Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilisation

Jeferson Diekow[1], João Mielniczuk[1], Heike Knicker[2], Cimélio Bayer[1,4], Deborah P. Dick[3] & Ingrid Kögel-Knabner[2]

[1]*Departamento de Solos, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul, P.O. Box 15100, 90001-970, Porto Alegre, RS, Brazil;* [2]*Lehrstuhl für Bodenkunde, Technische Universität München, D-85350 Freising-Weihenstephan, Germany;* [3]*Departamento de Físico-Química, Instituto de Química, Universidade Federal do Rio Grande do Sul, 90001-970, Porto Alegre, RS, Brazil.* [4]*Corresponding author**

Abstract

The long-term soil management effects on C and N stocks of soil physical fractions are still poorly understood for South American subtropical soils. This study aimed (i) to evaluate the influence of cereal- and legume-based cropping systems and N fertilisation on C and N stocks of the sand-, silt- and clay-size fractions of a no-tilled subtropical Acrisol in southern Brazil, (ii) to compute the Carbon Management Index (CMI) for those cropping systems using physical fractionation data, and (iii) to investigate the possible existence of finite capacity of those soil physical fractions to store C and N. Soil samples of a long-term experiment were collected from the 0–2.5 and 2.5–7.5 cm layers of three no-till cropping systems [fallow bare soil, oat/maize (O/M) and pigeon pea+maize (P+M)] under two N fertilisation levels (0 and 180 kg N ha^{-1}). However, for fallow bare soil, only the non-fertilised sub-plot was sampled. An adjacent native grassland soil was sampled as a reference. The C and N stocks of the three soil physical fractions were higher in the legume-based cropping system (P+M) than in O/M and bare soil, because of the higher residue input in the former. The P+M cropping system restored the C and N stocks in sand- and silt-size fractions to the same levels found in grassland soil. Higher C and N stocks in all physical fractions were also obtained with N fertilisation. The C and N stocks and the C:N ratio were most affected by cropping systems in the sand- and least in the clay-size fraction. Particulate organic matter was found in the silt-size fraction, showing this fraction is not only constituted by mineral-associated organic mater, as commonly believed. Taking grassland soil as reference (CMI = 100), the CMI ranged from 46, in O/M no N, to 517, in P+M with N, pointing to a better soil management in the latter. The clay-size fraction tended to show a finite capacity to store C and N (48.8 g C kg^{-1} and 4.9 g N kg^{-1} of clay), which was not verified in sand- and silt-size fractions. The adoption of no-tillage and legume-based cropping systems with high residue input are adequate soil management strategies to improve soil quality and make the agricultural production systems more sustainable in subtropical regions.

Introduction

Conservation management systems are efficient strategies to improve soil organic matter (SOM) stocks, atmospheric C sequestration and soil and environmental quality (Lal et al., 1999; Mielniczuk et al., 2003; West and Post, 2002). Among conservation management systems in subtropical soils, no-tillage reduces SOM losses by diminishing the mineralization and the erosion processes (Bayer et al. 2000; Sá et al., 2001). When associated with high-input cropping systems, no-tillage can even increase the SOM stocks (Amado

*FAX No: +55 51 33166050. E-mail: cimelio.bayer@ufrgs.br

et al., 2001; Bayer et al. 2000; Sisti et al., 2004). Many studies have already investigated how no-till cropping systems affect the total SOM stocks in humid subtropical soils, but little is known about how they affect the organic matter stocks in the physical fractions.

Two organic matter pools can be roughly established: the particulate organic matter (POM) and the mineral-associated organic matter. The POM is constituted by plant, animal and fungal residues with recognisable cellular structure (Baldock and Skjemstad, 2000; Gregorich and Janzen, 1996). Experimentally, the POM corresponds to the sand-size fraction or to the light fraction, depending on whether fractionation was based on particle-size or particle-density, respectively (Bayer et al., 2002; Cambardella and Elliott, 1992; Gregorich and Janzen, 1996). The mineral-associated SOM is held on mineral surfaces by several interaction mechanisms such as ligand exchange, hydrogen bonding, hydrophobic bonding and others (Cornejo and Hermosín, 1996), resulting in the primary organo-mineral complexes (Christensen, 1996). In such complexes the organic matter is more stable and therefore has a lower turnover rate (Balesdent, 1996; Feller and Beare, 1997). Commonly, the mineral-associated pool is considered as corresponding to the silt- and clay-size fractions (Bayer et al., 2001; Cambardella and Elliott, 1992; Feller and Beare, 1997) or to the heavy fraction (Greenland, 1965; Christensen, 1992), if fractionation is based on particle-size or particle-density, respectively.

The total C stock and the distribution of soil C in labile and non-labile fractions, compared to a reference system (native vegetation), can provide relevant information regarding the state and rate of change in SOM of agricultural systems (Blair et al., 1995). These authors proposed a Carbon Management Index (CMI), which encompasses both C stock (Carbon Pool Index, CPI) and C lability (Lability Index, LI) parameters. Hence, soils with higher values of CPI and LI, and thus CMI, are considered better managed than those with lower values. Considering the close relation among SOM and physical, chemical and biological characteristics of tropical and subtropical soil (Greenland et al., 1992; Vezzani, 2001), the CMI would also give indications about the soil quality in different agricultural systems.

To compute the LI, Blair et al. (1995) considered the labile fraction of the soil organic matter that was oxidised by potassium permanganate ($KMnO_4$, 0.333 mol L^{-1}). Instead, we suggest taking the POM, obtained by physical fractionation, as a labile fraction.

Since POM has a rapid turnover rate (Balesdent, 1996; Feller and Beare, 1997), is composed by plant and fungal fragments (Gregorich and Janzen, 1996) and is considered as the most sensitive pool of organic carbon to detect changes in SOM due to soil management (Freixo et al., 2002; Janzen et al., 1992), it would therefore be a good parameter to obtain the LI for soils under different management systems.

Considering that adequate soil management strategies improve SOM content, a related question is whether the soil, or the physical fractions, have a finite capacity to hold organic matter, as proposed by Hassink (1997) and Six et al. (2002). For the clay-size fraction of a Brazilian Ferralsol, Roscoe et al. (2001) estimated that the maximum C concentration was 32.5 g C kg^{-1} of clay, referring to it as the carbon saturation level. On the other hand, Christensen (2001) mentioned an unlimited capacity of mineral particles to accommodate organic matter.

The objectives of this study were (i) to evaluate the influence of long-term no-till cereal- and legume-based cropping systems and N fertilisation on the C and N stocks in physical fractions of a southern Brazilian Acrisol, (ii) to compute the Carbon Management Index (CMI) for those cropping systems based on physical fractionation data, and (iii) to investigate the existence of a finite capacity of the soil physical fractions to store C and N.

Material and methods

Field experiment and soil sampling

The study was based on a long-term (17 years) experiment located at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul, Eldorado do Sul-RS, Brazil (30° 51′ S and 51° 38′ W), in a humid subtropical climate. The experiment was established in 1983, on a degraded sandy clay loam Acrisol (FAO, 2002) that had been conventionally cultivated since 1969, the year when native grassland was converted into agricultural land. The clay mineralogy is composed mainly of kaolinite (720 g kg^{-1} of clay) and iron oxides (109 g kg^{-1} of clay) (Bayer, 1996).

The experiment was arranged in a complete randomised block design with three replications with no-till cropping systems in the main plots and N fertilisation levels in the sub-plots. Three cropping systems were selected for this study: i) fallow bare soil, without plants, except maize cultivated in 1988/89, 1993/94

and 1994/95 and some weeds that grew spontaneously but were periodically eliminated by glyphosate herbicide; ii) oat (*Avena strigosa* Schreb) / maize [O/M] sequential cropping and iii) pigeon pea (*Cajanus cajan* [L.] Millsp.) + maize [P+M] intercropping. Soil samples were taken from both N fertilisation level subplots: 0 [no N] and 180 kg N ha^{-1} yr^{-1} [with N]. However, for bare soil, only the non-fertilised subplot was sampled. The native grassland adjacent to the experimental field was sampled as a reference.

Soil samples of the bare soil and P+M were collected in August 2000, and those of native grassland and O/M in March 2001, in two layers: 0–2.5 and 2.5–7.5 cm. Soil samples were air dried (∼40 °C), crushed by a wooden roll and stored in plastic pots.

Soil physical fractionation and C and N analysis

Sand- (> 63 μm), silt- (63–2 μm) and clay-size (< 2 μm) separates were obtained through particle-size fractionation, performed in a laboratory at TUM, Germany. Soil samples were dispersed by combining shaking and sonification and the resulting fractions were isolated by wet sieving and gravity sedimentation. Initially, soil samples of the three field replications were mixed to obtain a composite sample. Thirty grams of this composite sample were weighed in a 200-mL plastic bottle and afterwards 100 mL distilled water was added. After one-hour-rest for pre-soaking, the sample was agitated on a rotary shaker (250 rpm) for an equal time, aiming to gently disperse soil aggregates > 63 μm and release the POM inside. With this shaking dispersion instead of direct sonification of the sample, rupture of POM and its redistribution into smaller size fractions is supposed to be minimised (Balesdent, 1996; Balesdent et al., 1991; Feller and Beare, 1997).

The shaken suspension was passed trough a 63-μm sieve to separate the sand-size fraction, which was submitted to density fractionation in Na-polytungstate solution of density 1.8 Mg m^{-3} to isolate the light- and the heavy-sand fraction. The silt+clay suspension (< 63 μm) was collected in a 1-L bottle and afterwards centrifuged to concentrate the material to be sonified. This material was transferred to a beaker and distilled water was added to bring the final suspension to 150 mL (silt+clay: solution rate ∼1:12). This suspension was sonified at an energy level of 450 J mL^{-1}. This energy output had already proved to be efficient for dispersion of even more clayey samples, and, moreover, the particle-size distribution after soni-

fication was comparable to that obtained after standard textural analysis (Diekow, 2003).

To separate the silt- and clay-size fractions, the sonified suspension was submitted to 7-8 daily gravity-sedimentation cycles under constant temperature (21 °C). The equivalent spherical diameter of the Stokes Law was considered. The silt-size fraction was further submitted to a density fractionation (d = 1.8 Mg m^{-3}) to separate the light and heavy fractions. Since this silt fractionation was carried out in a different laboratory (UFRGS, Brazil) and as Na-polytungstate was not available, NaI solution was used as the heavy liquid.

The C and N concentrations of the whole soil and physical fractions were determined by dry combustion methods, using a Vario EL CN analyser. For the light-silt fraction, however, the C analyses were performed in a Shimadzu TOC Analyser while the N concentration was not determined. The C concentration in the heavy-silt fraction was obtained from the difference between the whole silt-size fraction and the light-silt fraction. Elemental analyses were performed in duplicates.

The heavy-sand fraction was dismissed because of its low C (< 1 g kg^{-1}) and N (< 0.1 g kg^{-1}) concentrations, which were too low to be reliably analysed by the CN analyser. Therefore, hereafter, the light-sand fraction will be considered as the only constituent of the sand-size-fraction. The recovery of C after fractionation was between 90 to 92% and that of N between 94 to 98% (Diekow, 2003).

The C and N stocks in whole soil and particle-size fractions were calculated taking into account the equivalent soil mass of each layer (Angers et al., 1997; Ellert and Bettany, 1995), in order to eliminate the influence of soil compaction or loosening induced by treatments. The soil mass of the 0–2.5 and 2.5–7.5 cm layers of all treatments were calculated considering the soil bulk density (Diekow, 2003). The equivalent soil mass was considered the amount present in grassland soil (372.5 and 755.0 mg ha^{-1} in the 0–2.5 and 2.5–7.5 cm layers, respectively). For the calculation of C and N stocks in physical fractions, the elemental concentration (e.g., g C kg^{-1} of clay) was multiplied by the mass proportion of that fraction in the whole soil (e.g., g clay kg^{-1} of soil) and then by the correspondent equivalent soil mass.

Carbon management index (CMI)

Taking the results from the physical fractionation, and not from chemical fractionation as originally performed by Blair et al. (1995), the Carbon Management Index (CMI) was calculated for the whole 0–7.5 cm layer of all treatments. We considered the sand-size and in the light-silt fractions as the labile organic matter pool, since those fractions are constituted basically by POM. The heavy-silt fraction and the clay-size fraction were considered as the non labile C pool.

The CMI was calculated as follows:

$$CMI = CPI \times LI \times 100$$

where: CPI (carbon pool index) = total soil C stock in the treatment/total soil C stock in grassland,

LI (lability index) = soil C lability in the treatment/soil C lability in grassland,

Lability = labile C / non-labile C,

Labile C = C stock in the sand-size fraction and in the light-silt fraction,

Non labile C = C stock in the heavy-silt fraction and in the clay-size fraction.

Optical microscopy

To identify and examine POM fragments, the soil physical fractions were submitted to optical microscopy analysis in a light-transmitted microscope (Olympus CH30).

Results

At the beginning of the experiment, in 1983, the organic C stock in the 0–17.5 cm layer was 30.4 mg C ha^{-1} and after 17 years it was reduced to 24.9 Mg C ha^{-1} and 26.6 Mg C ha^{-1} in the bare soil and O/M (no N) treatments, respectively, as reported previously (Diekow et al., 2004). However, the initial C stock remained practically steady (29.2 Mg C ha^{-1}) in the O/M cropping system when 180 kg N ha^{-1} were annually applied, which favoured the maize phytomass production. On the other hand, in the P+M cropping system, the C stock increased to 38.3 Mg C ha^{-1} (no N) and to 45.4 Mg C ha^{-1} (with N). The high residue input of pigeon pea plants and the biological N fixation, which favoured the maize phytomass input, were the most likely explanation for the higher C stocks in this legume-based cropping system. Similar trends were observed in the results of total soil N stock.

C and N stocks in physical fractions and Carbon Management Index (CMI)

Bare soil and O/M contained lower C and N stocks than grassland and P+M in practically all physical fractions of both soil layers (Figure 1), following the same trend observed for the total C and N stocks in the whole soil (Diekow et al., 2004). In the sand-size fraction of the 0–2.5 cm layer, P+M contained at least three times more C and N than the other cropping systems (Figures 1a, 1b). P+M also restored or surpassed the original stocks of C and N stored in the sand- and silt-size fractions of native grassland, in both soil layers. However, for the clay-size fraction, the recovery was only obtained with N fertilisation, which also increased the C and N stocks in all other physical fractions, including those of the O/M cropping system.

The distribution of the total C and N stocks across the physical fractions was affected by cropping systems, but not by N fertilisation (Figure 2). In grassland, bare soil and O/M, most of the total C and N stocks were found in the clay-size fraction. This was not observed for the surface layer of P+M, where the proportion of C and N stored in the clay-size fraction was lower, and that stored in the sand-size fraction corresponded to around 30% of the total C and N stocks (Figure 2a, 2b). However, in the 2.5–7.5 cm layer, the proportion of the total C and N in the sand-size fraction of P+M ranged between 6.5 and 9.4% (Figures 2c, 2d). The organic matter in the sand-size fraction of all treatments was constituted mainly by partially-decomposed plant debris (microscopically observed, not shown). Similar material and fungal debris were also observed in the silt-size fraction (Figure 3).

With reference to the CMI, the highest values were observed in the P+M cropping system (372 and 517), supported by the highest CPIs (1.19 and 1.34) and mainly by the highest LIs (3.12 and 3.86) (Table 1). The reason for the relatively high LI values for P+M is due to the high labile C stocks, which ranged from 6.7 to 9.2 Mg C ha^{-1} in the 0-7.5 cm layer (Table 1). On the other hand, the lowest CMI values were associated to bare soil and O/M cropping systems, with values ranging from 46 to 67. For these treatments, both CPI and LI were lower than 1.00 (Table 1), since the total soil C stocks (11.7 to 14.7 Mg C ha^{-1}) and the labile C stocks (1.2 to 1.7 Mg C ha^{-1}) were lower than those found in the grassland soil (20.7 Mg total soil C ha^{-1} and 2.5 Mg labile C ha^{-1}) (Table 1).
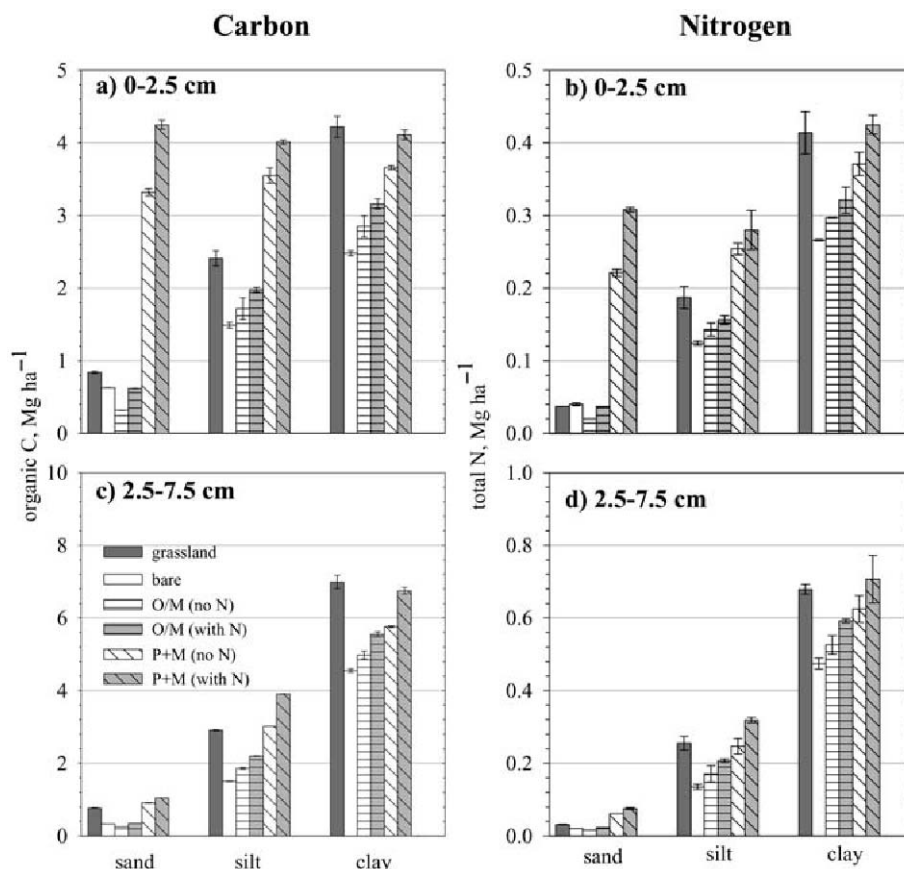
Figure 1. Carbon (a, c) and nitrogen (b, d) stocks in the soil physical fractions of the 0–2.5 cm (a, b) and 2.5–7.5 cm layers (c, d) as affected by no-till cropping systems and N fertilisation. Error bars refer to the standard deviation of the C and N analytical results.

Table 1. Carbon stocks in the whole soil and in physical fractions, carbon pool index (CPI), carbon lability (L), lability index (LI) and carbon management index (CMI) of the 0–7.5 cm layer, as affected by no-till cropping systems and N fertilisation. Grassland was taken as reference

Treatment	Total soil C	Sand C	Silt C		Clay C	Labile C[a]	CPI[b]	L[c]	LI[d]	CMI[e]
			Light	Heavy						
	Mg ha^{-1}									
Grassland	20.7 ± 1.6[f]	1.6 ± 0.1	0.9 ± 0.0	4.3 ± 0.0	11.2 ± 0.2	2.5 ± 0.1	1.00 ± 0.00	0.16 ± 0.00	1.00 ± 0.00	100 ± 0
Bare soil	11.7 ± 1.0	1.0 ± 0.0	0.5 ± 0.0	2.5 ± 0.0	7.0 ± 0.0	1.5 ± 0.0	0.55 ± 0.04	0.16 ± 0.00	0.99 ± 0.02	55 ± 5
O/M (no N)	13.1 ± 1.2	0.6 ± 0.0	0.6 ± 0.1	3.0 ± 0.1	7.8 ± 0.0	1.2 ± 0.1	0.68 ± 0.05	0.11 ± 0.00	0.67 ± 0.02	46 ± 5
O/M (with N)	14.7 ± 1.8	1.0 ± 0.0	0.7 ± 0.0	3.5 ± 0.0	8.7 ± 0.1	1.7 ± 0.0	0.77 ± 0.01	0.14 ± 0.00	0.87 ± 0.00	67 ± 0
P+M (no N)	22.6 ± 3.0	4.2 ± 0.1	2.4 ± 0.1	4.1 ± 0.1	9.4 ± 0.0	6.7 ± 0.1	1.19 ± 0.00	0.50 ± 0.01	3.12 ± 0.03	372 ± 3
P+M (with N)	27.0 ± 4.7	5.3 ± 0.1	3.8 ± 0.2	4.0 ± 0.2	10.9 ± 0.1	9.2 ± 0.2	1.34 ± 0.03	0.62 ± 0.02	3.86 ± 0.07	517 ± 20

[a]Labile C = sand C + light-silt C.
[b]CPI (carbon pool index) = total soil C in the treatment/total soil C in grassland.
[c]L (lability) = labile C/non labile C. The non labile C is referred to be heavy-silt C + clay C.
[d]LI (lability index) = lability in the treatment/lability in grassland.
[e]CMI (carbon management index) = CPI × LI × 100.
[f]Numbers on the right side of ± sign refer to the standard deviation of the C and N analytical results.
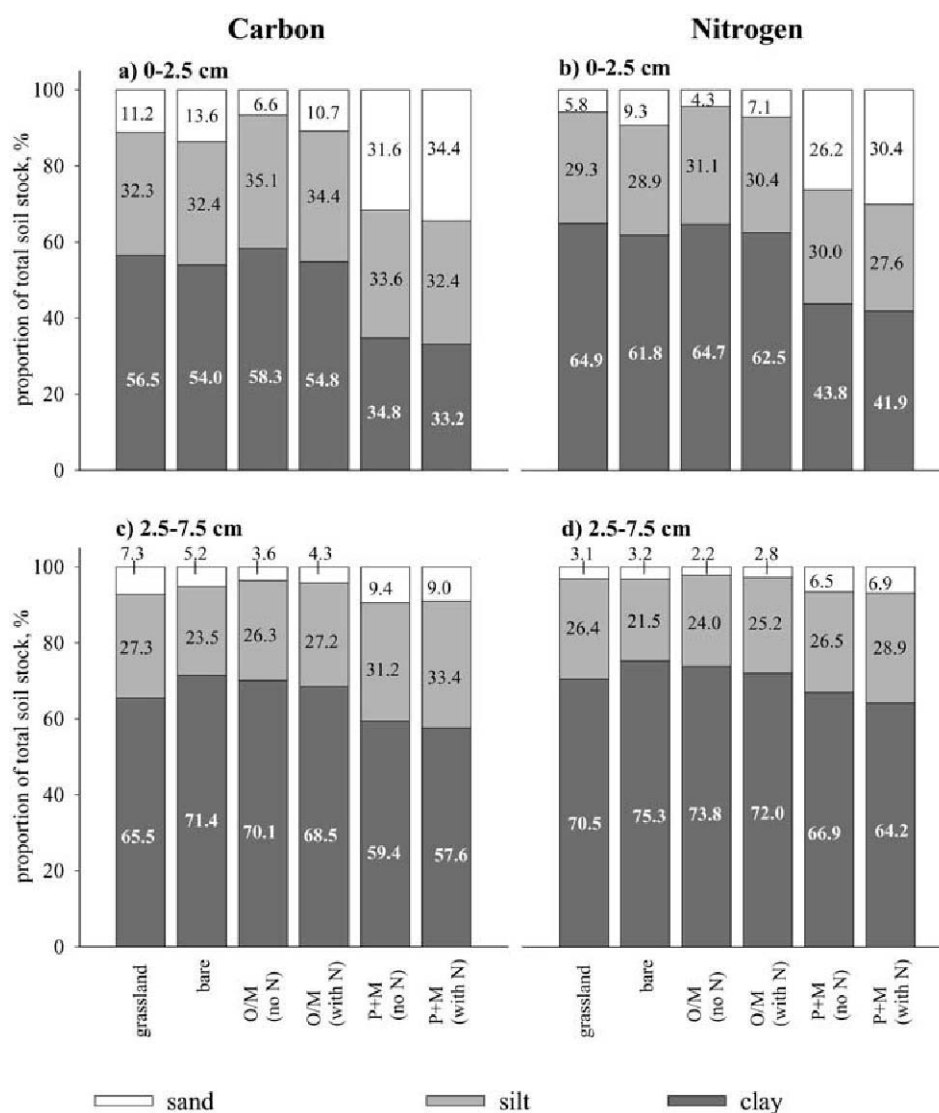
Carbon

Nitrogen

Figure 2. Distribution of carbon (a, c) and nitrogen (b, d) stocks along the soil physical fractions of the 0–2.5 cm (a, b) and 2.5–7.5 cm layers (c, d) as affected by no-till cropping systems and N fertilisation. Values were corrected to a C and N recovery after fractionation of 100%.

C:N ratio in the physical fractions

Among all treatments and the two layers, the widest variation in C:N ratio was observed in the sand-size fraction (13.8 to 25.2: 1) (Table 2). This variation was lower in silt- (10.7 to 14.3: 1) and minimal in clay-size fraction (9.2 to 10.3: 1). In the sand-size fraction, grassland showed the highest C:N ratio, followed by O/M and P+M. The same pattern was observed for the aboveground plant tissue of cover crops, where grassland and oat also had a higher C:N ratio than pigeon pea plants (Table 2). For the clay-size fraction, however, the C:N ratio was very similar among treatments,

regardless of the differences in the above ground plant and in the sand-size fraction.

Capacity of soil physical fractions to store C and N

The C and N stocks of each physical fraction were plotted against the corresponding stock in the whole soil (Figure 4). Different C and N accumulation patterns were observed for each physical fraction in the 0–2.5 cm layer (Figure 4a, 4c). For the clay-size fraction, an exponential-rise-to-maximum model was observed, indicating that further increases in the total C and N stocks nearly beyond 8.5 Mg C ha^{-1} (22.8 g

Table 2. C:N ratio of aboveground plant material and soil physical fractions as affected by no-till cropping systems and N fertilisation

Treatment	Aboveground plant		Sand	Silt	Clay
	Cover crop[a]	Maize			
			C:N ratio		
				0–2.25 cm	
Grassland	43.6 ± 1.7[b]	–	22.5 ± 0.2	12.9 ± 0.3	10.2 ± 0.2
Bare soil	–	–	15.6 ± 0.3	12.0 ± 0.0	9.3 ± 0.1
O/M (no N)	28.4 ± 2.2	70.6 ± 2.5	16.3 ± 0.1	12.0 ± 0.2	9.6 ± 0.3
O/M (with N)	29.2 ± 0.3	79.0 ± 9.2	17.0 ± 0.1	12.7 ± 0.2	9.9 ± 0.4
P+M (no N)	14.2 ± 0.8	91.4 ± 12.9	15.0 ± 0.3	14.0 ± 0.0	9.9 ± 0.2
P+M (with N)	13.8 ± 0.0	52.4 ± 3.0	13.8 ± 0.0	14.3 ± 0.6	9.7 ± 0.2
mean	*25.8 ± 12.4*	*73.4 ± 16.4*	*16.7 ± 3.0*	*13.0 ± 1.0*	*9.8 ± 0.3*
				2.5–7.5 cm	
Grassland			25.2 ± 0.5	11.4 ± 0.4	10.3 ± 0.0
Bare soil			16.5 ± 0.0	11.1 ± 0.2	9.6 ± 0.1
O/M (no N)			15.6 ± 0.0	10.9 ± 0.6	9.5 ± 0.1
O/M (with N)			14.9 ± 0.1	10.7 ± 0.1	9.4 ± 0.0
P+M (no N)			14.9 ± 0.0	12.2 ± 0.5	9.2 ± 0.2
P+M (with N)			14.0 ± 0.3	12.3 ± 0.2	9.6 ± 0.4
mean			*16.9 ± 4.2*	*11.4 ± 0.7*	*9.6 ± 0.4*

[a]Oat is the cover crop in O/M and pigeon pea in P+M cropping system.
[b]Numbers on the right side of ± sign refer to the standard deviation of the C and N analytical results.
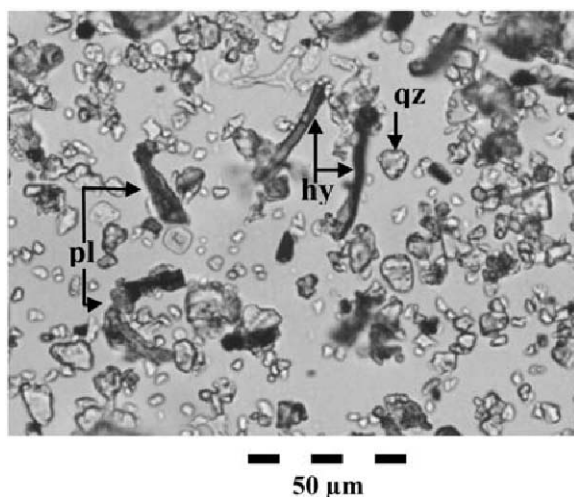

Figure 3. Light-transmission photomicrograph of the silt-size fraction of the 0–2.5 cm layer of P+M (no N) cropping system. pl – plant debris; hy – fungal hypha; qz – quartz.

C kg^{-1} of soil) and 0.70 Mg N ha^{-1} (1.88 g N kg^{-1} of soil) are no longer reflected on increases in the C and N stocks of this physical fraction. A linear model and an exponential-rise model were fitted for the silt- and sand-size fractions, respectively. In the 2.5–7.5 cm layer, all physical fractions showed a linear model (Figures 4b, 4d).

Discussion

Carbon and nitrogen stocks and Carbon Management Index (CMI)

The higher C and N stocks in the physical fractions of soils under P+M (Figure 1) express the significant potential of no-till legume-based cropping systems to increase the organic matter content, recover the original organic matter status and promote C sequestration. The huge increases in C and N stocks in the sand-size fraction of the top layer of P+M (Figure 1a, 1b), which made this fraction represent around 30% of the total soil C and N stock (Figure 2a, 2b), could be expected for this cropping system, taking into account that a high amount of residue is placed on the soil surface and not further incorporated.

The organic matter in the sand-size fraction basically consisted of POM, which is coherent with the fact that this fraction is the entrance pool of organic material in soil. However, the occurrence of plant and fungal fragments in the silt-size fraction (Figure 3) was an intriguing result that indicates that organic
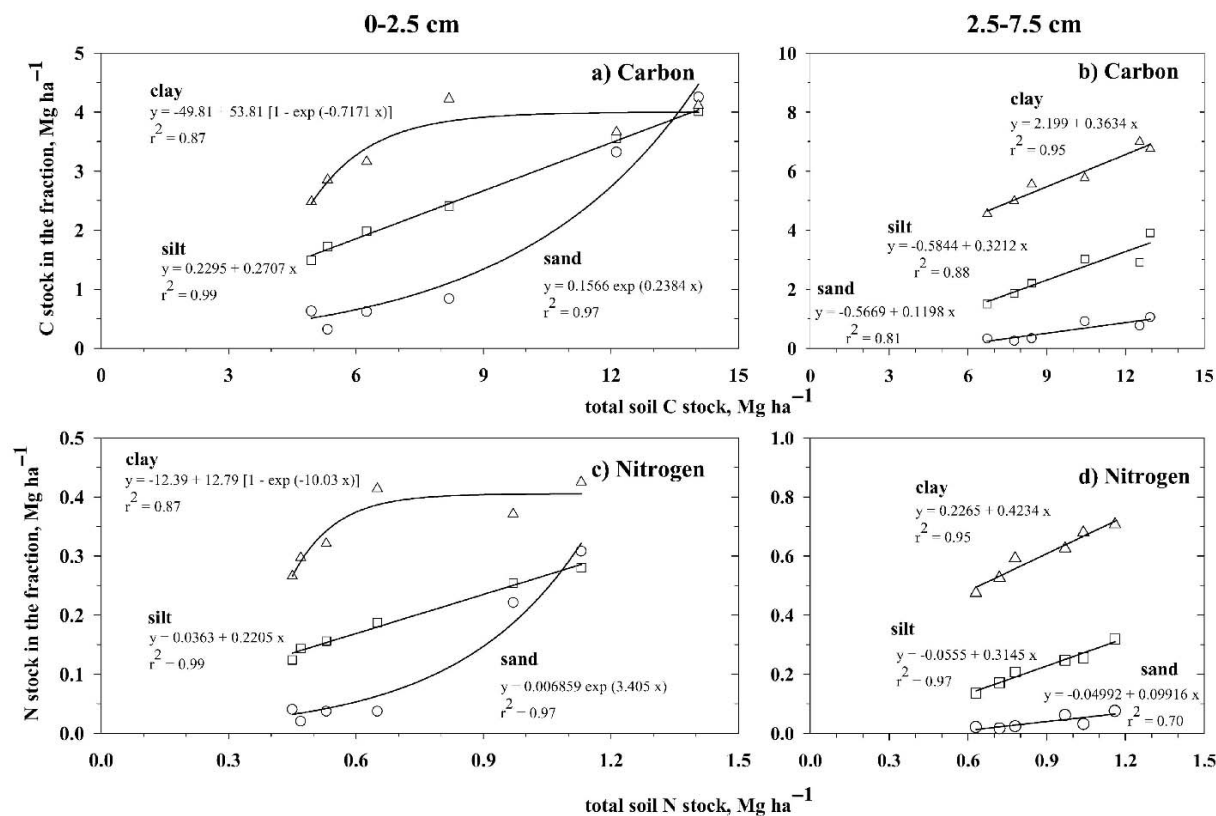
Figure 4. C (a, b) and N stocks (c, d) of the soil physical fractions related to the C and N stocks of the whole soil.

matter in this granulometrically-isolated fraction is not only mineral-associated, as commonly reported (Bayer et al., 2001; Cambardella and Elliott, 1992; Feller and Beare, 1997). After the densimetric isolation of the light portion of the silt-size fraction, it was observed that for the 0–7.5 cm layer of P+M cropping system (with N), this light portion represented 49% (3.8 Mg C ha^{-1}) of the total C stored in the silt-size fraction (Table 1). Since the initial dispersion was carried out only with gentle shaking, this silt-associated light fraction can not be considered as resulting from a breakdown of sand-POM, which reinforces the fact that it naturally occurs as silt-size particles.

The highest C:N ratio values for the sand-size fraction (Table 2) are coherent with the fact that this fraction is composed basically of POM. However, the lowest values in the clay-size fraction indicates a higher humification degree of the organic matter in this fraction (Christensen, 1992; Tiessen and Stewart, 1983), showing a high content of microbial debris in it, considering that fungi have a C:N ratio of about 15:1 to 5:1 and bacteria 5:1 to 3:1 (Paul and Clark, 1996). The intermediate C:N ratio values for silt-size fraction

reflect the fact that this material is a mixture of POM and mineral-associated organic matter.

With reference to the CMI, the highest values found for the treatment P+M (Table 1) indicate that soil management in this legume-based cropping system is more appropriate to improve the SOM status in this subtropical soil than O/M cropping systems. This also indicates that P+M can provide conditions for the improvement of soil quality to levels even in excess of that of grassland. On the other hand, soils under O/M and bare soil, due to the low residue input, could not reach the same status as those under native grassland.

Changes on LI as induced by management treatments were of a higher degree than changes on CPI (Table 1), a tendency also observed in other studies carried out in tropical and subtropical conditions (Leite et al., 2003; Whitbread et al., 2000). This result shows that the C lability parameter gives the CMI the capacity to detect changes on SOM status in short- or medium-term, which are more difficult to detect when considering only changes on SOM stocks. With reference to the possibility of using soil physical fractionation data to compute the LI, our results

were consistent in showing that POM may be suitable to represent the labile C pool, since coherent and notable distinctions could be observed among management systems (Table 1). However, it is important to note that although POM may be defined as plant and fungal fragments, its isolation is somewhat subjective, since different densities of the floatation agent can give different yields of POM.

Capacity of particle-size fractions to store C and N

The rise-to-maximum exponential model observed for the C and N accumulation in the clay-size fraction of the 0–2.5 cm layer is similar to a sorption isotherm (Figures 4a, 4c). Probably this is because the organic matter storage capacity becomes saturated when all interaction sites on clay mineral surfaces are occupied. The estimated saturation levels for C and N in this fraction were 4.00 Mg C ha^{-1} and 0.40 Mg N ha^{-1} (48.8 g C kg^{-1} clay and 4.9 g N kg^{-1} clay, considering the equivalent soil mass of 372.5 mg ha^{-1} and 220 g kg^{-1} of clay (Bayer, 1996)). This means that the clay-size fractions of native grassland and P+M (with N) cropping system have already achieved C and N saturation levels (Figure 1a, 1b). This observed C saturation value is higher to that estimated by Roscoe et al. (2001), of 32.5 g C kg^{-1} clay, in a Cerrado Oxisol, where kaolinite was also the predominant mineral in the clay fraction.

The linear C and N accumulation pattern for silt-size fraction did not show a tendency for saturation and can be considered as an intermediate between the patterns for clay- and sand-size fractions (Figure 4a, 4c). This is coherent, considering that the silt-size fraction is a mixture of POM and mineral-associated organic matter. Possibly POM was responsible for this unlimited linear increase of C and N stocks, considering that the higher the residue input, the higher the POM stock.

For the sand-size fraction, it is expected that beyond the presented experimental data the C and N accumulation will follow a linear model, as in silt-size fraction, and no longer the fitted exponential-rise model (Figure 4a, 4c). Thus, it is possible to conclude that both sand- and silt-size fractions do not have a finite capacity to store C and N, and that they will be the only fractions where further increases of total soil organic C stock will take place when the clay-size fraction becomes saturated.

In the 2.5–7.5 cm layer, all fractions presented a linear model for C and N accumulation (Figure 4b, 4d). However, with future increases in total soil C and N stocks in this layer, possibly the rise-to-maximum-exponential model and the exponential rise model will also be fitted for the clay-size and sand-size fractions, respectively, as observed in the surface layer.

Summary and conclusions

The adoption of no-tillage and legume-based cropping systems with high residue input are appropriate soil management strategies to increase the C and N stocks in all physical fractions of soil. The N fertilisation also enhances the C and N stocks in the soil physical fractions of both legume- and cereal-based cropping systems. The silt-size fraction, commonly considered as mineral-associated organic matter pool, shows a high proportion of particulate organic matter like plant and fungal debris. The Carbon Management Index, based on physical fractionation data, seems to be a reliable indicator of the influence of management on SOM status, suggesting that no-till legume-based cropping systems may improve soil quality in subtropical regions. The clay-size fraction presents a clear evidence for a finite capacity to store organic matter, but this is not observed in sand- and silt-size fractions.

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