1016/j.soilbio.2009.03.020