Building Up Organic Matter in a Subtropical Paleudult under Legume Cover-Crop-Based Rotations

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The potential of conservation management systems to ameliorate degraded agricultural soils and mitigate global warming is related to their potential for long-term stabilization of soil organic matter (SOM). This study was performed in a 19-yr-old experiment that was set up on a degraded Paleudult (220 g kg^{-1} clay) in southern Brazil to (i) evaluate the effect of seven no-till crop rotations (grass- and legume-based cover crop systems) and mineral N fertilization (0 and 145 kg ha^{-1} yr^{-1}) on soil organic C (SOC) stocks (0–17.5-cm depth) and (ii) estimate rates of SOM dynamics in these systems under subtropical climate conditions. Annual C input (shoot + root) ranged from 2.61 to 7.84 Mg ha^{-1}, with the highest values in legume-based and N-fertilized cropping systems. The SOC stocks were closely related to C input levels, and a minimum C input of 4.05 Mg ha^{-1} yr^{-1} was estimated to maintain the original SOC stock of 31.38 Mg ha^{-1}. Based on the one-compartment model of SOM dynamics, the SOM decomposition rate was estimated to be 1.2% and the humification coefficient was estimated to be 9.6%. After 19 yr, the stock of the original SOC decreased to about 24.78 Mg ha^{-1}, while accumulation of SOC derived from the crops ranged from 4.26 to 12.79 Mg ha^{-1}. Our results highlighted the benefits of legume cover crop species in no-till systems for the stabilization of SOC in degraded agricultural soils.

Abbreviations: F/M, fallow/maize; L+M, lablab+maize; O+V/M+C, black oat+vetch/maize+cowpea; O/M, black oat/maize; O+V/M, black oat+vetch/maize; P+M, pigeon pea+maize; SOC, soil organic carbon; SOM, soil organic matter; 0 N, 0 kg N ha^{-1} yr^{-1}; 145 N, mean of 145 kg N ha^{-1} yr^{-1}.

Soil organic matter is an essential component of high-quality agricultural soils because it affects many soil processes, such as microbial activity, nutrient release, and soil tilth formation (Balota et al., 2004; Causarano et al., 2008). Therefore, management practices aiming at building up or maintaining SOM levels through increasing annual C and N inputs to the soil and reducing losses of SOM are crucial to soil conservation and recovery of degraded soils. In this context, the inclusion of legume species and mineral N fertilization in no-till production systems are key strategies of soil management (Diekow et al., 2005; Lal, 2006; Vieira et al., 2007; Zotarelli et al., 2007).

The SOC accumulation rates in contrasting no-till crop rotations have been evaluated, as well as the effect of soil type and climate conditions (Bayer et al., 2000; Campbell et al., 2005; Diekow et al., 2005; Jantalia et al., 2007). These rates were summarized by Bayer et al. (2006b) for Brazilian soils and the average rate was 0.48 Mg ha^{-1} yr^{-1} for the subtropical southern region and 0.35 Mg ha^{-1} yr^{-1} for the Cerrado tropical region. Few studies, however, have evaluated the role of legume cover crop species and mineral N fertilization on SOM dynamics and stabilization in no-till systems, especially in southern Brazil. Although both legume species and mineral N fertilization can promote an increase in SOC stocks, Zanatta et al. (2007) observed that, per unit of increase in added C through residues, legume cover crop inclusion was more efficient in accumulating SOC than increasing biomass production through mineral N fertilization. This result has been attributed to an increased decomposition of the native SOM when fertilizer is added (Kuzyakov et al., 2000; Khan et al., 2007).

Long-term experiments are very valuable for evaluating the influence of soil management practices on SOC stocks and they allow the estimation of average rates of SOM decomposition and stabilization in different soils under distinct climatic conditions (Bayer et al., 2006a). Based on these estimates, future scenarios of soil management and their role in building up SOM and mitigating increased atmospheric CO_2 can be forecast (Bayer et al., 2000, 2006a; Lal, 2004b). In a long-term experiment, Bayer et al. (2006a) estimated the SOM decomposition rate under no-till conditions as being about half (0.019 yr^{-1}) that found under conventional tillage (0.040 yr^{-1}), but the humification coefficient was not affected by the tillage system (14.8% under no-till and 14.6% under conventional tillage). Based on these results, they estimated a minimal requirement of 8.8 Mg ha^{-1} of annual C input by the crops under conventional tillage to maintain the original SOC stock in the soil. This C input requirement is more than twice the 3.1 and 3.56 Mg ha^{-1} yr^{-1} estimated by Kong et al. (2005) and Majumder et al. (2008) under conventional tillage systems on a Mediterranean soil from the United States and a subtropical soil from India, respectively. This difference in C input to maintain

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SOC levels highlights the favorable climatic conditions for microbial SOM decomposition under the humid and hot subtropical climate in southern Brazil. Only half of that quantity was required in a no-till system (3.9 Mg C ha^{-1} yr^{-1}), however, thereby indicating the importance of the no-till system on the SOM stabilization and the improvement of soil quality in this subtropical region.

This study evaluated the effect of crop rotations and mineral N fertilization on SOC stocks and estimated rates of SOM stabilization in a no-till Paleudult under subtropical conditions.

MATERIALS AND METHODS

Soil and Climate Conditions

This study was based on a long-term experiment (19 yr) established at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul, in Eldorado do Sul (RS), southern Brazil (30°51′ S and 51°38′W). The local climate is subtropical humid, Cfa type according to the Köppen classification, with a mean annual temperature of 19.4°C and a mean annual rainfall of 1440 mm evenly distributed throughout the year. The soil is classified as a Paleudult by the U.S. Soil Taxonomy and as a sandy clay loam Acrisol by the FAO classification system. The soil particle size distribution is 540 g kg^{-1} sand, 240 g kg^{-1} silt, and 220 g kg^{-1} clay, with the clay fraction dominated by kaolinite (720 g kg^{-1}) and Fe oxides (109 g kg^{-1} Fe_2O_3). When the experiment was initiated in 1983, the soil showed visible signs of physical degradation, indicated by poor soil aggregation and low water infiltration, caused by conventional tillage that had been implemented during the previous 13 yr.

Experimental Site and Soil Sampling

The long-term field experiment (which is ongoing) consists of 10 no-till crop rotations in the main plots (8 by 5 m) and two N-fertilization levels, 0 (0 N) and 145 kg N ha^{-1} yr^{-1} (145 N) applied to the maize crop as urea in the subplots (4 by 5 m); the 145 N is the average fertilization rate during the 19 yr, as between 1983 and 1994 the N fertilization rate was 120 kg N ha^{-1} yr^{-1} and thereafter was increased to 180 kg N ha^{-1} yr^{-1}, resulting in a mean of 145 kg N ha^{-1} yr^{-1}. The design is a split-plot randomized block design with three field replications. We sampled the soil in October 2002 in the following crop rotations (winter–summer crop system species): fallow/maize (*Zea mays* L.) (F/M), black oat (*Avena strigosa* Schreb.)/maize (O/M), black oat+vetch (*Vigna sativa* L.)/maize (O+V/M), lablab [*Lablab purpureus* (L.) Sweet ssp. *purpureus*]+maize (L+M), black oat+vetch/maize+cowpea [*Vigna unguiculata* (L.) Walp.] (O+V/M+C), pigeon pea [*Cajanus cajan* (L.) Millsp.]+maize (P+M), and digitaria (*Digitaria decumbens* Stent). The first four crop rotations were evaluated under the two N rates, while the last three systems were evaluated without N application. In the F/M system, the soil under winter fallow was usually vegetated with a few spontaneous plants of *Spergula arvensis* L., *Digitaria horizontalis* Willd. and *Ipomoea* sp. Soil samples from the layers 0- to 2.5-, 2.5- to 5.0-, 5.0- to 7.5-, 7.5- to 12.5-, and 12.5- to 17.5-cm depth were manually collected, air dried, ground, and sieved (<2 mm). A subsample was then ground to <0.5 mm to analyze for total SOC content.

Organic Carbon Analysis and Calculation of Soil Organic Carbon Stocks

The SOC concentration was determined by dry combustion using a total organic C analyzer (Shimadzu TOC-VCSH, Shimadzu Corp., Kyoto, Japan), and the stocks were calculated using the equivalent soil mass approach (Ellert and Bettany, 1995), taking the soil mass from an adjacent native grassland as a reference. To track the temporal evolution of SOC stocks, we compared our results (2002) with those obtained at the beginning of the experiment in 1983 (C_0), 1986 (third year), 1988 (fifth year), 1991 (eighth year), 1993 (10th year), and 1999 (16th year), which were also recalculated based on the equivalent soil mass. In these previous years, the experimental methods were the same as those used in 2002, except for the analytical C determination method. The SOC data from the previous studies were determined by the Walkley–Black analytical method (Nelson and Sommers, 1996). Consequently, the Walkley–Black data were corrected by a factor of 0.9422 for valid comparison with the data obtained by the dry combustion TOC method used in 2002. This correction factor was determined in previous tests where we compared results from the Walkley–Black and the dry combustion TOC methods for a wide range of SOC contents (data not shown). This temporal evaluation was performed only for samples from the treatments without applied N-based fertilizer because samples from the N-fertilized plots had not been assessed for SOC in most of the previous determinations.

Values of soil bulk density from the treatments and native grassland were assessed through the core method (Blake and Hartage, 1986) for the 0- to 2.5-, 2.5- to 7.5-, and 7.5- to 17.5-cm soil layers (Table 1). Therefore, the C stocks from 2.5- to 5.0- and 5.0- to 7.5-cm soil layers were assessed by taking the soil density of the 2.5- to 7.5-cm soil layer, while C stocks from the 7.5- to 12.5- and 12.5- to 17.5-cm layers were assessed by taking the bulk density of 7.5- to 17.5-cm layer. Because soil bulk density was not measured in the past sampling events, the current soil bulk densities reported in Table 1 were used to calculate the SOC stocks from all experimental periods. We assumed that drastic changes in bulk density did not occur among crop rotations between 1983 and 2002.

Annual Carbon Inputs by Crops

The mean annual C input (Mg ha^{-1} yr^{-1}) to the soil by crop rotations during the whole experimental period (1983–2002) was calculated by taking into account the biomass production of maize plus cover crops as

$$\text{Annual C input} = 1.30\left(0.40\,\text{DM}_{\text{cover crops}} + C_{\text{maize}}\right) \qquad [1]$$

where $\text{DM}_{\text{cover crops}}$ is the annual aboveground biomass production by the cover crops (Mg dry mass ha^{-1}), and C_{maize} is the mean annual C input from the shoots of maize plants (Mg C ha^{-1}). The value of $\text{DM}_{\text{cover crops}}$ was calculated from the average biomass production determined by Bragagnolo (1986), Testa (1989), Pavinato (1993), and Burle (1995) in previous years, and our own estimates determined in September 2002. We measured dry mass production of the winter species by sampling an area of 0.5 m^2 in each subplot. The value of C_{maize} was calculated by using the maize grain yield (Y_{grain}, Mg ha^{-1}) measured for each of the 19 yr of the experiment and converting it to C input from maize the shoots by using the equation $C_{\text{maize}} = 0.84Y_{\text{grain}} + 2.9$

Table 1. Soil bulk density in a Paleudult under no-till crop rotations† and mineral N fertilization for 19 yr (Vieira et al., 2008).

Depth	F/M	O/M	O/V–M/C	L/M	O/V+M	P/M	Digitaria	NG
cm	Mg m^{-3}							
0–2.5	1.54	1.54	1.54	1.55	1.54	1.44	1.14	1.49
2.5–7.5	1.56	1.56	1.58	1.64	1.58	1.65	1.47	1.51
7.5–17.5	1.62	1.62	1.66	1.66	1.66	1.65	1.58	1.63

† F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, P = pigeon pea, and NG = native grassland.

developed by Lovato et al. (2004) in an adjacent experiment. In addition, we considered a mean C content of 40% of the dry mass (factor 0.40 in Eq. [1]) for conversion of biomass to C addition from cover crops, and the mean C input contribution by the root system of maize and the cover crops equivalent to 30% of that from the shoot (factor 1.30 in Eq. [1]), which is a mean value from the results observed by several researchers (Balesdent and Balabane, 1992; Bolinder et al., 1997; Buyanovsky and Wagner, 1986; Crozier and King, 1993).

Estimation of Rates of Soil Organic Matter Dynamics

The SOM decomposition rate (k_2) and humification coefficient (k_1) were estimated based on the relationship between the changes in SOC and the annual C inputs to the soil summarized by the following one-compartment model (Dalal and Mayer, 1986; Bayer et al., 2006a):

$$C_t = C_0 \exp\left(-k_2 t\right) + \frac{Ak_1}{k_2}\left[1 - \exp\left(-k_2 t\right)\right] \qquad [2]$$

where C_t is the SOC stock in a defined soil layer (Mg ha^{-1}) at time t (yr), C_0 is the original SOC stock (Mg ha^{-1}) at time $t = 0$, k_1 is the humification coefficient (unitless), k_2 is the decomposition rate (yr^{-1}), and A is the annual C addition (Mg ha^{-1}). The humification coefficient represents the annual rate at which added C is incorporated into SOC. The first term, $C_0 \exp(-k_2 t)$, is the exponential decrease in the original SOC with time, while the second term, $(Ak_1/k_2)[1 - \exp(-k_2 t)]$, denotes the contribution of crop C input to SOC. Consequently, the k_2 and k_1 coefficients can be calculated by fitting a linear equation ($y = a + bx$) between annual C inputs by the plants (x) and the SOC stocks (0–17.5 cm) in the 19th year (y) (see Fig. 1). The intercept (a) corresponds to the remaining original SOC stock $[C_0 \exp(-k_2 t)]$. Therefore, if C_0 and SOC stocks at time t = 19 yr are known, the k_2 value can be assessed by substituting the terms of the equation. Similarly, the bx term corresponds to the SOC stock accumulated due to the C input by plants during the 19 yr, thus $bx = (Ak_1/k_2)[1 - \exp(-k_2 t)]$. Subsequently, if the annual C input by the plants (A) is known, the humification coefficient (k_1) can be calculated by substituting the other terms of the equation.

By using the parameters of SOC dynamics in the soil (k_2 and k_1) and the annual C input by the plants (A), the changes in the stocks of total SOC, original SOC, and the accumulation of SOC derived from the C input by the crop rotations were predicted for a period of 40 yr after the beginning of the experiment. The predictions were compared with the SOC stocks (0–17.5 cm) measured at the third year (1986), fifth year (1988), eighth year (1991), 10th year (1993), 16th year (1999), and 19th year (2002). The long-term equilibrium SOC stock for each crop rotation under the current management and climate conditions was then estimated as $C_e = k_1 A/k_2$.

Statistical Analysis

The effects of crop rotations and mineral N fertilization were statistically analyzed by ANOVA, with the exception of C input values, which are the means across the experimental period calculated from published results. Treatment means were separated by the Tukey test ($P < 0.05$). Relationships between variables were evaluated by means of the coefficient of determination (r^2) of polynomial regressions. To evaluate the performance of the estimated parameters (k_1 and k_2), SOC stocks predicted by the one-compartment model were compared with those measured in the soil in the different years of evaluation (with the exception of the 19th year, which was used to estimate the SOM coefficients), and the statistical analyses of lack of fit and RMSE were performed according to Smith et al. (1997) for long-term experiments with replication data available.

RESULTS AND DISCUSSION

Carbon Input as Affected by Crop Rotations and Mineral Nitrogen Fertilization

Mean annual C inputs of the different cropping systems ranged from 2.61 to 7.84 Mg ha^{-1} (Table 2). In the absence of mineral N fertilization, legume-based rotations had greater organic C inputs (mean of 6.56 Mg ha^{-1} yr^{-1}) than those essentially composed of grass species (mean of 3.59 Mg ha^{-1} yr^{-1}). Among legume-based treatments, those including tropical legume species (L+M, P+M, and O+V/M+C) had greater C inputs than that including subtropical legumes (O+V/M). It is important to note that, in addition to their own contribution to the annual C input, the legume species also contribute to the increase in C addition by the subsequent crop due to increased soil N availability (Lovato et al., 2004; Zanatta et al., 2007).

Mean application of 145 kg N-urea ha^{-1} increased the C input by maize by 0.65 to 1.21 Mg C ha^{-1} yr^{-1} in comparison to treatments without N fertilization. The increase in C input due to N fertilization was observed in all N-fertilized crop systems (Table 2), but the greatest effect was manifested in the rotations without legume species (F/M and O/M, with an increase of 1.19 and 1.21 Mg C ha^{-1} yr^{-1}, respectively). Nitrogen fertilization applied to maize did not have any effect on the biomass production of cover crops because it resulted in only a small effect on soil N stocks

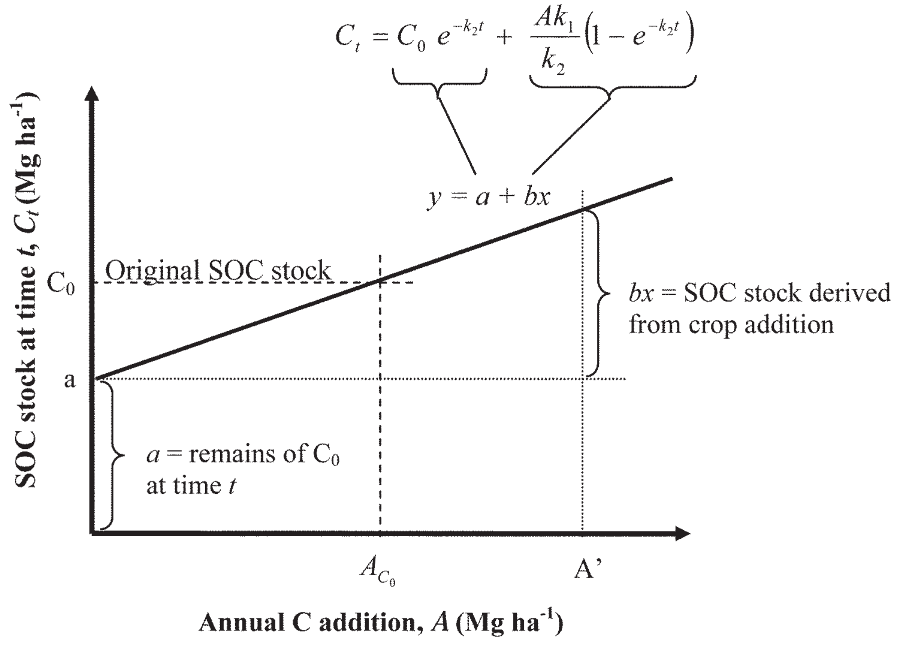

Fig. 1. The conceptual relationship between soil organic C (SOC) stock and annual C addition in cropping systems, and its relationship to the one-compartment model used to obtain the humification (*k*1) and decomposition (*k*2) coefficients (A_{C0}, annual C addition required to maintain the original C stock [*C*0]; *A*′, illustrative crop C addition rate with its respective contribution [*bx*] to the total SOC stock.

Table 2. Annual C input to the soil by cover crops and maize when fertilized at two rates of mineral N. Presented data are the mean of C inputs during a 19-yr period.

Crop rotation†	0 kg N ha^{-1} yr^{-1}			145 kg N ha^{-1} yr^{-1}		
	Cover crop‡	Maize‡	Total	Cover crop	Maize§	Total
	Mg C ha^{-1} yr^{-1}					
F/M	0.73	1.88	2.61	0.73	3.07	3.80
O/M	1.79	2.60	4.39	1.79	3.81	5.60
O+V/M	2.37	3.17	5.54	2.37	3.95	6.32
L+M	3.06	3.21	6.27	3.06	3.86	6.92
O+V/M+C	3.20	3.40	6.60	–	–	–
P+M	5.03	2.81	7.84	–	–	–
Digitaria	3.39	0.39¶	3.78	–	–	–

† F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, and P = pigeon pea.

‡ Annual C addition by shoot of plants plus 30% from the root system.

§ C input by cover crops was not affected by N fertilization on maize during the 19 yr of the experiment (J. Mielniczuk, unpublished data, 2004).

¶ Contribution of 4 yr of maize cultivation during the 19 yr of the experiment.

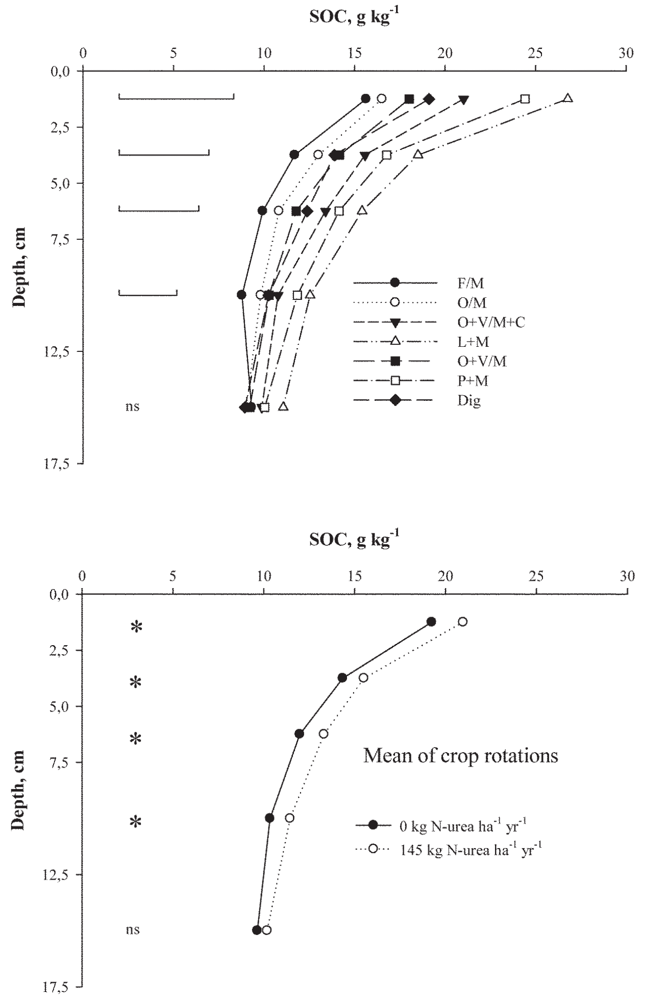

Fig. 2. Soil organic C (SOC) contents in the profile (0–17.5 cm) of a Paleudult under no-till crop rotations with two different mineral N fertilization rates for 19 yr (F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, P = pigeon pea, and Dig = digitaria). Horizontal bars represent the LSD by the Tukey test ($P < 0.05$). *Significantly different by the Tukey test ($P < 0.05$); ns = not significant.

(data not shown) and thus on N availability for the subsequent crop. Consequently, a single value of biomass addition by cover crops was used across the two fertilization regimes (Table 2).

Soil Carbon Stock and Its Relationship with Carbon Input

Long-term cropping systems influenced the SOC concentration in practically the entire no-till soil profile, but the major effect was observed in the surface soil layers (Fig. 2). This pattern is commonly observed in no-till conservation systems, where there is minimal soil disturbance and little incorporation of plant residues at depth (Bayer et al., 2000; Diekow et al., 2005). As a consequence, the soil quality in the surface layers of agricultural soils is improved, especially in relation to nutrient cycling and supply to the crops in these low-fertility tropical soils (Balota et al., 2004).

The SOC stocks ranged from 28.74 to 45.01 Mg ha^{-1} in the 0- to 17.5-cm soil layer and were significantly correlated ($r^2 = 0.86$, $P < 0.001$) with the mean annual C input when the L/M rotation was not considered (Fig. 3). The L/M crop system was disregarded in the regression because of uncertainty in the correct value for annual C input in this system. Lablab is characterized by a continuous senescence and renewal of leaves in the vegetative period. Therefore, one-time sampling probably underestimates the annual biomass production by lablab (7.5 Mg ha^{-1}). This probable underestimation is supported by reported values of lablab biomass production >9 Mg ha^{-1} (Muldoon, 1985; Muir et al., 2001) and 14 Mg ha^{-1} (Devkota and Rerkasem, 2000) in other studies.

From this relationship between SOC stocks and C input, it can be determined that the annual C input requirement to maintain the original SOC stock is 4.05 Mg ha^{-1}, which is very close to the value of 3.9 Mg ha^{-1} found by Bayer et al. (2006a) for no-till soil in an adjacent experiment, but it is almost half of the minimum requirement of 8.8 Mg ha^{-1} reported by those researchers for the same soil under conventional tillage. This minimum requirement is high in comparison to the 3.1 Mg ha^{-1} yr^{-1} estimated by Kong et al. (2005) and 3.56 Mg ha^{-1} yr^{-1} estimated by Majumder et al. (2008) for a Mediterranean soil (280 g kg^{-1} clay) from Davis (northern California) and for a subtropical soil (205 g kg^{-1} clay) from West Bengal (India), respectively. Our high estimates are probably a result of the highly favorable climatic conditions for SOM decomposition at the site. We conclude that it is very difficult to maintain SOC levels in the warm and humid subtropical climate in the south of Brazil, especially in conventionally tilled systems, because there are very few cropping systems that are able to meet the high annual biomass production requirement of 20 Mg ha^{-1} of dry mass (Mielniczuk et al., 2003). Even considering the positive effect of no-till on SOM stability, our results show that 10 Mg ha^{-1} of annual biomass input is required to maintain the SOM level, which can only be attained in cover-crop-based crop rotations (Mielniczuk et al., 2003).

The close linear relationship between SOC level and annual C input suggests that, after 19 yr of continuous no-till management in cropping systems with a large range of biomass additions (50–150 Mg ha^{-1}), this sandy clay loam soil is not C saturated and, therefore, still has great potential for further C storage. These results are similar to those reported by Kong et al. (2005) and Majumder et al. (2008) in 10- and 19-yr-old experiments, respectively, indicating that soils can sequester C in the long term. Kong et al. (2005) related the increased SOC stabilization in cropping systems with high annual input to the increase in macroaggregation and the stabilization of SOC in the microaggregates contained within macroaggregates. The physical protection of SOM in micro- and macroaggregates has been considered one of the main mechanisms of SOM stabilization in no-till soils from tropical and temperate regions (Six et al., 1999; Denef et al., 2004; Zotarelli et al., 2007). Conceição et al. (2007) estimated that up to 30% of the total SOM accumulation in no-till soils was due to the physical protection of SOM into soil aggregates in southern and middle-west Brazilian regions.

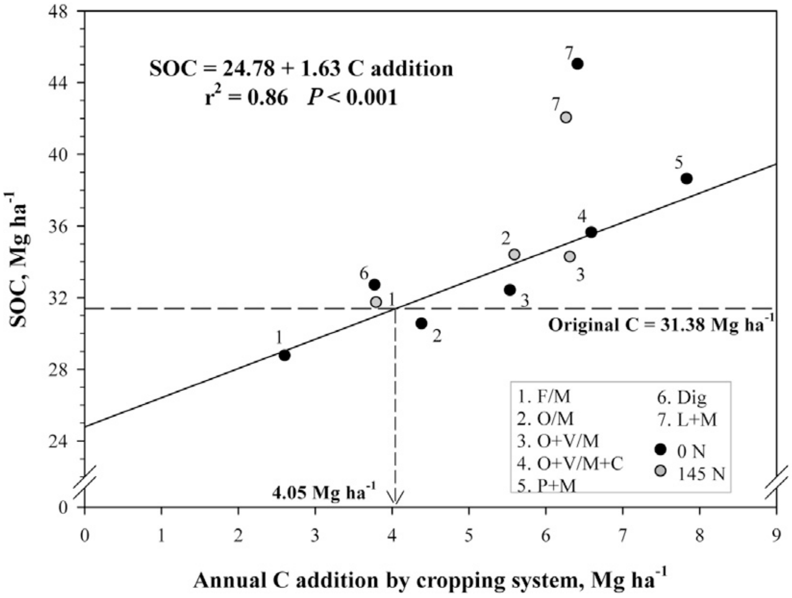

Fig. 3. Relationship between annual C addition and soil organic C (SOC) stock in the 0- to 17.5 cm layer of a Paleudult under no-till crop rotations with two different mineral N fertilization rates for 19 yr (F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, P = pigeon pea, and Dig = digitaria; 0 N and 145 N = 0 and 145 kg N-urea ha^{-}1 yr^{-1}, respectively). Note: the L/M system was disregarded in the regression.

Mineral N fertilization resulted in greater SOC stocks (Table 2, Fig. 3), but the increases were restricted to the surface soil layers (Fig. 2). The N fertilization was more effective in increasing SOC stocks where the rotations essentially included only grass species (F/M and O/M, mean of 11.5%) than in the legume-based rotations (L+M and O+V/M, mean of 6.5%). This result reflects the restriction of N availability for biomass production (Table 2) in mainly the F/M and O/M systems and thereby limiting SOC accumulation. The increase in SOC stocks due to N fertilization was similar to those reported by Campbell et al. (2005), Lovato et al. (2004), and Zanatta et al. (2007). It is important to note, however, that although the increment in SOC is agronomically desirable, when the increments are made at the expense of mineral N fertilization, the CO_2–C costs of N fertilizers and the N_2O-derived emissions should be considered to estimate the net mitigation of greenhouse gas emissions (Schlesinger, 2000; Lal, 2004a; Zanatta et al., 2007).

In general, the cropping systems that had greater SOC concentrations in the surface layers also tended to have larger SOC concentrations in deep layers (Fig. 2). In addition to the root contribution, the high quantity of SOM in the surface feeds soil fauna, which is instrumental in the incorporation of litter and SOM into the deep layers, increasing also the leaching of dissolved organic C (Lavelle et al., 1992). A historical analysis of SOC results from this experiment elucidates a short-term effect of no-till cropping systems on SOC accumulation in the surface layer (0–2.5 cm, third year) and an increase in SOM accumulation at depth with time; the SOM accumulation reached a depth of 7.5 cm at the fifth year, 12.5 cm at the ninth year, and at 17.5 cm at the 11th year (Bayer et al., 2000; Burle et al., 1997; Pavinato, 1993; Testa, 1989). Such changes strengthen the assertion that, although the highest accumulation of SOC in no-till soils happens in the surface layers, studies aiming to evaluate the long-term effect of conservation tillage practices on soil C sequestration should include deeper soil layers (Blanco-Canqui and Lal, 2008). The potential of C storage in deeper soil layers amplifies the option to sequester atmospheric CO_2 as SOC in tropical and subtropical soils under no-till management (Diekow et al., 2005; Jantalia et al., 2007).

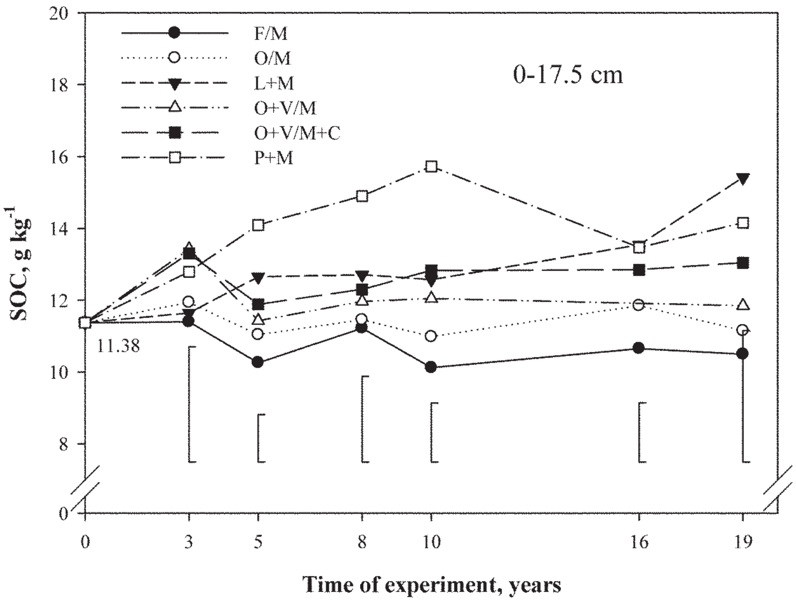

Fig. 4. Weighted mean of soil organic C (SOC) contents in the 0- to 17.5-cm layer of a Paleudult under no-till crop rotations with two different mineral N fertilization rates for 19 yr. Data obtained from Medeiros (1985), Teixeira (1988), Testa (1989), Pavinato (1993), Burle (1995), Pillon (2002), and this study. Vertical bars represent the LSD by the Tukey test ($P < 0.05$) (F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, and P = pigeon pea).

Changes in Soil Organic Carbon Stocks during the Experimental Period

Because of the intense soil plowing in the years before establishment of the no-till practices, the SOC content at the initiation of the experiment was 11.38 g kg^{-1} in the 0- to 17.5-cm soil

Table 3. **Soil organic C stocks measured at the 19th year (0–17.5 cm) and estimated by the model for the different no-till crop rotations.**

Crop rotation†	Measured total C	Estimated			
		Total C	Original C‡	C from crops§	C_e¶
	Mg ha^{-1}				
F/M	28.74	29.04	24.78	4.26	20.24
O/M	30.52	31.94	24.78	7.16	34.05
O+V/M	32.39	33.82	24.78	9.04	42.97
O+V/M+C	35.61	35.55	24.78	10.77	51.19
P+M	38.60	37.57	24.78	12.79	60.81

† F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, L = lablab, and P = pigeon pea.

‡ Original organic C remaining at the 19th year.

§ Organic C from the crops accumulated in the soil until the 19th year.

¶ Total organic stock at which the soil tends stabilize after a long term under the different cropping systems [$C_e = (k_1A)/k_2$, where k_1 is the humification coefficient, k_2 is the decomposition rate, and A is the annual addition].

layer (Fig. 4). This is a relatively low SOC content and led to a relatively fast increase in SOC once the higher C input systems were established. An increase in SOC was already apparent in the third year of the experiment (Fig. 4). In subsequent years, there were almost no changes in the order of SOC accumulation rates across the rotations, but, in general, the differences were amplified among rotations by the 19th year of implementation (Fig. 4).

The soils under F/M and O/M had the smallest SOC contents by the 19th year, with values even lower than the original content in 1983, which was due to the low input of biomass C in these systems. The P+M system substantially increased SOC in the first 10 yr, but a decline in SOC contents was observed in the last 9 yr. The reason for this decrease is the change in crop management in this system after the 10th year. After the 10th year, biomass production by pigeon pea was favored over maize grain yield. Therefore, after this change, the relative contribution by maize to the total C input in this crop system was reduced. Even though the pigeon pea had a high biomass-C production, the relatively low C/N ratio and resulting fast decomposition rate of this biomass probably contributed to the decrease in SOC content after the 10th year.

Table 4. **Analysis of significance of lack of fit (LOFIT) and RMSE among the predicted organic C stocks and those measured at the third, fifth, 10th, and 16th years of experiment.**

Crop rotation†	n‡	LOFIT	F§	$F_{5\%}$	RMSE¶	RMSE 95%
F/M	5	34.66	2.29	3.33	5.15	10.82
O/M	5	24.26	1.00	3.33	4.06	12.92
O+V/M	4	81.89	3.92	3.84	7.81	16.98
O+V/M+C	5	64.02	3.19	3.33	6.01	10.72
P+M	5	446.99	10.31	3.33	14.11	13.98

† F = fallow, M = maize, O = Black oat, V = vetch, C = cowpea, L = lablab, and *P* = pigeon pea.

‡ Number of evaluations (years in the period of experiment) accounted for in the statistical analysis.

§ The *F* test determines the significance of LOFIT, where values $F < F_{5\%}$ indicate that the simulated values do not differ statistically from the measured ones.

¶ Values of RMSE < RMSE 95% indicate that the simulated values are placed inside the confidence interval (95%) of the measured values.

Parameters of Soil Organic Matter Dynamics

Based on the relationship between annual C input and SOC stocks in the 0- to 17.5-cm layer, we estimated a k_2 of 0.0124. This means that about 1.2% of the original SOC is annually lost due to microbial decomposition, erosion, and leaching. On the other hand, k_1 was estimated as 0.096, which implies that about 9.6% of the added C remains in the soil as SOC. The decomposition rate estimated in this study is a little lower than the value of 1.9% reported by Bayer et al. (2006a) for the same site, but it is almost three times lower than the decomposition rate of SOM under conventional tillage (Bayer et al., 2006a), reinforcing the profound effect of no-till management on SOM stabilization in this subtropical soil.

The value of 9.6% obtained for k_1 falls well within the range (7.6–23%) reported in the literature (Rasmussen and Collins, 1991; Gregorich et al., 1995; Bolinder et al., 1999; Kong et al., 2005; Majumder et al., 2008). Lower values within the range indicate low C sequestration efficiency as a consequence of climatic conditions highly conducive for microbial activity, or input of high-quality shoot crop residues or organic manures, or a low capacity of the soil to protect SOM (Kong et al., 2005). Our k_1 value is slightly smaller than the value of 14.6% estimated by Bayer et al. (2006a) under the same climatic and soil conditions, which is probably related to the higher lability of the biomass resulting from the larger contribution of legume species in our study (Vieira et al., 2007). On the other hand, the k_2 coefficient of 1.2% estimated in this study is also smaller than the value of 1.9% reported by Bayer et al. (2006a), suggesting that smaller residue-C conversion to SOC (smaller k_1) has been counterbalanced by SOC stabilization in this tropical soil under no-till rotations based on legume cover crops.

Prediction of Soil Organic Carbon Stocks

Once the k_1 and k_2 values were estimated, the SOC stocks for t = 19 yr were calculated by the one-compartment model (Table 3) and by summing the remaining original C, $C_{\mathrm{orig}} = C_0\exp(-k_2t)$, and the C from the crops, $C_{\mathrm{crop}} = k_1A/k_2[1 - \exp(-k_2t)]$.

The results from the one-compartment model predictions (Table 3) suggest that in the 0- to 17.5-cm soil layer, 24.78 Mg C ha^{-1} of the original C still remained after 19 yr of cultivation. Hence, the model suggests that the C added by the different cropping systems contributed between 4.26 Mg ha^{-1} in the F/M system and 12.79 Mg ha^{-1} in the P+M system. Therefore, in the P+M system, about 34% of the SOC present in the 0- to 17.5-cm soil layer was derived from the new C addition by the crops.

According to the model, the equilibrium SOC stock (C_e) is the highest for the P+M rotation, i.e., 61 Mg ha^{-1}. In contrast, the lowest C_e among the systems is found for the F/M system, which is predicted to stabilize at about 20 Mg ha^{-1}. Consequently, the F/M system stabilizes less than a third of the P+M stock in the 0- to 17.5-cm layer. This indicates that more than 40 Mg ha^{-1} C could be sequestered in the 0- to 17.5-cm soil layer by including legumes in the rotations. Furthermore, even greater amounts of SOC accumulation could probably be achieved if deeper layers were take into account; the results in Fig. 3 and in the literature support this (Diekow et al., 2005; Jantalia et al., 2007).

Our results highlight the importance of including plant species into crop rotations that have the potential for high biomass production and, consequently, high annual C input to the soil. Additionally, intercropped legume and grass species could be used to increase SOM stocks. By including only black oat in the

F/M system (resulting in the O/M system), the estimated C_e value already increased from 20 to about 34 Mg ha^{-1} (equivalent to a 70% increment). Adding legume species and diversifying the legume system can increase the C sequestration potential even more. The adoption of no-till crop rotations with high annual C input to the soil, mainly the legume-based ones, and mineral N fertilization contribute not just to increased SOC stock but also to the labile C stock (Vieira et al., 2007), which plays a decisive role in improving soil biological, physical, and chemical attributes.

The predicted SOC stocks for a 40-yr period after the beginning of the experiment in 1983 (Fig. 5) were, in general, close to the observed ones. The P+M system had the greatest variation in the measured SOC stocks due to reasons discussed above.

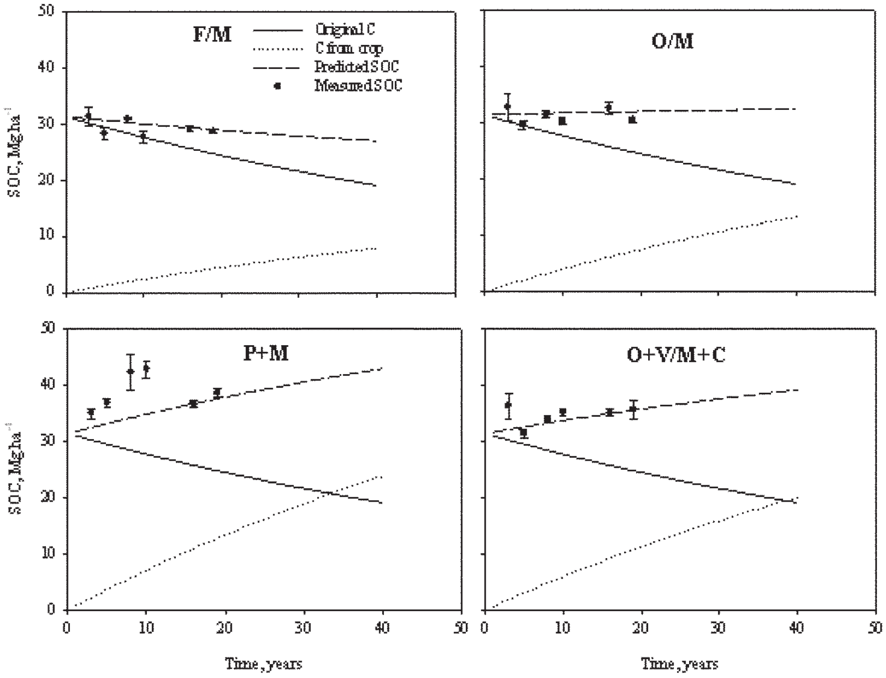

Fig. 5. Prediction of total soil organic C (SOC) stock, original C remaining in the soil, and C from crop residues that accumulated in the 0- to 17.5-cm layer of a Paleudult under no-till crop rotations with two different mineral N fertilization rates for 19 yr. Prediction was performed for a period of 40 yr after the establishment of the experiment (1983). Horizontal bars represent the standard error within each cropping system in each year (*n* = 3) (F = fallow, M = maize, O = black oat, V = vetch, C = cowpea, P = pigeon pea).

The *F* test for the significance of lack of fit suggested that the total error in the simulated values was significantly smaller than the error inherent in the values observed in the field ($F < F_{5\%}$) for most cropping systems, with the exception of the P+M system and O+V/M (Table 4). Besides, the cropping systems (apart from P+M) had RMSE < RMSE 95%, indicating that the simulated values are inside the confidence interval (95%) of the measured results. Hence, in general, the estimation of the k_1 and k_2 coefficients and the subsequent prediction using these coefficients in the one-compartment model demonstrated that this methodology was feasible and suitable for the SOC dynamics studies under the current experimental conditions.

CONCLUSIONS

The inclusion of legume species, especially tropical legume species, in the crop rotations promoted SOC stabilization in no-till managed subtropical cropping systems. Mineral N fertilization also contributed to higher SOC levels, but this effect was more pronounced in the rotations including grass species rather than legumes. The minimal annual C input required to maintain the original SOC stock was equivalent to 10 Mg ha^{-1} yr^{-1} of dry mass production. The SOC accumulation occurred mainly in the soil surface layers, but a trend of SOC increase was also observed in the deeper soil layers of the legume-based crop rotations. The close linear relationship between SOC stocks and annual C input indicate that the soil is not C saturated and, therefore, still has potential for C sequestration. Based on the concepts of the one-compartment model applied to long-term results of SOM, we estimated the annual decomposition rate of SOM as 1.24% and a residue-C conversion to SOC as 9.60%, which allowed prediction of the long-term potential of these cropping systems on SOC sequestration.

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